MODELING OF GUIDE SIGN ILLUMINATION AND RETROREFLECTIVITY TO IMPROVE DRIVER'S VISIBILITY AND SAFETY

by

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B.A., Jordan University of Science and Technology, 2004
M.S., Jordan University of Science and Technology, 2008

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Industrial and Manufacturing Systems Engineering
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Abstract

This dissertation is the result of studying different methods of increasing guide sign visibility and legibility to drivers during nighttime, to increase safety on roadways. It also studies intersection lighting to indicate the lighting benefits on nighttime crash frequency reduction.

From a survey conducted, practices related to overhead guide sign illumination and retroreflectivity in United States were summarized. A laboratory experiment was conducted to compare light distribution of five light sources: Metal Halide, Mercury Vapor, High Pressure Sodium, induction lighting, and Light Emitting Diode (LED). Cost analysis of the five light sources was performed. Combining results of the laboratory experiment and the cost analysis, induction lighting was recommended for states that want to continue external sign illumination. A retroreflectivity experiment was conducted to compare three types of retroreflective sheeting: Engineering Grade (type I), Diamond Grade (type XI), and High Intensity (type IV), to determine the sheeting that best increases visibility and legibility. Diamond Grade (type XI) was found to be the optimal sheeting that increases visibility and legibility to drivers during nighttime. A glare experiment was conducted to expand the retroreflectivity experiment results. Four sheeting-font combinations of High Intensity (type IV) and Diamond Grade (type XI) materials and Series E (Modified) and Clearview fonts were compared. Results revealed an optimal sheeting-font combination of Diamond Grade (type XI) sheeting and Clearview font which increases the visibility and legibility of guide signs to drivers under presence of oncoming glare source. The Highway Safety Information System (HSIS) database was used to study the effect of intersection lighting on the expected crash frequency. Illuminated intersections showed 3.61% and 6.54% decrease in the expected nighttime crash frequency as compared to dark intersections in Minnesota and California, respectively. In addition, partial lighting at intersections decreases the expected nighttime crash frequency by 4.72% compared to continuous lighting in Minnesota.

The recommended sheeting-font combination for Departments of Transportation was Diamond Grade (type XI) and Clearview. This combination will increase signs' visibility and legibility to drivers, and consequently increase safety on roadways. Adding partial lighting at intersections will reduce the expected nighttime crash frequency, and increase safety on roadways.

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Table of Contents

List of Figures

List of Tables

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Dedication

This dissertation is dedicated to my parents for their love, endless support and encouragement. Thank you from the bottom of my heart.

Chapter 1 - General Issues Related to Elderly Drivers

Introduction

Currently, the elderly population in the United States (U.S.) has increased dramatically. Population projections report that seniors, ages 65 and older, is expected to more than double between 2012 and 2060, from 43.1 million to 92 million (U.S. Census Bureau, 2012). In 2060, the older population would represent just over one in five U.S. residents as compared to one in seven in 2012 (U.S. Census Bureau, 2012). In addition, the increase in the "oldest old" number would be even more dramatic, those 85 and older are projected to more than triple, from 5.9 million to 18.2 million, reaching 4.3% of the total population in the same time interval (U.S. Census Bureau, 2012).

Worldwide, cars represent important modes of transportation for drivers of all ages. In order to operate a car safely, drivers must simultaneously utilize various skills and perform multiple tasks while accounting for factors such as other roadway users, traffic signals, signs, and environment (Dukic & Broberg, 2012). Among the most important driving skills are the acquisition and processing of information and the ability to make appropriate decisions at the needed time according to road statistics (Dewar & Olson, 2007).

As people age, physical changes affecting vision, hearing, reaction time, and cognitive and motor ability may make driving or walking difficult (Houser, 2005). Increasing age may cause visual, physical, and cognitive abilities to deteriorate, thus causing safe driving to be a challenge.

In addition, senior drivers are more likely to die or suffer injuries in motor vehicle accidents as compared to young drivers because of greater frailty resulting from age (Kohl & Smith, 2007). According to the Federal Highway Administration's (FHWA) publication, Highway Design Handbook for Older Drivers and Pedestrians (Staplin, et al., 2001), seniors are more likely to be involved in motor vehicle crashes at intersections, when making left turns, and on limited-access highways when exiting, merging, or changing lanes than other drivers.

Senior drivers' safety issues will become more significant in the future because older adults are the fastest growing segment of the U.S. population; by the year 2030, the number of licensed drivers over age 65 is expected to be approximately 57 million (Kohl & Smith, 2007). As a result, helping seniors continue to drive safely and maintain mobility, health, and independence is extremely important. Assistance includes building safer roads and developing more efficient ways of assessing drivers' fitness in order to improve overall driver safety.

To improve the safety of older drivers, the FHWA has recommended several safe driving practices, such as placing street name signs in advance before intersections, using larger road signs and letters on signs, and improving intersection layouts for the purpose of making roadways safer. FHWA also provides funding available for states to complete projects that enhance senior driver safety.

The Importance of Driving for Older Populations

For an independent and active elderly person, maintaining mobility outside the home is essential (Born, et al., 2010). However, for seniors in the U.S., travel options other than driving are extremely limited, as driving is the primary means of transportation among elderly people (Foley, et al., 2002). This trend is becoming increasingly popular in Europe, as well (Talbot, et al., 2005). Driving is the most convenient and reliable form of transportation, especially in areas with few or no public transportation (Born, et al., 2010). Driving can help maintain the physical and social benefits of personal transportation and mobility for seniors. Conversely, loss of personal mobility, especially for seniors, may lead to negative effects such as depression, resulting in physical and mental illnesses (Phillips, et al., 2006). Driving cessation can lead to negative economic and psychosocial consequences (Born, et al., 2010). For example, loosing driving privilege will make it difficult to former drivers to obtain the required services and goods, i.e., hospitals appointments and groceries; their frequency of contact with friends and relatives as a social opportunity will be reduced (Born, et al., 2010).

People over 65 years of age utilize private vehicles, either as drivers or passengers, for approximately 90% of their daily errands (Houser, 2005). Forty-four percent of these errands are for shopping; 27% are for meals, social activities, and recreation; 13% are for school, religious issues, and family; 5% are for medical issues; 4% are related to work; and 7% are as passengers (Houser, 2005). A private vehicle connects seniors to services, goods, and other activities for which they need to have a high level of independence.

To enhance the mobility of seniors, individual state Departments of Transportation (DOTs) must account for special needs of elderly residents when making decisions regarding the U.S. transportation system and devices. Physical changes experienced by the older population challenge transportation agencies with finding and implementing solutions to help seniors maintain safe mobility in their communities. The U.S. Department of Transportation (USDOT) and state DOTs realize the importance of preserving seniors' mobility, as several DOTs have already begun to improve roadway traffic devices by enhancing visual information, thus increasing safety for roadway users, especially senior drivers. Other states have broadened and brightened pavement markings to better distinguish traffic lanes and road edges (Amparano & Morena, 2006). Several other states have increased the conspicuousness of traffic signs using larger signs (Amparano & Morena, 2006).

Working and Retiring Behavior in the U.S.

During most of the last half of the twentieth century, a growing percentage of older working Americans left their jobs in order to spend their later years in leisure and relaxation (Shattuck, 2010). In addition to Medicare health insurance, motivations for leaving the labor force were fueled by the three-part retirement income system in the U.S., consisting of Social Security, private pensions, and personal savings (Shattuck, 2010). In 1990, however, Social Security rules changed in such a way that encouraged older Americans to spend more years in the labor force, thus reversing the trend toward earlier retirement (Shattuck, 2010).

From 1995-2009, men and women worked for longer number of years in both rural and urban areas (Shattuck, 2010). In 2009, more than 25% of woman and more than 33% of men between ages 65-69 were active participants in the U.S. labor force; for ages 70-74, the proportion of women in the workforce was 14% and men 24% (Shattuck, 2010).

Research revealed a correlation between education level and the length of working period before retirement. When education level increases, a person tends to work farther into advanced age. This finding holds true for both rural and urban areas in the U.S. (Shattuck, 2010). College graduates have the highest participation rate among workers ages 65 or older, with greater participation among men, but both men and women demonstrate a dramatic increase in employment age related to higher levels of education as compared to those who have not graduated from college (Shattuck, 2010). Several factors may explain why people with more education continue longer in the labor force, including increased financial position, greater overall health, opportunities for higher earnings, less likelihood of involvement in physically demanding jobs that are difficult to perform in old age, and greater job satisfaction with a preference to continue (Shattuck, 2010). On the other hand, minimally educated workers are commonly associated with less overall health, resulting in the termination of their career at an early age (Shattuck, 2010). In addition, Social Security replaces a greater portion of preretirement earnings for low wage workers compared to high wage workers, thus making the retirement option for less educated people more competitive (Shattuck, 2010).

Divorce is another factor which forces many women to continue working even as they advance in age. Divorced women, especially those raising children outside of marriage, on average have less income and are less financially secure in later life as compared to married women or men, consequently requiring divorced women to participate longer in the labor force (Shattuck, 2010).

In summary, people in U.S. may be working beyond retirement age because of many reasons: 1) high cost of health insurance and obvious decline of crucial retiree health benefits, especially health insurance; 2) increased life expectancy, resulting in more years spent at home or in retirement; 3) lower rates of the traditionally-defined benefit pension coverage; 4) desire to accumulate more Social Security or other personal retirement savings wealth; 5) improve emotional wellbeing and physical health by remaining active in daily life; and 6) enjoying the social integration and social support that work promotes (Holder & Clark, 2008).

Older Population Statistics

Seniors are the fastest growing population segment in the U.S. According to the National Highway Traffic Safety Administration (NHTSA), from 1993 to 2003, growth of the senior population among the total U.S. population was 15% (NHTSA, 2005). More than 40 million older adults will be licensed drivers in 2020 as the baby boomer generation becomes 65 years or older (Bayam, et al., 2005), and (Dellinger, et al., 2002).

The proportion of drivers is growing as the population grows. In the U.S., the percentage of licensed drivers ages 65 or older has increased from 61% in 1980 to 72% in 1990 and 80% in 2003 (Houser, 2005). In 2003, one out of seven licensed drivers was age 65 or older (Houser, 2005). By 2029, one out of four licensed drivers will be 65 years or older (Houser, 2005).

Based on driver records, senior drivers have the lowest crash rate per licensed driver (Keall & Frith, 2004), and (Braver & Trempel, 2004). The main reason for this statistic is that senior drivers tend to drive shorter distances, take fewer trips, and drive in more familiar areas compared to younger drivers (Collia, et al., 2003). In a study by Hing et al., a driver's age and gender were shown to have an important impact on crash causes. They found that senior drivers ages 75 and older were more likely to cause a vehicle crash than drivers between 65 and 74 years old (Hing, et al., 2003).

The NHTSA fact sheet published in 2011 reported that "in 2009, 13% of the total U.S. resident population (40 million) was people age 65 and older" (NHTSA, 2011). Among that age category, 5,288 people were killed in traffic crashes and 187,000 were injured, Fatalities of older individuals comprised 16% of all traffic fatalities and 8% of all people injured in traffic crashes during 2009 (NHTSA, 2011). In comparison to 2008, senior fatalities comprised 21% of all traffic fatalities and 6% of all people injured in traffic crashes during 2008 (NHTSA, 2011).

The most common crashes for senior drivers occur during lane changes and left-hand turns primarily because of physical limitations related to the upper body motion made when looking behind before backing up or checking blind spots before changing lanes (Bayam, et al., 2005).

In general, four main factors contribute most to vehicle collisions: 1) equipment failure; 2) roadway design; 3) poor roadway maintenance; and 4) driver's behavior (SmartMotorists, 2008). According to USDOT, senior drivers are 17 times more likely to die in traffic accidents as people aged 25-65. Based on the NHTSA, in 2010, 32,885 fatalities occurred as a result of 30,196 fatal crashes. In the U.S., urban areas accounted for 45% (13,608) of fatal crashes and 44% (14,546) of fatalities, as compared to rural areas which accounted for 54% (16,292) of fatal crashes and 55% (18,026) of fatalities (NHTSA, 2012a) .

In fatal crashes involving two vehicles driven by a senior and a younger driver, the vehicle driven by the older person was 58% more likely to be the one struck compared to 34% of the vehicle driven by the younger driver (NHTSA, 2011). Among these crashes, 46% occurred while both vehicles were proceeding straight at the time of the collision, and, in 24% of the incidences, when the older driver was turning left (NHTSA, 2011).

Age-Driving Related Issues

As a person ages, physical changes occur which can affect daily life, including functions which may cause driving skills to decline. While many drivers age 65 and older are able to compensate for declined functions with experience and safe driving habits, aging uniquely affects each individual (Houser, 2005).

Houser's research also identified another risk factor specific to older drivers which is environment; roadways environment is important to the safety of older drivers (Houser, 2005). At night, signs and roadway markings are difficult to see and small lettering on road signs may be difficult to read even during the day. Large roadway intersections with multiple lanes and access roads can be complicated and confusing for any driver, but especially for older drivers (Houser, 2005). In addition, seniors typically prefer to drive older vehicles, most of which lack advanced safety features which can be found in modern vehicles. As a result, driver safety is reduced (Houser, 2005).

Studies related to senior drivers have shown that crash rates associated with increasing age are most likely related to declining driving abilities and medical conditions that can affect and impair driving (Bayam, et al., 2005). According to Zhang et al. (2000), although physical health and medical conditions did not predict fatality risk for drivers aged 65 to 74, medical conditions, such as diabetes mellitus, epilepsy, and chronic heart disease, were found to significantly increase fatality risks for drivers over the age of 75.

Visual Acuity

Declining vision is a significant issue affecting seniors' driving, causing difficulty in seeing roadway signs, traffic signals, pavement markings, and pedestrians or passing animals. Nighttime driving is especially challenging because of low-level lighting and glare from other vehicle headlights interfering with a driver's vision (FHWA, 2003).

Visual changes for older drivers often affect the distance at which they can see traffic signs and recognize sign lettering. These vision changes may also affect the ability to see and detect pavement markings (Amparano & Morena, 2006). Because of these visual deficiencies, senior drivers can be hesitant in making decisions regarding lane changes or exiting, thus affecting their safety and the safety of other roadway users.

Visual declines are believed to be a prominent cause of driving problems for seniors. Often, senior drivers experience a decline in their ability to clearly distinguish stimuli under various driving conditions, and many seniors experience visual field narrowing (Bayam, et al., 2005). Senior drivers commonly fail to notice objects in motion (Bayam, et al., 2005). In addition, eye changes related to aging also make nighttime visibility even more difficult. Contrast sensitivity is defined as “the ability to discern brightness differences between adjacent areas” (Phillips, et al., 2006). Declining contrast sensitivity makes it harder for older drivers to notice faded pavement markings during nighttime driving.

Based on Phillips et al. (2008), the function of a lens in the human eye is to focus light onto the retina. Two key changes occur to an eye lens with age: 1) the lens becomes less flexible; and 2) yellowing of the lens. Flexibility reduction makes it harder to shift focus from near objects to objects farther away. In fact, Presbyopia, or nearsightedness, is a vision condition in which the eye’s crystalline lens loses its flexibility, resulting in making it difficult for the person to focus on close objects (American Optometric Association, 2006). Eye lens yellowing causes older adults to require more light in order to see objects clearly. Although seniors’ eyes benefit from additional light, they are sensitive to glare. Another important change that occurs as a result of increasing age is declining peripheral vision (Phillips, et al., 2006). As a result of these vision changes, older adults are often slow to react to objects outside their central focus.

Visual acuity is defined as “the ability to resolve detail” (Owsley & McGwin, 2010). The World Health Organization lists several categories of visual disability such as low vision and blindness. Low vision is defined as “visual acuity between 20/60 and 20/200 or corresponding visual field loss to less than 20 degrees in better eye with best possible correction” (Steinkuller, 2010). Blindness is defined as “visual acuity of less than 20/400 or corresponding visual field loss to less than 10 degrees in the better eye with the best possible correction” (Steinkuller, 2010). According to Steinkuller, generally accepted testing parameters for vision disabilities in the U.S. are: 1) best corrected visual acuity in each eye, 2) the uncorrected visual acuity in each eye, and 3) binocular or monocular horizontal visual fields (Steinkuller, 2010). Some states also differentiate between additional vision disabilities such as diplopia, impaired night vision, monocularity, and retinitis pigmentosa (Steinkuller, 2010).

Visual acuity screenings that are performed for first-time driver’s license applicants and drivers periodically seeking re-licensure is reasonable. In the U.S., the design of roadway signs is based on sight distances that assume binocular visual acuity for drivers to be 20/30, minimally (FHWA, 2009). Drivers with less visual acuity experience difficulty in reading directional road signs at safe distances in order to make common driving decisions such as changing lanes or exiting (Owsley & McGwin, 2010).

In a study examining the impact of age, vehicle speed, and duration of monotonous driving on a driver's visual field, results showed that increased driver age, driving distance, and vehicle speed resulted in deteriorating a driver's visual field (Rogé, et al., 2004). For example, if a senior drives at a speed of 70 miles per hour (mph), he/she perceives less road signs than when driving at a speed of 50 mph (Rogé, et al., 2004).

Visual field is the space within which objects are visible to the immobile eyes at a specific time. Visual field testing is individually performed by states and specific visual field requirements are highly variable. For example, in Arizona, the visual field must be 60 degrees plus 35 degrees on the opposite side of the nose in at least one eye (Owsley & McGwin, 2010). In Texas, the visual field standard is recognition of the visual field test object within an uninterrupted arc of 140 degrees, with both eyes open during the test. In Kansas, the visual field must be greater than 55 degrees in one eye, or 110 degrees for both eyes; and in Florida, the minimum acceptable visual field is 130 degrees (TransAnalytics, 2003). As a person's age increases, the visual field and the area of visual attention become narrow.

In the U.S., a driver's license can either be restricted or unrestricted. An unrestricted license gives its owner permission to drive without the requirement of corrective lenses in all lighting conditions during day or night, in any location or road at any time for any distance, at any legal roadway speed, and in any legal and normally-equipped vehicle without extra or special mirrors (Steinkuller, 2010). Restrictions based on vision testing for driver's licenses vary from state to state. A restricted license requires the use of mandated corrective lenses, prohibits freeway driving, limits driving time between sunrise and sunset, restricts the area in which driving is allowed, and requires additional mirrors such as left and right outside, wide-angle, panoramic, and fender-mounted mirrors (Steinkuller, 2010).

The testing parameter that varies the least from state to state is the visual acuity test. For unrestricted licensed drivers, all states have similar visual acuity requirements for licensure (either first time or re-license), and most states, including Kansas, have set the minimum best-corrected visual acuity (BCVA) requirement at 20/40.

Visual acuity requirements for driver's licenses in Europe are affected by the minimum standard established by the European Union (Born, et al., 2010). Drivers of cars and motorcycles are required to have a binocular visual acuity of at least 20/40 with or without correction, and binocular visual field standards are limited to no less than 120^o (Born, et al., 2010). For example, in the United Kingdom, visual acuity should be between 6/10 and 6/15 meter and the visual field should be at least 120^{o} horizontally; in France, visual acuity should not be lower than 20/40 and the visual field should be horizontal with 60^{o} right and left, and vertically it should be 30^{o} above and below; in Germany, visual acuity should meet the minimum of number plate test between 6/10 and 6/15, and the visual field should be at least 120^{o} horizontally and perfect within 30^{o}.

Increasing Reaction Time

Another problem faced by senior drivers is a decline in reaction time, defined by the response speed of a person to an event (Green, 2000). Reaction time is a measure of the processing speed of the central nervous system of the body (Der & Deary, 2006), and (Madden, 2001). According to Der and Deary (2006), reaction time is strongly associated with age; as age increases, reaction time decreases. Older drivers typically respond more slowly to traffic control devices and changes in traffic or roadway conditions, such as a motor vehicle accident or a detour.

Reaction time is divided into several components according to occurrence sequence. The first component is mental processing time, defined as “the time it takes for the responder to perceive that a signal has occurred and to decide on a response” (Green, 2000). For example, mental processing time is the time required for a driver to detect that the traffic signal directly ahead has become yellow and decide that the brake should be applied. This segment of time is referred to as perception reaction time (Warshawsky-Livne & Shinar, 2002). The second component of reaction time is movement time: This requires the performance of certain muscle movements after determining an appropriate response (Green, 2000). For example, movement time includes the time required to lift the foot off the accelerator pedal, move it to the brake pedal, and then depress the brake pedal. In general, movement time increases with more complex movements (Green, 2000). The third component of reaction time is device response time. After the responder acts, the mechanical devices require certain time to engage (Green, 2000). For example, when the driver depresses the brake pedal, the car does not stop immediately because the stopping is controlled by gravity and friction (Green, 2000). Time is required for the devices within the car to overcome those forces and stop the vehicle.

Physical Limitations

Physical changes to senior drivers often contribute to difficulty in head movements in order to scan right and left sides at intersections or interchanges or look over their shoulders for lane changes (FHWA 2003). McKnight stated that senior drivers often experience difficulty when backing up because elderly drivers encounter physical limitations in head and upper body motion related to backward driving (McKnight, 2003).

One of the primary reasons why senior drivers crash during lane changes and left turns is because some senior drivers' physical limitations in head and upper body motion, such as neck and back pain, often make looking behind before reversing more difficult, or they may fail to carefully check vehicle blind spots before changing lanes (Bayam, et al., 2005).

A decline in hearing is another physical limitation due to increased age. Hearing is essential for safe driving because it allows drivers to react properly to emergency vehicles such as ambulances or police sirens. Hearing also allows drivers to respond to honking horns of other drivers when warning of dangers or mistakes. As a result, seniors' hearing decline reduces driver safety.

Cognitive Functions

Cognitive ability is “the ability to acquire, store, and apply knowledge, including short-term and long-term memory as well as performing mental operations” (Bayam, et al., 2005). Older drivers often have difficulty cognitively sorting the huge amount of roadway information incurred while driving. This difficulty is especially dangerous when encountering critical zones on roadways, such as navigating a temporary traffic control zone because of a detour (FHWA 2003). Cognitive ability declines as age increases (Bayam, et al., 2005), and cognitive functions and visual attention measures have been shown to be accurate accident frequency predictors for senior drivers (Daigneault, et al., 2002).

The ability of senior drivers to share attention while driving also declines with age. Certain driving situations can be especially challenging, such as making left turns at intersections in which drivers must divide their attention between oncoming traffic and pedestrian traffic on either side of the vehicle (Bayam, et al., 2005). Other situations requiring shared attention involve interaction with traffic control devices such as red light traffic signals or stop signs (Bayam, et al., 2005).

In addition to senior drivers’ deficiency in attention-sharing, impaired judgment regarding traffic gaps may lead to indecisive crossing or entering traffic at intersections (Bayam, et al., 2005). Senior drivers often have difficulty judging the position of approaching traffic in relation to their ability to accelerate into gaps (McKnight, 2003). Senior drivers often resolve the conflict created by their inability to handle the situation they faced while driving by slowing down or stopping, which can cause additional dangers (Bayam, et al., 2005).

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Possible Solutions for Improving Roadways to Enhance Population Safety

Navigating U.S. roadways can be confusing and challenging for all drivers if driving routes are not easily understood or clearly marked, especially when the driver is unfamiliar with the driving location (Amparano & Morena, 2006). This problem can be enormous for older drivers, especially those who have cognitive or physical disabilities (Amparano & Morena, 2006). However, engineering opportunities such as sign placement, legibility of sign lettering, retroreflectivity, and sign size can enhance a driver's ability to detect signs and comprehend sign messages. Solutions for improving roadway navigation and increasing safety are discussed in the following sections.

Reducing the Impact of Vision Decline

Based on research conducted by Phillips et al., a number of infrastructure measures can be used to reduce vision declining impacts for senior drivers (Phillips, et al., 2006). One direct step is to increase the size of roadway signs and lettering. If drivers are able to read sign information from a greater distance, they have more time to make navigation decisions, thus enabling increased focus on safe maneuvers. The Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) of 2009 recommends minimum sign and font sizes for various types of signs. In the MUTCD of 2009, minimum upper case letter size is 8 in (200 mm) and lower case letter size is 6 in (or 150 mm). These sizes are used for multi-lane streets with speed limits greater than 40 mph (or 65 km/hr) (FHWA, 2009). To enhance guide sign visibility for nighttime driving, a light source may be installed or, in other cases, guide sign sheet metal material can be replaced by a brighter retroreflective material which has the effect of enhancing sign visibility at night.

Roadway curves present another major visual challenge. Older drivers have difficulty detecting sharp curves, especially during nighttime driving. One effective technique to improve curve detection during nighttime driving is to install retroreflective pavement markings (Phillips, et al., 2006).

Improving Intersections to Overcome Physical Changes

As previously mentioned, personal mobility often becomes more limited as people age. Some seniors experience loss of limb strength, flexibility, and sensitivity; limited range of motion; or reduced ability to rotate their head and neck (Phillips, et al., 2006). Chronic illnesses such as coronary artery disease and heart failure also can greatly restrict physical mobility and, therefore, limit involvement in certain activities. For drivers of all ages, general body flexibility and head movements are required when driving a vehicle, especially when merging into traffic, changing lane positions, parking a vehicle, and encountering intersections (Phillips, et al., 2006).

Reduction in body flexibility can affect various driving tasks, specifically when drivers must visually scan a portion of the roadway to ensure safe driving. Some types of visual scanning are essential, such as watching for approaching vehicles, registering traffic signals, and yielding the right-of-way to pedestrians and others (Phillips, et al., 2006).

The design nature of skewed intersection (with a 60^o angle as an example) requires more head movement and scanning as compared to a right angle intersection (Phillips, et al., 2006). Skewed intersection’s designs should be avoided in the new highway projects as much as possible; in the case when a skewed intersection cannot be avoided, right turn on red should be prohibited because it will be harder for some older drivers to detect safe gaps in the traffic at that location, and prohibiting the right turn on red will enable older drivers to have some time to focus on a safe turn (Phillips, et al., 2006).

Making Roadway Navigation Easier

The use of redundant street name signs can improve the chances of a driver remembering critical navigation information (Phillips, et al., 2006). Often, when drivers see a road sign, they are quickly distracted and forget the required intersection. This distraction initially deletes necessary navigation information from working memory (Phillips, et al., 2006). Because working memory capacity declines with age, these memory lapses are more common for older drivers. Providing roadway navigation information several times to a driver (using redundant street name signs) helps limit this issue.

Seniors commonly prefer driving on familiar roadways (Phillips, et al., 2006). Unfortunately, even familiar areas often change, as in work zones or required detours. Changeable message signs are an important method for transportation agencies to alert drivers to new road situations. However, appropriate design of these signs is crucial so that drivers of all ages can easily navigate roadways.

One smart-modern solution to improve safety for older people on roadways is to implement autonomous vehicles’ “self-driving cars” service. Google has begun building a fleet of electric power vehicles to be used for experimentation in California (Markoff, 2014). These vehicles are based on a principle of completely removing driver responsibility from the vehicle; no steering wheel, gas pedal, brake pedal, or gear shift is necessary (Markoff, 2014). The only element available in the vehicle is a red “e-stop” button that can be used by the passenger in emergency stops and a separate start button (Markoff, 2014). These vehicles are requested via a smart phone application. The speed limit of these vehicles is limited to 25 mph, however, and these vehicles are designed for urban and suburban areas, not on highways. One potential use for these vehicles is driverless taxi cabs (Markoff, 2014).

Based on Markoff (2014), Google’s autonomous vehicle will have sensors that can detect approximately 600 ft in all directions. This vehicle will also have a rear view mirror according to California code. A foam-like material will be used in the construction of the front of the vehicle in case the vehicle’s computer fails and the vehicle hits a pedestrian. Google’s vehicle differs from vehicles introduced by Mercedes, BMW, and Volvo because those vehicles are able to travel within limited circumstances without a driver but they do not completely eliminate the driver as in Google’s vehicle. Laws permit autonomous vehicles in California, Nevada, and Florida. In California, the regulations of autonomous vehicle testing were adopted on May 19, 2014, and these regulations became effective on September 16, 2014.

Comparing to the other modes of transportation, autonomous vehicles are better in terms of time, safety, convenience, and peace of mind (Burns, et al., 2013). Based on Burns, initial estimates of the new autonomous vehicles are $4 per customer per day, or $2 per customer per trip. The fleet system of autonomous vehicles can be an alternative transportation mode, competing with taxicabs and public transportation. Yellow taxicab fare in Manhattan, N.Y. is approximately $5 per mile, while initial estimates of the fleet fare of a shared, driverless vehicle are approximately $0.50 per mile (Burns, et al., 2013). In addition, the autonomous shared, driverless vehicle service is more convenient and less expensive than the bus or subway, resulting in the reduction of empty miles and labor costs and increased energy efficiency.

Chapter 2 - Overhead Guide Signs and Senior Drivers

Introduction

One primary mission of the Federal Highway Administration is to improve roadway safety in the United States. According to NHTSA's 2011 Fatality Analysis Reporting System, in 2011, 32,367 people were killed in motor vehicle traffic crash in the U.S., and this number was 32,999 in 2010 (NHTSA, 2012b). Statistics show that 25% of all motor vehicle travel occurs at night, but approximately 50% of all traffic fatalities occur during nighttime hours (FHWA, 2008).

Drivers of all ages often experience more difficulty driving at night as compared to daytime driving. Different issues related to the driver which may control visibility of the road such as: driver's visual acuity, contrast sensitivity, distance judgment, and color discrimination (Lagergren, 1987). Guide signs are typically green signs located along a highway to notify drivers of destinations and exit information. Overhead highway signs are important for improving driver guidance. The objective of these signs is to provide drivers with information regarding destinations and necessary instructions for reaching specific destinations. In fact, "overhead highway signs must be highly visible and legible so that drivers can detect, read and interpret the information contained on the signs in time to respond appropriately" (Bullough, et al., 2008).

Many DOTs in the U.S. are considering whether to add light sources to current highway overhead guide signs or replace these signs with modern retroreflective sheeting to improve visibility for drivers, especially older drivers, during nighttime and possibly reduce potential accidents due to driver confusion and resulting improper maneuvers. As a requirement in the MUTCD, overhead guide signs must either be illuminated or retroreflective (FHWA, 2009). The objective of the new minimum retroreflectivity requirement is to improve safety on U.S. roadways, especially highways, and to ensure that roadway users, especially the elderly, are able to detect and react completely to traffic signs in order to facilitate safe, uniform, and efficient travel (Jonathan & Carlson, 2012).

Overhead guide signs can be illuminated from the back, known as back-illuminated, and utilizing external light sources to illuminate the sign face (Bullough, et al., 2008). Another way of illuminating guide signs is by using luminous sources or elements such as Light Emitting

Diode (LED) to produce required characters of the signs (Bullough, et al., 2008). Retroreflective sheeting materials also can be used to enhance highway overhead guide sign visibility for drivers. Retroreflective signs either include individual "button" elements, which produce characters on a sign, or retroreflective sheeting material that provides retroreflection capability over the entire surface of the sign (Bullough, et al., 2008).

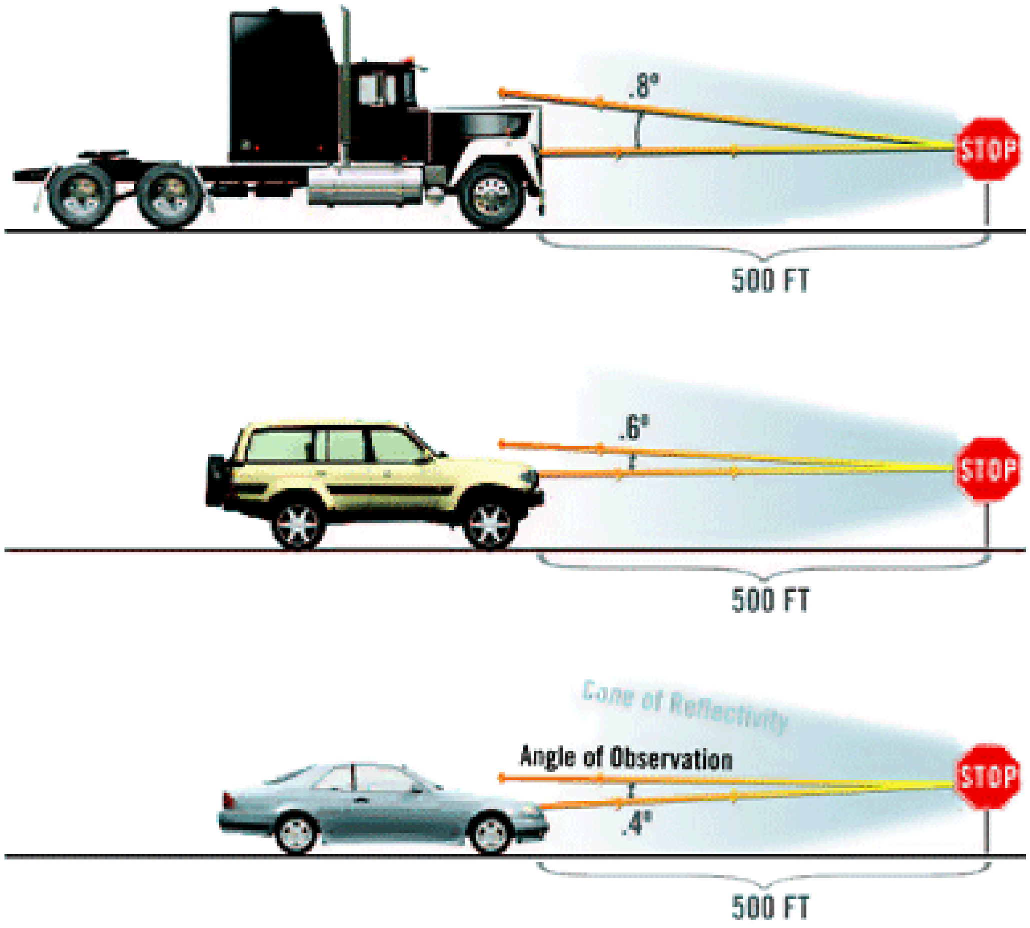
Signs manufactured from retroreflective sheeting materials are commonly used on U.S. highways (Bullough, et al., 2008). One important advantage of using retroreflective sheeting materials is that they do not require electrical power because they rely on efficient passive retroreflection of oncoming vehicle headlamps (illuminance) which are reflected back toward the vehicle (luminance). Based on Bullough et al. (2008), the observation angle between light rays from the driver's vehicle headlights and sight line to a roadway sign is relatively small, especially for far-viewing distances.

The Observation Angle

Observation angle is defined as the angle between a retroreflected beam toward an observer's eye and the line formed by the light beam striking a surface, as shown in Figure 2.1. The observation angle will be larger for the driver of a truck or bus than that of a driver of a standard passenger vehicle (ORAFOL, 2012). If a driver in a vehicle is close to a retroreflective sign or device, the observation angle will be larger (ORAFOL, 2012).

Understanding observation angles is helpful when installing signs with retroreflective materials so that light is accurately reflected from headlamps back toward a driver's eyes, thus enhancing visibility and sign luminance. An inverse relationship exists between the observation angle and the luminance amount of retroreflective material. In other words, as the angle increases, the luminance of the retroreflective sign decreases. The entrance angle is the angle between a headlamp ray to the sign and a line perpendicular to the sign face, as shown in Figure 2.2. Large differences in the entrance angle are a function of sign location and orientation.

Figure 2.1 Observation Angle and Variation with Vehicle Size (MyParkingSign.com, 2012)

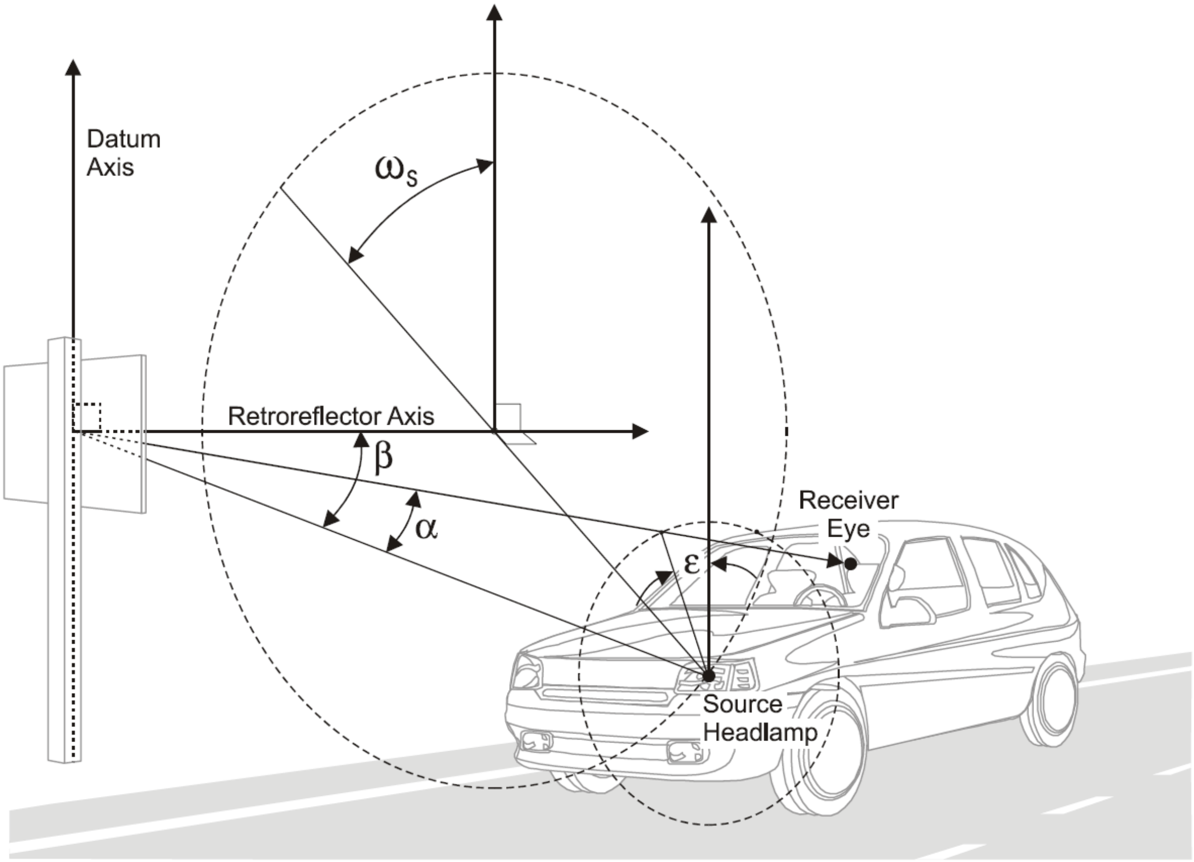


Retroreflective Traffic Sign Sheeting Materials

The American Society for Testing and Materials (ASTM) details components of sheeting materials that can be used in constructing retroreflective guide signs. ASTM D4956 describes types of retroreflective sheeting materials that can be used on traffic signs (ASTM, 2011). "Retroreflective sheeting shall consist of white or colored sheeting having a smooth outer surface and that essentially has the property of a retro-reflector over its entire surface" (ASTM, 2011). According to ASTM, eleven types of retroreflective sheeting exist and they have various applications as follows:

- "Type I: a retroreflective sheeting referred to as "engineering grade", that is typically enclosed lens glass-bead sheeting. Applications for this material include permanent highway signing, construction zone devices, and delineators.
- Type II: a retroreflective sheeting referred to as "super engineer grade", that is typically an enclosed lens glass-bead sheeting. Applications for this material include permanent highway signing, construction zone devices, and delineators.

Figure 2.2 Interrelationship of Application System Angles, Where: Observation Angle Is (α), Entrance Angle Is (β), Rotation Angle Is (ε), and Orientation Angle Is (ω_s) (Brich, 2002)



- Type III: a retroreflective sheeting referred to as “high-intensity,” that is typically manufactured as an encapsulated glass-bead retroreflective material or an unmetalized, microprismatic retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators.
- Type IV: a retroreflective sheeting referred to as “high-intensity,” that is typically an unmetalized microprismatic retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators.
- Type V: a retroreflective sheeting referred to as “super high-intensity,” that is typically a metalized microprismatic retroreflective element material. This sheeting is typically used for delineators.
- Type VI: an elastomeric retroreflective sheeting without adhesive. This sheeting is typically a vinyl microprismatic retroreflective material. Applications include orange temporary roll-up warning signs, traffic cone collars, and post bands.
- Type VII: retroreflective sheeting materials previously classified as Type VII have been reclassified as Type VIII. The use of a designation as Type VII has been discontinued.

- Type VIII: a retroreflective sheeting typically manufactured as an unmetalized cube corner microprismatic retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators.
- Type IX: a retroreflective sheeting typically manufactured as an unmetalized cube corner microprismatic retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators.
- Type X: retroreflective sheeting materials previously classified as Type X have been reclassified as Type VIII. The use of a designation as Type X has been discontinued.
- Type XI: retroreflective sheeting typically manufactured as an unmetalized cube corner microprismatic, retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators." (ASTM, 2011)

The 2009 MUTCD minimum retroreflectivity requirements refer to sheeting types as defined in ASTM D4956. A common problem associated with retroreflective sheeting, however, is that even though a particular type of sheeting may initially meet minimum retroreflectivity levels, it may quickly degrade below minimum retroreflectivity levels because of weather or other environmental causes. The MUTCD of 2009 has no instructions about the longevity of sheeting materials used for overhead guide signs. Agencies may overcome this problem by using higher performance sheeting which may have a higher initial cost but remain above the minimum retroreflective requirement longer and provide a more efficient life-cycle cost.

Guide Signs

"Guide signs are essential elements to direct road users along streets and highways, to inform them of intersecting routes, to direct them to cities, towns, villages, or other important destinations, to identify nearby rivers and streams, parks, forests, and historical sites, and generally to give such information as will help them along their way in the most simple, direct manner possible" (FHWA, 2009).

MUTCD 2009 Standards Regarding Guide Signs

Guide signs must be visible and clear for intended drivers in order to allow for proper driving response time. Desirable attributes for guide signs include high visibility during day and night and high legibility. Legibility is defined as adequately-sized letters, symbols, or arrows, and a short legend for quick comprehension by a road user approaching a sign (Gowda, 2010). Many standard requirements are set in the MUTCD of 2009 regarding guide signs, including the following essential sections: section 2A.07, section 2A.08, section 2A.10, section 2D.01- 2D.55, and section 2E.01- 2E.54 (FHWA, 2009).

Standardization of Guide Sign Location

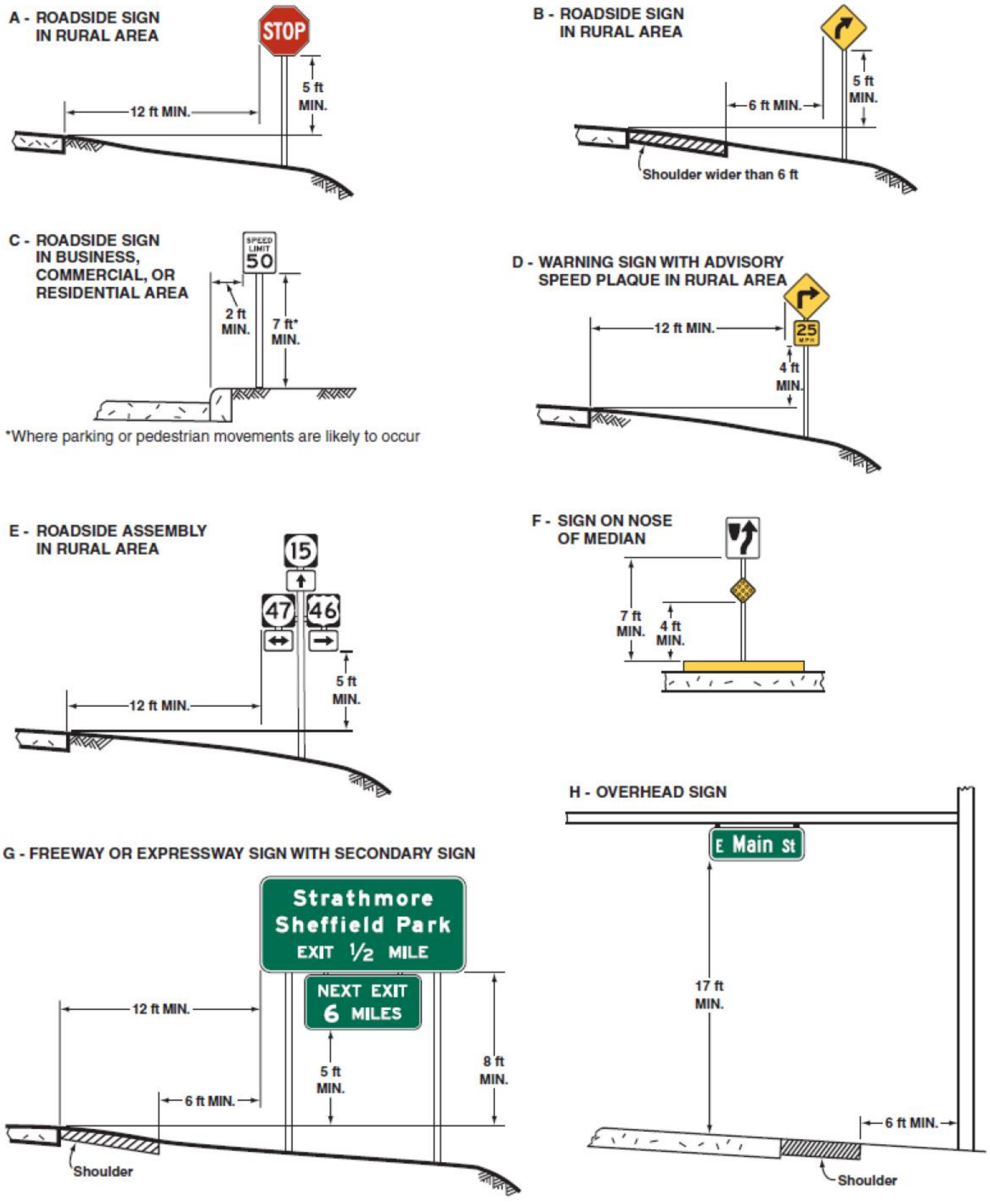
According to the MUTCD of 2009, signs should be located on the right-hand side of the roadway where they are easily recognized and understood by road users. Signs in other locations should be considered only as supplementary to signs in normal locations, except as otherwise detailed in the 2009 MUTCD. Signs should also be individually installed on separate posts or mountings except where one sign supplements another, or route or directional signs are grouped to clarify information to motorists. Examples of heights and lateral locations of signs for typical installations are shown in Figure 2.3.

One standard in the MUTCD is: “signs requiring separate decisions by the road user shall be spaced sufficiently far apart for the appropriate decisions to be made. One of the factors considered when determining the appropriate spacing shall be the posted or 85th percentile speed” (FHWA, 2009).

Lettering Style and Size on Conventional Road Guide Signs

According to the 2009 MUTCD, design of upper-case letters, lower-case letters, numerals, route shields, and spacing should meet the criteria provided in the “Standard Highway Signs and Markings” book (FHWA, 2009). Names of places, streets, and highway lettering on conventional road guide signs should be a combination of lower-case letters with initial upper-case letters (FHWA, 2009). The nominal loop height of lower-case letters should be ¾ the height of the initial upper-case letter (FHWA, 2009). This proportion must be used to determine the height of lower-case letters when a mixed-case legend letter height is specified, referring only to the initial upper-case letter. When the height of a lower-case letter is referenced, the reference is made to the nominal loop height and height of the initial upper-case letter should be determined by this proportion. All other word legends should be in upper-case letters on conventional road guide signs. For each of the Standard Alphabet series, unique letter forms should not be stretched, compressed, warped, or otherwise manipulated (FHWA, 2009).

Figure 2.3 Examples of Heights and Lateral Locations of Signs for Typical Installations (FHWA, 2009)



Note:
See Section 2A.19 for reduced lateral offset distances that may be used in areas where lateral offsets are limited, and in business, commercial, or residential areas where sidewalk width is limited or where existing poles are close to the curb.

Sign legibility is a function of letter size and spacing (FHWA, 2009). Legibility distance must be sufficient to give drivers or road users enough time to read and comprehend information provided by a sign. Under optimal conditions, a guide sign should be read and understood in a brief glance. Many factors affect legibility distance, such as inattention, blocked view by other vehicles, inclement weather, driver's inferior eyesight, and various other causes that may delay or slow reading (Gowda, 2010). Repetition of guide information on successive signs gives road users' more than one opportunity to obtain the information needed (FHWA, 2009).

Lettering Style and Size on Freeway and Expressway Guide Sign Standards

For all freeway and expressway signs that do not have a standardized design, message dimensions should be determined first and then followed by determining the outside dimensions (FHWA, 2009). Word messages in the legend of expressway guide signs must be at least 8 inches high (FHWA, 2009). Guide signs at or in advance of interchanges should contain larger lettering (FHWA, 2009). All names of places, streets, and highways on freeway and expressway guide signs should be composed of lower-case letters with initial upper-case letters (FHWA, 2009). The nominal loop height of the lower-case letters should be ¾ of the height of the initial upper-case letter (FHWA, 2009). Lettering size on freeway and expressway signs should be identical for both rural and urban conditions.

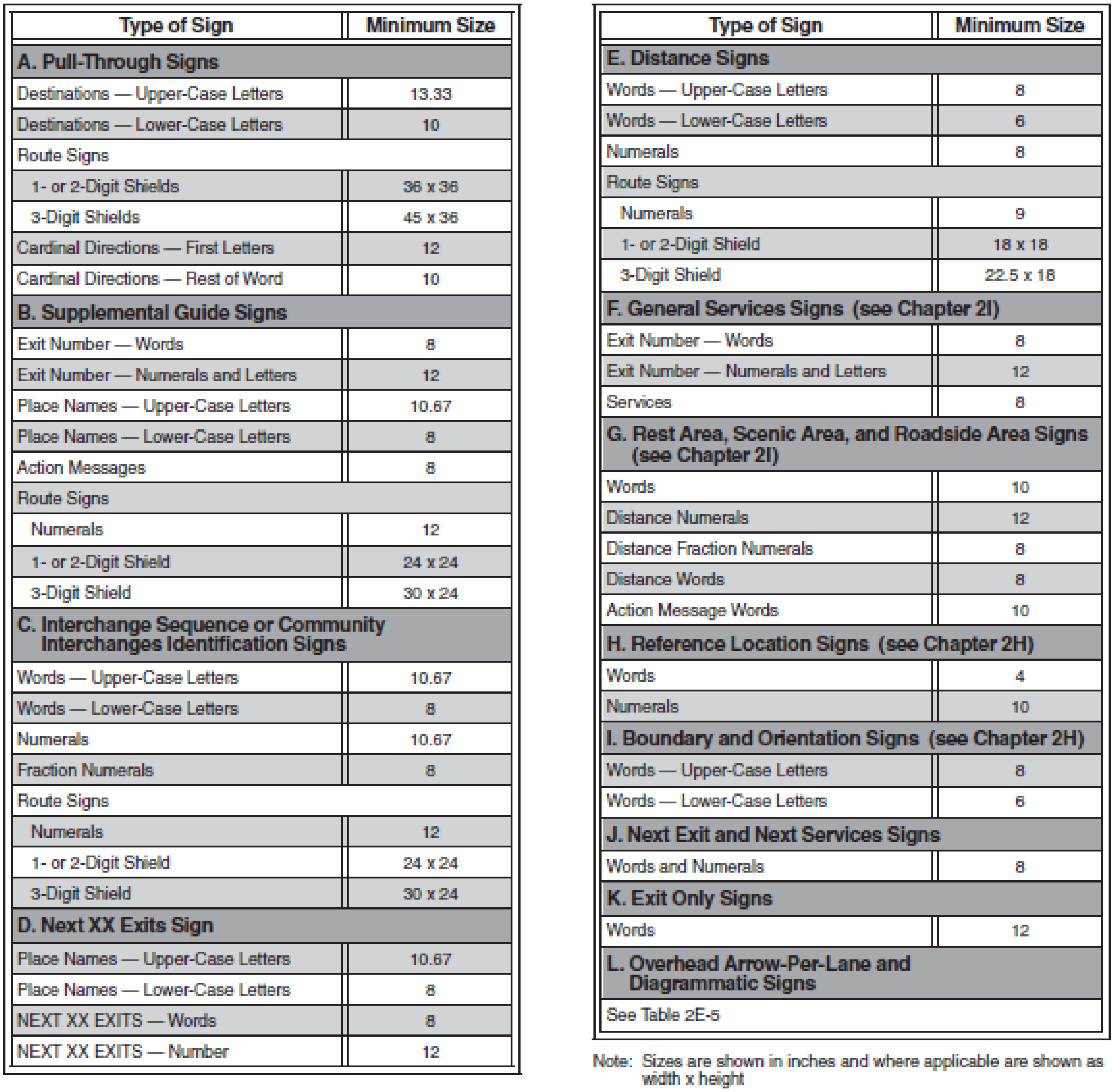
Figure 2.4 shows minimum letter and numeral sizes for guide signs according to MUTCD 2009 guidelines, while Figure 2.5 shows freeway or expressway guide signs and plaque sizes according to MUTCD 2009 guidelines.

ClearviewHwy^{TM} Font

The ClearviewHwy^{TM} (hereafter referred to as Clearview) font is a relatively new font developed to increase traffic sign legibility and improve the ease with which traffic legends can be recognized. ClearviewHwy^{TM} font was developed by Donald Meeker and Christopher O'hara of Meeker and Associates, Inc.; Martin Pietrucha, Ph.D., and Philip Garvey of the Pennsylvania Transportation Institute; and James Montalbano of Terminal Design, Inc., along with research supported by Paul Carlson, Ph.D., and Gene Hawkins, Ph.D., and research design advice by Susan Chrysler, Ph.D., of the Texas Transportation Institute (Holick, et al., 2006).

Irradiation or halation is "a phenomenon where in the stroke is so bright that it bleeds into the character's open spaces, creating a blobbing effect that reduces character legibility" (Gowda, 2010). Irradiation phenomenon observed in different font styles can be shown in Figure 2.6. The open spaces of Clearview font allow irradiation without decreasing the distance at which alphabets are legible (Gowda, 2010).

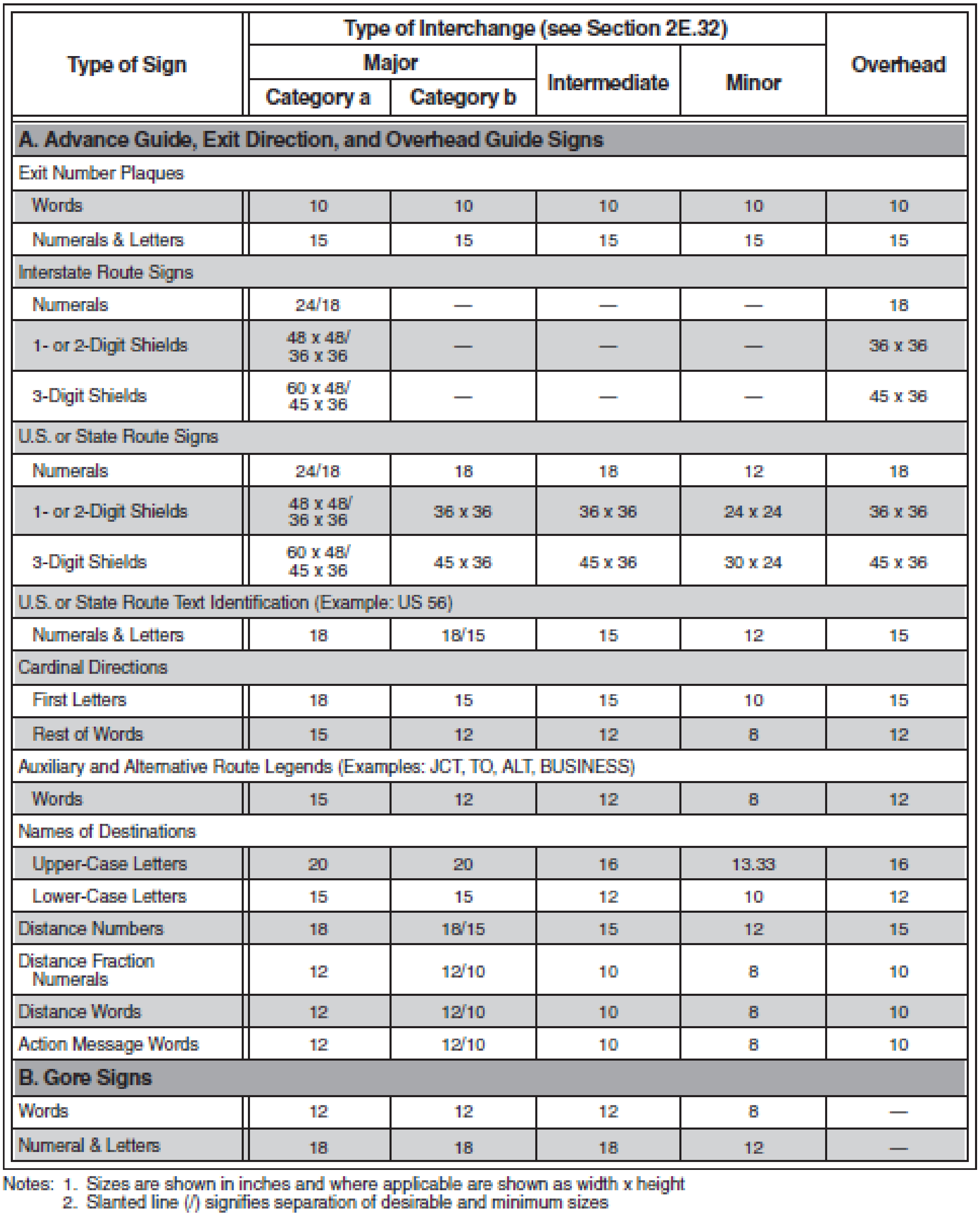
Figure 2.4 Minimum Letter and Numeral Sizes for Expressway Guide Signs According to Sign Type (FHWA, 2009)



Type of Sign	Minimum Size
A. Pull-Through Signs	
Destinations — Upper-Case Letters	13.33
Destinations — Lower-Case Letters	10
Route Signs	
1- or 2-Digit Shields	36 x 36
3-Digit Shields	45 x 36
Cardinal Directions — First Letters	12
Cardinal Directions — Rest of Word	10
B. Supplemental Guide Signs	
Exit Number — Words	8
Exit Number — Numerals and Letters	12
Place Names — Upper-Case Letters	10.67
Place Names — Lower-Case Letters	8
Action Messages	8
Route Signs	
Numerals	12
1- or 2-Digit Shield	24 x 24
3-Digit Shield	30 x 24
C. Interchange Sequence or Community Interchanges Identification Signs	
Words — Upper-Case Letters	10.67
Words — Lower-Case Letters	8
Numerals	10.67
Fraction Numerals	8
Route Signs	
Numerals	12
1- or 2-Digit Shield	24 x 24
3-Digit Shield	30 x 24
D. Next XX Exits Sign	
Place Names — Upper-Case Letters	10.67
Place Names — Lower-Case Letters	8
NEXT XX EXITS — Words	8
NEXT XX EXITS — Number	12
E. Distance Signs	
Words — Upper-Case Letters	8
Words — Lower-Case Letters	6
Numerals	8
Route Signs	
Numerals	9
1- or 2-Digit Shield	18 x 18
3-Digit Shield	22.5 x 18
F. General Services Signs (see Chapter 2I)	
Exit Number — Words	8
Exit Number — Numerals and Letters	12
Services	8
G. Rest Area, Scenic Area, and Roadside Area Signs (see Chapter 2I)	
Words	10
Distance Numerals	12
Distance Fraction Numerals	8
Distance Words	8
Action Message Words	10
H. Reference Location Signs (see Chapter 2H)	
Words	4
Numerals	10
I. Boundary and Orientation Signs (see Chapter 2H)	
Words — Upper-Case Letters	8
Words — Lower-Case Letters	6
J. Next Exit and Next Services Signs	
Words and Numerals	8
K. Exit Only Signs	
Words	12
L. Overhead Arrow-Per-Lane and Diagrammatic Signs	
See Table 2E-5	

Note: Sizes are shown in inches and where applicable are shown as width x height

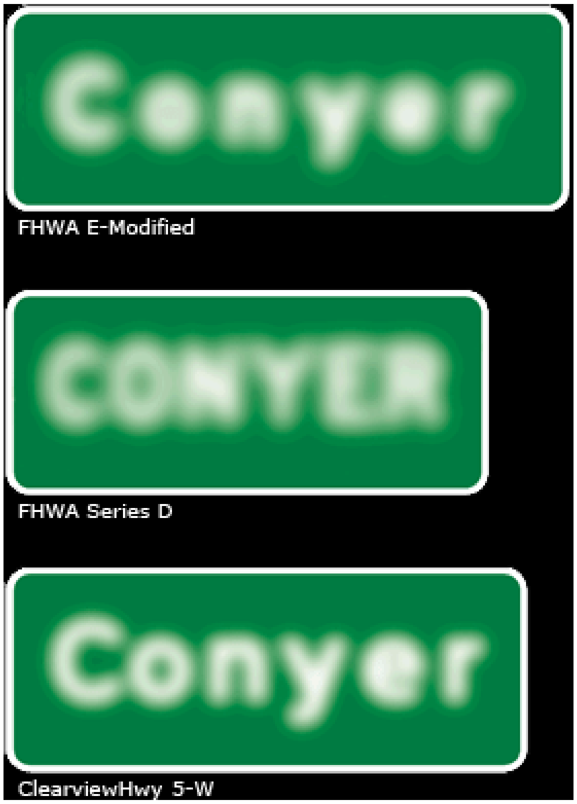
Figure 2.5 Minimum Letter and Numeral Sizes for Freeway Guide Signs According to Interchange Classification (FHWA, 2009)



Type of Sign	Type of Interchange (see Section 2E.32)				Overhead
	Major		Intermediate	Minor	
	Category a	Category b			
A. Advance Guide, Exit Direction, and Overhead Guide Signs					
Exit Number Plaques					
Words	10	10	10	10	10
Numerals & Letters	15	15	15	15	15
Interstate Route Signs					
Numerals	24/18	—	—	—	18
1- or 2-Digit Shields	48 x 48/ 36 x 36	—	—	—	36 x 36
3-Digit Shields	60 x 48/ 45 x 36	—	—	—	45 x 36
U.S. or State Route Signs					
Numerals	24/18	18	18	12	18
1- or 2-Digit Shields	48 x 48/ 36 x 36	36 x 36	36 x 36	24 x 24	36 x 36
3-Digit Shields	60 x 48/ 45 x 36	45 x 36	45 x 36	30 x 24	45 x 36
U.S. or State Route Text Identification (Example: US 56)					
Numerals & Letters	18	18/15	15	12	15
Cardinal Directions					
First Letters	18	15	15	10	15
Rest of Words	15	12	12	8	12
Auxiliary and Alternative Route Legends (Examples: JCT, TO, ALT, BUSINESS)					
Words	15	12	12	8	12
Names of Destinations					
Upper-Case Letters	20	20	16	13.33	16
Lower-Case Letters	15	15	12	10	12
Distance Numbers	18	18/15	15	12	15
Distance Fraction Numerals	12	12/10	10	8	10
Distance Words	12	12/10	10	8	10
Action Message Words	12	12/10	10	8	10
B. Gore Signs					
Words	12	12	12	8	—
Numeral & Letters	18	18	18	12	—

Notes: 1. Sizes are shown in inches and where applicable are shown as width x height
2. Slanted line (/) signifies separation of desirable and minimum sizes

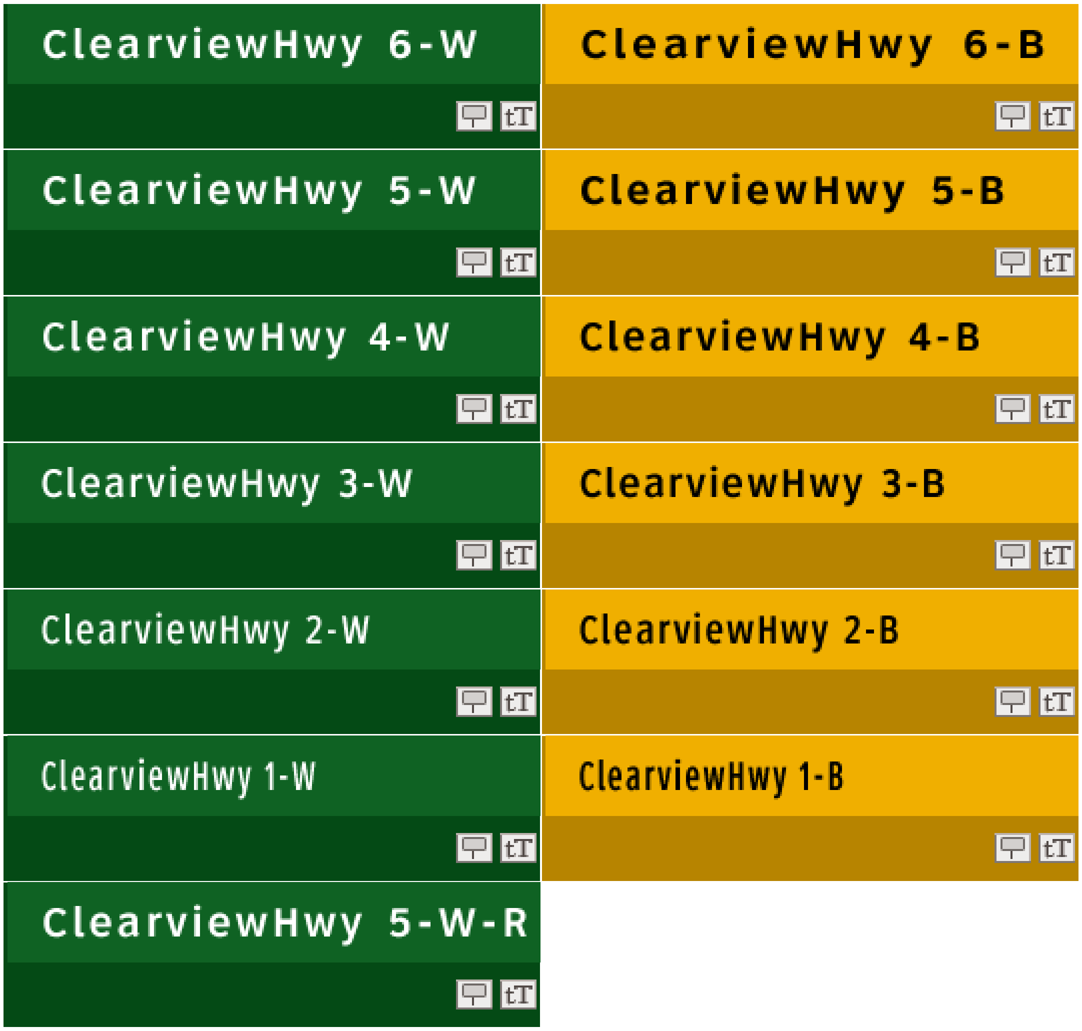
Figure 2.6 Irradiation or Halation Phenomenon for Three Font Styles (Terminal Design, 2004c)



Clearview Font Development

The ClearviewHwy font software is used to produce Clearview font. ClearviewHwy font software contains kerning data (kerning refers to data included in a font that specifies how to adjust spacing) in addition to approved letter spacing in default mode, and this software is compatible with all standard computer operating systems and sign manufacturing software tools. After 10 years of research and development, ClearviewHwy evolved into a type system of six distinct weights with each weight having a version for positive and negative contrast applications (Termina Design, 2004a). Contrast application may be positive or negative. The positive contrast application showcases lighter tone letters on a dark background, while the negative contrast version displays darker tone letters on a light background (Gowda, 2010). Clearview font is available in both positive and negative contrast. The positive contrast shows white letters on a dark green background, while the negative contrast displays black letters on a fluorescent yellow, fluorescent orange or white background. Figure 2.7 shows the Clearview distinct weights and two contrast types.

Figure 2.7 The Clearview Font Distinct Weights. Right Side Is Negative Contrast and Left Side Is Positive Contrast (Terminal Design, 2004b)



Guide Sign Enhancements

Various engineering opportunities such as sign placement, legibility of sign lettering, retroreflectivity, and sign size can enhance a driver’s ability to detect signs and comprehend sign messages.

Guide Sign Placement

According to the MUTCD of 2009, one common guide sign placement strategy is to double the use of signs by placing redundant signs on the left side of the roadway opposite the primary sign on the right side. Signs must be placed at locations that have unobstructed visibility and minimum background clutter. Based on the 2009 MUTCD, at intersection and interchange locations, preferred placement is overhead, creating optimum sign visibility. In addition, signs can be placed in a driver’s direct line of sight. For example, at T-intersections, the2009 MUTCD recommends a one-way sign be placed directly opposite the center of the approaching lane of traffic.

Sign Legibility

Legibility is defined as “the readability of a particular writing style, or font” (Amparano & Morena, 2006). The FHWA defines standard typefaces used for highway signs on U.S. roadways by the Standard Alphabets section in the MUTCD of 2009. The seven typefaces currently used for roadway signs are series A (the narrowest and discontinued), series B, series C, series D, series E, series E (modified), and series F (the widest). Research conducted in 1990 resulted in a new font: the Clearview. Clearview font provides faster recognition at greater distances by optimizing the legibility of letters and reducing halos around text messages (Amparano & Morena, 2006). Recent studies show that Clearview’s alphabet legibility represents a 16% improvement in distance recognition by older drivers and a 12% increase in legibility for all drivers when compared to the existing standard (series E (modified)) for guide signs (Amparano & Morena, 2006). These results imply that the Clearview font results in faster reading, recognition, comprehension, and reaction times for drivers, especially senior drivers. States such as Arizona, Iowa, Kentucky, Maryland, Michigan, Pennsylvania, Texas, and Virginia have adopted Clearview font for use on guide signs throughout all or part of their transportation systems.

Another approach states have considered to increase legibility is to expand letter heights on guide and street name signs. The minimum requirement for letter size is set in the MUTCD of 2009 in order to meet the driver’s requirements, especially elderly drivers. The use of uppercase and lowercase letters also adds to enhanced legibility on guide signs. In the 2009 MUTCD, the minimum size for upper case letters is 8 in (200 mm) and 6 in (or 150 mm) for lower case letters. These sizes are used on multi-lanes streets with speed limits greater than 40 mph (or 65 km/hr) (FHWA, 2009).

Sign Retroreflectivity

The use of retroreflective sheeting materials for signs is beneficial in making them more conspicuous, especially in high visual “noise” locations (Amparano & Morena, 2006). Research performed at the University of South Dakota shows that the time required by senior drivers to detect signs in complex backgrounds can be reduced significantly by using super-high-intensity sheeting materials (Amparano & Morena, 2006). Also, detection distance for fluorescent signs is significantly greater than non-fluorescent signs for both younger and older drivers, though older drivers benefited the most. The Kansas Department of Transportation (KDOT) currently uses High Intensity (type IV) sheeting material for guide signs in various locations throughout the state.

Increasing sign size can improve sign visibility, resulting in improved roadway safety for drivers and users. The MUTCD recommends the minimum sizes of different sign types as mentioned previously (FHWA, 2009).

Illuminating Guide Signs

Light Sources

A light source is a device that actually converts electrical energy to visible light in a specific manner based on source type. Light sources associated with little short-wavelength light are less effective for vision than light sources that produce greater short-wavelength (blue), even if the measured light level is similar, because of the human eye's shifted response to light at some nighttime light levels (Bullough, 2012a). Light sources used for roadway illuminating devices can be categorized into conventional light sources which include incandescent lamps, electric discharge lamps, and new light sources generation which include LED, induction lighting, and Light Emitting Plasma (LEP).

It is important to distinguish between two important terms: "efficiency" and "efficacy." "Efficiency" is used when both input and output units are equal, meaning that "efficiency" is without unit, while the term "efficacy" is used when both input and output have two different units, in the luminous efficacy, the input unit is in "watt" and the output is in "lumen" (USDOE, 2009b).

Incandescent Lamps

According to Lopez, two prominent types of incandescent lamps exist: the common incandescent and the Tungsten Halogen (Lopez, 2003). The common incandescent has relatively low initial and operating costs but has a low efficacy (lumens per watt) and a short lifespan ranging between 1000-2000 hours (BITS, 2012). The Tungsten Halogen (quartz iodide) is not used for highway lighting (Lopez, 2003).

Electric Discharge Lamps

There are several types of electric discharge light sources according to Lopez (Lopez, 2003):

- Conventional fluorescent: it has a relatively medium initial cost, long life, and high efficacy (30-70 lm/watt). The main disadvantage of this type is that light varies with ambient temperature.
- Induction fluorescent: some types have a high efficacy up to (75 lm/watt) with extremely long life (100,000 hours). Induction fluorescent is suitable for low mounting heights and other special applications (Lopez, 2003).
- Mercury Vapor (MV): two types of MV light sources are available in the market, clear light and phosphor-coated light. MV light sources include a phosphor-coated light source primarily used for sign lighting. The disadvantage of an MV light source is the extremely high initial cost. Some advantages of MV light include relatively long life and high efficacy (30-65 lm/watt). MV produces a smaller light than fluorescent.
- High Pressure Sodium (HPS): light is produced by an arc in a ceramic tube containing sodium and other elements. It provides light primarily in the yellow spectrum but other elements inside the bulb provide light in blue, green, orange and red to improve color rendition. This type of light source requires a starting aid to provide a pulse to begin the arc stream. HPS light has advantages such as relatively low initial cost, long useful life, high efficacy (45-150 lm/watt), and the ability to maintain relatively high light output throughout the lifespan (lumen maintenance) (Bullough, 2012b). Eighty percent of street and highway lighting in New York are HPS (Bullough, 2012a).
- Low Pressure Sodium (LPS): light is produced by an arc in long tubular glass envelope (bulb) containing sodium only. Light is monochromatic yellow with poor color rendering. The main disadvantage is the relatively high initial cost. Some of the advantages are moderately long life and high efficacy (145-185 lm/watt).
- Metal Halide (MH): the MH principle is similar to that of the mercury light sources, but it contains various metal halides in addition to mercury which provide excellent color rendering and result in a white light. MH light sources have been available for several decades, but primary problems associated with it in the past were low efficacy, low useful life, and poor lumen maintenance (Bullough, 2012b). This information regarding disadvantages of MH’s light source is outdated because recent technology has resulted in increasing the efficacy of MH light sources, increasing the useful life, and improving lumen maintenance (Bullough, 2012b). New MH light sources with ceramic arc tubes and new methods of starting the source have increased efficiency, lifespan, and lumen maintenance. KDOT currently uses 250W of MH light sources at various locations as an external source of illumination for guide signs. According to Bullough’s survey in New York, the only two types of

light sources used on streets and highways in New York are HPS and MH (Bullough, 2012a).

LED

Recent technologies and advances in solid-state lighting have resulted in an LED light source that produces white light by using short wavelength LED that produces blue light in combination with phosphor, thus converting blue light into yellow and resulting in a white mixture (Bullough, 2012b). LED-based roadway lighting products offer a number of key advantages over traditional lighting technologies. In terms of luminous efficacy, product life cycle, field or lumen maintenance requirements, color, and environmental considerations, technology employed in LED lighting is vastly superior to other light source technology. Solid state LED-based products are designed to provide long life through light source design, power supply, optics, and mechanical housing. LED light sources are also free of lead and mercury and are compliant for Restriction of Hazardous Substances (RoHS) (Tri-State, 2012).

A study was conducted along the main street of Woodridge, NY found that twelve 40W LED light sources replaced eight 150W HPS light sources, and the residents of that village judged LED light installation as having more visual effectiveness and brighter appearance than HPS (Born, 2009). Cook et al. concluded that LED roadway lighting can provide equivalent overall performance to HPS roadway lighting at lower energy levels (Cook, et al., 2008). LED or induction light sources with 65W power can replace 100W HPS light source in order to achieve the same average unified light source (Bullough, 2012a).

LED light source for roadway lighting is able to meet American Association of State Highway and Transportation Officials (AASHTO) requirements published in 2005 with approximately 7% reduction in energy. An energy savings of 30% to 50% can be achieved by replacing HPS with LED or induction lighting in residential areas, and 35% to 40% by replacing HPS with LED or induction lighting at rural intersections where peripheral visibility is essential (Bullough, 2012a).

Induction Lighting

Induction lighting is modern fluorescent lamps use radio frequencies to stimulate lamp material to produce light, unlike conventional fluorescent lamps that use electrodes at either end of the lamp tube (Bullough, 2012b). Induction lighting, however, use radio frequency or microwaves to create induced electrical fields which, in turn, excite gases to produce light.

Induction lighting have the same color as conventional fluorescents and share their diffuse appearance, but they do not require the longer tubular shape of most fluorescent sources. A crucial disadvantage of induction fluorescent lamps is the lamp large size needed to provide uniform distribution of light on roadways as compared to HPS and MH (Bullough, 2012b).

Induction lights have a rapid start-up and work at peak efficiency with minimal warm-up time, much like LED technology. Disadvantages of induction lighting include limited directionality when compared to LEDs, and the presence of lead. Rapidly evolving LED technology has led to limited adoption of induction-based roadway lighting systems (Deco Lighting, 2010)

Light Emitting Plasma (LEP)

Plasma is a solid state, high-intensity, lighting technology that utilizes a single, very small electrode-less lamp and an electronic power driver (Thomasnet, 2012). The driver generates high radio frequency energy to create a plasma light source with 23,000 lumens of brilliant white light. This powerful output far exceeds LED fixtures that require many LEDs in a single housing. Due to the miniature lamp size, plasma light sources are much smaller in size with more efficient optical designs than any High Intensity Discharge (HID), floodlight, or architectural area fixture. Advantages of LEP include powerful clean white light, energy savings of 50% or more than HID lighting, efficacy as high as 115 lm/watt at the source, 50,000 hour life, excellent color, and dimming capability (controlling light intensity) up to 20% (Thomasnet, 2012).

Guide Sign Retroreflectivity Studies

In 1987, Lagergren performed a study to measure retroreflectivity of traffic signs (limited to stop and warning signs) using trained observers (Lagergren, 1987). In this study, a sign rating scale from 0 to 4 was used to train selected observers. This scale was explained as 0 refers to worst sign visibility and 4 to best visibility throughout the experiment. Observers were trained to rate traffic signs in a dark laboratory and on a straight level section of road using a stationary car. Signs were located ranging from 100 to 300 ft. After observers became well-trained, the experiment was performed on a highway at night where observers rated 130 signs, including some signs with retroreflective sheeting. The retroreflectivity of those signs was measured using a retroreflectometer. Ratings were then obtained by observers for the selected signs and were compared to ratings obtained by the retroreflectometer. Results showed that a high percentage of signs were rated correctly by the observers. Recommendations of this study include:

- The participating observers should take an evaluation procedure before the start of participation in the research.
- Sign criticality should be considered while replacing signs because states use different levels of retroreflectivity for different highway classifications.
- Agencies should develop a training program for personnel who perform sign replacement decisions.

Paniati and Mace performed a study in 1993 aimed at identifying minimum nighttime visibility required for traffic signs (Paniati & Mace, 1993). The researchers created a number of measuring devices and a computer management system to implement these minimum requirements in an efficient manner. They developed a Computerized Analysis of Retroreflectorized Traffic Signals (CARTS) which considered time and distance required to identify and respond to a traffic sign, the amount of luminance required for sign detection and recognition, and retroreflectivity levels required to ensure the necessary performance level.

In a study performed by McGee and Paniati in 1998, they created an implementation guide for determining minimum retroreflectivity requirements for traffic signs, to assist governmental and private agencies in the establishment of a cost-effective program for the replacement of ineffective traffic signs (McGee & Paniati, 1998). This research provided an explanation of retroreflectivity which includes concepts of retroreflection, luminance, the entrance angle, the observation angle, and coefficient of retroreflection (R_a). The researchers provided a description of different types of retroreflective sheeting materials and the difference among them according to the coefficient of retroreflection at different entrance and observation angles. The researchers also quoted minimum retroreflectivity values for four groups of signs based on earlier research. In addition, the report presented the concept of Sign Management System that was defined by a coordinated program of policies and procedures, ensuring that highway agencies provide a sign system that meets drivers’ needs according to budget constraints (McGee & Paniati, 1998). The researchers explained the concept of sign inventory and its purpose of assisting in targeting sign replacement, problem identification, minimizing tort liability, planning and budgeting for sign replacement, and maximizing productivity. In their research , McGee and Paniati suggest planning and developing an effective sign inventory process, including the involvement of key personnel, selecting a location as a reference system, selecting data elements, selecting inventory software, preparing for data collection, starting initial data collection, and maintaining inventory.

In 1999, an additional study performed by Russell et al. to determine the minimum value for overhead highway sign illumination, discover whether vehicular headlamp luminance on the highway is sufficient to provide minimum required luminance for nighttime drivers (Russell, et al., 1999). Researchers began the first phase of the study by conducting an experiment in the Photometric and Visibility Building at Turner-Fairbank Highway Research Center in McLean, Virginia, in which observers drove toward signs with unknown words, at a speed of 4.97 mph (8 km/hr). Observers were asked to push a button to turn off the lighted sign when the sign became legible. After each experiment, the observer reported what words were written on this sign to ensure the sign was legible to them. If they recognized the word(s) correctly, the distance travelled by the observers was recorded and their distance to the sign was determined. Russell et al. also performed two field tests in this study. They performed the experiment in straight flat level sections on two highways, Interstate 70 (I-70) and Interstate 435 (I-435) in Kansas, using seven photometers “5 Minolta T-1 illuminance meters and 2 international light IL-1700 luminance meters” which were sensitive to very low values. Researchers collected illuminance values measured at the photometers which were placed at various heights above the roadway and corresponded to typical shoulder and overhead sign heights. These illuminance values were collected from a sample of approximately 2,500 vehicles approaching in the right lane and using low beam headlamps. Marker plate numbers were read and motor vehicle records provided so manufacturer and model of vehicle could be determined. Analysis of variance (ANOVA) was conducted to find differences in illuminance levels between various vehicle types. The research team initially found that illuminance values detected were higher than those forecasted because of a substantial amount of light reflected from the pavement, and this was included in the luminance readings. Thus, it was decided to obtain additional data with the reflected light removed (Russell, et al., 1999).

Russell et al. performed a second field test in which pavement reflection was eliminated from luminance readings by using optical occluders (Russell, et al., 1999). The sample in this study was divided between 50 known vehicles along with 1,500 unknown vehicles which passed through the data collection location. Statistical analysis was performed on the sample in two parts: one for the 50 known vehicles, and the other part for the unknown 1,500 vehicles. Results of this study showed that sufficient light was available for ground mounted signs on the left and the right of highway shoulders, but insufficient light was available for overhead guide signs. Researchers concluded that the values of minimum luminance for overhead guide signs were 0.316 cd/ft^2 at 275.59 ft in distance (3.4 cd/m^2 at 84 meter), 0.334 cd/ft^2 at 374.015 ft in distance (or 3.6 cd/m^2 at 114 meter), and 0.344 cd/ft^2 at 498.687 ft in distance (3.7 cd/m^2 at 152 meter).

In a study performed by Carlson and Hawkins in 2003 to find minimum retroreflectivity levels for overhead guide signs and street name signs, researchers developed a computational model based on the relationship between headlights and sign, and the geometric relationship between headlights, sign, and driver (Carlson & Hawkins, 2003). They developed Equation 2.1 for determining minimum retroreflectivity:

$$Minimum\ R_A = New\ R_{A,SG} \times \left(\frac{Demand\ R_{A,NSG}}{Supply\ R_{A,NSG}}\right) \tag{2.1}$$

Where; Minimum R_A = minimum retroreflectivity at standard measurement geometry (observation angle = 0.2 degree and entrance angle of -4.0 degree)

New $R_{A,\ SG}$ = averaged retroreflectivity of new sheeting at standard geometry (cd/lx/m^2)

Demand $R_{A,\ NSG}$ = retroreflectivity needed to produce minimum luminance at the nonstandard geometry (cd/lx/m^2)

Supply $R_{A,\ NSG}$ = retroreflectivity of new sheeting at the nonstandard geometry (cd/lx/m^2)

Carlson and Hawkins also conducted a field study on a sample of 30 subjects ages 55 or older, and they used 32 different headlight illumination levels (Carlson & Hawkins, 2003). The field study was performed during real world driving conditions on a closed course. Selected subjects were asked to read different types of retroreflective signs. This study analyzed various factors impacting minimum retroreflectivity levels for overhead guide signs, including distance, location of the sign, retroreflective sheeting material, headlamp illumination, accommodation level, vehicle speed, and vehicle type. In this study, three factors determined the model applicability in real life situations: 1) sign position relative to position of the vehicle; 2) accommodation level of drivers ages 55 or older; and 3) rounding the minimum retroreflectivity level for overhead and street name signs to the nearest integer that is dividable by five. Carlson and Hawkins (2003) performed follow up research that included updated factors such as the effect of changing accommodations of nighttime drivers, updated vehicle headlamp profiles, larger observation angles representing typical headlamps of many vehicles (truck, SUV, sedan, and minivan) used in developing minimum retroreflectivity levels for overhead guide signs were based on minimum luminance values of 2.3 and 3.2 cd/m^2 for drivers 55 and 65 years of age, respectively.

In 2003, Zwahlen et al. performed nighttime field evaluations of four different retroreflective overhead sign sheeting combinations (Zwahlen, et al., 2003). When externally lighted and unlighted (by low-beam headlight only), the sheeting materials were compared for appearance, legibility, and conspicuity. These sign sheeting material combinations were tested photometrically under low-beam illumination at distances ranging from 200 to 1,000 ft. The sheeting material combinations used in this study were as follows:

- Group A: Beaded Type III legend on beaded Type III background
- Group B: Type IX legend on beaded Type III background
- Group C: Type IX legend on Type IX background, and
- Group D: Type VII legend on beaded Type III background

Zwahlen et al. research was performed in two separate phases: 1) expert panel field evaluation, and 2) photometric evaluation. From these two phases, researchers concluded that the practice of external lighting of overhead signs can be discontinued if either white types VII or IX legend are used on green beaded type III backgrounds. Researchers recommended that this change from lighted to unlighted overhead signs with white micro prismatic legends on green type III backgrounds will provide many benefits, including eliminating the need for luminary installation, lower maintenance cost, and lower electricity cost.

In a study performed by Bullough et al. in 2005, a three-phase project was conducted to measure luminance and luminance contrast values of signs installed along a specific highway (Bullough, et al., 2008). The function of this study was to measure the appearance of signs under different luminance contrast values and to estimate the signs’ visual performance for approaching drivers compared to externally lighted signs that meet AASHTO recommendations for exterior sign lighting (AASHTO, 2005). A specific location was selected in order to perform photometric measurements of the sign luminance. This location was visited two times in 2006. Nighttime measurements were made during the visits, and the daytime measurement was performed in the later visit only. Measurements were made using a spectroradiometer equipped with a telephoto lens. The spectroradiometer was mounted onto a tripod in a Dodge Caravan vehicle, driven along the highway, and stopped approximately 328.08 ft (or 100 meter) and maximum 354.33 ft (or 108 meter) from the sign. The lens of the spectrometer was kept as close as possible to the driver's eye level. Nine signs were installed in the location using the following types of retroreflective sheeting materials to make the signs in the study:

- Two from VIIIa: meet ASTM (2007) type VIII specifications.
- Two from VIIIb: meet ASTM (2007) type VIII specifications.
- Four from IX: meet ASTM (2007) type IX specifications.
- One from the proposed XI: meet proposed type XI and existing ASTM (2007) type IX specifications.

Luminance measurements were made by positioning the measurement spot of the spectroradiometer onto three background and three character locations of the signs. Luminance contrasts were calculated using Equation 2.2:

$$C = \frac{|L_c - L_b|}{max(L_c, L_b)} \qquad 2.2$$

Where; C is the luminance contrast, L_c is the luminance of the character in cd/m^2, and L_b is the luminance of the background in cd/m^2

Luminance measures obtained for the new signs were compared to those obtained for regular signs along the same location of the study. This model provides some basis for calculating accuracy and speed at which visual information can be processed given the following input parameters: a) size of the visual target; b) background luminance around the visual target; c) luminance contrast between the visual target and its background; and d) age of the observer. The third phase was about subjective evaluations. The apparatus used in the evaluation consisted of two main systems: a tower with a dynamic presentation system and a computer-controlled system. Side-by-side observations were conducted during nighttime sessions. Observers sat in a vehicle parked behind a properly aimed Halogen headlamp set located at a distance of 328.083 ft (or 100 meter) from the apparatus. During the first session, some observers noticed that the letter "E" on the sign panel was difficult to read. Another session was performed at a 196.85 ft (or 60 meter) distance and the rating data obtained from both sessions were combined. Ratings were provided and three repetitions at each luminance contrast were conducted. ANOVA was conducted to analyze the differences. Sequential viewing observations in this phase were conducted as side-by-side observations during nighttime. The same headlamp set was used, but both sessions used a viewing distance of 196.85 ft (or 60 meter) from the sign panel. Three repetitions at each luminance contrast were observed as in side-by-side viewing, ratings were recorded, and ANOVA was used in the analysis.

In the study by Bullough et al. in 2008, researchers concluded that measured luminance values, resulting calculated luminance contrasts, and visual response values all indicated that, in terms of visual performance, unlighted highway signs and new signs constructed from four types of retroreflective materials are similar to externally lighted signs when compared to externally lighted signs meeting AASHTO (2005) recommendations for guide sign illumination from a 328.083 ft (or 100 meter) viewing distance (Bullough, et al., 2008). Important related factors included location of the signs relative to vehicles, headlight condition, ambient illumination, and other factors affecting actual luminance of sign background and characters.

In 2012, Jonathan and Carlson performed a research study in which four states (New York, Minnesota, Arizona, and Missouri) were selected to provide examples of effective and beneficial practices demonstrating how various agencies meet the MUTCD of 2009 roadway sign retroreflectivity requirements (Jonathan & Carlson, 2012). Researchers used three sources to gather information: 1) existing published research; 2) existing guidance and policies; and 3) a telephone survey. The survey included 14 questions, and 48 public agencies participated. Survey findings identified several strategies and techniques that were considered effective practices among the states. Among participating states and local agencies, the decision to replace a sign was made based on four methods: 1) The expected sign life method was the most selected method for replacing signs (approximately 37.5%); 2) The most popular practice among participating states was nighttime visual inspection, involving training programs to ensure inspector proficiency (32.5%); 3) Twenty percent of agencies performed the blanket replacement method ; 4) Five percent of agencies used the process of measuring retroreflectivity. However, the process of measuring retroreflectivity and control sign methods is associated with high cost due to the retroreflectometer used and time spent taking measurements. Cost and time are crucial deciding factors in whether to use these methods or not. Purchasing a retroreflectometer can be expensive; however, resulting measurements could be valuable enough to justify the extension of sign replacement periods. Replacing signs based on retroreflectivity measurements can be time-consuming, though.

Chapter 3 - Survey and Survey Analysis

Introduction

A guide sign illumination survey was distributed to the 50 state Departments of Transportation via e-mail during the period between August 9 and September 15, 2012. The survey consisted of six questions focused on the following:

- Current usage of overhead guide sign lighting,
- Light source types and optical package used in illuminating overhead guide signs,
- Policy and/or procedures used in designing and installing overhead guide signs, and
- Any new types of guide sign illumination used or planned to be used in the future.

Results and Discussion

During the survey period, responses were received from 31 of the DOTs (62%). In addition to the USDOT survey, another survey by Gund, administered between February and March 2011, was studied to enhance responses received to the USDOT survey (Gund, 2011). In addition, some related material that enhanced the USDOT survey was reported by the AASHTO joint technical committee in December 2010 (AASHTO, 2011). Responses to the USDOT survey questions are shown, followed by related material found in either Gund or AASHTO references:

Question 1: Does your state currently use lighting for some overhead guide signs?

As shown in Table 3.1, among the 31 states that responded, responses to this question were divided into two scenarios for analysis:

A. Twelve states (38.71%) responded “Yes,” fourteen states (45.16%) responded “No,” and five states (16.13%) responded that they had used sign lighting in the past but were currently phasing it out.
B. Considering the states that are currently lighting their guide signs but phasing it out to be as those who are illuminating their overhead guide signs, seventeen (54.84%) of these states responded “Yes,” and fourteen (45.16%) of these states responded “No.”

Table 3.1 Current Usage of Overhead Guide Sign Lighting in the U.S.: Verbatim Responses from USDOT Survey

	State	Response	Usage
1	Alabama	Some older overhead guide signs are illuminated; however, several years ago we stopped including lighting when installing new overhead guide signs.	Yes, phasing out
2	Alaska	No dedicated sign illumination. The limited number of overhead signs is illuminated by adjacent roadway illumination.	Yes, phasing out

	State	Response	Usage
3	Arkansas	We do not use lighting for any overhead guide signs. We did at one time but they became a maintenance issue.	No
4	Connecticut	The Connecticut Department of Transportation (ConnDOT) no longer utilizes sign lighting.	No
5	Delaware	No, we use all Type IX sheeting or above.	No
6	Florida	Yes	Yes
7	Hawaii	No	No
8	Idaho	Yes	Yes
9	Illinois	Yes, but current policy is no sign lighting.	Yes
10	Indiana	Currently INDOT does not light overhead guide signs.	No
11	Iowa	Existing lighting is maintained, but no new lighting is being installed with overhead guide signs.	Yes, phasing out
12	Kentucky	Kentucky does not light our overhead guide signs.	No
13	Louisiana	No, Louisiana does not light overhead signs.	No
14	Mississippi	Does not light any overhead guide signs.	No
15	Michigan	The Michigan Department of Transportation does not light overhead signs.	No
16	Nebraska	Yes	Yes
17	New Mexico	We don’t use any lighting for our overhead signs. There are a few left from the past that we are phasing out! We are also a dark sky state[1]. The fixtures must be full cutoff with flat glass. HID or any other lighting over 70 watts cannot be used 90 degrees above nadir.	Yes, phasing out
18	North Carolina	Yes	Yes
19	Ohio	No	No
20	Oklahoma	No	No
21	Oregon	Yes	Yes
22	Rhode Island	No	No
23	South Carolina	Yes. We use sign lighting in areas that have large amounts of ambient light from other sources.	Yes
24	South Dakota	South Dakota DOT just this summer added lighting to 4 overhead signs.	Yes

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1 An e-mail follow-up to the contacted person for the New Mexico response, asking about the meaning of dark sky state, answered: “We have night sky protection act that passed through our legislature in the year 2000. This limits the amount of light above horizontal. The intension is to limit light pollution” (Jian, 2012).

	State	Response	Usage
25	Tennessee	We do not use overhead guide sign lighting in the State of Tennessee.	No
26	Texas	We still have some sign lighting, but have been phasing it out over the last several years in favor of reflective sheeting.	Yes, Phasing out
27	Utah	Yes	Yes
28	Vermont	For overhead signs, we require signs to be sheeted with a minimum of AASHTO Type IX sheeting for both the background and the legend.	No
29	Virginia	Yes, at one time VDOT lit most overhead signs. During that period, we used an ASTM Type III sheeting. Many of these signs/sign lighting installations remain in place today. Beginning in 2005, we moved to using Clearview fonts on guide signs and required that the lettering and borders be an ASTM Type VIII or IX. With the use of these “premium” prismatic letters and borders, we advised our designers and maintenance staffs that the need for overhead sign lighting had diminished and that the use of sign lighting should be an engineering decision based in several factors (see response to question 6).	Yes
30	West Virginia	Yes	Yes
31	Wyoming	Yes	Yes

In the survey performed by Gund (2011), regarding guide sign retroreflectivity, two questions were related to the USDOT survey: questions 17 and 18. Answers to these two questions resulted in including three additional states to the USDOT survey (Missouri, Kansas, and Wisconsin). Their answers are shown in Table 3.2.

“17) Does your agency use external illumination for overhead guide signs? (Yes or No)

18) If your answer to the above question is ‘Yes,’ what source does your agency use for external illumination of the overhead guide signs?” (Gund, 2011)

Table 3.2 Related Results from Gund Survey (Gund, 2011)

	State	Response	Usage
1	Missouri	Our lighting structures are lit using Metal Halide lamps for color clarity and we have a couple of test LED fixtures that are under evaluation.	Yes
2	Kansas	Electricity, Hooked into Westar energy.	Yes
3	Wisconsin	Wisconsin DOT still illuminates some overhead signs in the Milwaukee metropolitan area. These are signs with the encapsulated bead high intensity legend and	Yes, phasing out

	State	Response	Usage
		background (ASTM D4956-09 Type II sheeting). As these signs are replaced to our new sheeting standard of Type IX or better, the lights are being turned off. Effectively, WisDOT is phasing out the usage of overhead sign lighting. No new overhead sign lighting is being installed. WisDOT uses 250 Watt Mercury Vapor sign lighting luminaires at various voltages. The lamp that is used is a deluxe mercury vapor.	

In another survey conducted by AASHTO Joint Technical Committee in December 2010, (AASHTO Survey) data was found for one additional state, Massachusetts, and this state does not illuminate highway signs (AASHTO, 2011).

In combining the three surveys, USDOT, Gund, and ASSHTO, a total of thirty-five states responded (thirty-one to the USDOT survey, three to the Gund survey, and one to the ASSHTO survey). The following scenarios, with modified statistics on overhead guide sign lighting, are:

A. In regard to whether states were using overhead guide sign lighting, fourteen states (40%) responded "Yes," fifteen states (42.86%) responded "No," and six states (17.14%) responded that they had used overhead guide sign lighting in the past but were currently phasing it out.
B. Considering only those who had responded that they are phasing out overhead guide sign lighting, twenty states (57.15%) responded "Yes" and 15 states (42.85%) responded "No."

Question 2: What lamp type is currently used in the illumination of overhead guide signs in your state? (E.g. Standard Metal Halide, Ceramic Metal Halide, induction lighting, LED, or others)?

For the seventeen states (54.84%) that responded to the survey and answered that they light overhead guide signs, the lamp types used for illumination were Standard MH, HPS, induction, MV and the LED. Table 3.3 shows responses from the states. Results shown in Table 3.2 were added to the calculations, as well.

Table 3.3 Lamp Types Reported in USDOT Survey as Used for Overhead Guide Sign Illumination: Verbatim Responses

	State	Response	Usage
1	Alabama	We use standard Metal Halide lamps.	Yes, phasing out
2	Alaska	Typically overhead sign illumination is from adjacent roadway illumination, including some high mast lighting systems rather than illumination positioned beneath the overhead sign. As a result HPS is typical.	Yes, phasing out

	State	Response	Usage
3	Arkansas	---[2]	No
4	Connecticut	Prior to the installation of more highly reflective signs, ConnDOT specified the use of 250 and 400 watt metal halide with prismatic glass lens, Holophane Panel-Vue sign lights.	No
5	Delaware	---	No
6	Florida	Induction	Yes
7	Hawaii	---	No
8	Idaho	Our currently approved sign lighting fixtures use 150 Watt HPS lamps.	Yes
9	Illinois	High Pressure Sodium (usually 150W).	Yes
10	Indiana	If required, 250W MV/HPS currently.	No
11	Iowa	HPS	Yes, phasing out
12	Kentucky	---	No
13	Louisiana	N/A	No
14	Mississippi	---	No
15	Michigan	---	No
16	Nebraska	High Pressure Sodium.	Yes
17	New Mexico	---	Yes, phasing out
18	North Carolina	Others - High Pressure Sodium and Mercury Vapor.	Yes
19	Ohio	N/A	No
20	Oklahoma	We did use 150 watt HPS.	No
21	Oregon	Metal Halide.	Yes
22	Rhode Island	N/A	No
23	South Carolina	We used mercury vapor until recently. We now use Metal Halide.	Yes
24	South Dakota	LED	Yes
25	Tennessee	---	No
26	Texas	All the remaining sign lighting is still Mercury Vapor.	Yes, phasing out
27	Utah	Mostly HPS (typically 250W), and some induction (70W - 165W).	Yes
28	Vermont	---	No
29	Virginia	HPS	Yes
30	West Virginia	Mostly Metal Halide, but we are currently looking at LED.	Yes
31	Wyoming	Metal Halide.	Yes

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[2] --- Means the state did not respond to this question.

Among the 20 states that use lighting for overhead guide signs, including states in Gund's survey, five states (25%) (Alabama, Missouri, Oregon, West Virginia, and Wyoming) use MH lighting only. Six states (30%) (Alaska, Idaho, Illinois, Iowa, Nebraska, and Virginia) use HPS and two states (10%) (Wisconsin and Texas) use MV. One state (5%), Florida, uses induction lighting, and South Dakota (5%) uses LED lighting. When combined (25%), the remaining states use two types of lighting. For example, Kansas and North Carolina use MV and HPS, South Carolina uses MV for greater light clarity, and Utah uses HPS and some Induction lighting. One state, New Mexico, did not disclose what type of lighting they use. Three states (Connecticut, Indiana, and Oklahoma) answered "No" to whether they used overhead guide sign lighting, but in their response to question 2 (type of lamp used), they mentioned the type of lighting they used for illuminating overhead guide signs. This could mean they are using guide sign lighting but are phasing it out.

Question 3: Which optical package is typically used for the lighting in your state? (e.g. reflector/clear flat glass, refractor, stippled flat glass, or others)

Among states that responded that they light overhead guide signs, seventeen states out of thirty-one respondents stated that several types of optical packages such as reflector with clear flat glass, full cut-off road side luminaire, high mast heads, refractor, and prismatic glass lens (glass diffuser) are used for guide sign lighting. Detailed responses are shown in Table 3.4. These answers included some optical package types related to street lighting, but only two types of glass that were related to overhead guide sign lighting, clear glass and prismatic glass, were considered.

Table 3.4 Optical Packages Used for Overhead Guide Sign Lighting: Verbatim Responses

	State	Response	Usage
1	Alabama	We use reflector/clear flat glass.	Yes, phasing out
2	Alaska	Clear flat - full cut-off road side luminaire, and high mast heads.	Yes, phasing out
3	Arkansas	---	No
4	Connecticut	Prismatic glass lens.	No
5	Delaware	---	No
6	Florida	Reflector/clear flat glass, refractor.	Yes
7	Hawaii	---	No
8	Idaho	We have a combination of reflector/clear flat glass and refractor.	Yes
9	Illinois	Refractor	Yes
10	Indiana	Refractor	No

	State	Response	Usage
11	Iowa	---	Yes, phasing out
12	Kentucky	---	No
13	Louisiana	N/A	No
14	Mississippi	---	No
15	Michigan	---	No
16	Nebraska	Reflector/clear flat glass.	Yes
17	New Mexico	---	Yes, phasing out
18	North Carolina	Glass diffuser.	Yes
19	Ohio	N/A	No
20	Oklahoma	Reflector/clear glass.	No
21	Oregon	Reflector and refractor.	Yes
22	Rhode Island	N/A	No
23	South Carolina	We typically use Holophane sign lights with refractors.	Yes
24	South Dakota	LEDs	Yes
25	Tennessee	---	No
26	Texas	Reflector with clear flat glass.	Yes, phasing out
27	Utah	Most of the old HPS's have a refractor lens. The inductions have a reflector with clear flat glass.	Yes
28	Vermont	---	No
29	Virginia	Reflector with flat glass is typical.	Yes
30	West Virginia	Flat Glass.	Yes
31	Wyoming	Reflector/clear flat glass.	Yes

Question 4: Are AASHTO or Illuminating Engineering Society (IES) sign lighting levels used in the design of your overhead guide sign lighting or are installations based on historical practice and/or experience?

Among the seventeen states that responded that they light their overhead guide signs, three states (17.65%) (Idaho, South Carolina, and South Dakota) follow AASHTO standards, four states (23.53%) (Alabama, Illinois, West Virginia, and Wyoming) use IES standards, three states (17.65%) (Florida, North Carolina, and Utah) use both AASHTO and IES standards, three states (17.65%) (Alaska, Oregon, and Texas) follow historical practice and experience, one state (5.87%), Virginia, has its own standards and policies, and three states (17.65%) (Iowa, Nebraska, and New Mexico) have or use no standards or specifications. Detailed responses are shown in Table 3.5.

Indiana and Oklahoma responded that they use historical data, meaning, as in question 3, their response seemingly contradicts their “No” answer to question 1. A possible explanation may be those two states are phasing out the lighting.

Table 3.5 States' Standards for Designing Overhead Guide Sign Illumination: Verbatim Responses

	State	Response	Usage
1	Alabama	In the past, our designers used IES sign lighting levels.	Yes, phasing out
2	Alaska	I'd say historical practice/experience.	Yes, phasing out
3	Arkansas	---	No
4	Connecticut	N/A - ConnDOT no longer specifies the illumination of overhead signs.	No
5	Delaware	---	No
6	Florida	Yes	Yes
7	Hawaii	---	No
8	Idaho	Yes, when possible AASHTO recommendations are met for average Fc levels and Max/Min uniformity.	Yes
9	Illinois	IES RP-19	Yes
10	Indiana	Historical practice based on the size of the sign.	No
11	Iowa	N/A	Yes, phasing out
12	Kentucky	---	No
13	Louisiana	N/A	No
14	Mississippi	---	No
15	Michigan	---	No
16	Nebraska	---	Yes
17	New Mexico	---	Yes, phasing out
18	North Carolina	Yes, AASHTO & IES lighting levels are used.	Yes
19	Ohio	N/A	No
20	Oklahoma	Installations were based on historical practice.	No
21	Oregon	Historical practice, currently no new sign lighting designed.	Yes
22	Rhode Island	N/A	No
23	South Carolina	Our lighting systems are designed using AASHTO's roadway lighting guide.	Yes
24	South Dakota	AASHTO standards.	Yes
25	Tennessee	---	No
26	Texas	Historical practice/experience.	Yes, phasing out
27	Utah	I would suspect a combination of both, but more recent installations have been AASHTO-based.	Yes
28	Vermont	---	No
29	Virginia	VDOT Specification for sign luminaires is based in a simple approach. It reads: Sign Luminaires: Luminaires shall be shielded to eliminate glare or extraneous light on the roadway and shall provide a maximum-to-minimum uniformity ratio of 1:1 to 6:1 when installed. When tested at the center of a 10-foot-square test panel, the	Yes

	State	Response	Usage
		luminaire shall provide at least 30 average initial foot candles and a gradient (ratio of illumination on any two adjacent square feet of sign surface) of 2:1 or less. Designers are required to design in compliance with IES Standards.	
30	West Virginia	IES	Yes
31	Wyoming	IES	Yes

Question 5: Are you looking at other emerging sources for your overhead guide signs lighting? (e.g. Ceramic Metal Halide, induction lighting, LED, Plasma, or other)

Among the seventeen states which answered “Yes” to question 1 in the USDOT survey, eleven states (64.7%) answered “Yes,” and six states (35.3%) answered “No.” The states that answered “Yes” were divided into four groups according to their reported future plans. The first group of six states (54.55%) (Florida, Idaho, South Dakota, South Carolina, Virginia, and West Virginia) includes those looking to switch to LED lighting. The second group included two states (18.18%) (Oregon, and Wyoming), that are transitioning to induction lighting. The third group, comprised of two states (18.18%) (North Carolina and Utah) included those hoping to use or upgrade retroreflective sheeting on overhead guide signs. The last group was comprised of one state (9.09%) (Illinois) which is trying to eliminate overhead guide sign lighting. (For more details, reader may refer to Illinois’ answer to question 6). States that answered “No,” such as Alabama, Alaska, Iowa, Nebraska, Texas, and North Carolina are attempting to eliminate guide sign lighting by using retroreflective sheeting guide signs. (For more information, reader may refer to the answer for question 6 by these states). Detailed responses to this question are shown below in Table 3.6.

Table 3.6 States’ Emerging Sources for Overhead Guide Sign Illumination: Verbatim Responses

	State	Response	Usage
1	Alabama	No. (See response to question 1.)	Yes, phasing out
2	Alaska	No	Yes, phasing out
3	Arkansas	---	No
4	Connecticut	Not at this time.	No
5	Delaware	----	No
6	Florida	LED	Yes
7	Hawaii	---	No
8	Idaho	Yes. We are currently experimenting with LED. We have 4 signs lit using LED fixtures with good	Yes

	State	Response	Usage
		results and an approx. 80 percent reduction in power.	
9	Illinois	Yes, but not officially since current policy is no sign lighting for new installations.	Yes
10	Indiana	N/A	No
11	Iowa	No	Yes, phasing out
12	Kentucky	---	No
13	Louisiana	N/A	No
14	Mississippi	---	No
15	Michigan	---	No
16	Nebraska	No	Yes
17	New Mexico	We are not	Yes, phasing out
18	North Carolina	No - we are moving towards using higher retroreflective sign sheeting.	Yes
19	Ohio	No	No
20	Oklahoma	We are discontinuing using overhead sign lighting due to the numerous hits on the structures that have overhead sign lighting.	No
21	Oregon	Induction lighting.	Yes
22	Rhode Island	N/A	No
23	South Carolina	We are looking at LED technology and have retrofitted one system with LED fixtures to examine how they compare with traditional fixtures.	Yes
24	South Dakota	LED	Yes
25	Tennessee	---	No
26	Texas	No, we are phasing out sign lighting.	Yes, phasing out
27	Utah	We have opted to eliminate sign lighting altogether. Our new standard is a type XI sheeting requirement with no sign lighting. We will remove sign lighting as old signs are replaced with upgrades.	Yes
28	Vermont	---	No
29	Virginia	At this time we are considering pursuing an evaluation of LEDs, including a comparison of the total cost of ownership of other technologies, and we are evaluating news and information as it is released. We have recently had the developer of a "Public/Private Partnership" roadway propose to use LED for sign lighting.	Yes
30	West Virginia	Yes, LED	Yes
31	Wyoming	Yes induction	Yes

Question 6: What does the future look like for overhead guide signs lighting in your state? (Continue its use, modify where/when it is used, or eliminate with use of different sign materials)

Responses to this question are shown in Table 3.7. In summary, some states are moving towards discontinuation of overhead guide sign illumination and transitioning to brighter retroreflective sheeting materials. Other states are modifying the lighting and moving toward new energy efficient light source types such as LEDs and induction lighting; they will maintain the procedure of illuminating guide signs. Others have already eliminated overhead guide sign lighting and will not illuminate guide signs. Others are transitioning to new lighting methods or retroreflective sheeting, and some states leave the decision of maintaining overhead guide sign illumination or using brighter retroreflective sign sheeting to their engineers who decide according to the situation.

Table 3.7 Future Plans for Overhead Guide Signs in States: Verbatim Responses

	State	Response	Usage
1	Alabama	We are moving towards eliminating lighting for overhead guide signs. We believe that the new Federal retroreflectivity requirements will make that type of lighting unnecessary.	Yes, phasing out
2	Alaska	No change from today.	Yes, phasing out
3	Arkansas	---	No
4	Connecticut	Maintain policy of no longer illuminating highly reflective signs.	No
5	Delaware	---	No
6	Florida	Modify where/when it is used.	Yes
7	Hawaii	We have started to use Type XI reflective sheet for overhead signs and removing the sign lighting. This approach seems to be working well.	No
8	Idaho	We are considering two options: 1) upgraded sheeting and no sign lighters, and 2) upgraded sheeting with LED sign lighters (either new or upgraded existing).	Yes
9	Illinois	Highly retroreflective sheeting material has eliminated the need for most sign lighting.	Yes
10	Indiana	INDOT already eliminated lighting the overhead guide signs.	No
11	Iowa	Do not plan to light overhead guide signs because of the new sign sheeting.	Yes, phasing out
12	Kentucky	Do not plan to pursue sign lighting.	No

	State	Response	Usage
13	Louisiana	We stopped using sign lighting in 1986 when we started using High Intensity Beaded Sheeting (type III). We are now using High Intensity Prismatic Sheeting.	No
14	Mississippi	---	No
15	Michigan	---	No
16	Nebraska	Replacing with sign material as signs are replaced.	Yes
17	New Mexico	---	Yes, phasing out
18	North Carolina	Elimination.	Yes
19	Ohio	Continue not using.	No
20	Oklahoma	As mentioned in previous question and answer, we are discontinuing overhead sign lighting. We are using type III sheeting for a background and type IX sheeting for legends and borders. That combination is working out well for Oklahoma.	No
21	Oregon	Not much of new installation. Remove existing sign lighting when we upgrade signs.	Yes
22	Rhode Island	We have no plans to change our overhead sign lighting policy. We have no plans to install lighting on overhead signs.	No
23	South Carolina	We will continue to use sign lighting in areas around larger metropolitan areas where extraneous light is most intense.	Yes
24	South Dakota	SDDOT is currently in the process of reviewing its practice of lighting overhead signs.	Yes
25	Tennessee	---	No
26	Texas	Eliminate with use of different sign materials.	Yes, Phasing out
27	Utah	See Question 5.	Yes
28	Vermont	---	No
29	Virginia	In 2008 Virginia was going through a transformation regarding lighting of overhead signs. Central Office Traffic Engineering instituted a policy about seven years ago that all new positive contrast overhead signs should use Clearview font and premium grade prismatic sheeting for the lettering and border. Basically, that equates to all new guide signs being fabricated with a Grade VIII or IX lettering on a Type III background. At nearly the same time, VDOT launched a statewide maintenance project that, in part, resulted in the removal of all OH sign maintenance "cat walks" as they lacked all the safety features that would be desirable. In doing that, we removed a large number of the existing lighting fixtures. Ultimately, we tested the remaining signs for adequate visibility. If it failed to provide the perceived human need, the sheeting was replaced with the premium prismatic sheeting and the	Yes

	State	Response	Usage
		lights were left off. Beginning with projects advertised in February of 2011, VDOT moved to requiring all signs be fabricated using ASTM Type IX sheeting, thus that a very high level of light return (headlamp) would be achieved. That specification may be viewed at: http://www.virginiadot.org/business/resources/const/07RevDiv_II.pdf Use word search: SS24701 to access the Special Provision Copied Note that goes with all projects. Today VDOT takes a position that the choice to use or not to use lighting on overhead signs is an engineering decision. We recommend it should remain as such. We presume that sign lighting is not necessary unless present and projected volumes, design speed, degree of horizontal curvature right, degree of horizontal curvature left, percent of positive grade change, percent of negative grade change, amount of ambient light present, amount of potential future ambient light, number of signs or length of messages being presented at one location, etc. Our designers maintain the concept that all new overhead signs structures are engineered to accommodate the future installation of sign lighting and a light retrieval system. It is our thought that while this may add a very small initial cost to the structures, it will, more importantly, allow for the addition of lighting in the future should unexpected volume increases occur, should the speed change, or should an unexpected increase of ambient lighting take place, but more than that, it would allow for adding lighting at locations that prove themselves to need it in spite of the best engineering decision that indicated it would not be needed. We made no public announcement about this change in stance and thus far public comments have not materialized, positive or negative.	
30	West Virginia	Modify where/when it is used.	Yes
31	Wyoming	Eliminated 95% to date. The remaining 5% is needed.	Yes

Summary

Based on the USDOT survey analysis, including analysis of two other surveys (Gund and AASHTO), states have two procedures or future plans for improving overhead guide sign visibility during nighttime: either illuminating signs, usually with newer, more efficient light sources, or by using newer, brighter retroreflective sheeting materials. The main objective was to provide adequate sign visibility while saving energy and reducing cost. The most common light sources currently used in illuminating overhead guide signs, according to states that responded to the surveys and illuminate signs, were MH, MV, HPS, induction, and LED.

In designing overhead guide sign lighting, states may refer to AASHTO standards, IES standards, both AASHTO and IES standards, historical practices and experiences, or to the state's own standards.

Future plans for states were distributed between modifying existing overhead guide sign lighting into new, more efficient methods of illumination which save energy and cost, or toward the use of new, brighter retroreflective sheeting on overhead guide signs.

From the USDOT survey, some states reported that they will continue using guide sign illumination, but they are seeking the best type of light source from two points of view: lighting efficiency and energy saving. Some states responded that they are transitioning from one type of light source to another, specifically to new lighting technologies: LED and induction. South Dakota started using LED lighting in the summer of 2012 for four overhead guide signs (as demonstrated by responses in question 1). In an email follow-up to the contacted person for South Dakota, the answer was, "the reason for the selection had more to do with maintenance of the lights, i.e., South Dakota DOT wanted the longest life possible due to the location of the signs" (Martell, 2012). In addition, in testing for LED efficiency, Idaho and South Carolina are using LED lighting to illuminate some overhead guide signs. (Refer to question 5). Two states are currently using induction lighting (Florida and Utah), and two states are looking into the use of induction lighting for overhead guide signs (Oregon, and Wyoming).

Chapter 4 - Light Emitting Diodes

Introduction

Personal security, traffic flow operations, and safety can be improved by efficient roadway lighting (Medina, et al., 2013). Roadway lighting is a basic public requirement that leads to a safer environment for both drivers and pedestrians. Drivers can easily recognize street conditions and geometry of the roadway with availability of proper roadway lighting. Proper roadway lighting also contributes to highway safety by increasing drivers' visual comfort and reducing drivers' fatigue (IDOT, 2002).

Energy conservation is essential in the midst of a worldwide energy crisis. As of 2007, in the U.S., total street and area light number was 131.356 million with a total annual consumption of 178.3 billion kWh (Navigant Consulting Inc., 2008). Table 4.1 shows street and area lights installed in 2007 based on Navigant Consulting Inc. In addition, U.S. road lighting consumes 14 billion kWh of the annual energy, which represents approximately 3% of total electricity consumption in the U.S. (Li, et al., 2009). Similarly, the public lighting system in China represents 6% consumption out of the annual electricity demand, making energy consumption essential in China (Li, et al., 2009). In addition, 24% of the energy consumed by municipalities in South Africa is contributed to street lighting (Avrenli, et al., 2012). All previous examples resulted in making energy conservation an essential priority in the midst of a spreading energy crisis due to decreasing oil and gas reserve levels and increasing demand.

Table 4.1 Street and Area Lights Installed in the U.S. as of 2007 (Navigant Consulting Inc., 2008)

Light Source	Percentage	Number of Lights (Million)
Incandescent	2.4	3.159
Halogen Quartz	7.5	9.917
Fluorescent	5.7	7.530
Mercury Vapor	13.5	17.675
Metal Halide	29.2	38.330
High Pressure Sodium	41.7	54.745
Total	100	131.356

LEDs are fourth generation light sources. LEDs have recently proven that they are an energy efficient solution to street lighting. When an electrical current runs through an LED, which is a semiconductor, light is emitted (Avrenli, et al., 2012).

Until a few years ago, LED lighting technology was limited for use as architecture or a niche-type white color lighting application because of LED characteristics being too dim and very expensive (Neary & Quijano, 2009). Recently, new LED technology has created an evolution in the overall technology of lighting as it shows enormous improvement in high LED brightness, which has resulted in increasing and expanding usage of LEDs in street lighting, parking garage lighting, and commercial and residential area lighting (Neary & Quijano, 2009). The value of using LEDs includes very long life, energy efficiency, and low operating cost as compared to conventional lighting (Neary & Quijano, 2009). In addition, LED is a robust lighting source that does not use any glass or filaments which support their usage in high vibration areas such as mining or power generation (Neary & Quijano, 2009). Moreover, LEDs cause no concern with the environment and they are free of mercury and heavy metals such as lead (Neary & Quijano, 2009).

Despite all LED benefits, transitioning to LEDs is challenging because the development of conventional lighting was around standard lamp style technologies and retrofitting existing fixtures can be achieved after careful engineering design and, in many cases, it does not fully optimize technology performance (Neary & Quijano, 2009). LEDs have drawbacks and limitations, however. The following sections provide a detailed discussion of LEDs.

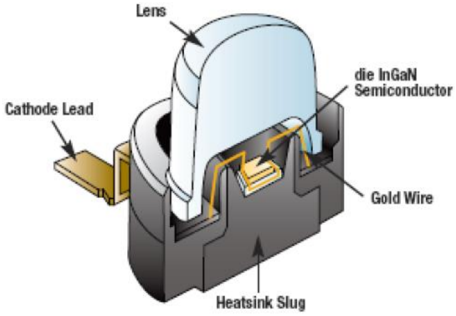
LED Illumination System

LED street lamps consist of the following: LED chip (package), LED module, driver or power supply, control circuit, optics, and heat sink for thermal management (Neary & Quijano, 2009). The following subsections explain these components in detail.

LED Chip (Package)

As shown in Figure 4.1, the LED chip consists of a thin layer of semiconductors that emit light when a voltage runs through. In order for an LED chip to be a source of functional light, it must be encased in a highly transmissive material such as epoxy with metallic leads like gold, a heat sink, and light reflector. All together these are referred to as “the LED chip or package” (Ton, et al., 2003). The used operating current ranges from 350 milliamperes (mAmps) to 1 ampere, while the range of luminous flux is between 20-150 lumens (Neary & Quijano, 2009).

Figure 4.1 Common LED Chip (Neary & Quijano, 2009)



LED Module

The building block of the larger system of the LED module is constructed from a circuit board with several LEDs and many other electronic components that may be used as a driver circuit or a current-regulating circuit (Neary & Quijano, 2009). In addition, the LED module may also have secondary optics to better focus, intensify, or direct optical energy for the desired application (Neary & Quijano, 2009), and (Ton, et al., 2003). Generally, the light distribution of most LEDs is in the range of 80º to 120º depending on the manufacturer and the LED package (Neary & Quijano, 2009).

Driver or Power Supply

LEDs will fail if they are subjected to reverse voltage. Similarly, the life of LEDs may be shortened if they are subjected to high peak electrical currents. Therefore, LEDs must be protected from reverse voltage and should be surged for output current regulations (Nuttall, et al., 2008). For that reason, LED systems require a driver or power circuit to convert the alternative current (AC) line voltage to appropriate direct current (DC) and voltage because LEDs are best operated with a constant current power supply (Neary & Quijano, 2009). The converted direct current usually ranges from 2-4 volts and 20-1,000 mAmps to obtain a high LED brightness (USDOE, 2009a). The standard high brightness LED is characterized by the minimum operating current of 350 mAmps and with higher levels of luminous flux that can be obtained using higher operating currents but will present additional challenges of thermal management (Neary & Quijano, 2009).

Control Circuit

The control circuit of LEDs is the unit that regulates the current flow (Avrenli, et al., 2012).

Optics

Optical components of LEDs can either be lenses or reflectors, and the main function of the optical component is to shape the pattern of radiation (Avrenli, et al., 2012). Success of LED light fixtures relies heavily on used optical components. The use of lenses is recommended for small LED light sources that have 1 to 4 dies. Since the lens has at least three surfaces, the light beam will be controlled efficiently (Avrenli, et al., 2012). In contrast, the cost of lens will be high if the light source consists of an array of dies beneath a common layer of phosphor. In this case, the lens will be large (Avrenli, et al., 2012). In some cases, mixing more than one lens will be required to obtain a required specific radiation pattern of light, especially in street lighting (Kuntze, 2009).

Heat Sink for Thermal Management

The main function of the heat sink is to provide heat removal from the LED to the immediate surroundings. Heat sink size depends on thermal properties of the material produced from the heat sink, and heat amount that has to be dissipated by (USDOE, 2007):

- “Conduction, which is defined as heat transfer from one solid to another.
- Convection, which is defined as heat transfer from a solid to a moving fluid.
- Radiation, in which heat transfer from two bodies of different surface temperatures occurs via electromagnetic waves.”

Approximately 90% of LED heat removal dissipated via conduction (Avrenli, et al., 2012).

LED Advantages

Major advantages of LEDs include energy efficiency, longer life, improved performance in mesopic vision conditions, high quality color, instant lighting, directional light, compact size, environment friendly characteristics, reduced light pollution, vibration and breakage resistance, and dimming capabilities (USDOE, 2009a). The following subsections provide a detailed discussion about LED advantages.

Energy Efficiency

The most important advantage of LEDs is their low energy consumption. LEDs can reduce energy consumption by approximately 80% compared to other conventional light sources (Avrenli, et al., 2012). Table 4.2 provides a summary of LED replacement power wattage as compared to different conventional light sources as of 2007. These power amounts were computed based on identical amounts of lumens delivered by the mentioned conventional light sources. LED replacement wattages shown in Table 4.2 also factor in 30-50% depreciation in light output from HID and fluorescent over their lifespans (Avrenli, et al., 2012). Results clearly show that LEDs are more efficient than all other conventional light sources.

Table 4.2 Conventional Light Sources Wattage and the Equivalent LED Replacement Wattage (Navigant Consulting Inc., 2008)

Light Source	Conventional Source Wattage	LED Replacement Wattage as of 2007	LED Saving Power
Incandescent	150	26	82.7%
Halogen Quartz	150	31	79.3%
Fluorescent	159	151	5%
Mercury Vapor	254	108	57.5%
Metal Halide	458	327	28.6%
High Pressure Sodium	283	276	2.5%

In the U.S., it was estimated that if the market used LEDs with an average lumen efficacy of 57.5 lumens per watt with a 100% complete penetration, an annual savings of 44.7 billion kWh in energy could be achieved. According to statistics from 2007, this savings constitutes 25% of electrical energy used for street lighting in the U.S. (Navigant Consulting Inc., 2008). The 44.7 billion kWh is equal to 482 trillion British thermal units (TBtu) per year, which is equivalent to the annual electricity consumption of seven large (100 MW) electrical power plants or the consumption of 3.7 million residential households (Navigant Consulting Inc., 2008). Moreover, it was estimated that if LEDs dominated the Chinese lighting market in 2010, one third of power consumption in China will be saved (Luo, et al., 2009), and (Luo, et al., 2007).

The Longer Life of LED

Lamp life can be defined as “the period in which a particular percentage of the tested lamps fail” (Avrenli, et al., 2012). This percentage is 40% for MH and 50% for MV and the HPS lamps (Avrenli, et al., 2012). The biggest advantage of LEDs is that they are not failing catastrophically, thus making their life defined differently as the point at which LED light output falls below a certain threshold of lumen output at installation, typically 70% (Neary & Quijano, 2009). The average life of conventional street light sources is approximately 50,000 hours (Timinger & Ries, 2008). Manufacturers claim that LEDs lifespan may last up to 100,000 hours with less than 40% of lumen depreciation (Tetra Tech EM-Inc., 2003). In contrast, the expected lifespan of some conventional street lamps such as HPS, MH, and MV is approximately 24,000 hours, 20,000 hours, and 10,000 hours, respectively (Timinger & Ries, 2008), and (USDOE, 2009b).

Although LEDs have a longer life than conventional light sources, their replacement can be difficult. Due to the high cost of labor needed to fix the failed LED, it might be more cost-effective to install a new LED luminaire rather than replace failed LEDs (Avrenli, et al., 2012). In comparison, HID light sources are designed to be utilized for a minimum of 30 years, and the only thing requiring replacement when it fails includes the lamp and ballast. Replacement is very simple (Avrenli, et al., 2012). Since LED street lights can last more than 10 years, it is recommended to be used in locations where it is difficult or costly to replace the light source, such as tunnels, and bridges (USDOE, 2009b). LEDs can be considered relatively maintenance-free, allowing them to be used in isolated lands and high mountainous regions (Aoyama & Yachi, 2008).

Improved Performance in Mesopic Vision Conditions

In the human retina, there are two types of photoreceptors: rods and cones. Both are responsible for sending visual signals to the brain. Cones are the principle photoreceptor of high light levels in photopic vision conditions; whereas rods are the main photoreceptors at low light levels in scotopic vision conditions (Costa, et al., 2009). Mesopic vision can be defined as the light levels at which cones and rods contribute to human vision (Avrenli, et al., 2012). In general, scotopic vision conditions can prevail below 0.001 cd/m^2, while photopic conditions prevail above 3 cd/m^2 (Avrenli, et al., 2012).

Currently, researchers are trying to combine the effect of Mesopic light sensitivities, color rendering, and color temperature on the human perception of brightness. White light emitted by LEDs can be perceived as brighter and more intense than conventional light sources when the lumen output is the same (Avrenli, et al., 2012). The spectrum of LED light has considerable blue content because most white LEDs consist of a yellow emitting phosphor material and a blue emitting chip. Under mesopic vision conditions, more light can be detected by the human eye if the light spectrum has significant blue content (Whitaker, 2007). As a result, LED light spectrum with higher bluish content can render LEDs brighter than other conventional light sources when lumen output is the same (Avrenli, et al., 2012).

High Quality Color

One of the most aspects of light source quality is color rendering and appearance. The correlated color temperature (CCT) describes the relative color appearance of the light source, and CCT indicates whether a source of light appears to be more bluish or more yellowish (Avrenli, et al., 2012). The CCT indicates the appearance of a black body when it is heated to high temperatures. When the black body is heated increasingly, its color turns to red, orange, yellow, white, and blue, respectively, based on temperature level. The unit of CCT is degrees Kelvin, and "CCT of a light source gives the temperature in degrees Kelvin at which the color of the heated black body matches the color of the light source in the question" (Avrenli, et al., 2012).

The color rendering index (CRI) shows how the colors of an object are rendered by a source of light (Avrenli, et al., 2012). The CRI has a scale from 0 to 100 with a comparison to a reference light source with a similar color index value. Increasing the CRI value means achieve a better source of light to render an object colors (USDOE, 2008). Color rendering is a major advantage of LEDs. Most LEDs used to have the CCT value of 5,000 Kelvin and a cool bluish-white appearance, but recently, natural and warm white LEDs are available (USDOE, 2009a). LEDs designed for street lighting and parking lots have a range of CRI between 85-90 (Avrenli, et al., 2012). The higher color rendering index of LEDs is helpful for improving traffic safety because the available lights allow pedestrians and drivers to easily see street signs and other objects illuminated by the lighting fixtures, thus resulting in a reduction of drivers' reaction times (Hamburger, 2008), and (Nuttall, et al., 2008).

Instant Lighting

Conventional light sources such as MH, MV, and HPS require re-strike time, or several minutes at startup until the light source reaches its full brightness (Avrenli, et al., 2012). In contrast, LEDs do not need a re-strike time to warm up, and they can instantly turn on to full brightness, allowing manufacturers to design LED street lights that contain an intelligent control coupled with instant sensors (Avrenli, et al., 2012). These sensors can be programmed and adjusted according to environmental conditions, which leads to more energy savings (Wang & Liu, 2007).

Directional Light

According to street lighting regulations, an observer should either obtain certain lumens level or certain average levels of illuminance, either of these should be maintained within a target area (Timinger & Ries, 2008). LEDs can be designed to emit light in a specific direction since they enable more optical control. This design reduces the number of reflectors and diffusers required (Avrenli, et al., 2012). Approximately 30-50% of conventional light sources light output may be lost inside the fixtures (USDOE, 2009b).

Compact Size

Compared to conventional light sources, one advantage of LEDs is their small size which allows a wide flexibility in design and forms, allowing manufacturers to produce many patterns of LED luminaires. Because of the compact size of LEDs, they allow for the development of unique fixtures with new light patterns and different colors can be mixed to fulfill required conditions (Neary & Quijano, 2009). In addition, the small size of LEDs allows more optical control (Tetra Tech EM Inc., 2003). One drawback of the LED small size is that a large number of LEDs is required in roadway light sources to produce appropriate lumen output.

Environment Friendly Characteristics

New laws restricting the disposal of mercury-based light sources have raised concerns over environmental waste and disposal (Neary & Quijano, 2009). Compared to other conventional light sources, LED light source is free of toxic materials such as mercury, which make it safe for landfills and also compliant with the RoHS directive of the European Union (Hamburger, 2008). In addition, the process of manufacturing and assembling LEDs is free of the use of heavy metals like lead (Neary & Quijano, 2009). Moreover, while LEDs are running, they do not produce infrared or ultraviolet lights, which make them more environmentally friendly as compared to conventional lights (City of Ann Arbor, 2008).

One important factor that also causes LEDs to be environmentally friendly is that they may contribute to considerable reductions of greenhouse gas emissions (Avrenli, et al., 2012). In

Toronto, it was estimated that if 160,000 street lights were converted into LEDs, greenhouse gas emissions could be reduced annually by 18,000 tons, equivalent to removing 3,600 cars from roadways (Whitaker, 2007). In Japan, if an LED street light system is adopted, approximately 6 to 9 million tons of CO_2 could be reduced (Aoyama & Yachi, 2008).

Reduced Light Pollution

Five kinds of light pollution are most common: light trespass, overillumination, glare, sky glow, and clutter. Unwanted light that enters one's property is called light trespass (Avrenli, et al., 2012). An example of light trespass is light that enters one's house through a window during night, possibly resulting in sleep deprivation. Overillumination is defined by excess use of light (Lay-Ekuakille, et al., 2007). Over illumination accounts for approximately 2 million oil barrels wasted every day in the U.S. (Lay-Ekuakille, et al., 2007). Glare can be defined as "stems from excessive contrast between bright and dark areas in the field of view" (Avrenli, et al., 2012). Glare is a serious concern in road safety because it complicates needed adjustments to differences in brightness during nighttime driving. Clutter can be defined as "the excessive grouping of lights, such as badly designed streetlights or brightly lit advertising boards surrounding roadways" (Avrenli, et al., 2012). Clutter may reduce traffic safety because it can confuse drivers and pedestrians and cause a distraction. Sky glow is the light effect that can be seen over populated areas caused by reflected light and due to badly directed light (Avrenli, et al., 2012). Careful consideration of street light design must be achieved so that a certain contrast level within the targeted area must not be exceeded in order to overcome the five types of light pollution.

Vibration and Breakage Resistance

Conventional light sources contain filament, arc tube, or fragile glass components that are affected by vibration. In comparison, LEDs do not contain any of these components. LEDs offer a more robust light with more resistance to breakage and vibration. As a result, using LEDs in areas of high vibration, such as mining operations or on bridges, is more suitable and efficient (Neary & Quijano, 2009).

Dimming Capabilities

Intelligent control and dimming is a method that can be employed for the purpose of saving energy (Avrenli, et al., 2012). Traffic always decreases at night and early mornings and, during these times, energy consumption may be reduced by limiting illumination levels offered by light sources. The amount of energy saving due to dimming may reach 30%. MH and MV lights have poor dimming capabilities (Timinger & Ries, 2008). For HPS, dimming can be achieved by changing illuminance steps by using ballasts of multi-levels (Li, et al., 2009). On the other hand, LED light intensity can be modified by adjusting the relative pulse and time between these pulses, called modulation of pulse width (Long, et al., 2009). LEDs can be dimmed as low as 10% of their maximum output and, with the use of pulse width modulation; they can be dimmed as low as 0.05% of their maximum output (Avrenli, et al., 2012).

Disadvantages of LEDs

Though LEDs have many advantages and benefits, there are many disadvantages related to their luminous efficacy, heat conversion rate, cost of installation, issues in obtaining white color, and the use of LEDs module arrays. The following subsections describe these problems in detail.

Luminous Efficacy

Luminous efficacy can be calculated by dividing the total luminous flux of that source by lamp power in wattage with the unit of lumen per watt. As with the luminaire, efficacy is calculated by dividing the total luminous flux by luminaire power.

The main challenge to LED outdoor lighting technology is luminous efficacy. LED street lights are not significantly superior to conventional light sources. Measured lumen output of the conventional light sources of MH, MV, and HPS are in the ranges of 60-110, 30-60, and 40-120 lumens per watt, respectively (Timinger & Ries, 2008), and (Tetra Tech EM Inc., 2003). In comparison, luminous efficacy of available commercial LEDs has recently approached 100 lumens per watt (Li, et al., 2009).

Heat Conversion Rate

While LEDs operate, they produce cold light, usually below 60^{o}C (or 140^{o}F), while HPS light sources operate based on molten metal inside an arc tube at a temperature greater than

300°C (572°F) (Avrenli, et al., 2012). LED has a higher rate of power to heat conversion as compared to other conventional street light sources (Avrenli, et al., 2012). The high power chips of LED generally transform approximately 80% of input power into heat, meaning that the remaining 20% of the input power is converted into light. In comparison to conventional street light sources, which have a heat removal mechanism based primarily on infrared radiation, LED heat removal mechanism is based mostly on conduction, resulting in the addition of thermal management challenges. Table 4.3 shows a comparison of heat removal mechanisms of different light sources. Table 4.3 clearly shows that, for the HID light sources, more than 90% of heat removal is lost by radiation, while in the case of LED, more than 90% of heat removal is lost by conduction and less than 5% is lost by radiation.

Table 4.3 Comparison of Heat Removal Mechanism of Light Sources (Arik, et al., 2007)

Light Source	% of Heat Lost by Radiation	% of Heat Lost by Convection	% of Heat Lost by Conduction
Incandescent	>90	<5	<5
Fluorescent	40	40	20
HID	>90	<5	<5
LED	<5	<5	>90

Issues in Obtaining White Light with LEDs

Light emitted by a single LED source falls within a very narrow wavelengths band in the visible spectrum, which means that LED emit virtually monochromatic light (Avrenli, et al., 2012). The emission of monochromatic light classifies LED sources as very efficient in the use of colored lights applications such as traffic signal lights. Three methods enable white light extraction from LED light sources (USDOE, 2008), (IESNA Light Sources Committee, 2005), and (Avrenli, et al., 2012): RGB (Red, Green, and Blue) systems, Binary Complementary Wavelength Conversion, Ultraviolet Wavelength Conversion. Currently, most white LED chips are obtained by using phosphor conversion (Avrenli, et al., 2012).

Use of LED Module Arrays

Illumination generated by a single LED package is significantly weaker as compared to other conventional street light sources such as HPS and MH. The power used to generate illumination using HPS light source is commonly sized at 100W, 250W, 400W, and higher, while for a single LED chip or package, the power used in lighting ranges from 1W to 10W (Sá Jr., et al., 2007). LEDs can be used to illuminate roadways only if numerous LED chips are incorporated together into a module of LED, and then several LED modules are incorporated into an LED module array (Avrenli, et al., 2012).

The use of LED module arrays provides redundancy in lighting, thus enabling the entire fixture to stay illuminated even if one or more of the chips fail (Neary & Quijano, 2009). The LED module arrays have some disadvantages, such as increasing the chance of component failure when the number of LED chips used is increased. If this type of breakdown occurs, a significant amount of time and energy is required to repair the LED module array. The reliability of an LED module array increases with decreasing the number of series connections and increasing the number of parallel connections (Aoyama & Yachi, 2008).

An additional disadvantage of the LED module array is that it may result in having distinct multiple shadows which could cause drivers and pedestrians visibility to be uncomfortable. Multiple shadows become more distinguishable as the light distribution of each LED module is narrowed, or as the spacing between the LED modules increases (Avrenli, et al., 2012).

The last disadvantage of the LED module arrays is over power supplying (overdriving) of individual LEDs in the array when some LEDs start to fail. LEDs in the array need a better power supplier (driver), instead each failed LED will cause the remaining LEDs to be hardly supplied with power, resulting in increasing temperature and reducing system’s life (Avrenli, et al., 2012).

Chapter 5 - Light Distribution Evaluation of Different Light Sources

Introduction

Based on results presented in Chapter 3, the most common light sources used by various states for illuminating overhead guide signs are MH, MV, HPS, induction lighting, and LED. KDOT provided the Kansas State University (KSU) Research team with two light source types: 250W MH and 250W MV. Lumi Trak, Inc. supported the KSU research team with three additional light sources: 62W LED, 250W HPS, and 85W induction lighting. Lights studied by the KSU research team were classified into conventional light sources and light sources of the new generation. Conventional light sources included the MH, MV, and HPS, while light sources of the new generation included the LED and induction lighting.

The following sections present details regarding the five light source received, the experimental setup, and procedure used for testing. For each light source being studied, the optimal light distribution was determined in the experiment. Eventually, a comparison between the five light sources was performed based on the light distribution results, to be able of recommending the optimal light source to DOTs.

Light Sources

The first light source was the 250W, MH. The fixture of this light source is shown in Figure 5.1. According to the manufacturer, “the optical system consists of vandal resistant, non-yellowing prismatic borosilicate glass refractor unaffected by environmental contaminants or ultra-violet radiation and a formed, anodized aluminum inner reflector to direct light onto the sign face with maximum uniformity” (Holophane, 2010). The input voltage was 480 volts. The second light source was the 250W, MV, shown in Figure 5.2. This light source has a clear, flat glass and input voltage of 480 volts. The third light source was the 62W, LED, shown in Figure 5.3. The input voltage was 120 volts. This light source includes independent and adjustable LED arrays with glass diffuser. The fourth light source was the 250W, HPS, shown in Figure 5.4. The input voltage of this light was 120 volts. The last light source was the 85W, induction lighting, shown in Figure 5.5. The 85W induction lighting distributes light through the borosilicate glass refractor. The input voltage of this light was 120 volts.

Figure 5.1 MH Light Unit

Figure 5.2 MV Light Unit

Figure 5.3 LED Light Unit

Figure 5.4 HPS Light Unit

Figure 5.5 Induction Lighting Unit

Overhead Guide Sign Lighting Recommendations

According to the AASHTO, overhead guide sign light sources may be placed on the bottom of the sign, top of the sign, or remotely on an adjacent support (AASHTO, 2005). Positioning the lighting unit on the bottom of the sign is preferred because:

1. “The reflected light is less likely to reduce the visual performance of the sign message or produce reflected glare into the eyes of motorists.
2. The lighting units do not produce daytime shadows and reflections from the sun on the face of the sign.
3. The lighting units are easier to access for maintenance.
4. The lighting unit may collect snow or dirt, but may also be cleaned by rain.
5. The face of the sign may only partially shield the light that spills onto traffic approaching from the rear of the sign. However, a separate shielding mechanism can be provided on the lighting units that will minimize this effect.
6. Express sky-glow or light pollution may be inherent. However, a separate shielding mechanism can be provided on the lighting units or optical control equipment can be utilized in order to minimize these effects.

7. The lighting units may obstruct the view of the sign message at some viewing angles. However, proper placement and installation of the lighting units can minimize this problem." (AASHTO, 2005).

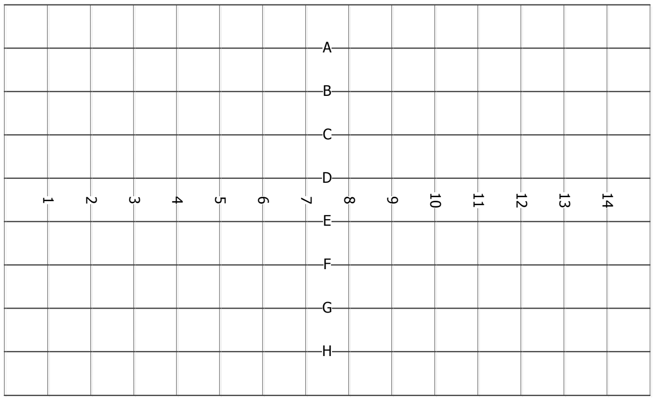
In the current experiment, AASHTO recommendations were followed by positioning the light source fixture at the bottom of the sign.

Experimental Setup

The purpose of the experiment was to determine optimal light distribution for each of the five light sources: MH, MV, LED, HPS, and induction lighting, and identify which light source provides the most efficient illuminance on the sign. According to KDOT, no specific size of overhead guide sign exists because the size of the overhead guide sign depends upon length of the destination name (Gund, 2011). The general size of an overhead guide sign for one line of legend is 15 ft in width and 9 ft in height (4.572 meters by 2.743 meters). For two lines of legend, general size is 15 ft by 12 ft (4.572 meters by 3.658 meters) (Gund, 2011). In a meeting with KDOT in May 2012, the state signing engineer and the permanent signing specialist stated that KDOT is considering the installation of large overhead guide signs on some highways, 48 ft wide by 18 ft in height (14.630 meters by 5.486 meters) (Nichol & Gwaltney, 2012).

The current experiment was conducted in the casting workshop in the Industrial and Manufacturing Systems Engineering (IMSE) Department at KSU. Black cardboard was used to cover all windows, and the emergency light in the room was turned off to ensure the room was completely dark. A white sheet of paper 15 ft in width and 9 ft in height was hung on the wall, representing an overhead guide sign of similar size. A grid of 1 ft increments was drawn on the paper as shown in Figure 5.6. At a height of 8 ft from the floor, the line on the paper was named row "A" and the line at 1 ft height was row "H." Similarly, the vertical line at the left side of the paper was named column "1" and the vertical line on the right side was column "14".

Figure 5.6 Grid Naming Mechanism of the White Paper



KDOT has a standard for distance between the light source unit and the sign. Based on a drawing provided to the KSU research team from KDOT, shown in Appendix A, the horizontal distance between the light source unit and the sign is between 5 ft and 6.5 ft. In this experiment, the light source unit was centered in front of the sign on the floor at a distance of 5 ft. This distance was measured horizontally from the white sheet on the wall to the nearest edge of the light source.

The Minolta Illuminance meter was used to measure illuminance (in lux) at each grid intersection (row-column intersection) starting from the top row (row A), left side of the white sheet of paper (column 1), to the bottom right side. Three measurement readings were taken at each intersection and the average was calculated at each intersection point. Illuminance in general can be measured in lux, which is lumen/m^2. Illuminance can also be measured by foot-candle, which is lumen/ft^2. When running the experiment, each light source was given a suitable warming period (re-strike time) by being turned on at least 45 minutes before starting illuminance readings to ensure the light source would run at its maximum brightness. In addition, the Minolta Illuminance meter was calibrated before beginning each experimental run.

Results and Discussion

Data obtained in this experiment were studied to eliminate any outliers or errors. At each row-column intersection on the white sheet of paper, the average of the filtered readings was calculated and used for further analysis. Illuminance readings for each light source for all angles used were summarized, and best light distribution for each light source was determined for each light source.

The MH Light Source

For the 250W MH light source, the light source unit was set in front of the white sheet of paper at four different angles. Angles were measured between the bottom of the light source unit and the floor. These angles were 0^{o}, 5^{o} down, 10^{o} down, and 15^{o} down. At each angle, illuminance readings were taken using the Minolta Illuminance meter.

Table 5.1 shows illuminance readings average at each intersection point at the specified angle for the 250W MH light source. The MUTCD of 2009 specifies minimum retroreflectivity values for signs, but it does not specify maximum retroreflectivity values. This information will be used in illuminance analysis sections, meaning that when illuminance readings on the white sheet of paper increase by changing the angles from 0^{o} to 5^{o} down, from 5^{o} to 10^{o} down, and from 10^{o} to 15^{o} down, as shown in Table 5.1, sign visibility for drivers will be much better. Therefore, the best light distribution of the 250W MH light source was found when the angle was 15^{o} down. To confirm that the 15^{o} angle was the optimal angle, the light distribution of the MH was studied at 20^{o} down angle, unfortunately, the light distribution at 20^{o} angle was not uniform; high illuminance values were obtained at the bottom of the sign and low illuminance values were obtained at the top of the sign, this concluded that the 15^{o} angle down was the optimal angle for the MH.

Figure 5.7 shows the optimal light distribution of the 250W MH light source, which obtained at 15^{o} angle down. The distribution appears to be more uniform, and illuminance values range between 200-700 lux, approximately. This light distribution could enable motorists to read the legend on the overhead guide signs wherever it is located on the sign, while meeting MUTCD requirements when the sign is illuminated with a 250W MH light source installed at a 15^{o} angle down with the horizontal.

MV Light Source

For the 250W MV light source, the light source unit was set in front of the white sheet of paper at four different angles. These angles were 0^{o}, 5^{o} up, 5^{o} down, and 10^{o} down. At each angle, illuminance readings were taken using the Minolta Illuminance meter.

Table 5.2 shows illuminance readings average at each intersection point at the specified angle for the 250W MV light source. Table 5.2 indicates that when the angle was changed from 0^{o} to 5^{o} up, the illuminance reading for all the rows decreases, meaning that movement in this direction (up) is not correct. Therefore, the KSU research team selected the opposite rotation direction. When illuminance readings for 0° and 5° down angles were compared, illuminance readings increased, indicating that this movement was in the correct direction of rotation. Maximum illuminance readings were observed when the angle was 10° down, meaning that the best light distribution of the 250W MV was obtained when the angle was 10° down. To confirm that the 10° angle down was the optimal angle, the light distribution of the MV was studied at 15° down angle, unfortunately, the light distribution at 15° angle was not uniform; high illuminance values were obtained at the bottom of the sign and low illuminance were values obtained at the top of the sign, this concluded that the 10° angle down was the optimal angle for the MV.

Figure 5.7 Optimal Light Distribution of MH (Angle 15° down)

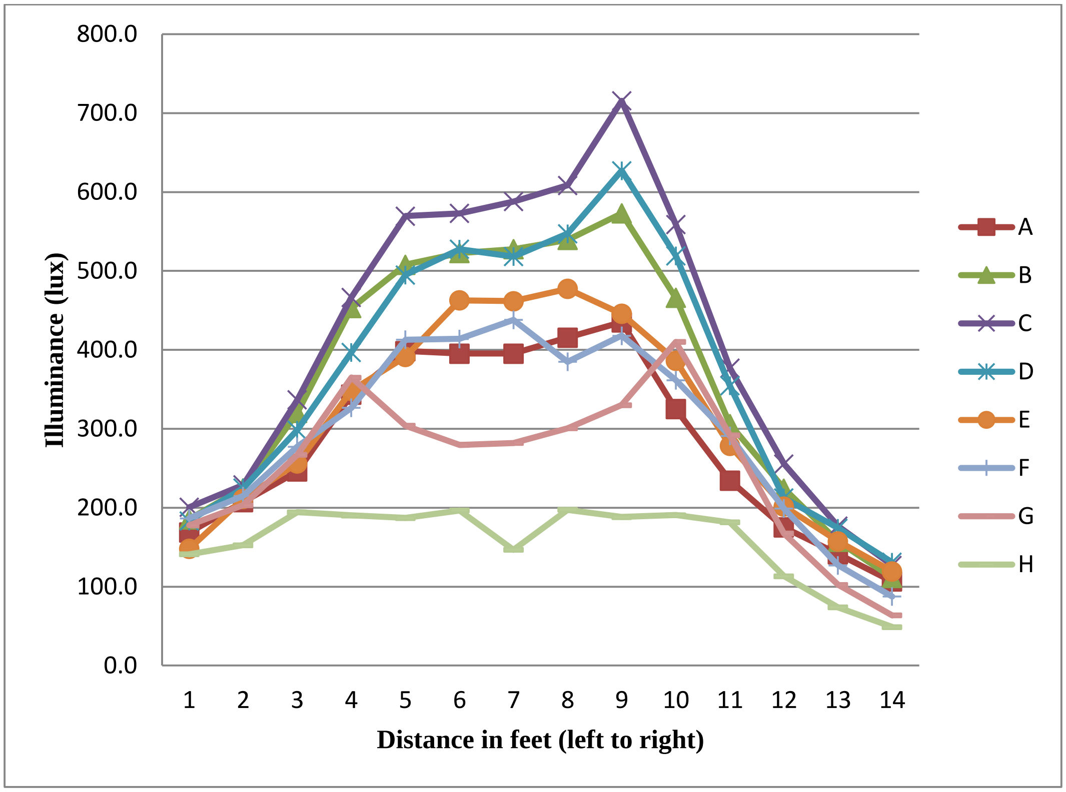
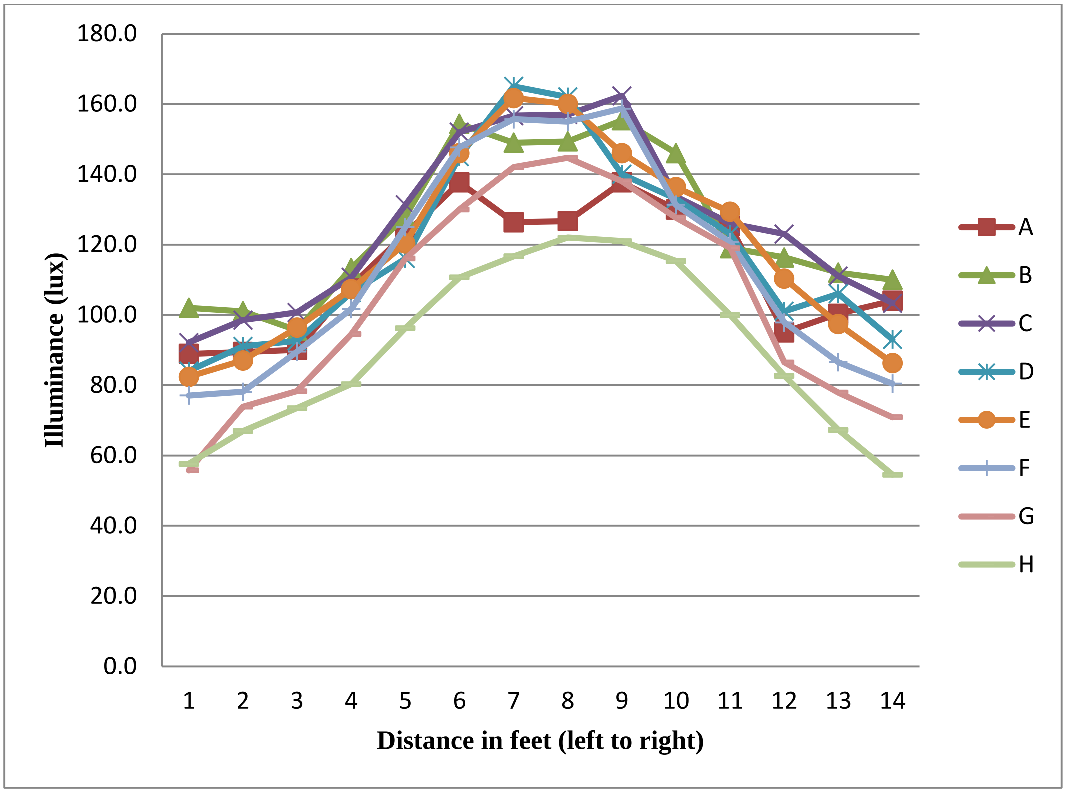


Figure 5.8 shows the optimal light distribution of the 250W MV light source at 10° down. This distribution appeared to be more uniform, with a maximum illuminance of 160 lux. For row “H,” the average illuminance level is approximately 110 lux. This light distribution ensure that motorists could read the legend on signs wherever it is located on the sign when illuminated using a 250W MV light source that installed with a 10° angle down with the horizontal.

Figure 5.8 Optimal Light Distribution of MV (Angle 10º down)



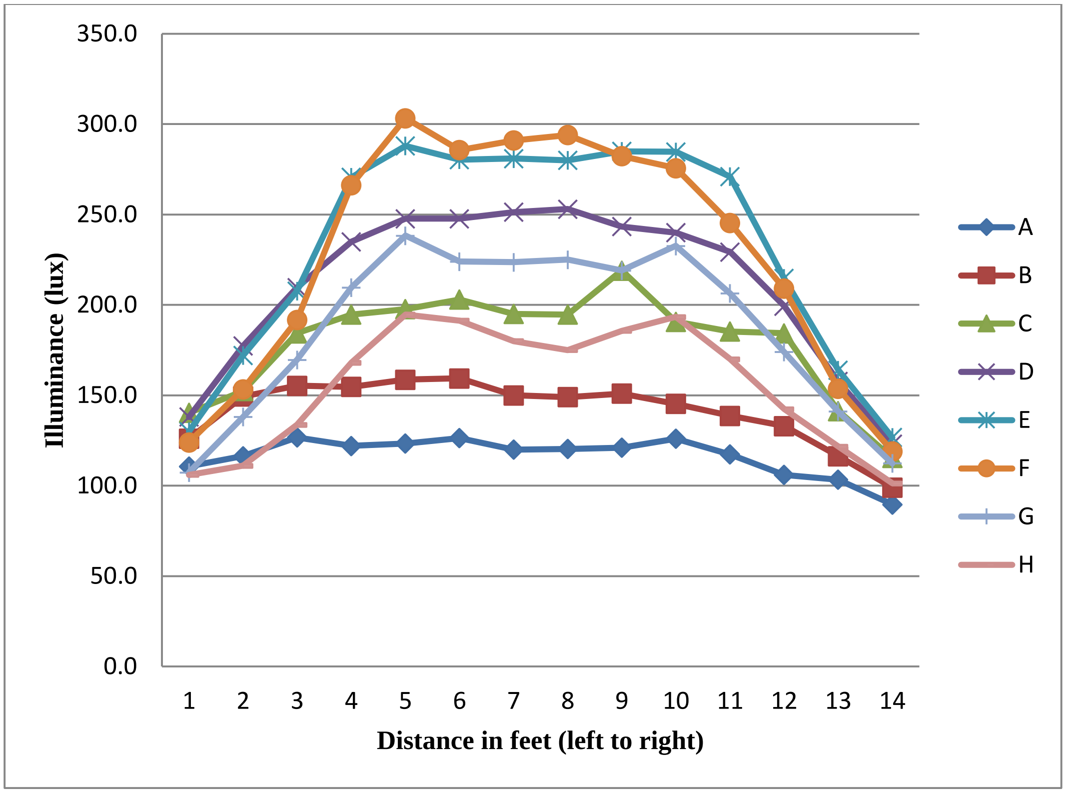
Induction Lighting Source

For the 85W induction light source, the light source unit was set in front of the white sheet of paper at four different angles. These angles were 0º, 5º down, 10º down, and 15º down. At each angle, illuminance readings were taken using the Minolta Illuminance meter.

Table 5.3 shows the illuminance reading average at each intersection point at the specified angle for the 85W induction light source. When comparing illuminance readings for the 0º and 5º down angles, an increase was occurred at 5º angle, meaning this movement was in the correct direction of rotation. When illuminance readings between 0º, 5º down, and 10 º down were compared, the illuminance readings were increasing. Between rows A to H, the maximum illuminance readings were shown when the angle was 15º down with one exception for row A. When moving from 10º to 15º, illuminance values at 10º angle were a little bit higher. In general, for the 85W induction light source, the best light distribution was produced when the angle was 15º. To confirm that the 15º angle down was the optimal angle for the induction lighting source, the light distribution of the induction was studied at 20º down angle, unfortunately, the light distribution at 20º angle was not uniform; high illuminance values were obtained at the bottom of the sign and low illuminance values were obtained at the top of the sign, this concluded that the 15° angle down was the optimal angle for the induction lighting source.

Figure 5.9 shows optimal light distribution of the 85W induction light source at 15° down. This distribution appeared to be more uniform with a maximum illuminance of 300 lux. This light distribution ensure that motorists could read the legend on overhead guide signs wherever it is located on the sign when illuminated using an 85W induction light source installed with a 15° angle down with the horizontal.

Figure 5.9 Optimal Light Distribution of Induction Lighting (Angle 15° down)



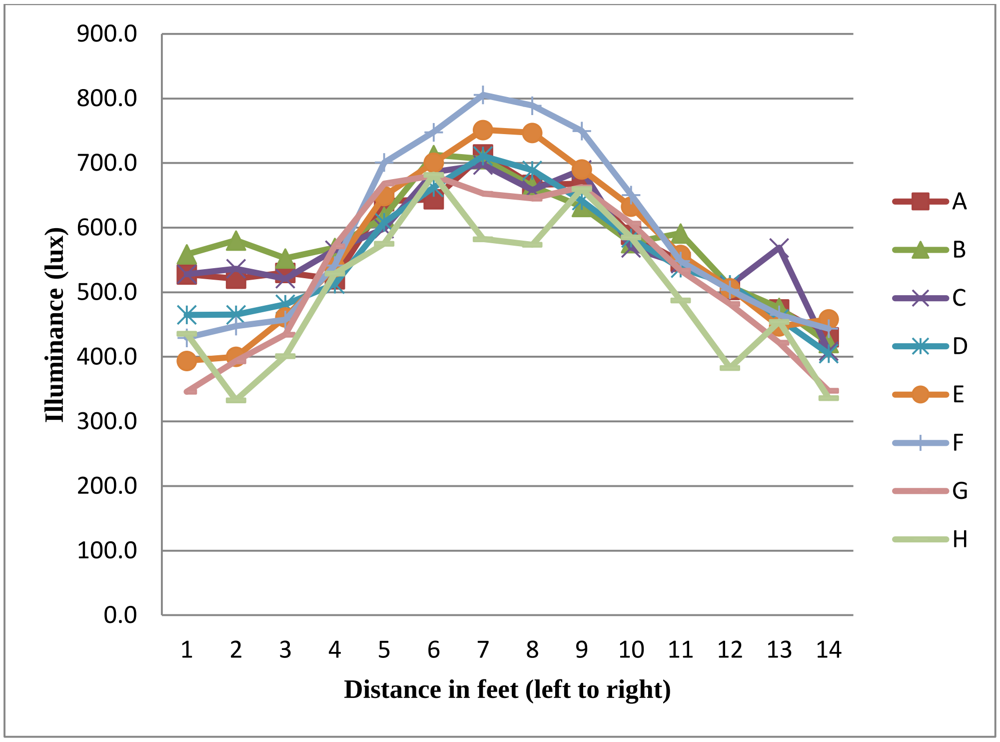
HPS Light Source

For the 250W HPS light source, the light source was set in front of the white sheet of paper at 0° angle only, because the output illuminance was very high. Illuminance readings were taken using the Minolta Illuminance meter.

Table 5.4 shows the illuminance reading average at each intersection point at the specified angle for the 250W HPS light source. Light distribution for the HPS at 0° angle was considered the best because the measured illuminance values were very high, consequently allowing motorists to read the sign because of increased illuminance on the sign, as shown in

Table 5.4. Figure 5.10 shows the best light distribution of the 250W HPS light source at 0^o. The light distribution appeared to be uniform with a maximum illuminance of 800 lux. This light distribution ensure that motorists could read the legend on overhead guide signs wherever it is located on the sign when illuminated using a 250W HPS light source fixed with a 0^o angle with the horizontal.

Figure 5.10 Optimal Light Distribution of HPS Light Source

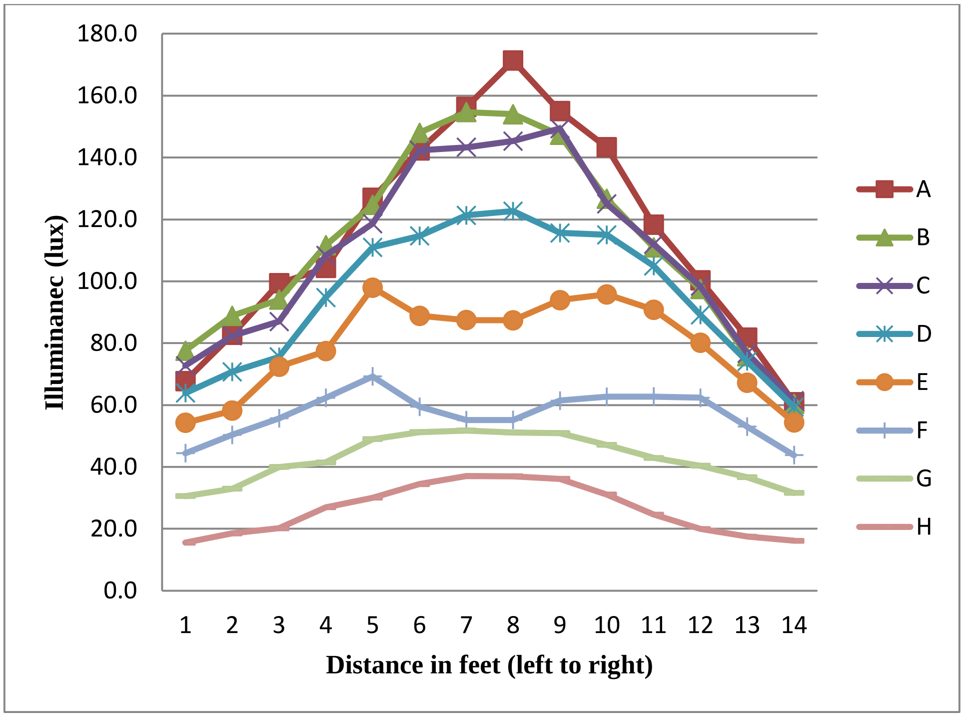


LED Light Source

For the 62W LED light source, the light source unit was set in front of the white sheet of paper at 0^o angle only, because the design of this LED included independent and adjustable LED arrays. By rotating these arrays, the LED light can be focused to any place on the sign. Manager of the manufacturing company of this LED informed the KSU research team that this LED unit is ready to be installed, since the angles of LED arrays were already fixed to the appropriate position to focus light along a sign of similar size to the sheet of paper. Illuminance readings were taken using the Minolta Illuminance meter.

Table 5.5 shows the illuminance reading average at each intersection point at the specified angle for the 62W LED light source. Light distribution for the LED at 0^o angle was considered the best because the LED arrays are already fixed to the appropriate position to focus the light. Figure 5.11 shows the best light distribution of the 62W LED light source at 0°. This distribution appears to be uniform with a maximum illuminance of 165 lux.

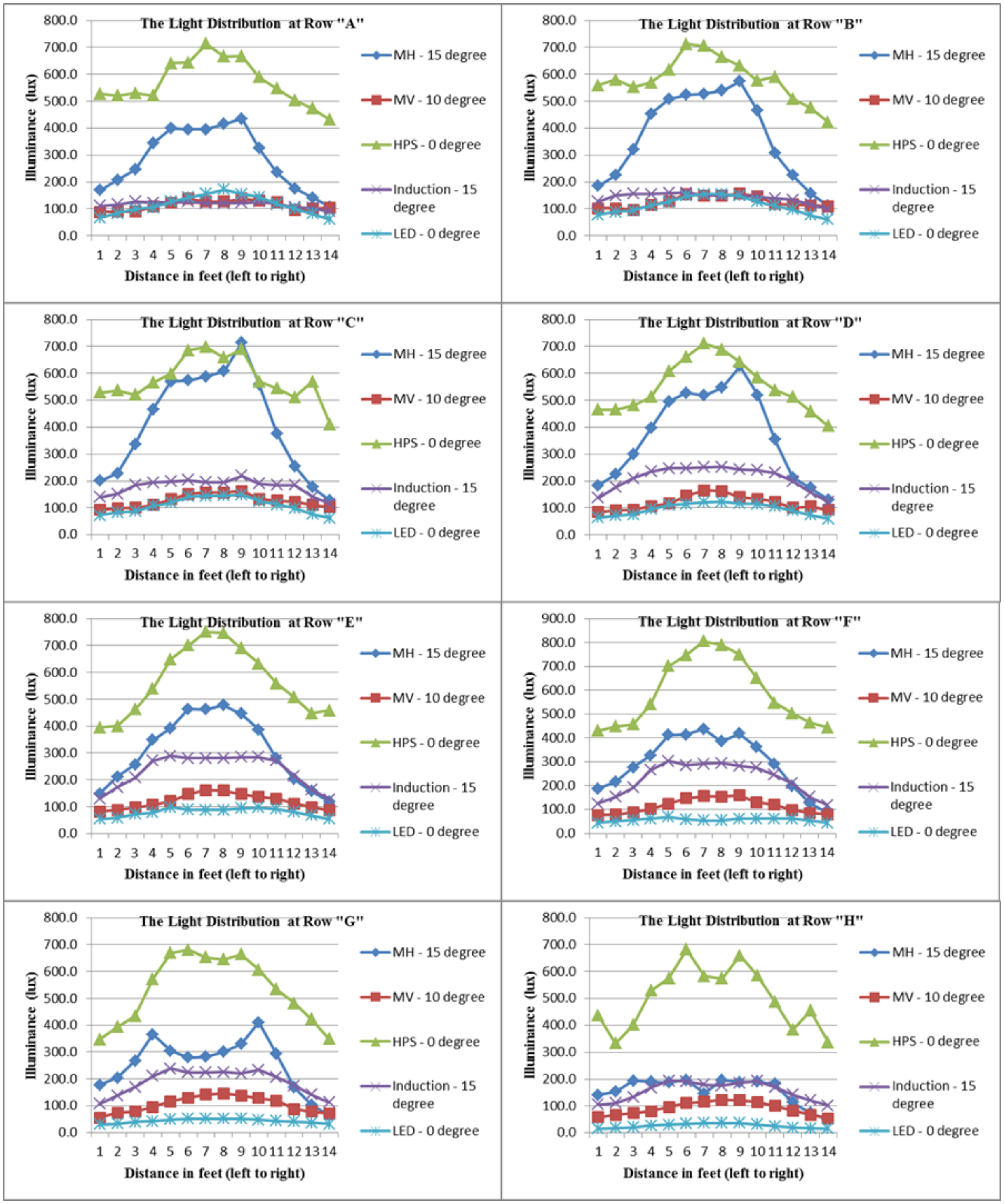
Figure 5.11 Optimal Light Distribution of LED Light Source



Comparison of Optimum Light Distributions of Five Light Sources

To determine the optimal light source for illuminating overhead guide signs, the optimum light distribution at each row of the white sheet of paper was compared for the five light sources. Figure 5.12 shows light distribution at each row on the sheet of paper (A to H) for the sources. In addition, Table 5.6 includes illuminance reading at the best light distribution of the five light sources studied. Comparing the five light sources based on Table 5.6 and Figure 5.12, for all rows (A to H), the HPS light source had the highest illuminance readings, meaning that it was the optimal light source. The MH is the next, followed by induction lighting, MV, and LED.

Figure 5.12 Optimal Light Distribution Comparison at Each Row on the White Paper



Summary

The 250W HPS light source provided highest illuminance values on the sign, meaning that the 250W HPS contributes to better visibility to drivers. The 250W MH light source provided the next highest illuminance values, followed by the 85W induction lighting, the 250W MV, and the 62W LED. In summary, the HPS light source was the best among conventional light sources, followed by MH and MV. Among light sources of the new generation, induction lighting was the optimal light source, followed by LED.

Table 5.1 Illuminance Readings of the MH Light Source at Different Angles

Row	**Angle**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
A	0^{o}	125.0	140.0	171.3	176.0	213.3	201.7	194.3	196.0	188.3	174.3	159.3	147.0	116.3	83.7
	5^{o}	147.3	181	213.5	277.3	308	320.5	297.7	311.3	310.7	295.7	277.7	191.7	151	109.7
	10^{o}	168	210.3	274	359	389.3	387	404.5	422	480.3	411.3	301.7	242	157	114
	15^{o}	168.7	207.3	246	343.3	398.5	395.3	395.3	415.5	435	325	234.5	175	141.3	106.7
B	0^{o}	119.7	144.7	155	188.3	204.3	217.3	200.3	214.3	217.3	199.7	187	117.7	115.3	92.4
	5^{o}	147.3	165	197.3	252.3	299.7	290.3	269	288.7	283.7	257.3	252.3	183.3	134	106
	10^{o}	169.7	204.7	261	348.3	383.3	412.3	395	417.3	441	408	379.5	220	154.7	114
	15^{o}	185.3	224.7	320.3	453	508	522.7	527.5	539.3	573	466	306	224.3	157	111.3
C	0^{o}	116	141.3	170.3	200.7	197	221	213.7	206.7	206	204.3	173	127.3	93.4	83.8
	5^{o}	134.7	156.7	184	235.3	250.5	278.5	281	293.5	282.5	257.7	223.7	162.7	126.3	98
	10^{o}	161	199.5	239.7	294.3	371	383.3	359.7	379	410.3	366.3	297.3	190	149	113
	15^{o}	200.7	229	336.7	466.7	569.5	573	588	608.3	715.7	559	377	255.5	176.7	127
D	0^{o}	122.3	154	187	206.3	216	204	220.7	203.3	194.7	208	196.7	151.7	113.7	79.8
	5^{o}	128.3	151.7	207.7	233	255.7	272.7	281.5	300	260	255	201	161	128	92.5
	10^{o}	139.7	174.7	212	268	297.5	339	346	356	347.3	315	247.5	171.7	135.3	105
	15^{o}	183.3	225	298.5	397	495	527.5	518.3	547.3	627	519.3	354.5	212.3	174	131
E	0^{o}	136.7	151.3	205.3	220.3	189.5	177.7	178	190	179	199	233	146.7	109	74.1
	5^{o}	154	176	223.5	271.5	240.3	244	265.3	249.7	239	262	232.5	172.5	133.7	88.5
	10^{o}	130.5	181	224.5	265	304	323	347	317	310	310.3	241.5	167	124.7	89.8
	15^{o}	148	211.3	256.3	348.3	391.3	462.7	461.7	477.3	445.7	386.3	278.7	201.7	157.5	119.3
F	0^{o}	100.3	115.3	158.7	147.3	143.7	152.7	120.0	144.0	148.0	134.7	160.0	118.3	80.9	57.0
	5^{o}	167	180	239.3	277.3	202.7	200.7	197	213.7	207.3	220.7	261	166	113	78.4
	10^{o}	175.3	198	248	313.3	288.5	275	273.3	272	302.5	348	275.5	175	111.7	66.8
	15^{o}	186.7	215	277.3	326.7	413	414	438	385	418	361.7	291	199	127	87.6
G	0^{o}	91.6	84.7	81.5	78.5	91.1	102	92.7	93.5	96.5	70.9	80.7	73.6	52.2	37.2
	5^{o}	106	122.3	135.7	147	142	154.7	115	136	137	133.3	124.5	99.2	74.6	51.1
	10^{o}	135.3	151.7	205.5	223	199	194.3	155.3	213	203.7	213.3	224	133	92.6	57.7
	15^{o}	177.7	203.3	267	365	304	279.7	282	300.7	330	410	292	167.3	102.3	63.7

Row	Angle	1	2	3	4	5	6	7	8	9	10	11	12	13	14
H	0^{o}	54.2	53.9	47.4	40.3	53.9	72.7	65.5	61.5	58.4	39.3	39.1	45	35.5	30.9
	5^{o}	93.2	83.4	66.3	66.8	79	98.5	88.3	86.7	86.6	64.6	55.8	62.6	44.4	36.1
	10^{o}	98.9	90	94.5	99.7	109.3	127.3	109.3	116.3	113.3	94.5	92.3	79	55.2	43.3
	15^{o}	141.0	152.7	194.3	190.3	187.0	196.7	146.7	197.3	188.3	190.7	181.7	113.3	73.7	48.9

Table 5.2 Illuminance Readings of the MV Light Source at Different Angles

Row	Angle	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	0^{o}	55.6	59.1	60.6	62.9	67.1	73.1	84.8	84.7	79.2	71.7	68.2	61.7	61.8	53.6
	5^{o} up	46.9	45.8	49.6	56	58.7	61.1	70.3	61	65.7	67	61.2	50.5	49.9	47.2
	5^{o} down	70.1	70.7	74.4	81.2	92.1	117.7	114	111	104.7	98.5	96.8	75.5	74	73.4
	10^{o}	88.9	89.4	90.1	108.3	123	137.7	126.3	126.7	137.7	130	125.3	95	100.3	104
B	0^{o}	58.8	60.7	62.5	69.1	75.1	83.3	85.5	86	79.5	74.6	74.4	64.6	59.8	53.3
	5^{o} up	44.6	47.7	47	53.1	49	65.7	71.8	70.2	67.8	64.5	65.7	61.9	53.4	48.7
	5^{o} down	74.5	74.1	73.8	85.3	88.7	110	111.7	122.5	105	95.7	95.1	83.3	77.3	71.1
	10^{o}	102	101	95.6	113.3	128	154.3	149	149.3	155.3	146	119	116.3	112	110
C	0^{o}	54.3	60.7	64.7	69.8	78.8	89.7	97.2	98.9	92.5	78.8	74.7	64.6	61.5	54.1
	5^{o} up	43.5	46.6	50.3	50.3	55.8	64.4	75.5	75.7	76.7	82.4	71	64.7	57	50.3
	5^{o} down	72.4	72.7	73.9	87.2	96.2	112.3	120.5	122	119.3	97.5	97.8	85.2	76.6	69.4
	10^{o}	92.1	98.5	100.7	110.7	131.3	152	156.7	157	162.3	133.7	126	123	111	103.3
D	0^{o}	58.6	60	65.2	71.8	82.1	93.4	99.7	97.4	87.8	86.9	79.7	66.7	64.7	54.1
	5^{o} up	40.6	47.1	50.5	57.6	65.9	76.5	82.1	82.2	82.4	74.8	76	58	57.3	50.2
	5^{o} down	69.5	78.8	79.6	85.6	100.5	109.3	124	128	117.3	101.7	99	78.2	77.3	68.6
	10^{o}	84	91	92.6	106.3	116	145	165	162	140	133	123	101	106	93
E	0^{o}	54.3	56.6	63.4	73.3	81.5	94.8	98.1	98.1	99.6	99.3	92.9	88.1	71.4	52.6
	5^{o} up	43.7	45	46.7	49.4	58.1	66	77.4	81.5	85.5	84.6	77.7	58.7	56.4	48.9
	5^{o} down	69.9	70.2	80.6	86.2	100.1	118.3	123.7	124.7	116.7	101.2	102.3	85.5	79.9	65.4
	10^{o}	82.4	87	96.4	107.3	120.3	146	161.7	160	146	136.3	129.3	110.3	97.3	86.3
F	0^{o}	46.3	47.3	65.1	74.5	84.0	98.7	97.1	98.0	99.3	91.3	88.1	65.5	59.0	49.6
	5^{o} up	40.4	44.4	48.6	59.8	60.1	70.9	72.4	81.3	87.3	83.7	78.9	64.1	53.6	44.6
	5^{o} down	72.6	67.6	73.6	85.7	90.8	117.7	126	125	125.7	112	104	85.3	75.1	63.4

Row	**Angle**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
	10°	77.1	78.1	89.5	101.7	125	147.7	155.7	155	158.7	131.3	120.7	97.8	86.5	80.4
G	0°	42.6	51.9	62.2	64.0	68.8	84.2	83.3	87.1	90.0	91.7	83.3	64.3	55.6	44.4
	5° up	25.6	29.9	36.4	41.1	48.2	50.2	35.1	45.6	61.9	67.9	63.8	44.4	34.8	14.3
	5° down	66.6	60.9	68.7	76.8	86.1	107.3	112	114.7	116.3	102	104.3	73	64.6	55.8
	10°	55.8	73.9	78.3	94.5	116.0	130.0	142.0	144.7	138.0	127.7	119.0	86.5	77.9	70.9
H	0°	38.1	42.6	45	56.1	61.4	68.5	58.9	64.6	76.8	78.1	71.4	52.2	46.6	33.7
	5° up	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	5° down	48.1	54.1	61.9	65.4	74.1	91.1	88.4	94.5	96.3	90.9	79.1	68.9	57	45.2
	10°	57.6	67.0	73.4	80.3	96.2	110.7	116.7	122.0	121.0	115.3	100.0	82.7	67.3	54.5

Table 5.3 Illuminance Readings of the Induction Lighting Source at Different Angles

Row	**Angle**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
A	0°	97.4	110.7	116.7	111.0	111.0	111.0	115.0	119.0	117.3	113.7	114.3	120.7	109.7	90.7
	5°	102.7	119.7	117.7	115	123.3	124.3	124.3	127.3	123	118	116.3	107.3	108	99.3
	10°	121.3	132	141.7	130.7	134.3	132.7	127.3	129	135.3	137.3	134.7	122.3	115.7	101
	15°	110.7	116.3	126.7	122	123.3	126.3	120	120.3	121	126	117.3	106	103.3	89.6
B	0°	105.7	117.3	120.3	127.7	129	132	125	124	126.3	124.3	125.3	123	101.7	86.7
	5°	122.3	135	143.3	142	143.3	148	137.3	135	134.7	131.7	131.7	129.7	113.3	94.4
	10°	124.7	148.3	156	150.7	154.3	164.7	153	152.7	150.3	145.3	142	135.7	119.7	101.7
	15°	126	149.3	155.3	154.7	158.7	159.3	150	149	151	145.3	138.7	133	116.3	99
C	0°	103.3	112.7	117.3	127.3	129.3	139.3	134	135	144.7	130	130	127.7	104	89.4
	5°	115.3	131	154	159	158	168	155	154.3	172	157	159	147	118	97.9
	10°	132.7	158	179.3	182.7	184.7	192.3	184.7	183.3	197	176.7	175.7	175.3	138	110
	15°	140.3	152.3	184.3	194.7	197.7	203	195	194.7	219	190.7	185.3	184.3	141.3	115.3
D	0°	94.1	98.8	104.3	125	126.7	124.7	128.3	129.3	131.7	129	129.3	117.3	105	89.7
	5°	110	129	140.7	160	164.3	164.3	169	171	165.7	163.3	157.3	138.7	117	97.1
	10°	130.3	144.7	177	201	215.3	203.3	205	205.3	207.7	208	206	175	140.7	112
	15°	138	177.3	209.7	235	247.7	247.7	251.3	253	243.3	240	229.3	199.3	157.7	123
E	0°	90.2	97.5	102.3	113.3	134	121	120	121	125	133.7	130.7	117.7	103	87.4
	5°	101.3	112.7	122	159.7	170.7	163	155	156.3	154.7	159.3	153.3	135.3	117	95.6

Row	**Angle**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
	10°	121.7	146	170.3	210.3	215.3	216.3	222	223	221.7	215	202.3	170.3	139.3	111.3
	15°	130	172	207.7	270.7	288	280.3	281	280	285	284.7	271	214.7	164	126.7
F	0°	81.8	88.9	104.7	127.3	145.0	128.0	117.7	116.0	123.0	132.0	125.0	110.3	96.6	84.1
	5°	90.3	105.7	129	151	170.3	145.7	138	136	143.3	155	144	127.7	107	90.7
	10°	104.7	129.7	156.3	202	211.7	190.7	190	191.7	189.7	197.7	181.3	155.7	131	104
	15°	124	153.3	191.7	266.3	303.3	285.7	291	294	282.3	275.7	245.3	209	153.7	119
G	0°	74.3	83.4	95.5	108.7	125.3	131	135.7	134	125	125	115.7	99	89.2	75.5
	5°	85.7	97.5	119.7	136	152	139	137	133.7	134	139	128	108	97.7	84.3
	10°	75.2	114.7	125.7	149.3	181.3	167.7	153.3	152	160	173.3	157.3	133	115	96.7
	15°	107.3	138	169.7	209.7	238.3	224	223.7	225	219	232.7	206.3	174	141	112.3
H	0°	61.6	69.2	76.3	92.8	117	137	144.3	142	132.3	116	102	93.8	79.3	64.7
	5°	76.4	79.7	94	113.7	124.3	145.3	151.7	150.3	137.3	128	117.3	103.3	85.6	73
	10°	81.7	90.3	105.3	122.7	150.3	161.7	167.7	163.7	155.3	138	117	100.7	82.7	71.3
	15°	106.0	111.0	133.7	168.0	194.7	191.3	180.0	175.0	185.7	193.3	170.0	142.3	121.7	101.3

Table 5.4 Illuminance Readings of the HPS Light Source at 0° Angle

Row	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
A	527.7	521.0	530.3	520.3	641.0	644.0	713.3	666.3	668.0	589.0	547.7	504.0	473.7	430.7
B	558.7	580.3	552.7	569.0	617.0	712.7	706.3	664.0	632.3	576.3	591.3	509.0	476.0	421.3
C	528.0	536.3	521.0	565.3	598.7	686.0	697.3	658.3	689.7	569.0	544.3	511.0	569.0	409.3
D	465.0	465.3	481.3	512.7	608.3	662.3	711.0	689.0	642.0	584.0	537.3	512.3	459.0	405.0
E	394.0	400.0	461.3	539.0	649.3	700.7	751.3	747.0	690.3	632.7	558.0	506.3	447.3	458.0
F	429.7	447.7	457.3	541.7	701.0	748.0	805.7	789.0	750.0	650.7	548.3	503.7	465.0	443.7
G	346.0	393.3	434.7	571.3	668.3	680.7	652.7	645.3	662.7	606.7	533.7	482.0	422.0	347.7
H	436.0	333.0	401.3	529.0	575.3	682.0	582.3	573.7	660.0	585.0	487.7	383.0	454.3	336.3

Table 5.5 Illuminance Readings of the LED Light Source at 0° Angle

Row	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
A	67.8	82.7	99.3	104.3	127.0	142.3	156.3	171.3	155.0	143.3	118.3	100.3	81.8	60.9
B	77.6	88.9	94.1	111.7	124.7	148.0	154.7	154.0	147.3	126.7	111.0	97.5	75.8	60.4
C	72.7	82.4	87.0	108.3	118.7	142.3	143.3	145.3	149.3	125.0	112.0	98.4	76.7	61.4

Row	1	2	3	4	5	6	7	8	9	10	11	12	13	14
D	63.9	70.7	75.6	94.7	111.0	114.7	121.3	122.7	115.7	115.0	105.0	89.2	74.1	59.4
E	54.3	58.2	72.4	77.4	98.0	88.8	87.5	87.4	93.9	95.8	90.8	80.1	67.2	54.4
F	44.4	50.4	55.7	62.3	69.3	59.5	55.1	55.2	61.5	62.7	62.7	62.4	53.0	43.8
G	30.6	33.0	40.0	41.5	49.0	51.3	51.8	51.1	50.9	47.1	42.9	40.4	36.7	31.6
H	15.5	18.5	20.2	26.9	30.0	34.4	37.0	37.0	36.2	31.1	24.6	20.0	17.5	16.1

Table 5.6 Comparison of the best Light Distribution of the Five Light Sources

Row	Source	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	MH	168.7	207.3	246	343.3	398.5	395.3	395.3	415.5	435	325	234.5	175	141.3	106.7
	MV	88.9	89.4	90.1	108.3	123	137.7	126.3	126.7	137.7	130	125.3	95	100.3	104
	HPS	527.7	521.0	530.3	520.3	641.0	644.0	713.3	666.3	668.0	589.0	547.7	504.0	473.7	430.7
	Induction	110.7	116.3	126.7	122	123.3	126.3	120	120.3	121	126	117.3	106	103.3	89.6
	LED	67.8	82.7	99.3	104.3	127.0	142.3	156.3	171.3	155.0	143.3	118.3	100.3	81.8	60.9
B	MH	185.3	224.7	320.3	453	508	522.7	527.5	539.3	573	466	306	224.3	157	111.3
	MV	102	101	95.6	113.3	128	154.3	149	149.3	155.3	146	119	116.3	112	110
	HPS	558.7	580.3	552.7	569.0	617.0	712.7	706.3	664.0	632.3	576.3	591.3	509.0	476.0	421.3
	Induction	126	149.3	155.3	154.7	158.7	159.3	150	149	151	145.3	138.7	133	116.3	99
	LED	77.6	88.9	94.1	111.7	124.7	148.0	154.7	154.0	147.3	126.7	111.0	97.5	75.8	60.4
C	MH	183.3	225	298.5	397	495	527.5	518.3	547.3	627	519.3	354.5	212.3	174	131
	MV	92.1	98.5	100.7	110.7	131.3	152	156.7	157	162.3	133.7	126	123	111	103.3
	HPS	528.0	536.3	521.0	565.3	598.7	686.0	697.3	658.3	689.7	569.0	544.3	511.0	569.0	409.3
	Induction	140.3	152.3	184.3	194.7	197.7	203	195	194.7	219	190.7	185.3	184.3	141.3	115.3
	LED	72.7	82.4	87.0	108.3	118.7	142.3	143.3	145.3	149.3	125.0	112.0	98.4	76.7	61.4
D	MH	183.3	225	298.5	397	495	527.5	518.3	547.3	627	519.3	354.5	212.3	174	131
	MV	84	91	92.6	106.3	116	145	165	162	140	133	123	101	106	93
	HPS	465.0	465.3	481.3	512.7	608.3	662.3	711.0	689.0	642.0	584.0	537.3	512.3	459.0	405.0
	Induction	138	177.3	209.7	235	247.7	247.7	251.3	253	243.3	240	229.3	199.3	157.7	123
	LED	63.9	70.7	75.6	94.7	111.0	114.7	121.3	122.7	115.7	115.0	105.0	89.2	74.1	59.4
E	MH	148	211.3	256.3	348.3	391.3	462.7	461.7	477.3	445.7	386.3	278.7	201.7	157.5	119.3
	MV	82.4	87	96.4	107.3	120.3	146	161.7	160	146	136.3	129.3	110.3	97.3	86.3

Row	**Source**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
	HPS	394.0	400.0	461.3	539.0	649.3	700.7	751.3	747.0	690.3	632.7	558.0	506.3	447.3	458.0
	Induction	130	172	207.7	270.7	288	280.3	281	280	285	284.7	271	214.7	164	126.7
	LED	54.3	58.2	72.4	77.4	98.0	88.8	87.5	87.4	93.9	95.8	90.8	80.1	67.2	54.4
F	MH	186.7	215	277.3	326.7	413	414	438	385	418	361.7	291	199	127	87.6
	MV	77.1	78.1	89.5	101.7	125	147.7	155.7	155	158.7	131.3	120.7	97.8	86.5	80.4
	HPS	429.7	447.7	457.3	541.7	701.0	748.0	805.7	789.0	750.0	650.7	548.3	503.7	465.0	443.7
	Induction	124	153.3	191.7	266.3	303.3	285.7	291	294	282.3	275.7	245.3	209	153.7	119
	LED	44.4	50.4	55.7	62.3	69.3	59.5	55.1	55.2	61.5	62.7	62.7	62.4	53.0	43.8
G	MH	177.7	203.3	267	365	304	279.7	282	300.7	330	410	292	167.3	102.3	63.7
	MV	55.8	73.9	78.3	94.5	116	130	142	144.7	138	127.7	119	86.5	77.9	70.9
	HPS	346.0	393.3	434.7	571.3	668.3	680.7	652.7	645.3	662.7	606.7	533.7	482.0	422.0	347.7
	Induction	107.3	138	169.7	209.7	238.3	224	223.7	225	219	232.7	206.3	174	141	112.3
	LED	30.6	33.0	40.0	41.5	49.0	51.3	51.8	51.1	50.9	47.1	42.9	40.4	36.7	31.6
H	MH	141	152.7	194.3	190.3	187	196.7	146.7	197.3	188.3	190.7	181.7	113.3	73.7	48.9
	MV	57.6	67	73.4	80.3	96.2	110.7	116.7	122	121	115.3	100	82.7	67.3	54.5
	HPS	436.0	333.0	401.3	529.0	575.3	682.0	582.3	573.7	660.0	585.0	487.7	383.0	454.3	336.3
	Induction	106	111	133.7	168	194.7	191.3	180	175	185.7	193.3	170	142.3	121.7	101.3
	LED	15.5	18.5	20.2	26.9	30.0	34.4	37.0	37.0	36.2	31.1	24.6	20.0	17.5	16.1

Chapter 6 - Sign Retroreflectivity Evaluation Based on Statistical Analysis of Field Experiment Data

Introduction

Sign visibility can be improved with the usage of brighter retroreflective sheeting on the signs. KDOT provided the KSU research team with signs with various retroreflective sheeting to be used on overhead guide signs. These sheeting types are were categorized into the following categories: Engineering Grade (type I), Diamond Grade (type XI), and High Intensity (type IV). A field experiment was performed using human participants of different age categories in order to determine which retroreflective sheeting provides the highest visibility and legibility to drivers from a specific distance during nighttime. This experiment was approved by the Committee on Research Involving Human participants at KSU, and the approval letter is shown in Appendix B.

In this experiment (hereafter refer to as retroreflectivity experiment), the low beam headlight of a vehicle was divided into 16 brightness levels using an illumination controlling device. For each brightness level, the illuminance on one sign at the specified distance was measured using a Minolta Illuminance meter. A statistical analysis was run to determine significant variables that contribute to sign visibility and to conclude which sign was judged based on visibility and legibility during nighttime. The statistical analysis of this research was generated using Statistical Analysis System (SAS®) Software, version [9.4] of the SAS System for [MS-Windows], Copyright © [2013] SAS Institute Inc. The following sections provide the experiment details.

Retroreflective Sheeting Details

Three signs were used in the retroreflectivity experiment. Sign letters were a combination of an upper-case letter for the initial word and lower-case letters for the other letters. Upper-case letters were 6 inches (2.362 cm) in height, and lower case letters were 4.5 inches (1.772 cm), as required in the MUTCD. The legend font on all used signs was Series E (Modified). Signs were 5 ft (152.4 cm) wide and 1.5 ft (45.72 cm) in height. Figures 6.1, 6.2, and 6.3 show Engineering Grade (type I), Diamond Grade (type XI), and High Intensity (type IV) signs used in the experiment, respectively.

Retroreflectivity of each sign background and legend was measured using a 920 SEL retroreflectometer in the Human Factors Laboratory in the IMSE Department at KSU. Retroreflectivity of the background was measured by dividing each sign into 10 columns and four rows. At each row-column intersection, the 920 SEL retroreflectometer measured retroreflectivity at the green background of the sign and then the sign's background retroreflectivity values were averaged to find the overall background retroreflectivity. For the sign legend, the 920 SEL retroreflectometer measured retroreflectivity of the first letter of each word on signs 'M' three times, and the average of these readings was calculated to obtain the overall legend retroreflectivity value for each sign. This procedure was repeated for the sheeting of all three signs. Retroreflectivity values are shown in Table 6.1. According to Table 6.1, the three signs had the minimum retroreflectivity values for both legend and background as required in the MUTCD of 2009.

Table 6.1 Retroreflectivity Values of the Retroreflective Sheeting

Sign Sheeting	Background Retroreflectivity ($cd.m^{-2}.lux^{-1}$)	Legend Retroreflectivity ($cd.m^{-2}.lux^{-1}$)
Engineering Grade (type I)	32.9	64.9
Diamond Grade (type XI)	140.9	716.3
High Intensity (type IV)	97.3	553.3

Figure 6.1 Engineering Grade (Type I) Sheeting Sign

Figure 6.2 Diamond Grade (Type XI) Sheeting Sign

Figure 6.3 High Intensity (Type IV) Sheeting Sign

Building an Illumination Controlling Device

An illumination controlling device (also called PWM headlight dimmer module) for vehicle headlamps was built in the electrical engineering laboratory at KSU. In this device, the Pulse-Width-Modulation (PWM) headlight dimmer uses a pulse-width modulation to allow the user to dim vehicle headlights to one of 16 brightness levels recorded in even increments between 0 and 15. The PWM dimmer is composed of an ATMEL AT91SAM7s-EK microprocessor development board and a custom analog breadboard with four headlight driver circuits.

On startup, the PWM peripheral microprocessor is configured to produce a 12.5 kHz square wave with a variable duty cycle, and the Periodic Interrupt Timer (PIT) of the microprocessor generates a software interrupt every millisecond. When the PIT interrupts, the microprocessor reads the value of the duty cycle selector knob, which is a 16-position binary encoder. When the value of the duty cycle is changed since the last time it was read, the microprocessor retrieves a new configuration value for the PWM peripheral from the duty cycle lookup table. Then, the microprocessor reconfigures and enables the PWM module to produce a waveform with the desired duty cycle. The custom analog breadboard contains four headlight driver circuits controlled by the PWM signal from the microprocessor. Large P-channel power Metal Oxide Semiconductor Field Effect Transistors (MOSFET) act as a voltage-controlled current switch connected in series with the vehicle’s headlight. The P-channel model number is IRF9540. Changing the duty cycle of the generated PWM waveform changes how long the current is allowed to flow through the headlights, increasing or decreasing their brightness. Power transistors are mounted on external heat sinks, allowing the dissipation of heat generated by large headlight currents. Because the microprocessor is unable to directly drive the gates of the large power Field Effect Transistor (FET), the PWM signal to each headlight driver circuit is buffered by a 74HC04 hex inverter and a smaller 2N7000 n-channel MOSFET.

The PWM headlight dimmer module is connected to the vehicle's electrical system by custom fuse-connector cables. To connect the dimmer to the vehicle, the vehicle headlight fuses must be removed and the dimmer's cable must be plugged into the empty sockets. When the dimmer is switched on, the current that is normally flow to the headlights is routed through the dimmer's power MOSFETs, thus replacing vehicle headlight fuses with voltage-controlled switches. The PWM headlight dimmer is compatible with all vehicles that utilize Auto or Mini-style blades fuses. The dimmer can be powered if headlight fuses are located in the fuse boxes in the driver's cabin or the dimmer module can be plugged into the car cigarette lighter. If the headlight fuses are located in the fuse box under the vehicle's hood, dimmer power can be obtained by connecting dimmer to the vehicle's battery terminals.

After connecting the PWM headlight dimmer to the vehicle, the user starts the vehicle and turns on the headlights. Then, the user turns the PWM dimmer's power switch on and powers the headlights by turning the duty cycle select knob located on top of the dimmer. Figure 6.4 shows the headlight dimmer with its knob, the power FETs, and the printed-circuit boards of the microcontroller and custom analog breadboard.

Figure 6.4 PWM Headlight Dimmer, Printed Circuit Board, and Custom Analog Breadboard

Experimental Setup

The field experiment was performed on the Saint Thomas More Church rear parking lot at night after 8:30 pm to ensure a complete darkness. All lights in the church building and parking lot were turned off by church management to ensure darkness. No moon was present, guaranteeing that the only source of present light was the vehicle's headlight. The vehicle used was a 2011 Chevrolet Impala from the KSU Motor Pool. A total of 43 human subjects of various age groups were selected to find the effect of driver's age on nighttime visibility.

A post was designed in the IMSE workshop to mount the signs while conducting the experiment, as shown in Figure 6.5. The post height was 8 ft (243.84 cm), measured from the bottom of the sign to the road surface. This height is in compliance with MUTCD of 2009 requirements. The lateral offset for the post was 6 ft (182.88 cm) from the edge of the driving lane to the nearest edge of the sign. The lateral offset is also in compliance with MUTCD of 2009 requirements.

Based on section 2.18 (Mounting Height) in the MUTCD of 2009, the standard is:

"Directional signs on freeways and expressways shall be installed with a minimum height of 7 feet, measured vertically from the bottom of the sign to the elevation of the near edge of the pavement. All route signs, warning signs, and regulatory signs on freeways and expressways shall be installed with a minimum height of 7 feet, measured vertically from the bottom of the sign to the elevation of the near edge of the pavement. If a secondary sign is mounted below another sign on a freeway or expressway, the major sign shall be installed with a minimum height of 8 feet and the secondary sign shall be installed with a minimum height of 5 feet, measured vertically from the bottom of the sign to the elevation of the near edge of the pavement.

Where large signs having an area exceeding 50 square feet are installed on multiple breakaway posts, the clearance from the ground to the bottom of the sign shall be at least 7 ft."

Based on section 2.19 (lateral offset) in the MUTCD of 2009, the standard is:

"For overhead sign supports, the minimum lateral offset from the edge of the shoulder (or if no shoulder exists, from the edge of the pavement) to the near edge of overhead sign supports (cantilever or sign bridges) shall be 6 ft. Overhead sign supports shall have a barrier or crash cushion to shield them if they are within the clear zone.

Post-mounted sign and object marker supports shall be crashworthy (breakaway, yielding, or shielded with a longitudinal barrier or crash cushion) if within the clear zone."

While running the experiment, the vehicle was stationary at two distances from the sign on the parking lot driving lane - 240 ft, and 180 ft.

Figure 6.5 Post Used in the Experiment with One Mounted Sign

Procedure

The field experiment was carried out at night, and the illumination control device (PWM headlight dimmer) which controls vehicle headlight brightness at 16 levels was connected to the vehicle fuse box located under the vehicle hood. Fuses of the vehicle front safety lights were removed to ensure only light from the headlights was the main source of illuminating while performing the experiment. The sign post was placed on its specified position according to the MUTCD of 2009 requirements. The field experiment was conducted in 30 minutes sessions; only one human subject was present at the experiment location for each session. At the beginning of each session, the subject was asked to complete a consent form shown in Appendix C. The age of each subject was also recorded.

Before beginning the experiment, instructions were given to each participant:

- You will be seated in the driver’s seat of a sedan vehicle and one of the experimenters will be seated in the passenger seat.
- Initially, the vehicle headlights will be turned off and then turned on to level 0 of the illumination.
- You will be asked to read the legend on the sign without stressing your eyes. If you cannot read the word on the sign without stressing your eyes, ask the experimenter to go to the next level of illumination.
- When you are able to see the word on the sign, read it aloud so the experimenter knows that you have read the word and he can record the reading.

- This procedure is repeated for two more signs.
- After the first stage, you will be taken to the other location and the same procedure will be repeated for a total of three signs.

Results

For each subject, the subject number, age, and knob position of illuminance controlling device at which the subject read the legend on each sign at the specified distance was recorded.

The Minolta Illuminance meter was used to measure the illuminance level for each of the 16 brightness levels. When measuring illuminance for each brightness level, three positions on the sign legend were selected: the right side, the center, and the left side. For each position, three illuminance readings were taken and then the readings average was calculated. The average of illuminance readings at each headlights brightness level was calculated as shown in Table 6.2.

Table 6.2 Illuminance Readings for Each Brightness Level at Two Distances from Sign

Knob Position	240 ft Distance				180 ft Distance			
	Left	Center	Right	Average	Left	Center	Right	Average
0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
1	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
3	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03
4	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.04
5	0.05	0.05	0.05	0.05	0.06	0.05	0.06	0.06
6	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07
7	0.08	0.07	0.07	0.07	0.10	0.09	0.09	0.09
8	0.09	0.09	0.08	0.09	0.12	0.11	0.11	0.11
9	0.11	0.11	0.11	0.11	0.14	0.14	0.13	0.14
10	0.14	0.13	0.12	0.13	0.17	0.16	0.16	0.16
11	0.15	0.15	0.14	0.15	0.20	0.19	0.18	0.19
12	0.18	0.17	0.17	0.17	0.22	0.22	0.21	0.22
13	0.20	0.20	0.19	0.20	0.25	0.25	0.24	0.25
14	0.23	0.22	0.21	0.22	0.29	0.28	0.27	0.28
15	0.26	0.25	0.23	0.25	0.32	0.31	0.30	0.31

Refining and Analyzing Data

Refining the collected data resulted in 41 subjects, 12 females and 29 males, used for statistical analysis using SAS Software. Data collected from two subjects were dropped because they had vision problems. Subject ages were between 20 and 81 years old. The subjects were divided into three groups according to age: 20-29, 30-49, and above 50 years old. For each sign, the frequency of subjects when reading the sign legend at each brightness level (knob position) was calculated and presented in Table 6.3.

Table 6.3 Frequency of Human Subjects at Each Knob Position when Reading Signs

Knob Position	180 ft Distance			240 ft Distance		
	Type I	Type XI	Type IV	Type I	Type XI	Type IV
0	0	0	0	0	0	0
1	0	1	0	0	0	0
2	0	5	0	0	3	0
3	0	17	7	0	11	3
4	5	10	11	0	12	9
5	7	5	9	2	6	8
6	6	3	5	3	2	7
7	7	0	3	6	2	3
8	2	0	0	2	3	1
9	4	0	3	4	0	0
10	2	0	1	3	1	2
11	2	0	0	0	0	3
12	0	0	1	2	0	0
13	1	0	1	2	0	0
14	2	0	0	2	1	1
15	2	0	0	4	0	0
Can't read	1	0	0	11	0	4

For the Engineering Grade (type I) sign at 180 ft, the highest frequencies of subjects read the sign’s legend were at knob positions 5, 7, 6, 4, and 9 in sequence, with a total of 29 subjects out of 40 after removing the disqualifying subject, who could not read the sign. Corresponding illuminance values were 0.06 lux, 0.09 lux, 0.07 lux, 0.04 lux, and 0.14 lux, respectively, with an average of 0.08 lux. At 240 ft for Engineering Grade (type I) sign, 11 subjects did not read the legend. The highest frequencies of subjects who read the legend were at knob positions 7, 15, 9, and 10 in sequence, with a total of 17 subjects out of 30 after removing the 11 disqualifying subjects who did not read the sign. Corresponding illuminance values were 0.07 lux, 0.25 lux, 0.11 lux, and 0.13 lux, respectively, with an average of 0.14 lux. For the Diamond Grade (type XI) sign at 180 ft, the highest frequencies of subjects read the sign’s legend were at knob 3 and 4 in sequence, with a total of 27 subjects out of 41. Corresponding illuminance values were 0.03 lux, and 0.04 lux, respectively, with an average of 0.035 lux. At 240 ft for Diamond Grade (type XI) sign, the highest frequencies of subjects who read the sign’s legend were at knob positions 4, 3, and 5 in sequence, with a total of 29 subjects out of 41. Corresponding illuminance values were 0.04 lux, 0.02 lux, and 0.05, respectively, with an average of 0.037 lux. Finally, for the High Intensity (type IV) sign at 180 ft, the highest frequencies of subjects who read the sign's legend were at knob positions 4, 5, 3, and 6 in sequence, with a total of 32 subjects out of 41. Corresponding illuminance values were 0.04 lux, 0.06 lux, 0.03 lux, and 0.07 lux, respectively, with an average of 0.05 lux. At 240 ft for the High Intensity (type IV) sign, four subjects could not read the sign's legend. The highest frequencies of subjects who read the sign's legend were at knob positions 4, 5, and 6 in sequence, with a total of 24 subjects out of 37 after removing the four disqualifying subjects who did not read the sign. Corresponding illuminance values were 0.04 lux, 0.05 lux, and 0.06 lux, respectively, with an average of 0.05 lux.

Statistical Analysis

Repeated Measures Experimental Design was used to analyze collected data. This design analyzes statistical data in which identical measures are collected multiple times for the same subject but under varying conditions. The term "repeated" means that any factor for which each subject is measured, is repeated at every level for that factor (Neter, et al., 1996). This design involves a repeated measurement on the unit of analysis in one or more independent variables (Neter, et al., 1996). These designs are often called mixed designs or designs with within-subjects factors.

SAS Software was used to analyze the refined data. SAS Software input variables were divided between three independent variables, subject, distance, and sign type number, and one dependent variable, illuminance level. The blocking factor was the subject in this design and units for the selected variables were lux for illuminance, and feet for distance.

The selected SAS Software procedure was "PROC MIXED," which is a generalization of the General Linear Model (GLM) procedure because "PROC GLM" fits standard linear models and "PROC MIXED" fits the wider class of mixed linear models (Wolfinger & Chang, 1995). Both procedures have similar Class, Model, Contrast, Estimate, and LSMEANS statements, but their RANDOM and REPEATED statements differ.

In order for SAS Software to read and analyze the data, a number coding was assigned for the used signs: number 1 for Engineering Grade 'type I' sign sheeting, number 2 for Diamond Grade 'type XI' sign sheeting, and number 3 for High Intensity 'type IV' sign sheeting.

The data were arranged so that SAS Software could analyze the data with the repeated measure design format. SAS Software codes used in the analysis are shown in Appendix D.

Discussion

Based on SAS Software output, 230 observations were used in the analysis instead of 246. The missing 16 observations were cancelled by SAS Software because some subjects could not read the sign legend for all 16 levels of the illumination controlling device. For the missing values, an illuminance level could not be fitted as a dependent value using the Minolta Illuminance meter because the maximum headlight brightness level was obtained at the last knob position.

The backward elimination procedure was considered to select the significant variables and to fit the final model. This means the first statistical model was found first, and then the least significant variable or variable interaction was removed from the model. Table 6.4 is the SAS Software output for type 3 tests of the fixed effects of the first model. Based on p-value and considering a significance level of 0.05, the significant variables were the distance, the sign, and the distance-sign interaction. Age group variable was insignificant. Based on Table 6.4, it is clearly shown that all two and three-way variable interactions are not significant according to their p-value.

Table 6.4 Type 3 Tests of Fixed Effects for the First Model

Effect	No. DF	Den DF	F Value	Pr > F
Distance	1	175	8.39	0.0043
Sign	2	174	93.17	<.0001
Distance*Sign	2	174	3.31	0.0387
Age group	2	37.3	0.76	0.4743
Distance*Age group	2	175	1.13	0.3249
Sign*Age group	4	174	0.29	0.8839
Distance*Sign*Age group	4	174	0.95	0.4388

Table 6.5 shows the SAS Software output for type 3 tests of the fixed effects for the reduced model in which all the variables are significant.

Table 6.5 Type 3 Tests of Fixed Effects for the Final Model

Effect	No. DF	Den DF	F Value	Pr > F
Distance	1	186	5.75	0.0175
Sign	2	186	100.95	<.0001

The SAS Software output of the least square means of the three significant variables (distance, sign) is shown in Table 6.6. Based on the p-value for all levels of distance (180 ft, and

240 ft), and sign levels (sign 1, sign 2, and sign 3), all are significant. Since the objective of this study was to find the minimum amount of illuminance that enables the driver to read the sign, the estimates of each variable's level can be used for driver's visibility and legibility of each sign. For the distance variable, the estimate of the 180 ft distance is 0.07456 which is smaller than the estimate of the 240 ft distance (0.08632). This means shorter distance between the vehicle and the sign influences the driver with higher visibility of the sign. For sign variables, the estimate of sign 2 (Diamond Grade 'type XI') is 0.04280, which is the smallest among the other sign levels: sign 3 (High Intensity 'type IV') is 0.07085 and for sign 1 (Engineering Grade 'type I') is 0.1277. This means sign 2 (Diamond Grade 'type XI') required less illuminance and had the highest visibility, followed by sign 3 (High Intensity 'type IV').

Table 6.6 Least Square Means of the Significant Variables

Effect	Distance	Sign	Estimate	Standard Error	DF	t Value	Pr > |t|
Distance	180		0.07456	0.006822	49.2	10.93	<.0001
Distance	240		0.08632	0.006963	53.1	12.40	<.0001
Sign		1	0.1277	0.007446	68.3	17.15	<.0001
Sign		2	0.04280	0.007206	60.8	5.94	<.0001
Sign		3	0.07085	0.007277	62.9	9.74	<.0001

Table 6.7 shows SAS Software output for the difference of least square means for the variables distance, and sign. This SAS Software output shows pairwise comparison for the different variable levels. The difference of least square means output can be used to find significant variables based on the p-value.

Based on Table 6.7, when comparing the three signs sheeting in pairs, a statistical difference existed between the following combinations of signs: sign 1 (Engineering Grade 'type I') and sign 2 (Diamond Grade 'type XI'), sign 1 (Engineering Grade 'type I') and sign 3 (High Intensity 'type IV'), and sign 2 (Diamond Grade 'type XI') and sign 3 (High Intensity 'type IV'). The difference occurs because the p-value of each combination is smaller than 0.05. Similarly, comparing the two distances resulted in a statistical difference between them based on the p-value.

Based on the subjects' frequency data at each brightness level of vehicle headlights shown in Table 6.3, results showed that the legend of the Diamond Grade (type XI) retroreflective sheeting was read by all subjects at 180 ft and 240 ft, while 11 subjects could not read the legend of the Engineering Grade (type I) retroreflective sheeting at 240 ft, four subjects could not read the legend of the High Intensity (type IV) retroreflective sheeting at 240 ft, and one subject could not read the Engineering Grade (type I) retroreflective at 180 ft, meaning that visibility of the Diamond Grade retroreflective sheeting was the highest. In addition, the highest frequency of human subjects when reading the legend of the Diamond Grade (type XI) was at knob positions 3 and 4, totaling 27 subjects with an average illuminance of 0.035 lux at 180 ft, and at knob positions 4, 3, and 5 in sequence, for a total of 29 subjects with an average illuminance of 0.037 lux at 240 ft. Because four subjects who could not read the High Intensity (type IV) sign legend at 240 ft was less than the 11 subjects who could not read the legend on the Engineering Grade (type I) sign at 240 ft, High Intensity (type IV) sheeting visibility was better than the Engineering Grade (type I) sheeting. Comparing of the average illuminance values that enabled the subject to read the signs revealed that the minimum illuminance values were for Diamond Grade (type XI) sign's legend at the both distances, followed by the High Intensity (type IV) sign.

Summary

According to statistical analysis results using SAS Software, distance and sign sheeting material type were the significant variables based on 5% significance level. The age group variable was not significant, meaning that sign visibility was not affected by the age of the subject. A possible explanation of this is that any subject, regardless of age, with a vision problem was using corrective lenses or glasses at the time of the experiment.

Based on the frequency of human subjects at each headlights brightness level, the Diamond Grade (type XI) sign was read by a majority of subjects at lower illuminance averages: 0.035 lux and 0.037 lux at 180 ft and 240 ft, respectively. In addition, all participating subjects read the legend on the Diamond Grade (type XI) sign, but not the High Intensity (type IV) and Engineering Grade (type I) sheeting. Therefore, the Diamond Grade (type XI) ranked first based on nighttime visibility and legibility. Consequently, using Diamond Grade (type XI) retroreflective sheeting will increase safety on roadways during nighttime. High Intensity (type IV) ranked second based on the visibility.

Table 6.7 Differences of Least Square Means

Effect	Distance	Sign	Distance	Sign	Estimate	Standard Error	DF	t Value	Pr > |t|	Adjustment	Adj P
Distance	180		240		-0.01176	0.004906	186	-2.40	0.0175	Tukey-Kramer	0.0175
Sign		1		2	0.08487	0.006039	186	14.05	<.0001	Tukey-Kramer	<.0001
Sign		1		3	0.05683	0.006090	186	9.33	<.0001	Tukey-Kramer	<.0001
Sign		2		3	-0.02804	0.005829	186	-4.81	<.0001	Tukey-Kramer	<.0001

Chapter 7 - Cost Analysis of Overhead Guide Signs Light Sources and Retroreflective Sheeting Materials

Introduction

Sign visibility for drivers during nighttime can be increased by adding external illumination sources or by using retroreflective sheeting on signs. The cost of various sign illuminating sources studied in Chapter 5 is evaluated in this chapter to ascertain the cost-effective source. A cost analysis was performed for the five light sources studied in Chapter 5: the 250W HPS, the 250W MH, the 250W MV, the 85W induction, and the 62W LED, to find the cost-effective light source. Similarly, a cost analysis of the retroreflective sheeting studied in Chapter 6 was performed to find the cost-effective sheeting, these sheeting were: Engineering Grade (type I), Diamond Grade (type XI), and High Intensity (type IV).

Several companies were contacted regarding the cost of light sources and retroreflective sheeting materials used with overhead guide signs. Three companies returned valuable information regarding the cost, maintenance, and lifespan of the studied light sources.

Similarly, several companies were contacted regarding the cost of retroreflective sign sheeting and their lifespan. Cost information and expected lifespan for the three retroreflective sheeting being studied in the retroreflectivity experiment were obtained from three companies.

The conclusion of this chapter provides a summary of the cost effective option for each visibility increasing method for overhead guide signs (illuminating or retroreflectivity), and the overall cost-effective option for sign improvements will be determined. Finally, decision criteria that have been studied in previous chapters in this report for each method will be combined, to find the overall best method of increasing overhead guide sign visibility.

Energy Independence and Security Act of 2007

The Energy Independence and Security Act (EISA) of 2007 issued a new energy standard to make efficient use of U.S. energy resources and to increase U.S. energy independence. This energy standard is commonly known as the “light bulb” law because screw-based light bulbs use fewer watts for similar lumen output (EISA, 2007). This standard means that any type of bulbs can be sold in the U.S. as long as they meet the corresponding efficiency requirement. The first phase of this law went into effect January 2012. Table 7.1 shows the law requirement and effective date.

Table 7.1 EISA Light-Bulb Law of 2007 Requirement and Effective Date (EISA, 2007)

Today’s Bulbs (2007)	After the Standard	Standard Effective Date
100 watt	≤72 watt	January 1, 2012
75 watt	≤ 53 watt	January 1, 2013
60 watt	≤ 43 watt	January 1, 2014
40 watt	≤ 29 watt	January 1, 2014

A lumen identifies how bright the light is, and watt describes how much energy the light bulb uses or consumes. Light bulbs can be compared in the following manner. Standard 60W incandescent light bulb provides 13-14 lumens per watt (EISA, 2007), the compact fluorescent bulbs (CFBs) provide the equivalent of 55-70 lumens per watt, and the LED equivalent provides 60-100 lumens per watt (EISA, 2007). The second phase of the light bulb law requires that a majority of light bulbs be 60-70% more efficient than standards require for the incandescent bulb in 2007.

Light Source Cost Analysis

In this section, a detailed cost comparison is presented for the 62W LED, the 85W induction, the 250W MH, the 250W HPS, and the 250W MV light sources. Calculations in the following sections were based on light source usage for an average of 11-hour per night with a cost of $0.08 per kWh for electricity consumed. Costs related to labor were not included.

The 62W LED

The average lifespan of an LED is 50,000 hours and the initial cost is $600. Electrical consumption for this LED is 62 watt per hour, or 0.682 kW per night. The daily operating cost is $0.05456 (0.682 kW × $0.08), and the annual operating cost is $19.91 ($0.05456 × 365 day). Based on an 11-hour night, the 62W LED will operate for 12.45 years (approximately 12.5 years). No maintenance cost is required after or during the lifespan of this LED because the entire light source unit must be replaced after 12.5 years. The 62W LED consumes 248.9 kW per year and 3,100 kW during its lifespan, with a total operating cost of $248 per lifespan. According to the manufacturer, no defrost option is required.

The 85W Induction

Based on information obtained from the manufacturer of the 85W induction lighting source, the average lifespan of this light source is 100,000 hours, and the initial cost is $678.3. The 85W induction lighting source consumes 85 watt per hour, or 0.935 kW per night. The daily operating cost is $0.0748 (0.935 kW × $0.08), and the annual operating cost is $27.3 ($0.0748 × 365 day). Based on an 11-hour night, the 85W induction lighting source will operate 24.91 years (approximately 25 years). The lamp requires replacement after 25 years, at a cost of $75, not including installation. The 85W induction lighting source consumes 341.3 kW per year and 8,500 kW during its lifespan, with a total operating cost of $680 per lifespan.

The 250W MH

The average lifespan of the 250W MH light source is 30,000 hours, and the initial cost is $678.30. This light source consumes 250 watt per hour, or 2.75 kW per night. The daily operating cost is $0.22 (2.75 kW × $0.08), and the annual operating cost is $80.30 ($0.22 × 365 day). Based on an 11-hour night, the 250W MH light source will operate 7.472 years (approximately 7.5 years). According to companies' information, lamp replacement cost is $30, excluding labor cost. The 250W MH light source consumes 1,003.75 kW per year and 7,500 kW during its lifespan, with a total operating cost of $600 per lifespan.

The 250W HPS

According to information from several manufacturers, the average lifespan of the 250W HPS light source is 30,000 hours, and the initial cost is $678.30. This light source consumes 250 watt per hour, or 2.75 kW per night. The daily operating cost is $0.22 (2.75 kW × $0.08), and the annual operating cost is $80.30 ($0.22 × 365 day). Based on an 11-hour operation day, the 250W HPS light source will operate 7.472 years (approximately 7.5 years). Companies' information indicates that the lamp replacement cost is $16, excluding labor cost. The 250W HPS light source consumes 1,003.75 kW per year and 7,500 kW during its lifespan, with a total operating cost of $600 per lifespan.

The 250W MV

According to information from several manufacturers, the average lifespan of the 250W MV light source is 30,000 hours, and the initial cost is $678.30. This light source consumes 250 watt per hour, or 2.75 kW per night. The daily operating cost is \$0.22 (2.75 kW × \$0.08), and the annual operating cost is \$80.30 (\$0.22 × 365 day). Based on an 11-hour night, the 250W MV light source will operate 7.472 years (approximately 7.5 years). Based on company information, the lamp replacement cost is \$25, excluding labor cost. The 250W MV light source consumes 1,003.75 kW per year and 7,500 kW during its lifespan, with a total operating cost of \$600 per lifespan.

Overhead Guide Sign Lighting Sources Cost Comparison

In this section, a detailed comparison of the five light sources is presented. A 50-year cycle is considered to determine the maintenance contribution for light sources over the time. Table 7.2 compares the light sources in detail, and the provided cost analysis includes initial, operating, and maintenance cost components for each light source. Based on cost analysis results shown in Table 7.2, the 85W induction lighting source is the cost-effective light source, followed by the 62W LED, 250W HPS, 250 MV, and 250W MH.

Some light source manufacturers doubt the 100,000 hour lifespan of induction lighting since no real experimental testing has been performed. Therefore, another cost comparison of the five light sources was performed using a 50,000-hour lifespan for the 85W induction lighting. Updated cost results are shown in Table 7.3. The lifespan change of the 85W induction lighting has no effect on previous results of the cost-effective light source based on cost, i.e., the cost-effective light source continued to be the 85W induction lighting.

Table 7.2 Cost Comparison of the Five Light Sources

	Details	**62W LED**	**85W induction**	**250W MH**	**250W HPS**	**250W MV**
1	Initial cost (\$)	600	678.3	678.3	678.3	678.3
2	Life (hours)	50,000	100,000	30,000	30,000	30,000
3	Life (years)	≅ 12.5	≅ 25	≅ 7.5	≅ 7.5	≅ 7.5
4	Daily power consumption (kW)	0.682	0.935	2.75	2.75	2.75
5	Annual power consumption (kW/year)	248.93	341.3	1,003.75	1,003.75	1,003.75
6	Life power consumption (kW)	3,100	8,500	7,500	7,500	7,500
7	Number of maintenance in 50 years	3	1	5.66	5.66	5.66
8	Total power consumption (kW/50 years)	12,446.5	17,065	50,187.5	50,187.5	50,187.5

	Details	**62W LED**	**85W induction**	**250W MH**	**250W HPS**	**250W MV**
9	Maintenance required	A[1]	C[2]	C	C	C
10	Daily operating cost ($)	0.05456	0.0748	0.22	0.22	0.22
11	Annual operating cost ($)	19.91	27.30	80.30	80.30	80.30
12	Life operating cost ($)	248	680	600	600	600
13	Maintenance cost ($/each time required)	600	75	30	16	25
14	Total maintenance cost ($/50 years)	1,800	75.00	170	90.67	141.67
15	Total operating cost ($/50 years)	995.6	1,365	4,015	4,015	4,015
16	Total cost ($/50 years)	3,395.6	2,118.30	4,863.3	4783.97	4834.97
17	Average annual cost ($)	67.91	42.37	97.27	95.68	96.70

Table 7.3 Cost Comparison of Light Sources after Changing the 85W Induction Lifespan

	Details	**62W LED**	**85W induction**	**250W MH**	**250W HPS**	**250W MV**
1	Initial cost ($)	600	678.3	678.3	678.3	678.3
2	Life (hours)	50,000	50,000	30,000	30,000	30,000
3	Life (years)	≅ 12.5	≅ 12.5	≅ 7.5	≅ 7.5	≅ 7.5
4	Daily power consumption (kW)	0.682	0.935	2.75	2.75	2.75
5	Annual power consumption (kW/year)	248.93	341.3	1,003.75	1,003.75	1,003.75
6	Life power consumption (kW)	3,100	4,250	7,500	7,500	7,500
7	Number of maintenance in 50 years	3	3	5.66	5.66	5.66
8	Total power consumption (kW/50 years)	12,446.5	17,065	50,187.5	50,187.5	50,187.5
9	Maintenance required	A	C	C	C	C
10	Daily operating cost ($)	0.05456	0.0748	0.22	0.22	0.22
11	Annual operating cost ($)	19.91	27.30	80.30	80.30	80.30
12	Life operating cost ($)	248	340	600	600	600
13	Maintenance cost ($/each time required)	600	75	30	16	25
14	Total maintenance cost ($/50 years)	1,800	225	170	90.67	141.67
15	Total operating cost ($/50 years)	995.6	1,365	4,015	4,015	4,015

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[1] Replacing the whole light fixture.

[2] Replace the lamp only.

	Details	62W LED	85W induction	250W MH	250W HPS	250W MV
16	Total cost ($/50 years)	3,395.6	2,268.3	4,863.3	4783.97	4834.97
17	Average annual cost ($)	67.91	45.37	97.27	95.68	96.70

Retroreflective Sign Sheeting Cost Analysis

In this section, a detailed cost analysis is presented for the following retroreflective sheeting materials: Engineering Grade (type I), Diamond Grade (type XI), and High Intensity (type IV). The following sections provide cost details for the three types of sheeting materials. Labor and equipment costs for installing or reinstalling the sign sheeting were similar for all the three retroreflective sheeting, and this cost was estimated to be $200 for initial sign installment, or replacement.

Retroreflective Sheeting Cost Comparison

In this section, a detailed comparison between the three retroreflective sheeting materials is presented. Labor costs and equipment are identical for the three types of retroreflective sheeting material. A 50-year life cycle is considered to obtain the replacement contribution for the three retroreflective sheeting based on lifespan. Table 7.4 compares the retroreflective sheeting costs in detail, and the provided cost analysis included initial, and maintenance or replacement cost components of each retroreflective sheeting for a 15 ft × by 9 ft sign size during lifespan of each sheeting type. Based on cost analysis results shown in Table 7.4, The High Intensity (type IV) is the cheapest sign sheeting, followed by Engineering Grade (type I), and then by the Diamond Grade (type XI).

Table 7.4 Cost Comparison for the Retroreflective Sheeting

	Details	Engineering Grade (type I)	Diamond Grade (type XI)	High Intensity (type IV)
1	Initial cost ($/ft^2)	0.80	3.93	1.45
2	Life (years)	7	12	10
3	Cost of (15 ft × 9 ft) sign sheeting ($)	108	530.55	195.75
4	Labor cost per each installment or replacement ($)	200	200	200
5	Number of sign replacements in 50 years	7.14	4.17	5
6	Required sign sheeting cost ($/ 50 years)	771.12	2,212.40	957.5

	Details	Engineering Grade (type I)	Diamond Grade (type XI)	High Intensity (type IV)
7	Required labor cost ($/ 50 years)	1,428	834	1000
8	Total cost ($/ 50 years)	2,199.12	3,046.4	1,957.5
9	Average annual cost ($)	43.98	60.93	39.15

Combining Decision Criteria to Find the Best Sign External Light Source

Based on light distribution of light sources, HPS ranked first providing the highest illuminance on the sign, followed by MH, induction lighting, MV, and LED. In summary, the HPS light source was the best conventional light source, followed by MH and MV. Among the new generation light sources, induction lighting is recommended to be used by DOTs. Among those light sources that can be used in the U.S., based on light distribution, the 85W induction lighting is the best, followed by the 62W LED. Based on cost analysis of the five light sources, excluding labor costs, the 85W induction lighting source is the most cost-effective light source, followed by the 62W LED, 250W HPS, 250 MV, and 250W MH.

The combination of decision criteria, light distribution, and light source cost revealed that the 85W induction lighting was the optimal light source being tested, followed by the 62W LED.

Combining Decision Criteria to find the Best Sign Retroreflective Sheeting

Based on statistical analysis results of the retroreflectivity experiment in Chapter 6, Diamond Grade (type XI) sheeting was the optimal sheeting based on nighttime visibility, followed by High Intensity (type IV) sheeting and then Engineering Grade (type I). The cost analysis of retroreflective sheeting showed that High Intensity (type IV) retroreflective sheeting material was the cheapest retroreflective sheeting, followed by Engineering Grade (type I), and then by Diamond Grade (type XI).

DOTs with limited budget could use High Intensity (type IV) as an alternative solution for increasing the visibility and legibility of overhead guide signs.

Summary

When combining the decision criteria (cost, light distribution, and usability in U.S. based on EISA), the cost effective light source for overhead guide sign illumination was the 85W induction, followed by the 62W LED. For retroreflective sheeting, Diamond Grade (type XI) was the optimal sheeting for guide signs, however, combining the decision criteria (cost and visibility), High Intensity (type IV) retroreflective sheeting could be an alternative choice for DOTs with limited budgets.

The average annual cost for the 85W induction lighting was $45.37, and $67.91 for the 62W LED, not including labor cost. The yearly cost when using High Intensity (type IV) retroreflective sheeting was $39.15 including labor cost, meaning High Intensity (type IV) retroreflective sheeting is more cost-effective than illuminating overhead guide sign for DOTs with limited budgets.

Chapter 8 - Determining the Optimal Sheeting-Font Combination to Increase Shoulder-Mounted Guide Signs' Visibility under the Presence of Glare

Introduction

Glare is defined as a steady, dazzling, bright light or as brilliant reflection that is present when luminous or luminance intensity within the visual field is larger than the target to which eyes are accustomed (Mace, et al., 2001). Glare is caused by a significant ratio of luminance between the target and the glare source. Several factors significantly impact glare production, including the angle between the task and glare source, and the eyes adaptation to light. Glare creates visual difficulty in the presence of bright light, such as direct or reflected sunlight during the day, or artificial light, such as vehicle headlights, at night. Therefore, glare represents a critical deterrent for nighttime road safety because it hinders visual adjustments a driver must make in order to account for brightness differences.

Guide sign legibility is commonly thought to increase with increased luminance; however, beyond a certain point, a sign's overglow and irradiation begin to blur letter edges, consequently degrading sign legibility (Carlson, et al., 2014). According to Carlson et al. (2014), legibility loss is difficult to determine, and previous research has not identified the exact point at which legibility decreases. Signs negatively impact visibility by becoming glare sources when they are very bright and located in areas with low or no visual complexity (Carlson et al., 2014).

The addition of light sources or use of retroreflective sheeting material can increase guide sign visibility. Types of retroreflective sheeting include Engineering Grade, Diamond Grade, and High Intensity. Several font types including Series A (discontinued), Series B, Series C, Series D, Series E, Series E (Modified), Series F, and ClearviewHwyTM font can be used on signs.

According to surveys in Chapter 3, the most commonly used retroreflective sheeting material in the U.S. for overhead guide sign legends is Diamond Grade (type IX, followed by type XI), and High Intensity (types III and IV) is the most common retroreflective sheeting used for backgrounds. In addition, a majority of states use Series E (Modified) font, followed by Clearview 5W and 5WR for guide signs.

The focus of this Chapter was on increasing visibility of shoulder-mounted guide signs and reducing the effect of glare from an oncoming vehicle’s low beam headlights, by selecting the best combination of retroreflective sheeting and font type to be used on shoulder-mounted guide signs. A field experiment under the presence of a glare source from an oncoming vehicle’s low beam headlights was conducted to compare four guide signs produced by combining Diamond Grade (type XI) and High Intensity (type IV) sheeting materials, with Series E (Modified) and Clearview fonts. This experiment was approved by the Committee on Research Involving Human participants at KSU University, and the approval letter is shown in Appendix E.

Statistical analysis was conducted using SAS Software to determine the sheeting-font combination that most effectively increases visibility under the presence of glare. The cost analysis conducted in Chapter 7 for the tested retroreflective sheeting materials was considered to find the efficient retroreflective sheeting. Results of this research were combined to determine the optimal sheeting-font combination that increases legibility distance and visibility of shoulder-mounted guide signs to drivers under the presence of glare, and consequently boosts roadway safety.

Literature Review

One primary mission of the Federal Highway Administration (FHWA) is to increase roadway safety in the U.S. Statistics show that 25% of all motor vehicle travel occurs at night, but approximately 50% of all traffic fatalities occur during nighttime hours (Hasson & Lutkevich, 2002), and (FHWA, 2008). According NHTSA Fatality Analysis Reporting System, fatal crashes in the years 2009, 2010, 2011, and 2012 numbered 23,447, 22,187, 21,316, and 21,667, respectively; totals of nighttime crashes for those years were 11,630 (49.6%), 10,647 (48.0%), 10,183 (47.8%), and 10,480 (48.3%), respectively (NHTSA, 2012b) and (NHTSA, 2013).

Based on Schreuder (1998), there are three aspects of glare including the physiological glare, psychological glare, and absolute glare (Schreuder, 1998). Physiological glare is also known as disability glare (Schreuder, 1998). Disability glare, identified by Holladay (Holladay, 1926), is typically caused by light interreflection within a driver’s eyeball, thereby reducing the contrast between the target and glare source to a point in which the target cannot be distinguished

(Carlson et al., 2014). Psychological glare is also known as discomfort glare (Schreuder, 1998). Discomfort glare hinders a driver from seeing a target or creates a desire to look away from a bright light source. Discomfort glare produces visual discomfort and annoyance, sometimes resulting in visual fatigue and pain (Schreuder, 1998) and (Mace et al., 2001). Absolute glare is also known as dazzle which occurs when glare intensity completely impairs vision (Schreuder, 1998). Dazzle often experienced while driving, one example of dazzle is when leaving a tunnel during daylight (Schreuder, 1998).

Based on the direction, glare is also categorized as direct and reflected. Direct glare is produced by light sources, such as headlights, taillights, and street lighting, in the field of view (Mace et al., 2001). Specular reflections from glossy or polished surfaces can cause reflected glare; examples of glossy surfaces susceptible to reflected glare include vehicle rearview mirrors, bright matte surfaces inside the vehicle (e.g., dashboards), and steel or aluminum doors on nearby trailers (Mace et al., 2001).

Discomfort glare and disability glare can be faced during nighttime driving. The automotive head-lighting industry thought that discomfort glare was of greater consequence than disability glare because drivers consistently complain about discomfort glare (Mace et al., 2001). However, disability glare is equally significant and more likely to affect driver safety on roadways (Hankey, et al., 2005). Certain people, especially the elderly, those suffering from cataracts, and people with light-colored eyes, are most sensitive to disability glare (Mace et al., 2001) and (Bullough, et al., 2003). Glare affects daytime and nighttime driving, but nighttime glare can be mitigated by careful improvements in the design of vehicle lighting systems, roadways, and automobiles (Mace et al., 2001).

According to research by Hemion, objects' detection distance decreases in the presence of glare from oncoming high beam headlights (Hemion, 1969). However, Hemion (1969) found that detection distance is greater when both vehicles used high beam headlights compared to low beam headlights, even though both glare types (discomfort and disability) increased. Additional illumination from high beam headlights increased the target contrast, thereby negating contrast loss that caused disability glare, leading to the conclusion that visibility increases with the use of high beam headlights (Hemion, 1969).

According to Mace et al. (2001), discomfort and disability glare have differing physiological origins, thereby complicating glare comparison. The sensation of discomfort glare is related to neuronal interactions similar to physiological functions such as pupillary light response or skin resistance (Fry & King, 1975). However, disability glare results from light scattering in the ocular media. Both glare types also are uniquely affected by environmental parameters (Fry & King, 1975). For example, apparent luminance and size of the source are essential parameters for discomfort glare (Mace et al., 2001). On the other hand, disability glare is not affected by the size of glare source or luminance, but it is affected by the angular offset from the sight line and luminous flux (Mace et al., 2001).

Theeuwes, Alferdinck, and Perel (2002) performed an experiment to determine the correlation between glare and driving performance (Theeuwes et al., 2002). Participants of various ages were exposed to a simulated low beam headlights fixed to an instrumented vehicle hood. The simulated low beam headlights represented a relatively low glare source. A driving route of 23.555 km in length was divided into nine sections; each section represented a specific road type with distinct characteristics. Participants drove the instrumented vehicle at night in actual traffic. Results showed that the relatively low source of glare resulted in significantly decreased detection of simulated pedestrians along the roadside and caused participants to decrease vehicle speed on dark and winding roads in order to compensate for negative effects of the glare.

Carlson et al. (2014) performed an experiment to determine if rural highway signs overbrightness causes legibility reduction and glare and consequential safety concerns (Carlson et al., 2014). They selected white and yellow shoulder-mounted signs located on rural two-lane highways in which drivers use high beam headlights during nighttime driving. They conducted this experiment during night using high beam headlights. Detection distances of three variously sized objects located at three positions relative to highway signs for the experiment were measured. These targets were located 200 ft in front the sign, adjacent to the sign, and 200 ft behind the sign. In addition to the three objects, Carlson et al. used several speed limit signs with two types of retroreflective sheeting materials (type III and type XI). Participants drove a vehicle at a speed of 35 mile per hour (mph), and detection distances for the signs and objects were recorded by the experimenters. Driver’s age, object location, sign type, and object type were considered as variables. Analysis of variance showed that sign sheeting type and driver’s age were significant variables, with significance level of 5%. Researchers concluded that the shoulder-mounted signs could be excessively bright in rural areas, so unnecessary signs should be removed, regardless of sheeting type. Although they did not observe a significant reduction in legibility, they found a large reduction in the drivers' overall ability to detect hazardous objects near the roadway.

Porter, Hankey, Binder, and Dingus (2005) performed an experiment to evaluate discomfort glare during nighttime driving in clear weather using various types of headlights (Porter et al., 2005). Empirical testing was performed on the Virginia Smart Road which was designed according to UUSDOT specifications for two-lane undivided highway with a 104.7 km/hr (65 mph) speed limit. Sixty participants of various ages participated in the study. Participants drove toward a fixed glare source and rated it twice based on a DeBoer discomfort rating scale. The first rating occurred when the participant experienced discomfort from oncoming headlights at a range of 1,300-1,000 ft. The second rating reflected participant's discomfort within a range of 450-150 ft. Halogen, ultraviolet A, high output halogen, and high intensity discharge headlights were compared. Results of the empirical testing suggested that halogen headlights produce more discomfort glare than high intensity discharge headlights.

Methods

Participants

A total of 29 participants comprised of 21 males and 8 females, each with a valid driving license, voluntarily participated in the experiment. Participants' ages ranged between 18 and 53 years. Some participant's information collected and included in the statistical analysis as independent variables including whether the participant uses corrective lenses or glasses, when the participant performed the last vision checkup, the participant's nighttime driving frequency, the driving history of the participant, and if the participant involved as a driver in a vehicle accident in the past three years during nighttime.

Retroreflective Sheeting and Font Details

Combinations of two types of retroreflective sheeting and two types of fonts were used in this research's experiment (hereafter referred to as the glare experiment). Selection of these retroreflective sheeting materials and font types was based on previous chapters' results. The selected signs were received from the Kansas Department of Transportation. Table 8.1 provides a detailed summary of retroreflective sheeting materials and font types for each shoulder-mounted guide sign. The signs had green background and white legend. Each sign's legend consisted from one word only, and this word was different at each sign. Sign letters consisted of an upper-case initial word letter and lower-case letters for the remaining letters. Upper-case letters were 6 in (2.362 cm) in height and lower-case letters were 4.5 in (1.772 cm), as required in the MUTCD of 2009. The signs were 5 ft (152.4 cm) wide and 1.5 ft (45.72 cm) high.

Table 8.1 Used Signs Retroreflective Sheeting and Font Types

Sign Number	Retroreflective Sheeting Type	Font Type
1	High Intensity (type IV)	Series E (Modified)
2	High Intensity (type IV)	Clearview
3	Diamond Grade (type XI)	Clearview
4	Diamond Grade (type XI)	Series E (Modified)

Retroreflectivity of each sign background and legend was measured using a 920 SEL retroreflectometer in the Human Factors Laboratory in the Industrial and Manufacturing Systems Engineering Department at Kansas State University, Manhattan, KS. Retroreflectivity values, as shown in Table 8.2, are in compliance with minimum retroreflectivity values required by ASTM D4956.

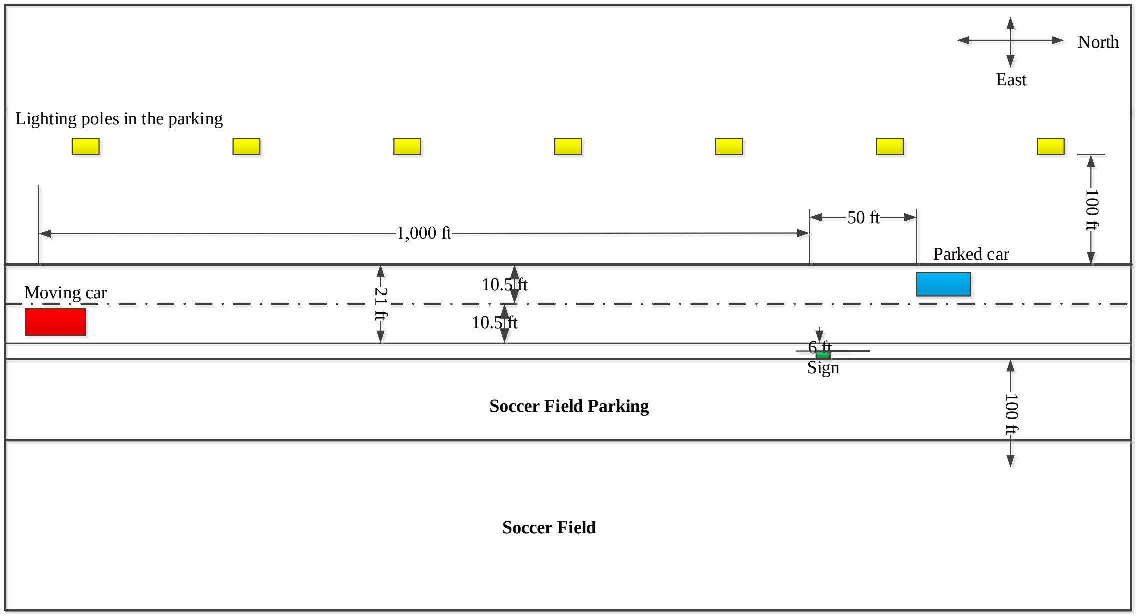
Table 8.2 Signs Retroreflectivity Values

Sign	Sign Sheeting	Background Retroreflectivity ($cd.m^{-2}.lux^{-1}$)	Legend Retroreflectivity ($cd.m^{-2}.lux^{-1}$)
1 and 2	High Intensity (type IV)	97.3	553.3
3 and 4	Diamond Grade (type XI)	140.9	716.3

Experimental Setup

The glare experiment was performed in the east parking lot of Bill Snyder Family Stadium at Kansas State University. Figure 8.1 shows the layout of the experiment location. A local street on the east side of the parking lot consisted of two-direction lanes separated by a white dashed-marking was selected to run the glare experiment. The width of each lane was 10.5 ft, as in compliance with USDOT requirements for local streets.

Figure 8.1 Schematic Sketch for the Experiment Location (Not Drawn to Scale)



A post to mount the signs during the experiment was designed in the Industrial and Manufacturing Systems Engineering Department workshop. The post measured 8 ft (243.84 cm) high from the bottom of the sign to the road surface. The lateral offset for the post was 6 ft (182.88 cm) from the edge of the driving lane to the nearest edge of the sign. The post height and lateral offset were in compliance with MUTCD 2009 requirements. The post was placed 1,000 ft from the south side of the imitated street on the parking lot, as shown in Figure 8.1.

Lighting poles located 100 ft to the west of the imitated street were continuously lit while conducting the experiment. The condition of lights in the neighboring soccer field was recorded for each participant and included as an independent variable in the statistical analysis.

The glare experiment was conducted after 8:00 p.m., during night over a week of clear weather, in September 2014. The sign post was placed on its specified location, as shown in Figure 1, and 2009 MUTCD requirements for lateral distance and sign height were observed. The glare experiment was conducted in 45 min sessions for each participant. Only one participant at a time was allowed at the experiment site.

The glare experiment involved the use of two sedan vehicles (2011 Chevrolet Impala), both vehicles used halogen headlights. One vehicle was driven by participants in the lane closest to the shoulder-mounted guide sign (right lane) at a speed of 30 mph, and the other vehicle was parked 50 ft behind the sign on the opposing lane (left lane). Low beam headlights of the parked vehicle remained on throughout the experiment in order to generate an artificial glare source from an oncoming vehicle's headlights.

Procedure

At the beginning of each session, the participant was asked to complete a consent form. Approval for using a human subject was obtained from the University Research and Compliance Office, Committee on Research Involving Human Subjects at Kansas State University.

Before beginning the glare experiment, instructions and guidelines were given to each participant:

1. You will be seated in the driver's seat of a sedan vehicle and the experimenter will be seated in the passenger seat. You will use only low beam headlights of the vehicle and you cannot change to high beam headlights.
2. Initially, you will drive the vehicle under guidance from the experimenter until you reach the starting point in the street that has a shoulder-mounted sign. The experimenter will ask you to stop there. At this point you are 1,000 ft from a shoulder-mounted guide sign.
3. The experimenter will explain that you have to drive the vehicle on the right lane of the imitated street at a speed of 30 mph. Once you are able to read the sign's legend, speak it aloud, and continue driving. If you read the sign correctly, the experimenter will drop a sand bag out the window on the street in order to measure legibility distance. If you do not read the sign correctly, the experimenter will notify you and you will continue driving until you are able to read the sign correctly.
4. Steps (1-3) will be repeated for a total of four signs.

Results

Repeated measures experimental design was used to analyze collected data using version 9.4 of SAS Software. Satterthwaite approximation for the denominator degrees of freedom was selected in the analysis. The first model included all main effects and interactions between explanatory variables. A significance level of 5% was considered. The backward elimination procedure was carried out to remove the least significant variable or variables' interaction until the final model was obtained.

Dependent and Independent Variables

The response was the legibility distance from the sign face at which the participant correctly read the legends of the four signs. Table 8.3 shows the independent variables and their categories.

Table 8.3 List of Independent Variables

Variable	Categories
Sheeting/font combination (refer to Table 1 for details)	Sign 1, Sign 2, Sign 3, and Sign 4
Participant age	18-29 years, and 30 years and above
Participant gender	Male, and female
Participant status of using lenses/glasses	Yes, and no
Participant last vision check-up	Less than 2 years, and 2 years or more
Participant nighttime driving frequency	1-2 times/week, 3-4 times/week, and 5-7 times/week
Participant accidents during night in the past three years	Yes, and no
Participant driving history	3 years or less, 3-5 years, 6 years or more
Time of the experiment	8-10 p.m., and 10-11:45 p.m.
Lighting condition of the soccer field	On, and off

Each participant tested four signs and the legibility distance at which the participant correctly read the sign was recorded. Based on SAS Software output, 114 observations were used in the analysis instead of 116 because of two missing legibility distances.

Statistical Analysis

The first model is shown in Table 8.4. Table 8.5 presents the final model result for Type 3 test of the fixed effects. Of all dependent variables and interactions studied, the sheeting/font combination was found to be the only significant variable in the final model based on its p-value which was less than 0.0001, and is smaller than 5%. All the other dependent variables studied were removed from the model when backward elimination procedure was carried out.

Table 8.4 Type 3 Tests of Fixed Effects for the First Model

Effect	No. DF	Den DF	F Value	Pr > F
Age	1	16.2	0.10	0.7615
Gender	1	16.1	1.00	0.3322
Nighttime driving frequency	2	16.1	0.51	0.6092
Accidents during night in the past three years	1	16	0.34	0.5654
Participant status of using lenses/glasses	1	16	0.34	0.5683
Participant last vision check-up	1	16	0.01	0.9301
Participant driving history	2	16.1	2.01	0.1668
Sheeting/font combination (sign)	3	46	2.68	0.0575
Time of the experiment	1	16	0.10	0.7583
Lighting condition of the soccer field	1	16.2	0.00	0.9634
Age*Sign	3	46.1	0.67	0.5757
Gender*Sign	3	46.1	1.57	0.2084
driving frequency*Sign	6	46.1	1.51	0.1972

Effect	No. DF	Den DF	F Value	Pr > F
Accident*Sign	3	46.1	0.18	0.9109
Using lenses/glasses*Sign	3	46.1	1.82	0.1574
vision check-up*Sign	3	46.1	1.54	0.2168
Driving history *Sign	6	46.1	0.62	0.7137
Time of the experiment*Sign	3	46.1	2.18	0.1030
Lighting condition of the soccer field*Sign	3	46.2	0.30	0.8248

Table 8.5 Tests of Fixed Effects for the Final Model

Effect	No. DF	Den DF	F Value	Pr > F
Sheeting/font combination	3	82.1	9.65	<.0001

SAS Software output of the least square means is shown in Table 8.6. Based on the p-value for all sign levels, all levels were significant. Table 8.6 shows the estimated influence for each sheeting/font combination on the legibility distance. Based on the estimate of each sheeting/font combination, sign 3 had the largest estimate (340.93), followed by sign 2 (307.97), sign 1 (295.90), and sign 4 (294.25).

Table 8.6 Least Square Means of Sign Levels

Effect	Sign Number	Estimate	Standard Error	DF	t Value	Pr > |t|
Sheeting/font combination	1	295.90	18.06	35.2	16.38	<.0001
Sheeting/font combination	2	307.97	18.06	35.2	17.05	<.0001
Sheeting/font combination	3	340.93	18.06	35.2	18.87	<.0001
Sheeting/font combination	4	294.25	18.19	35.1	16.18	<.0001

Discussion

Improved visibility was measured by the participants’ ability to read the legend on the sign from a greater legibility distance. Based on the tests of fixed effects, the only significant variable at a 5% significance level was the sheeting/font combination, in other words, the sign. All the other dependent variables and variables’ interactions were insignificant and eliminated one after the other while conducting the backward elimination procedure.

Considering the least square means of sheeting/font levels, a greater level estimate has a greater influence on the predicted response, which was the legibility distance in the glare experiment. Based on the levels’ estimates of sheeting/font variable, sign 3, which was Diamond Grade (type XI) sheeting combined with Clearview font, was ranked first in providing the highest legibility distance, and consequently provided drivers with the highest visibility when glare was presented from an oncoming vehicle’s low beam headlights. Sign 2, which was High Intensity (type IV) sheeting combined with Clearview font, was ranked second, sign 1 was ranked third, which was High Intensity (type IV) sheeting combined with Series E (Modified) font, and sign 4 was ranked fourth, which was Diamond Grade (type XI) sheeting combined with Series E (Modified) font, meaning that, regardless the retroreflective sheeting material, Clearview font was found to be the better font that increases legibility distance for drivers experiencing glare from an oncoming vehicle’s low beam headlights. The cost analysis of the two retroreflective sheeting which is shown in Chapter 7 showed that High Intensity (type IV) sheeting had cheaper average annual cost than Diamond Grade (type XI) sheeting.

Limitations of this study included the inability of finding participants older than 53 years, and the inability to have the chance of measuring participants’ visual acuity at the time of the experiment. To avoid problems related to visual acuity, participants were asked if they have a vision problem that is not corrected, and those who answered yes were not allowed to participate in the glare experiment.

Summary

Results of the glare experiment revealed that Diamond Grade (type XI) retroreflective sheeting combined with Clearview font represented the optimal sheeting-font combination. However, for DOTs with limited budgets, High Intensity (type IV) retroreflective sheeting combined with Clearview font could be an alternative solution. The conclusion regarding the alternative solution of combining High Intensity (type IV) retroreflective sheeting with Clearview font was drawn from the influence of the sheeting-font combination on the legibility distance of shoulder-mounted guide signs when drivers experienced glare from an oncoming vehicle’s low beam headlights, and from cost analysis of the retroreflective sheeting. Consequently, this alternative solution of High Intensity (type IV) sheeting and Clearview font increases visibility, legibility and drivers’ safety on roadways. Regardless the sheeting type, Clearview font was found to be the better font that increases legibility distance for drivers experiencing glare from an oncoming vehicle’s low beam headlights.

Chapter 9 - Impacts of Roadway Lighting on Crashes Reduction and Safety Improvement

Introduction

All the previous chapters of the dissertation were about increasing the visibility of guide signs for drivers during nighttime. The two methods of increasing guide signs visibility (illumination and retroreflectivity) were studied in details. The rational and motivation behind including this chapter in the dissertation was to confirm the effectiveness of intersection lighting in increasing drivers' safety during nighttime by reducing crash frequency. Crash data were used to confirm the result of previous chapters in that increasing drivers' visibility will increase safety and reduce crashes.

Roadway lighting is a public amenity that increases driver and pedestrian safety (Medina, et al., 2013). Efficient roadway lighting can increase personal security, traffic flow operations, and public safety because motorists can more readily recognize roadway conditions and geometry (Medina, et al., 2013). Public lighting, including roadway, sidewalk, and sign lighting, is a basic requirement that creates a safer environment for motorists, cyclists, and pedestrians (AASHTO, 2005). Drivers more easily recognize street conditions and roadway geometry because of efficient lighting. Efficient roadway lighting also increases highway safety by enhancing drivers' visual comfort and reducing drivers' fatigue (IDOT, 2002). A primary purpose of roadway lighting is to increase the visual range that vehicle headlights afford during nighttime driving (IES, 2000).

Lighting is considered a significant countermeasure in all Federal Highway Administration (FHWA) safety focus areas, including intersections, pedestrians, and horizontal curves/roadway departures. Studies have shown that the use of roadway lighting results in an approximate 60% reduction in fatal nighttime crashes (Lutkevich, et al., 2012). To compare the impact of roadway lighting on previously unlit roadways, Elvik and Vaa reviewed 38 studies related to roadway lighting. They discovered the following results after roadways were lit: a 64% reduction in fatal crashes, a 17% reduction in property-damage-only crashes, and a 28% reduction in injury crashes (Elvik & Vaa, 2004).

Departments of Transportation (DOTs) and agencies in U.S. currently use several roadway lighting systems to increase roadway safety, including the designed lighting system and roadway feature identification lighting. Many studies analyzed the effect of roadway lighting on safety by using crash analysis, considering the two roadway lighting systems, performing comparative studies of various roadway locations with and without lighting, or performing a before and after lighting comparison for identical roadway locations.

Statistical analysis of data from 20 European Union countries showed that in dark 35.5% of fatal crashes occurred in rural area locations, approximately 39.7% of fatal crashes occurred in urban areas, and 44.6% of fatal crashes occurred on motorways (ERSO, 2011). In addition, with absence of street lighting, about 20% of fatalities occurred in darkness (ERSO, 2011).

The objective of this research was to evaluate safety benefit of roadway lighting at intersections on reducing nighttime crashes by increasing visibility, and consequently safety. Crash data from the Highway Safety Information System (HSIS) were used to investigate the effect of intersection lighting on crashes reduction during nighttime. Recent data from Minnesota and California were used to estimate nighttime and daytime crash frequency models. The reason behind selecting only these two states is that their data files contain the needed intersection-level geometric design, traffic volume data, and lighting information. The negative binomial regression model was used to estimate nighttime and daytime crash frequency models to generate conclusions.

Roadway Lighting Systems

For roadway lighting, illuminance is defined by the density of luminous flux incident on a surface measured in lux or foot-candles (Swanson & Carlson, 2012). Luminance, however, is a measure of reflected light from the pavement surface and it is visible to a motorist’s eyes (AASHTO, 2005). Lux is the unit of illuminance based on the International System of Units (SI). Recent developments in the lighting industry have resulted in well-developed techniques for roadway lighting system design. Several methods are available for achieving specified lighting conditions with specific luminance or illuminance. These methods provide analysis based on available lamp alternatives, luminaires, luminaries spacing, mounting heights, and energy consumption to determine the preferred lighting design (AASHTO, 2005). Based on the AASHTO, roadway lighting installation process includes the application of specified photometric characteristics of selected lamp-luminaire combinations.

Several factors control the luminance and illuminance level and uniformity along a highway, including light source lumen output, mounting height, luminaire light distribution, luminaire position, reflectance of pavement, and poles arrangement and spacing (AASHTO, 2005). Various installation arrangements of luminaire can be used to obtain the desired average illuminance or luminance level, including greater number of low-output luminaires or few high-output luminaires (AASHTO, 2005). Lighting systems that use high efficacy (lumen per watt) lamps can be used to obtain illuminance or luminance uniformity at the required level.

Roadway lighting can be categorized as designed roadway lighting (standard roadway lighting or continuous lighting) system and roadway feature identification lighting (nonstandard lighting or fixed lighting) system. For feature identification lighting, fixed lighting units are installed to help identify one of the FHWA safety focus areas, such as intersections.

According to AASHTO Roadway Lighting Design Guide, roadway lighting systems are classified into three categories: continuous freeway lighting, complete interchange lighting, and partial interchange lighting (AASHTO, 2005). Continuous freeway lighting provides approximately uniform lighting on all main lanes, direct connections, and interchanges within the section. Complete interchange lighting provides relatively uniform lighting within interchange limits that include main lane ramp terminals, direct connections, and crossroad intersections. Partial interchange lighting provides illumination on roadways at specified areas, including ramp terminals, crossroads at ramp intersections, acceleration and deceleration lanes, and areas with nighttime hazards.

The primary difference between the roadway standard and nonstandard lighting systems is the type of pole used (Bruneau & Morin, 2005). In standard lighting, the pole is designed exclusively for lighting purposes, but in nonstandard lighting, an existing public utilities pole is used with a fastened small lamp (Bruneau & Morin, 2005). Poles used with nonstandard lighting currently exist, meaning they will not increase the risk of fixed object collisions unless new poles are installed for lighting purposes (Bruneau & Morin, 2005). Lamp supports used with nonstandard lighting units are generally shorter than supports used with standard lighting poles, resulting in less roadway illumination with nonstandard lighting systems compared to standard lighting which almost completely illuminates the roadway (Bruneau & Morin, 2005). For standard lighting systems, lamp overhang is close to the roadway center, thereby increasing the lateral distance separating the pole anchor and the lamp (Bruneau & Morin, 2005). For nonstandard lighting, utility poles are not necessarily ideally located to provide sufficient lighting; therefore, optimal pole placement is a concern for nonstandard lighting (Bruneau & Morin, 2005). Finally, differing light intensity based on lamp type must also be considered for comparison purpose. An additional benefit of standard lighting is that light intensity can be modified, thereby allowing this lighting type to dominate other types of undesired light sources, such as light originating from nearby motorways or gas stations (Bruneau & Morin, 2005).

Literature Review

Several factors complicate the study of roadway lighting effects on safety (IES, 1989) and (Bullough, et al., 2013a). First, vehicle crashes in nature are rare events, creating difficulty for the collection of relevant data for safety benefits evaluation based on statistical analysis. Second, assigning roadway lighting to various locations is not random; instead, lighting is installed on the required locations based on expert highway engineers' decisions. Third, roadway lighting is installed with other treatments of safety engineering, including signals, signs, road markings, geometric features, and rumble strips. All the safety features may interact with traffic safety at night, causing safety improvement.

The cost of nighttime crashes is very high in comparison to daytime crashes. Therefore, a primary mission of the FHWA is to improve roadway safety in the U.S., thereby reducing expenses associated with nighttime vehicle crashes. Statistics show that 25% of all motor vehicle travel occurs at night, but approximately 50% of all traffic fatalities occur during nighttime hours (Hasson & Lutkevich, 2002), and (FHWA, 2008). According NHTSA, Fatality Analysis Reporting System, fatal crash numbers in the years 2009, 2010, 2011, and 2012 were 23,447, 22,187, 21,316, and 21, 667, respectively, and for those years, the numbers of nighttime crashes were 11,630 (49.6%), 10,647 (48.0%), 10,183 (47.8%), and 10,480 (48.3%), respectively (NHTSA, 2012b), and (NHTSA, 2013).

According to Isebrands et al., approximately 31% of fatal crashes in Minnesota were intersection-related crashes, and approximately 37% of those crashes occurred at night, dusk, or dawn (Isebrands, et al., 2010). In comparison, intersection-related fatal crashes accounted for 21% of total U.S. fatal crashes, with 40% of fatal crashes occurring at night, dusk, or dawn; only 25-33% of total vehicle miles travelled (VMT) are travelled at night (Isebrands, et al., 2010). Fatal crashes in Minnesota in rural areas account for approximately 70% of the state's total fatal crashes, compared to 58% in U.S. (Isebrands, et al., 2010). In general, rural roadway intersections are associated with a higher crash risk at night.

For data collected between October 2005 and September 2006 for 274 intersections in Iowa, a total of 26% of intersection crashes occurred at rural locations at night (Hallmark, et al., 2008). For single vehicle crashes at rural intersections, the most common crash causes are run-off the road (27%), animal-related crashes (17%), and running-a-stop-sign crashes (16%) (Hallmark, et al., 2008). For multiple vehicle crashes at rural intersections, the common causes of rural intersection crashes include running-a-stop-sign crashes (21%), failure to yield the right-of-the-way at yield or stop signs (20%), and other failure to right-of-way yielding (10%) (Hallmark, et al., 2008). In general, non-signalized rural intersection crashes could be reduced by implementing several strategies, including the use of retroreflective materials to improve sign visibility, use of advance signing before intersections to warn drivers, use of sign beacons on stop signs, improved signing and roadway marking, use of advance stop sign rumble strips, use of flashing overhead beacons at intersections, and lighting installation (Hallmark, et al., 2008).

FHWA has deemed roadway lighting to be an effective strategy to reduce nighttime crashes. Lighting is considered a significant countermeasure in all FHWA safety focus areas which include intersections, pedestrians, and horizontal curves/roadway departures. Roadway lighting supplements vehicle headlights, enhance drivers’ visibility, and helps drivers obtain the required visual information to accomplish driving with increased safety (Hasson & Lutkevich, 2002).

Several studies have evaluated the effectiveness of roadway lighting on crash reduction and safety. Some of these studies evaluated designed lighting systems and others evaluated roadway feature identification lighting. These lighting studies selected candidate in rural and/or urban locations to perform safety analysis. The following is a review of previous studies performed to evaluate safety benefits of lighting systems.

Lighting-Safety Studies at Rural Intersections

Wortman et al. reported a comparative study in Illinois that evaluated the impacts of roadway lighting on crashes at rural and highway intersections (Wortman, et al., 1972). Wortman et al. performed comparison analysis based on a random sample of illuminated and unilluminated intersections using the Analysis of Variance (ANOVA) at 10% significance level. At each intersection, they compared the ratio between night and total crashes and found that roadway lighting correlates to night crash reductions when the number of night crashes was at least one-third the number of day crashes. They did not find a relationship between lighting and crash severity. The researchers also reported that roadway lighting reduced nighttime crashes by 45% and a 22% reduction was observed in the ratio of night-to-total crashes.

Walker and Roberts studied the influence of lighting on crash frequency of rural at-grade intersections in Iowa. They conducted before-and-after lighting analysis over a six-year period for a total of 47 intersections (Walker & Roberts, 1976). They considered several independent variables, including channelization, route turns at the intersection, number of intersection legs (number of approaches), and number of available lights at the intersection. They performed ANOVA that included full consideration of the situation that connects the effect of lighting and time during the day, and then they studied specific effects using the student's t test. Overall, they found a 49% reduction in crash frequency after lighting was installed. The average night crashes rate was also reduced from 1.89 to 0.91 crashes per million entering vehicles, with a reduction of 52%. Their results were statistically significant at 1% significance level. More precisely, although they found no statistical differences in before-and-after nighttime crash rates after lighting for non-channelized intersections, their analysis showed significance of 1% in overall night crash reduction after lighting for channelized intersections. For intersections with route turns, a significant reduction in nighttime crash rate was found. No change in crash rate occurred for "Y" and "T" intersections after lighting, but a significant reduction in nighttime crash rate occurred for four-leg intersections. The researchers found no significant differences in nighttime crash rate and number of lights at an intersection. They suggested that driving difficulty at complicated intersections could be reduced after lighting.

Preston and Schoenecker evaluated 12 rural intersections in a before-and-after study in Minnesota (Preston & Schoenecker, 1999). They found that the installation of roadway lighting resulted in 25-40% reduced nighttime crash frequency. Nighttime crash severity was also reduced 8-25% after light installation.

Kim et al. evaluated 165 rural intersections, including 114 signalized and 51 non-signalized intersections of two-lane and four-legged roads in Georgia (Kim, et al., 2006). A total of 837 crashes occurred, divided between 345 crashes at non-signalized intersections and 492 at signalized intersections. Several models were developed to estimate various covariates of rural intersection crashes, including Poisson and negative binomial models. They found that the presence of intersection lighting reduced crashes.

Hallmark et al. conducted a cross-sectional statistical analysis to determine safety benefits of roadway lighting and other low-cost measures such as advanced stop sign rumble strips and overhead flashing beacons at 223 rural, non-signalized intersections in Iowa (Hallmark, et al., 2008). A hierarchical Bayesian model with Poisson distribution was used to fit two separate models for daytime and nighttime driving. Variables considered for evaluation in the two models included the presence of overhead beacons, presence of advanced stop line rumble strips, and traffic control type. The presence of overhead street lighting was also considered in the nighttime model. Significant variables in the daytime model included whether or not the intersection was a high crash location and the number of approaches with channelization. However, in the nighttime model, significant variables were found to be whether or not lighting was present and whether or not the intersection was a high crash location. The nighttime model indicated that the expected mean number of nighttime crashes was 2.01 times higher for unlighted intersections than for lighted intersections.

Isebrands et al. evaluated the effectiveness of roadway lighting in nighttime crash reduction at isolated rural intersections in Minnesota (Isebrands, et al., 2010). The impact of lighting at 33 intersections was evaluated in a before-and-after study, data were collected during a 3-year-before and 3-year-after lighting installation. In this study, approximately 75% of lighting types for selected intersections was roadway feature identification lighting and approximately 25% was designed roadway lighting. Poisson regression model was used to compare the change in expected number of nighttime crashes and to test the statistical significance of the model's explanatory variables at a 10% significance level. Several explanatory variables were evaluated, including crash time (day/night), presence or absence of lighting, number of intersection's approaches, and type of intersection control. The researchers found that the crash rate was statistically significant and decreased by 37% after lighting.

Lighting-Safety Study at Urban Intersections

Box performed an experiment to evaluate roadway lighting based on crash reduction (Box, 1989). Box selected a 2.8 km portion of a 5-lane roadway, 18 m in width, in an urban area (Ogden, IL) that had some intersections. A continuous street lighting system was installed; the mounting height was approximately 15 m with a setback and mast arm length to provide 0.6 m as an overhang. A one-side arrangement was selected because the ratio of road width to mounting height was 1.2. An average illumination level of 15 lux was maintained, given that a 13 lux was recommended by the American National Standard Practice for roadway lighting at the time of study. A 400 watt HPS lamp was used in the lighting system, and calculated spacing between poles to provide required illumination level was 64 m. Box studied crashes throughout a 4-year period on the selected roadway section, 2 years before and after lighting system installation. More than 800 crashes occurred during the study period. Box analyzed the crashes by classifying them into fatal, property-damage-only, and injury/fatal crashes. Overall, nighttime crashes decreased from 31% to 23% in the after period, with a nighttime crash reduction of 35%. Using student's t test, Box found that the reduction of nighttime crashes was statistically significant at 1% significance level.

Lighting-Safety Studies at Rural and Urban Intersections

Green et al. analyzed driver safety in a before-and-after lighting study at nine intersections in Kentucky (Green, et al., 2003). For the selected intersections, the number of nighttime crashes per year was obtained for a 4-year period before lighting and a 3-year period after lighting was installed. The selected intersections included urban and rural locations. The researchers developed a procedure to identify locations in Kentucky that experience high rates of nighttime crashes. They found a higher number of nighttime crashes at rural locations; nighttime crashes were reduced by 45% after lighting.

Bruneau and Morin compared safety aspects of designed lighting systems and roadway feature identification lighting of 3- and 4-leg intersections in Quebec, Canada. They compared a total of 376 illuminated and unilluminated intersections at rural and near-urban locations (Bruneau & Morin, 2005). They analyzed nighttime crash rates using student's t test at 5% significance level. They found that the nighttime crash rate decreased by 29% when roadway feature identification lighting was used and by 39% when designed lighting system was used, compared to darkness. The researchers found that any system of lighting increased safety at rural intersections. They suggested that roadway feature identification lighting at intersections could be a suitable solution and an initial effective step for improving roadway safety. They also indicated that safety effectiveness at rural intersections could be improved by using a designed lighting system, especially at risky intersections.

Donnell et al. described a proposed framework to estimate fixed lighting safety effects at various intersection types and locations (Donnell, et al., 2010). Data was obtained from the Highway Safety Information System (HSIS), a multistate database. Researchers selected California and Minnesota data because the HSIS files had required information related to intersection-level geometric design, fixed lighting, and traffic volume. Several cross-sectional modeling approaches were considered in the proposed framework. The initial step of each modeling method was to estimate the expected crash frequency during nighttime and daytime driving as a function of explanatory variables. Explanatory variables included presence or absence of lighting, intersection type (skew or cross), location (rural or urban), and speed limit. The negative binomial regression model was used to estimate annual expected number of intersection crashes. The proposed framework included night and day crash frequency analysis to promote a cost-effective comparison of other safety countermeasures that do not require a specific time of day in order to be effective. The researchers merged the presence of roadway lighting, traffic volume, roadway geometric, and control data with nighttime and daytime crash data to evaluate the statistical association between the presence of intersection lighting and night-to-day crash ratio in Minnesota. Many variables that affect safety not previously considered in lighting-safety research were considered in the statistical analysis and model estimation for this study. Using Minnesota data, the presence of roadway lighting at intersections was associated with approximately 12% lower night-to-day crash ratio than that of unlighted intersections. Using only observed Minnesota crash numbers without controlling for other safety-related features, the framework resulted in 28% reduction in night-to-day crash ratio, which was similar to past researches.

Rea et al. performed an analytical study to evaluate the improvement in visual performance associated with roadway lighting at intersections in Minnesota (Rea, et al., 2010). They used a relative visual performance (RVP) model to estimate the area of visibility coverage at lighted and unlighted intersections. They also used photometrically accurate software to generate model intersection’s luminous environment (lighted or unlighted). Photometric data created for the various lighting models were used in the RVP model to estimate the speed and accuracy of visual information processing provided to drivers of different ages at rural, urban, and suburban intersections to make systematic evaluation of potential visibility hazards. In this study, vehicle headlights were included in the generated photometrically accurate models, so other factors related to visibility coverage area at intersections were considered, such as glare and hazard contrast. Researchers concluded that intersections must be illuminated at high and low speeds in order to provide older drivers a high level of illumination especially on high-speed roadway intersections.

Bullough et al. performed a study to examine theoretical relationships between lighting, visibility, and safety at intersections in Minnesota (Bullough, et al., 2013b). A statistical approach and an analytical approach were considered for the same lighting context. In the statistical approach, a count regression model was used to evaluate the effects of roadway lighting on crash frequency for various types of intersections. The model included variables such as presence or absence of lighting, intersection type (skew or cross), location (rural or urban), and speed in order to estimate the relationship between roadway lighting and daytime and nighttime crashes and the ratio of night-to-day crashes. They found that the presence of intersection lighting contributes to approximately 12% reduction in a night-to-day crash ratio as compared to unlighted intersections. In their analytical approach, for the same intersections used in the statistical analysis, the researchers made visual performance analysis based on Minnesota's intersection lighting. Both approaches led to the result that the improvement of visual performance caused by intersection lighting could serve as input for forecasting crash frequency improvements. The researchers suggested that when relationships between lighting, traffic safety, and visibility have been identified, highway engineers can specify various roadway lighting scenarios based on expected costs and benefits.

Johansson et al. evaluated the risk of crashes associated with darkness using three crash counts of datasets from Norway, Sweden, and Netherlands (Johansson, et al., 2009). Their method estimated the crash risk associated with darkness based on the odds ratio. This method relied on crash counts only, considering that some day hours will be dark at certain times of the year but will be daylight during the rest of the year. Dark hours throughout the year were called case hours. Case hours were considered when calculating the odds ratio. For one case hour, the ratio between the number of crashes occurring during darkness and the number of crashes occurring during daylight at selective times of the year was calculated first. A comparison hour that has daylight the whole year was selected in order to control seasonal variation in the crash number. Similarly, a case hour was selected to find the ratio between the crash number during dark case hours and the number of crashes when the case hour was daylight. The odds ratio was calculated by dividing the darkness crash ratio by the daylight crash ratio for the case hour and then by the corresponding ratio of the compared hour. Results of the study suggested that the increase of crashes during darkness was moderate. For pedestrians, cyclists, and car occupants, relative risks during darkness were 2.1, 12.6, and approximately 1.0, respectively, meaning that pedestrians and cyclists were more affected by risk, while car occupants did not have any increased risk.

Yannis et al. investigated lighting conditions effects on roadway accident frequency and severity on Greece's rural and urban roads (Yannis, et al., 2013). They used three log-normal regression models to analyze a large dataset containing 358,485 crashes that occurred between 1996 and 2008 in Greece. The developed models provided the number of fatalities, light injuries, and serious injuries along with explanatory variables, including lighting conditions, crash area type, road surface conditions, type of collision, weather conditions, and driver-specific characteristics such as age and gender. Using parameter elasticity analysis, the researchers found that the absence of roadway lighting had the highest impact on serious injuries and fatality number compared to when lighting was present. They found that roadway lighting significantly improved traffic safety and reduced crash severity.

The Negative Binomial Regression Model

The negative binomial regression model can accommodate overdispersion comparing to Poisson model. According to Washington et al., the negative binomial model is a common approach to model intersection crash frequency, and the best choice to estimate the expected number of crashes at intersection per year (Washington, et al., 2005).

All the following equations or definitions are based on (Hilbe, 2011).

For regression purpose, assume that:

$$y_i \sim negbin(\mu_i, k)$$

$$\mu_i = E(y_i) \tag{9.1}$$

y_i is the observed crashes occurring at intersection i, and $E(y_i)$ is the expected crash frequency at intersection i.

The density function of the negative binomial is given by:

$$P(y_i) = \binom{k^{-1}+y_i^{-1}}{y_i}\left(\frac{k\mu_i}{1+k\mu_i}\right)^{y_i}\left(\frac{1}{1+k\mu_i}\right)^{\frac{1}{k}}, i = 1, 2, \dots, n \qquad 9.2$$

Where $k = 1/\alpha,$ and α is the overdispersion parameter.

The negative binomial link function is:

$$\ln(\mu_i) = \beta^T X_i \qquad 9.3$$

Where, μ_i is the expected number of crashes at intersection i, β is the matrix of the estimated regression parameters, X_i is the matrix of predictor variables.

The relationship between the mean and variance in the negative binomial distribution is:

$$Var(y_i) = \mu_i + k\mu_i^2 \qquad 9.4$$

Where $Var(y_i)$ is the variance of observed crashes y_i occurring at intersection *i*.

Methodology

Crashes data from the HSIS database were used to investigate the effect of intersection lighting on crashes reduction during nighttime. The HSIS is a multistate database that contains crash, roadway inventory, and traffic volume data for a select group of states. These states are California, Minnesota, North Carolina, Illinois, Ohio, Maine, Utah, Michigan, and Washington. HSIS is managed by the University of North Carolina Highway Safety Research Center (HSRC) under contract with FHWA. Minnesota and California data were used to estimate daytime and nighttime crash frequency models for roadway lighting with other variables related to the intersection. For each selected state, a total of 60 intersections were selected randomly from the HSIS database, divided between 30 urban intersections and 30 rural intersections. Data from 2006 to 2011 were used for Minnesota, and from 2006 to 2010 were used for California.

Two models were constructed for each state to evaluate the safety benefit of roadway lighting at intersection, these were:

- Estimation of negative binomial regression model for nighttime crash frequency.
- Estimation of negative binomial regression model for daytime crash frequency.

Results

Studied Variables

Table 9.1 shows the definitions of the studied variables for Minnesota, and Table 9.2 shows the definitions of the studied variables for California.

Table 9.1 Variables Definitions and Statistics Description of Minnesota Crash Data

Continuous Variables	Min	Max	Mean	Standard Deviation
Night crash frequency per year (Nit_Freq)	1	29	1.52	1.27
Day crash frequency per year (Day_freq)	1	45	2.05	1.96
Average daily traffic (AADT): day model	1,553	110,400	44,238	41,822
Average daily traffic (AADT) night model	1,227	110,400	41,204	38,589
Categorical Variables	**Categories**			
Area type indicator (Urb_Rur)	(1= urban, and 0= rural)			
Weather condition (weather1)	(1= not clear , and 0= clear)			
Road surface condition (rdsurf)	(1= not clear, wet, snow, etc., and 0= dry)			
Intersection light condition (light)	*Night model:* (1= street lights on, dawn, or dusk, and 0= dark) *Day model:* (1= daylight, and 0=otherwise)			
Traffic control indicator (TRF_CNTL)	(1= signal, and 0= stop or yield)			
Intersection lighting type (rdwy_lgh)	(1= partial lighting, and 0= continuous lighting)			
Intersection type indicator (nbr_legs)	(3= T or Y, and 4= Cross)			
Surface type (surf_typ)	(1= concrete or asphalt, 0= otherwise)			
Curbs (curb1)	(1= both sides, 0= otherwise)			
Number of lanes (no_lanes)	(1= 3 or more, and 0= 2 or less)			
Lane width (Lanewid)	(1= 12 ft or more, and 0= otherwise)			

Table 9.2 Variables Definitions and Statistics Description of California Crash Data

Continuous Variables	Min	Max	Mean	Standard Deviation
Night crash frequency per year (Nit_Freq)	1	9	1.27	0.59
Day crash frequency per year (Day_Freq)	1	71	1.69	1.220
Average daily traffic (AADT) day model	2,949	228,132	67,478	59,100
Average daily traffic (AADT) night model	2,949	228,132	72,397	59,937
Categorical Variables	**Categories**			
Area type indicator (rururb)	(1= urban, and 0= rural)			
Weather condition (weather1)	(1= not clear , and 0= clear)			
Road surface condition (rdsurf)	(1= not clear, wet, snow, etc., and 0= dry)			
Intersection light condition (light)	*Night model:* (1= street lights on, dawn, or dusk, and 0= dark) *Day model:* (1= daylight, and 0=otherwise)			
Traffic control indicator (trf_cntl)	(1= signal, and 0= stop or yield)			
Speed indicator (desg_spd)	(1= 45 mph or more, and 0= less than 45 mph)			
Intersection type indicator (typedesc)	(3= T or Y, and 4= Cross)			
Surface type (surf_ty1)	(1= concrete or bridge deck, 0= otherwise)			
Number of lanes (no_lanes)	(1= 3 or more, and 0= 2 or less)			
Lane width (Lanewid)	(1= 12 ft or more, and 0= otherwise)			

Statistical Analysis

The assumption was made in that all matrix *X* variables in equation 9.1 were independent for both states. For each state, both daytime and nighttime crash frequency models for roadway lighting with other variables related to the intersection were estimated. A significance level of 5% was considered. The backward elimination procedure was carried out to remove the least significant variable until the final model was obtained. The Akaike Information Criterion (AIC) was considered in which minimum value is better when performing the backward elimination procedure. SAS Software was used to analyze data, all used SAS Software codes for the following sections can be seen in Appendix F.

Minnesota Statistical Analysis

In the studied period, a total of 19,293 crashes occurred during nighttime in Minnesota selected intersections. Nighttime Crashes frequencies were determined manually by counting number of crashes occurred in the same night at the same intersection per year. The analysis of maximum likelihood parameter estimates for the first model is shown in Table 9.3. After performing the backward elimination procedure to eliminate insignificant variables based on the 5% significance level, the analysis of maximum likelihood parameter estimates for the final model is shown in Table 9.4.

Table 9.3 Analysis of Maximum Likelihood Parameter Estimates for First Nighttime Model of Minnesota

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	0.9607	0.1309	0.7041	1.2173	53.84	<.0001
weather1	1	0.0440	0.0175	0.0097	0.0783	6.32	0.0119
rdsurf	1	0.2857	0.0177	0.2510	0.3204	260.54	<.0001
light	1	-0.0372	0.0192	-0.0750	0.0005	3.74	0.0530
trf_cntl	1	-0.0632	0.0223	-0.1068	-0.0195	8.05	0.0045
Urb_Rur	1	-0.2673	0.0296	-0.3253	-0.2092	81.48	<.0001
rdwy_lgh	1	-0.0482	0.0198	-0.0871	-0.0093	5.91	0.0151
nbr_legs	1	-0.2195	0.0272	-0.2729	-0.1662	64.98	<.0001
aadt	1	0.0000	0.0000	0.0000	0.0000	285.81	<.0001
surf_typ	1	0.1522	0.0251	0.1031	0.2014	36.81	<.0001
curb1	1	0.0022	0.0179	-0.0328	0.0373	0.02	0.9009
no_lanes	1	0.2568	0.0279	0.2021	0.3114	84.86	<.0001
lanewid	1	-0.0805	0.0674	-0.2126	0.0517	1.42	0.2326
Dispersion	1	0.0000	0.0001	0.0000	5.34E129		

Table 9.4 Analysis of Maximum Likelihood Parameter Estimates for Final Nighttime Model of Minnesota

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	0.8853	0.1149	0.6600	1.1106	59.32	<.0001
weather1	1	0.0438	0.0175	0.0095	0.0781	6.27	0.0123
rdsurf	1	0.2859	0.0177	0.2512	0.3205	261.10	<.0001
light	1	-0.0368	0.0192	-0.0744	0.0008	3.68	0.0550
trf_cntl	1	-0.0634	0.0222	-0.1069	-0.0199	8.16	0.0043
Urb_Rur	1	-0.2677	0.0296	-0.3257	-0.2098	81.94	<.0001
rdwy_lgh	1	-0.0484	0.0193	-0.0861	-0.0106	6.30	0.0121
nbr_legs	1	-0.2193	0.0272	-0.2726	-0.1661	65.15	<.0001
aadt	1	0.0000	0.0000	0.0000	0.0000	289.40	<.0001
surf_typ	1	0.1496	0.0248	0.1009	0.1982	36.27	<.0001
no_lanes	1	0.2541	0.0278	0.1997	0.3085	83.81	<.0001
Dispersion	0	0.0000	0.0000	0.0000	0.0000		

For the Minnesota daytime model, a total of 44,322 crashes occurred at the selected intersections during daytime in the selected period. Daytime crashes frequencies were determined manually by counting number of crashes occurred in the same day at the same intersection per year. The analysis of maximum likelihood parameter estimates for the first daytime model of Minnesota is shown in Table 9.5. After performing the backward elimination procedure to eliminate insignificant variables, the analysis of maximum likelihood parameter estimates for the final daytime model of Minnesota is shown in Table 9.6.

Table 9.5 Analysis of Maximum Likelihood Parameter Estimates for First Daytime Model of Minnesota

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	1.9866	0.1239	1.7437	2.2296	256.89	<.0001
weather1	1	0.0177	0.0152	-0.0121	0.0475	1.36	0.2439
rdsurf	1	0.3795	0.0164	0.3472	0.4117	532.92	<.0001
light	1	-0.2450	0.0578	-0.3582	-0.1317	17.97	<.0001
trf_cntl	1	0.0195	0.0179	-0.0155	0.0545	1.20	0.2741
Urb_Rur	1	-0.1545	0.0238	-0.2011	-0.1079	42.20	<.0001
nbr_legs	1	-0.4055	0.0236	-0.4518	-0.3592	294.56	<.0001
aadt	1	0.0000	0.0000	0.0000	0.0000	573.25	<.0001
surf_typ	1	0.2049	0.0201	0.1654	0.2443	103.62	<.0001
curb1	1	0.1198	0.0164	0.0876	0.1520	53.17	<.0001
no_lanes	1	0.2624	0.0232	0.2169	0.3080	127.44	<.0001
lanewid	1	-0.1506	0.0616	-0.2713	-0.0300	5.99	0.0144
Dispersion	1	0.0778	0.0046	0.0692	0.0873		

Table 9.6 Analysis of Maximum Likelihood Parameter Estimates for Final Daytime Model of Minnesota

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	1.9830	0.1239	1.7402	2.2258	256.22	<.0001
rdsurf	1	0.3891	0.0140	0.3617	0.4166	772.51	<.0001
light	1	-0.2396	0.0576	-0.3526	-0.1267	17.29	<.0001
Urb_Rur	1	-0.1475	0.0226	-0.1917	-0.1032	42.65	<.0001
nbr_legs	1	-0.4045	0.0236	-0.4507	-0.3583	293.89	<.0001
aadt	1	0.0000	0.0000	0.0000	0.0000	617.80	<.0001
surf_typ	1	0.2055	0.0201	0.1660	0.2449	104.23	<.0001
curb1	1	0.1199	0.0164	0.0877	0.1520	53.28	<.0001
no_lanes	1	0.2618	0.0232	0.2163	0.3074	127.06	<.0001
lanewid	1	-0.1490	0.0615	-0.2696	-0.0284	5.86	0.0155
Dispersion	1	0.0778	0.0046	0.0693	0.0874		

California Statistical Analysis

In the studied period, a total of 18,773 crashes occurred during nighttime in California selected intersections. Nighttime Crashes frequencies were determined manually by counting number of crashes occurred in the same night at the same intersection per year. The analysis of maximum likelihood parameter estimates for the California first nighttime model is shown in Table 9.7. After performing the backward elimination procedure to eliminate insignificant variables based on 5% significance level, the analysis of maximum likelihood parameter estimates for the California final nighttime model is shown in Table 9.8.

Table 9.7 Analysis of Maximum Likelihood Parameter Estimates for First Nighttime Model of California

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-0.4305	0.0812	-0.5897	-0.2712	28.08	<.0001
weather1	1	0.0145	0.0222	-0.0290	0.0581	0.43	0.5127
rdsurf	1	0.0931	0.0269	0.0405	0.1458	12.02	0.0005
light	1	-0.0667	0.0164	-0.0989	-0.0345	16.51	<.0001
trf_cntl	1	0.0013	0.0217	-0.0412	0.0438	0.00	0.9530
no_lanes	1	0.0813	0.0210	0.0401	0.1225	14.94	0.0001
desg_spd	1	0.0294	0.0486	-0.0658	0.1247	0.37	0.5451
aadt	1	0.0000	0.0000	0.0000	0.0000	9.41	0.0022
rururb	1	0.0451	0.0190	0.0078	0.0825	5.63	0.0177
surf_ty1	1	-0.0023	0.0239	-0.0492	0.0447	0.01	0.9247
lanewid	1	0.0846	0.0333	0.0194	0.1498	6.46	0.0110
typedesc	1	0.1213	0.0181	0.0858	0.1568	44.80	<.0001
Dispersion	1	0.0000	0.0001	0.0000	1.32E113		

Table 9.8 Analysis of Maximum Likelihood Parameter Estimates for Final Nighttime Model of California

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-0.4034	0.0714	-0.5434	-0.2633	31.88	<.0001
rdsurf	1	0.1043	0.0205	0.0641	0.1444	25.90	<.0001
light	1	-0.0676	0.0163	-0.0995	-0.0357	17.24	<.0001
no_lanes	1	0.0835	0.0204	0.0436	0.1234	16.81	<.0001
aadt	1	0.0000	0.0000	0.0000	0.0000	21.01	<.0001
rururb	1	0.0471	0.0171	0.0135	0.0806	7.56	0.0060
lanewid	1	0.0826	0.0327	0.0184	0.1467	6.36	0.0117
typedesc	1	0.1221	0.0179	0.0871	0.1571	46.76	<.0001
Dispersion	1	0.0000	0.0001	0.0000	7.35E222		

For the California daytime model, a total of 57,285 crashes occurred during daytime in California intersections in the selected period. Daytime crashes frequencies were determined manually by counting number of crashes occurred in the same day at the same intersection per year. The analysis of maximum likelihood parameter estimates for California first daytime model is shown in Table 9.9. After performing the backward elimination procedure to eliminate insignificant variables, the analysis of maximum likelihood parameter estimates for the final daytime model of California is shown in Table 9.10.

Table 9.9 Analysis of Maximum Likelihood Parameter Estimates for First Daytime Model of California

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-1.4228	0.0485	-1.5178	-1.3277	860.94	<.0001
weather1	1	-0.0419	0.0128	-0.0669	-0.0169	10.80	0.0010
rdsurf	1	0.1524	0.0168	0.1194	0.1854	81.99	<.0001
light	1	0.2767	0.0132	0.2509	0.3026	440.36	<.0001
trf_cntl	1	0.1031	0.0122	0.0792	0.1271	71.06	<.0001
no_lanes	1	0.2043	0.0120	0.1808	0.2278	289.77	<.0001
desg_spd	1	0.1476	0.0290	0.0908	0.2045	25.90	<.0001
aadt	1	0.0000	0.0000	0.0000	0.0000	4.93	0.0264
rururb	1	0.0985	0.0106	0.0777	0.1193	86.17	<.0001
surf_ty1	1	-0.0200	0.0132	-0.0459	0.0060	2.28	0.1310
lanewid	1	0.2544	0.0186	0.2179	0.2910	186.11	<.0001
typedesc	1	0.2922	0.0104	0.2719	0.3125	794.96	<.0001
Dispersion	0	0.0000	0.0000	0.0000	0.0000		

Table 9.10 Analysis of Maximum Likelihood Parameter Estimates for Final Daytime Model of California

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-1.4451	0.0460	-1.5352	-1.3550	987.51	<.0001
weather1	1	-0.0413	0.0128	-0.0663	-0.0163	10.50	0.0012
rdsurf	1	0.1510	0.0168	0.1180	0.1839	80.57	<.0001
light	1	0.2769	0.0132	0.2511	0.3027	442.23	<.0001
trf_cntl	1	0.1113	0.0110	0.0897	0.1329	102.20	<.0001
no_lanes	1	0.2069	0.0119	0.1836	0.2303	301.06	<.0001
desg_spd	1	0.1501	0.0290	0.0933	0.2069	26.85	<.0001
rururb	1	0.0996	0.0105	0.0791	0.1201	90.79	<.0001
lanewid	1	0.2617	0.0178	0.2268	0.2966	215.95	<.0001
typedesc	1	0.2979	0.0096	0.2791	0.3167	963.31	<.0001
Dispersion	1	0.0000	0.0001	0.0000	1.059E80		

Calculating the Relative Effect for Variables

The relative effects of each indicator variable were calculated as $e^{\beta} - 1$. The relative effect for Minnesota daytime and nighttime models are shown in Table 9.11, and for California are shown in Table 9.12.

Table 9.11 Relative Effects for Indicator Variables in Minnesota Crash Frequency Models

Parameter	Nighttime Relative Effect (%)	Daytime Relative Effect (%)
weather1	4.48	N/A
rdsurf	33.10	47.57
light	-3.61	-21.31
trf_cntl	-6.14	N/A
Urb_Rur	-23.49	-13.71
rdwy_lgh	-4.72	N/A
nbr_legs	-19.69	-33.27
surf_typ	16.14	22.81
no_lanes	28.93	29.93
curb1	N/A	12.74
lanewid	N/A	-13.84

Table 9.12 Relative Effects for Indicator Variables in California Crash Frequency Models

Parameter	Nighttime Relative Effect (%)	Daytime Relative Effect (%)
rdsurf	10.99	16.30
light	-6.54	31.90
no_lanes	8.71	22.99
rururb	4.82	10.47
lanewid	8.61	29.91
typedesc	12.99	34.70
weather1	N/A	-4.05

Parameter	Nighttime Relative Effect (%)	Daytime Relative Effect (%)
trf_cntl	N/A	11.77
desg_spd	N/A	16.20

Discussion

Part 1: Minnesota

Considering the final nighttime crash frequency model of Minnesota, intersection light condition (light) variable was not statistically significant at 5% significance level, however, the light variable was considered border line significance variable, because the light p-value was 0.055 which is a border line value. The intersection lighting type (rdwy_lgh) variable, was significant at 5%. This variable compared partial lighting (or roadway feature identification lighting) with continuous lighting (or designed roadway lighting) at intersections. The rest of the variables in the model were significant at the 5% level, these include: Weather condition, road surface condition, traffic control indicator, area type indicator, intersection type indicator, AADT, surface type, and number of lanes at intersection.

Considering final daytime crash frequency model of Minnesota, the intersection lighting type variable was not considered in the initial model because during the day street lights are off. In the final daytime crash frequency model of Minnesota, the following variables were found significant at 5%: Intersection light condition, road surface condition, area type indicator, intersection type indicator, AADT, surface type, curbs, number of lanes, and lane width.

The explanatory variables that were negatively correlated with the expected nighttime crash frequency model of Minnesota were the intersection light condition (light), traffic control indicator, area type indicator, intersection lighting type, and intersection type indicator. The explanatory variables that were positively correlated with the expected nighttime crash frequency were weather condition, road surface condition, surface type condition, and number of lanes.

The explanatory variables that were negatively correlated with the expected daytime crash frequency in Minnesota were intersection light condition, area type indicator, intersection type indicator, and lane width. The explanatory variables that were positively correlated with the expected daytime crash frequency in Minnesota were road surface condition, surface type, curbs, and number of lanes.

To explain the negative and positive correlation between explanatory variables and expected crash frequency in the daytime and nighttime models, the relative effects for indicator variables in the crash frequency models of Minnesota were calculated. The relative effects for indicator variables in the models can be interpreted as follows.

Assuming all other explanatory variables in Minnesota daytime and nighttime modes are held constant, the relative effects of illuminated intersections are a 3.61% decrease in the expected nighttime crash frequency when compared to dark intersections. Urban areas decrease the expected nighttime crash frequency by 23.49% compared to rural areas. Partial lighting decreases the expected nighttime crash frequency by 4.72% compared to continuous lighting. Three legs (T or Y) intersections decrease the expected nighttime crash frequency by 19.69% compared to four legs (cross) intersections. Traffic signals decrease the expected nighttime crash frequency by 6.14% compared to stop or yield signs. Not clear weather conditions increase the expected nighttime crash frequency by 4.48% compared to clear weather conditions. Not clear road surface conditions increase the expected nighttime crash frequency by 33.1% compared to dry intersections. Roads of three lanes or more increase the expected nighttime crash frequency by 28.93% compared to roads of two lanes or less. Not clear road surface conditions increase the daytime crash frequency by 47.57% compared to dry intersections. Daylight decreases the expected daytime crash frequency by 21.31% compared to dark. Urban areas decrease the expected daytime crash frequency by 13.71% compared to rural areas. Three legs (T or Y) intersections decrease the expected daytime crash frequency by 33.27% compared to four legs (cross) intersections. Roads of three lanes or more increase the expected daytime crash frequency by 29.93% compared to roads of two lanes or less. Roads of 12 ft or more lane width decrease the expected daytime crash frequency by 13.84% compared with roads of less than 12 ft lane width.

Part 2: California

Considering the final nighttime crash frequency model of California, the significant variables at the 5% significance level are intersection light condition, road surface condition, lanes number, AADT, area type indicator, lane width, and intersection type indicator.

Considering final daytime crash frequency model of California, the significant variables at 5% significance level are weather condition, road surface condition, intersection light condition, traffic control indicator, lanes number, speed indicator, area type indicator, lane width, and intersection type indicator.

The only explanatory variable that was negatively correlated with the expected nighttime crash frequency in California model was the intersection light condition. The explanatory variables that were positively correlated with the expected nighttime crash frequency were road surface condition, lanes number, area type indicator, lane width, and intersection type indicator.

The only explanatory variable that was negatively correlated with the expected daytime crash frequency in California was the weather condition. The explanatory variables that were positively correlated with the expected daytime crash frequency in California were road surface condition, intersection light condition, traffic control indicator, lanes number, speed indicator, area type indicator, lane width, and intersection type indicator.

To explain the negative and positive correlation between explanatory variables and expected crash frequency in the daytime and nighttime models, the relative effects for indicator variables in the crash frequency models of California were calculated. The relative effects for indicator variables in the models can be interpreted as follows.

Assuming all other explanatory variables in California daytime and nighttime modes are held constant, the relative effects of illuminated intersections are a 6.54% decrease in the expected nighttime crash frequency when compared to dark intersections. Urban areas increase the expected nighttime crash frequency by 4.82% compared to rural areas. Roads of 12 ft or more lane width increase the expected nighttime crash frequency by 8.61% compared to roads of less than 12 ft in lane width. Three legs (Y or T) intersections increase the expected nighttime crash frequency by 12.99% compared to four legs (cross) intersections. Roads of 3 lanes or more increase the expected nighttime crash frequency by 8.71% compared to roads of 2 lanes or less. Daylight increases the expected daytime crash frequency by 31.9% compared to dark. Roads of three lanes or more increase the expected daytime crash frequency by 22.99% compared to roads of two lanes or less. Urban areas increase the expected daytime crash frequency by 10.47% compared to rural areas. Roads of 12 ft or more lane width increase the expected daytime crash frequency by 29.91% compared to roads of less than 12 ft in lane width. Three legs (Y or T) intersections increase the expected daytime crash frequency by 34.7% compared to four legs (cross) intersections. Not clear weather conditions decrease the expected daytime crash frequency by 4.05% compared to clear weather conditions. Traffic signals increase the expected daytime crash frequency by 11.77% compared to stop or yield signs. Driving at a speed of 45 mph or more increases the expected daytime crash frequency by 16.2% compared to speeds lower than 45 mph.

Summary

In studying the effect of intersection lighting on the expected crash frequency reduction, both Minnesota and California nighttime crash frequency models showed that the expected nighttime crash frequency was reduced for illuminated intersections. In Minnesota, assuming all studied variables are held constant, the relative effects of illuminated intersections are a 3.61% decrease in the expected nighttime crash frequency when compared to dark intersections, and daylight decreases the expected daytime crash frequency at intersections by 21.31% compared to dark intersections. In California, assuming all studied variables are held constant, the relative effects of illuminated intersections are a 6.54% decrease in the expected nighttime crash frequency when compared to dark intersections, but daylight increases the expected daytime crash frequency at intersections by 31.9% compared to dark.

In addition, for Minnesota nighttime model, partial lighting at intersections decreases the expected nighttime crash frequency by 4.72% compared to continuous lighting. This is a unique finding, which indicates that partial lighting at intersections performs better than continuous lighting at intersections, by reducing the expected nighttime crash frequency.

Chapter 10 - Conclusions

Based on a national survey, approximately 57% of state DOTs illuminate their overhead guide signs, while 43% do not. Among those states which illuminate their overhead guide signs, the most common light sources used currently are MH, MV, HPS, induction lighting, and LED. States’ future plans for increasing overhead guide sign visibility include modifying existing lights into new, cost-efficient sources, or using new, brighter retroreflective sheeting for signs.

Based on a light distribution experiment, the HPS light source provided the best light distribution among the conventional light sources followed by MH. Induction lighting source provided the best light distribution among light sources of the new generation, followed by the LED. The light sources cost analysis showed that induction lighting was the most cost-effective light source, followed by LED. In conclusion, combining three decision criteria for light sources comparison (light distribution, compliancy with EISA of 2007, and cost), the recommended light source to be used by DOTs for overhead guide sign illumination is induction lighting, followed by LED.

According to statistical analysis of the retroreflectivity experiment, Diamond Grade (type XI) retroreflective sheeting enabled drivers to read signs’ legend from a longer distance and at lower illuminance, followed by High Intensity (type IV). Engineering Grade (type I) was the worst performing retroreflective sheeting. Based on the frequency of human subjects at each headlights brightness level in the field experiment, the Diamond Grade (type XI) sign was read by a majority of subjects at lower illuminance averages: 0.035 lux and 0.037 lux at 180 ft and 240 ft, respectively. In addition, all participating subjects were able to read the legend on the Diamond Grade (type XI) sign, but not the High Intensity (type IV) and Engineering Grade (type I) sheeting. Therefore, it was concluded that Diamond Grade (type XI) sheeting provided drivers with the highest visibility and legibility compared to High Intensity (type IV). The cost analysis of the retroreflective sheeting showed that High Intensity (type IV) retroreflective sheeting could be a cost-effective choice for those DOTs with limited budgets to increase overhead guide sign visibility and legibility.

In comparing the best option of each method of increasing sign visibility, external illumination and retroreflectivity, the average annual cost when using the 85W induction lighting was $45.37, not including labor cost. On the other hand, the annual cost when using High

Intensity (type IV) retroreflective sheeting was $39.15, including labor cost, meaning that High Intensity (type IV) retroreflective sheeting, which is the alternative solution for DOTs with limited budgets, is the most cost-effective method that increases overhead guide sign visibility for drivers, and consequently increasing safety on roadways during nighttime.

Glare experiment for shoulder-mounted guide signs revealed that Diamond Grade (type XI) retroreflective sheeting combined with Clearview was the optimal sheeting-font combination that provided highest signs' visibility and legibility to drivers. However, since the Diamond Grade (type XI) sheeting is more costly than that for High Intensity (type IV) retroreflective sheeting, DOTs with limited budgets can use an alternative sheeting-font combination between High Intensity (type IV) and Clearview. Based on the conducted experiment, this combination provides sufficient visibility and legibility for drivers, at lower cost. Consequently, the alternative combination between High Intensity (type IV) sheeting and Clearview font increases visibility, legibility and boosts drivers' safety on roadways.

Regardless the sheeting type, the glare experiment showed that Clearview font was a better font that increases legibility distance for drivers experiencing glare from an oncoming vehicle's low beam headlights during nighttime. Results of this research will assist DOTs in selecting the optimal combination of retroreflective sheeting material and font type for shoulder-mounted guide sign, to increase signs' visibility under the presence of glare from an oncoming vehicle's low beam headlights, and consequently increase safety on roadways.

The glare experiment result could be also generalized for overhead guide signs, in that the optimal sheeting-font combination is Diamond Grade (type XI) and Clearview, and the alternative combination for DOTs with limited budgets is High Intensity (type IV) and Clearview.

In studying the effect of intersection lighting on the expected crash frequency, both Minnesota and California nighttime crash frequency models showed that the expected nighttime crash frequency was reduced for illuminated intersections, compared to dark intersections. Assuming all the studied variables are held constant, the relative effects of illuminated intersections are a 3.61% decrease in the expected nighttime crash frequency when compared to dark intersections in Minnesota, and the relative effects of illuminated intersections are a 6.54% decrease in the expected nighttime crash frequency when compared to dark intersections in California. In addition, for Minnesota nighttime model, partial lighting at intersections decreases the expected nighttime crash frequency by 4.72% compared to continuous lighting. This is a unique finding, which indicates that partial lighting performs better than continuous lighting at intersections during nighttime.

Future Research

The relation between illuminance and retroreflectivity will be studied to establish a mathematical relationship between these variables. The established theoretical relationship will be verified in laboratory and field experiments.

Introduction

Retroreflectivity is an optical phenomenon in which the reflected light rays returned in an opposite direction that is close to the direction from which the rays came (Austin & Schultz, 2009). Multiple reflections within a retroreflector can cause retroreflectivity. Examples on those retroreflectors are microspheres of glass plastic and cube corners (Austin & Schultz, 2009). Retroreflectivity is the ratio between the light that is visible to the driver and the amount of light entering the highway target such as sign or marking (Austin & Schultz, 2009).

In studying retroreflection, it is useful to review some related photometric quantities. Luminous flux (φ) is “the light power emitted by a light source” (Beacco, et al., 2003). It is the sum of the weighted radiated power within the band of the visible frequency, and in the vision case the sensitivity of the human eye is the weight (Beacco, et al., 2003). The luminous intensity (I) is “the derivative of the luminous flux along a direction in the space identified by the spatial angle ω” (Beacco, et al., 2003). Equation 10.1 represents the luminance intensity.

$$I = \frac{\partial \varphi}{\partial \omega} \qquad 10.1$$

Illuminance (E) is “the incident luminous flux on a unit area of a surface” (Beacco, et al., 2003). Illuminance can be calculated based on equation 10.2.

$$E = \frac{\partial \varphi}{\partial A} \qquad 10.2$$

Where A is the surface area.

Luminance (L) is “the intensity of the light emitted from an area A observed from a given direction” (Beacco, et al., 2003). Luminance can be calculated based on equation 10.3.

$$L = \frac{\partial I}{\partial (A \cos v)} \qquad 10.3$$

Where v is the angle between the normal of the surface A and the observation direction.

The surface reflection factor (ρ) is “the ratio between the reflected and the incident flux” (Beacco, et al., 2003). Surface reflection factor should be determined for each pair of incident and reflection directions because the luminous intensity depends on the observation direction (Beacco, et al., 2003). The relationship between luminance and illuminance can be found in equation 10.4.

$$L(v) = \rho \frac{E}{\pi} = qE \qquad 10.4$$

Where q is the luminance coefficient.

Based on equation 4, for a uniform reflector, if the surface reflection factor is known, and if either the illuminance or the luminance is known, the other quantity can be obtained. The luminous intensity of the reflected lights depends on the material and it can be vary based on the light incident direction (Beacco, et al., 2003). Reflectivity (*R*) is “the luminance divided by illuminance” (Siegmann, et al., 2008).

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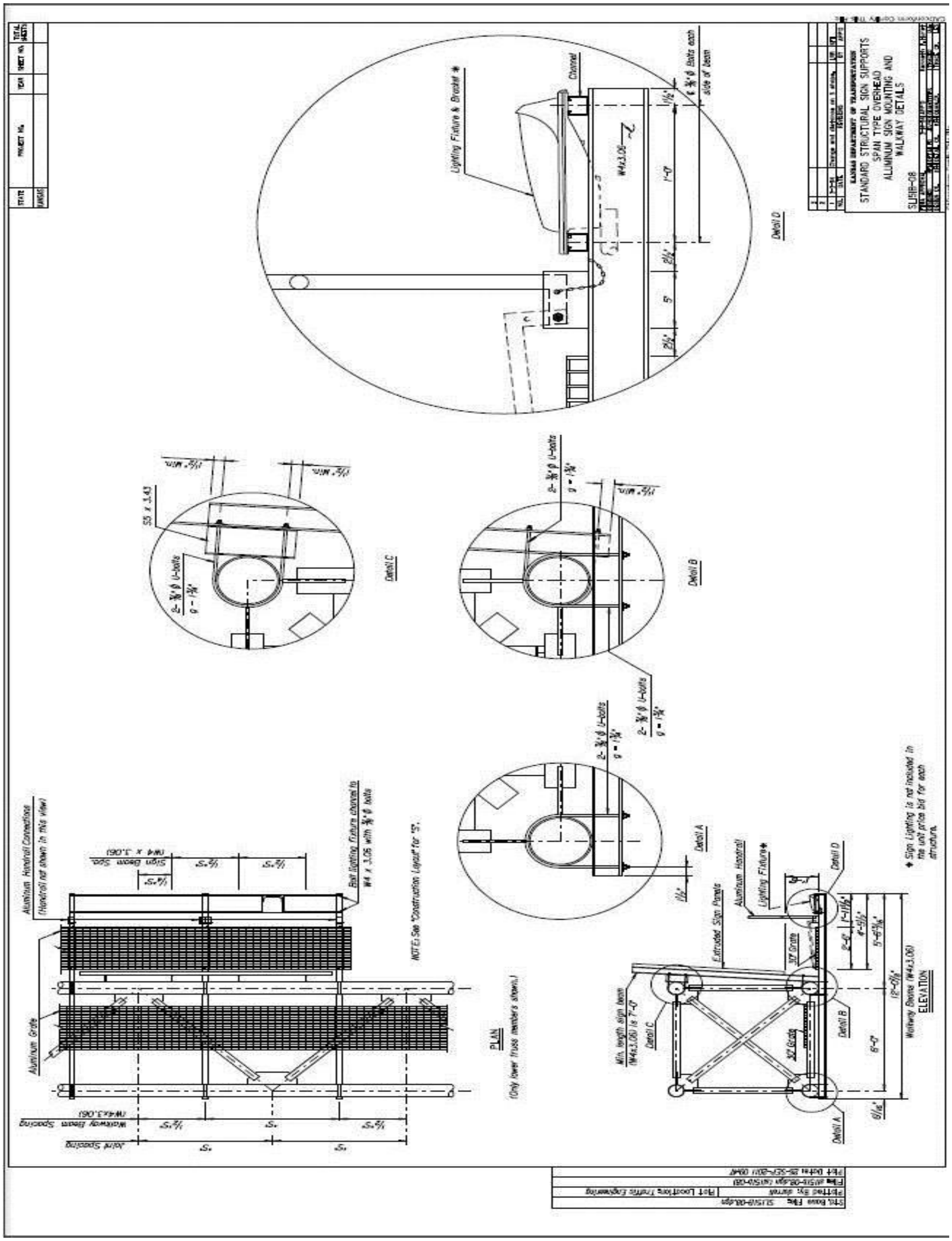
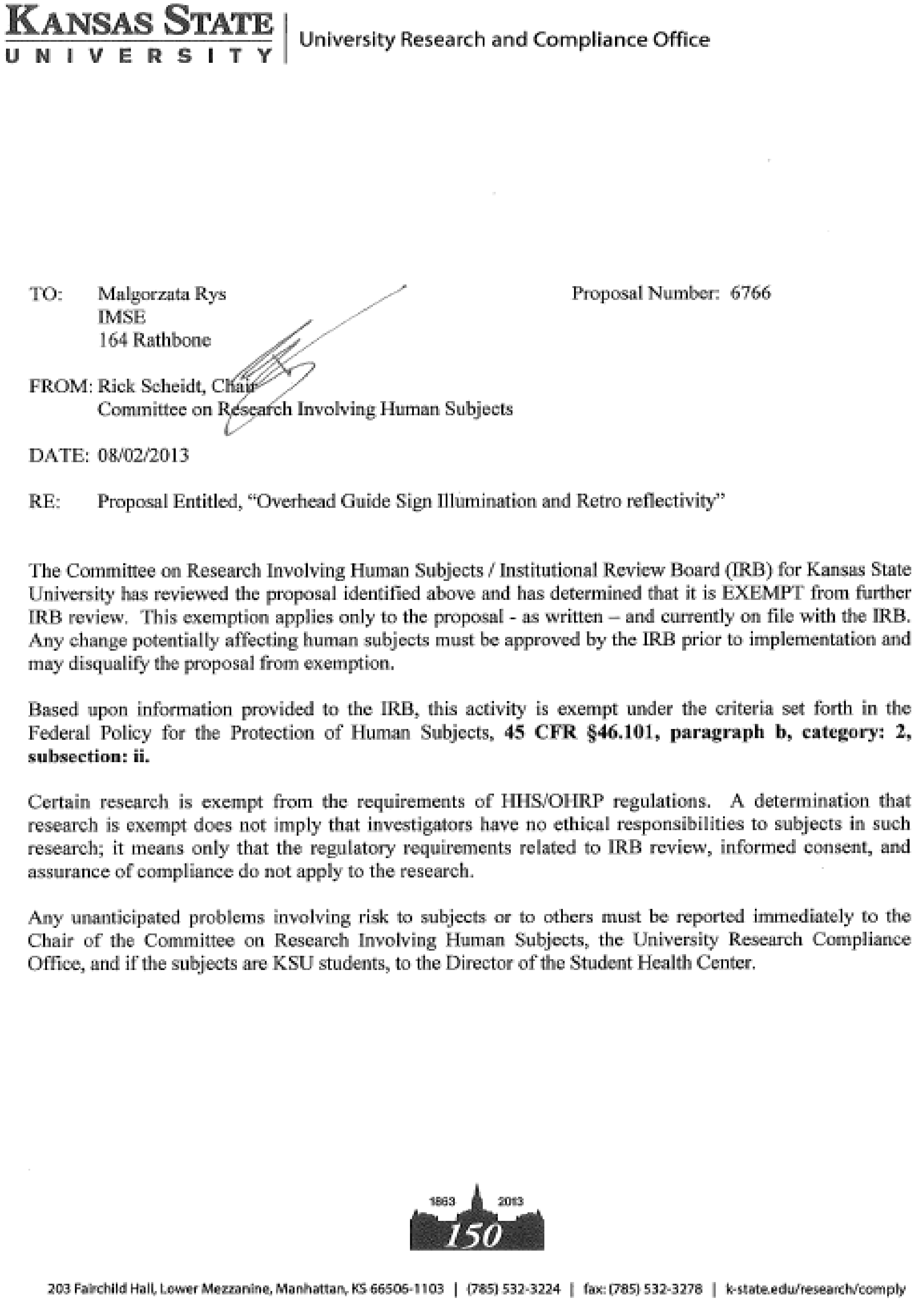
Appendix A - Standard Position of Light Unit Installed for Guide Sign Illumination



Appendix B - Retroreflectivity Experiment IRB Approval Form



KANSAS STATE UNIVERSITY | University Research and Compliance Office

TO: Malgorzata Rys
IMSE
164 Rathbone

Proposal Number: 6766

FROM: Rick Scheidt, Chair
Committee on Research Involving Human Subjects

DATE: 08/02/2013

RE: Proposal Entitled, "Overhead Guide Sign Illumination and Retro reflectivity"

The Committee on Research Involving Human Subjects / Institutional Review Board (IRB) for Kansas State University has reviewed the proposal identified above and has determined that it is EXEMPT from further IRB review. This exemption applies only to the proposal - as written – and currently on file with the IRB. Any change potentially affecting human subjects must be approved by the IRB prior to implementation and may disqualify the proposal from exemption.

Based upon information provided to the IRB, this activity is exempt under the criteria set forth in the Federal Policy for the Protection of Human Subjects, **45 CFR §46.101, paragraph b, category: 2, subsection: ii.**

Certain research is exempt from the requirements of HHS/OHRP regulations. A determination that research is exempt does not imply that investigators have no ethical responsibilities to subjects in such research; it means only that the regulatory requirements related to IRB review, informed consent, and assurance of compliance do not apply to the research.

Any unanticipated problems involving risk to subjects or to others must be reported immediately to the Chair of the Committee on Research Involving Human Subjects, the University Research Compliance Office, and if the subjects are KSU students, to the Director of the Student Health Center.

203 Fairchild Hall, Lower Mezzanine, Manhattan, KS 66506-1103 | (785) 532-3224 | fax: (785) 532-3278 | k-state.edu/research/comply

Appendix C - Field Experiment Consent Form

I verify that my signature below indicates that I have read and understand this consent form, and willingly agree to participate in this study under the terms described, and that my signature acknowledges that I have received a signed and dated copy of this consent form.

(Remember that it is a requirement for the P.I. to maintain a signed and dated copy of the same consent form signed and kept by the participant

Participant Name:

Participant Signature:

Date:

Witness to Signature: (project staff)

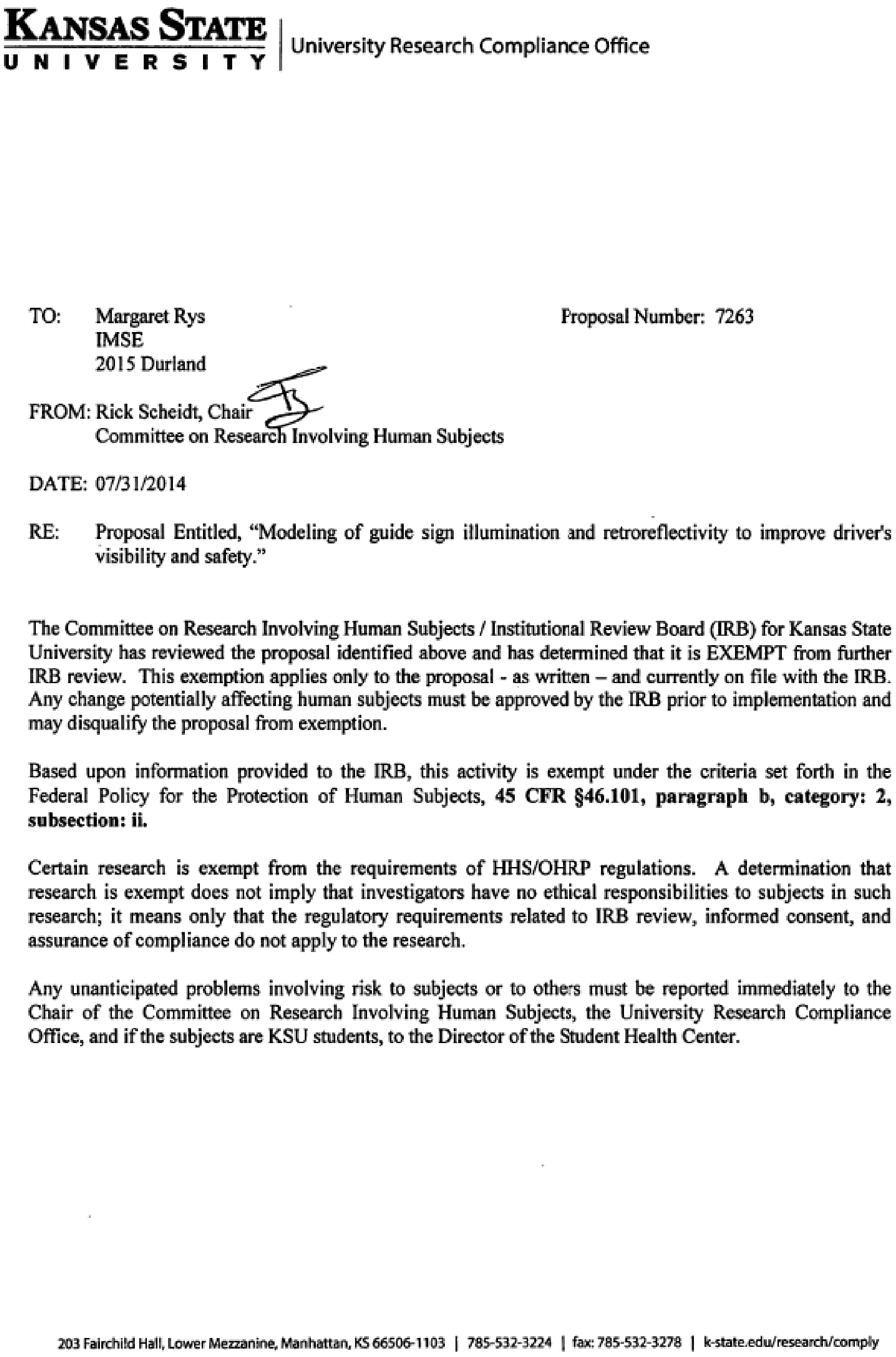
Date:

Appendix D - Retroreflectivity Experiment SAS Software Codes

```
Libname Exp 'C:\Mohammed Obeidat\Dissertation\Statistic';
Proc Format;
Value Agegroup
                     20-<30 = '20-29'
                     30-<50 = '30-49'
                     50-High = '51 and above';
Run;
Data Exp.Data;
Input Subject Age Distance Sign Knob_pos Ill_Lux;
Datalines;
1      20     240    1      6      0.06
1      20     240    2      3      0.02
1      20     240    3      4      0.04
1      20     180    1      5      0.06
1      20     180    2      3      0.03
1      20     180    3      3      0.03
2      20     240    1      .      .
2      20     240    2      14     0.22
2      20     240    3      11     0.15
2      20     180    1      10     0.16
2      20     180    2      5      0.06
2      20     180    3      12     0.22
3      20     240    1      14     0.22
3      20     240    2      8      0.09
3      20     240    3      14     0.22
3      20     180    1      15     0.31
3      20     180    2      6      0.07
...
41     35     240    2      2      0.02
41     35     240    3      5      0.05
41     35     180    1      4      0.04
41     35     180    2      2      0.02
41     35     180    3      3      0.03
;
Run;
Data Exp.Data1;
      Set Exp.Data;
      Agegroup = Put(age, Agegroup.);
Run;
Proc Print Data=Exp.Data1 Label;
Title 'Retroreflectivity Experiment Formatted Data';
Label Agegroup ='Age Group'
        Knob_pos= 'Knob Position'
        Ill_Lux='Illuminance';
Run;
Title 'Repeated Measure Design';
Title 'Finding Significant Variables from Data';
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign Agegroup;
Model Ill_lux= Distance|sign|Agegroup/ddfm=satterth;
Random Subject(Agegroup);
Run;
Proc Mixed Data=Exp.Data1;
```

```
Class Subject Distance Sign Agegroup;
Model Ill_lux= Distance sign Agegroup Distance*sign Distance*Agegroup
sign*Agegroup/ddfm=satterth;
Random Subject(Agegroup);
Run;
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign Agegroup;
Model Ill_lux= Distance sign Agegroup Distance*sign Distance*Agegroup
/ddfm=satterth;
Random Subject(Agegroup);
Run;
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign Agegroup;
Model Ill_lux= Distance sign Agegroup Distance*sign /ddfm=satterth;
Random Subject(Agegroup);
Run;
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign;
Model Ill_lux= Distance sign Distance*sign /ddfm=satterth;
Random Subject;
Run;
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign;
Model Ill_lux= Distance sign /ddfm=satterth;
Random Subject;
Run;
Title 'Keeping Significant Variables Only and/or Interactions';
Title1 ' Finding the Least Mean Square for Significant Variables';
Title2 'Difference of Least Square Mean';
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign;
Model Ill_lux= Distance sign /ddfm=satterth;
Random Subject;
Lsmeans Distance Sign /pdiff Adjust =Tukey;
Run;
```

Appendix E - Glare Experiment IRB Approval Form



KANSAS STATE UNIVERSITY | University Research Compliance Office

TO: Margaret Rys
IMSE
2015 Durland

Proposal Number: 7263

FROM: Rick Scheidt, Chair
Committee on Research Involving Human Subjects

DATE: 07/31/2014

RE: Proposal Entitled, "Modeling of guide sign illumination and retroreflectivity to improve driver's visibility and safety."

The Committee on Research Involving Human Subjects / Institutional Review Board (IRB) for Kansas State University has reviewed the proposal identified above and has determined that it is EXEMPT from further IRB review. This exemption applies only to the proposal - as written – and currently on file with the IRB. Any change potentially affecting human subjects must be approved by the IRB prior to implementation and may disqualify the proposal from exemption.

Based upon information provided to the IRB, this activity is exempt under the criteria set forth in the Federal Policy for the Protection of Human Subjects, **45 CFR §46.101, paragraph b, category: 2, subsection: ii.**

Certain research is exempt from the requirements of HHS/OHRP regulations. A determination that research is exempt does not imply that investigators have no ethical responsibilities to subjects in such research; it means only that the regulatory requirements related to IRB review, informed consent, and assurance of compliance do not apply to the research.

Any unanticipated problems involving risk to subjects or to others must be reported immediately to the Chair of the Committee on Research Involving Human Subjects, the University Research Compliance Office, and if the subjects are KSU students, to the Director of the Student Health Center.

203 Fairchild Hall, Lower Mezzanine, Manhattan, KS 66506-1103 | 785-532-3224 | fax: 785-532-3278 | k-state.edu/research/comply

Appendix F - Database Research SAS Software Codes

Minnesota Nighttime Model

```
PROC IMPORT OUT= WORK.MNDay DATAFILE= "F:\Mohammed Obeidat New\PhD
Dissertation\Database research\Working on Data\SAS Analysis\Minnesota
SAS\Files for dissertation\MN Night Frequency Final.xlsx"
DBMS=xlsx REPLACE;
GETNAMES=YES;
RUN;
Title "Initila Model";
Proc genmod data = work.MNDay;
model Nit_Freq = weather1     rdsurf      light trf_cntl    Urb_Rur
      rdwy_lgh    nbr_legs    aadt  surf_typ    curb1 no_lanes    lanewid
 /dist=negbin link=log;
Run;

Title "Remove curb1";
Proc genmod data = work.MNDay;
model Nit_Freq = weather1     rdsurf      light trf_cntl    Urb_Rur
      rdwy_lgh    nbr_legs    aadt  surf_typ    no_lanes    lanewid
 /dist=negbin link=log;
Run;

Title "Remove lanewid";
Proc genmod data = work.MNDay;
model Nit_Freq = weather1     rdsurf      light trf_cntl    Urb_Rur
      rdwy_lgh    nbr_legs    aadt  surf_typ    no_lanes
 /dist=negbin link=log;
Run;
```

Minnesota Daytime Model

```
PROC IMPORT OUT= WORK.MNDay DATAFILE= "F:\Mohammed Obeidat New\PhD
Dissertation\Database research\Working on Data\SAS Analysis\Minnesota
SAS\Files for dissertation\MN Day Frequency Final.xlsx"
            DBMS=xlsx REPLACE;
        GETNAMES=YES;
RUN;
Title "First Model";
Proc genmod data = work.MNDay;
model Day_freq  = weather1    rdsurf      light trf_cntl    Urb_Rur
      nbr_legs    aadt  surf_typ    curb1 no_lanes    lanewid
 /dist=negbin link=log;
Run;

Title "Remove trf_cntl";
Proc genmod data = work.MNDay;
model Day_freq  = weather1    rdsurf      light Urb_Rur     nbr_legs    aadt
      surf_typ    curb1 no_lanes    lanewid
 /dist=negbin link=log;
Run;
```

```
Title "Remove weather1";
Proc genmod data = work.MNDay;
model Day_freq  = rdsurf      light Urb_Rur     nbr_legs    aadt  surf_typ
      curb1 no_lanes    lanewid
 /dist=negbin link=log;Run;
```

California Nighttime Model

```
PROC IMPORT OUT= WORK.MNDay DATAFILE= "F:\Mohammed Obeidat New\PhD
Dissertation\Database research\Working on Data\SAS Analysis\California
Data\Files for dessertation\CA Night data.xlsx"
        DBMS=xlsx REPLACE;
        GETNAMES=YES;
RUN;
Title "First Model";
Proc genmod data = work.MNDay;
model Nit_Freq = weather1     rdsurf      light trf_cntl    no_lanes
      desg_spd    aadt  rururb      surf_ty1    lanewid     typedesc
 /dist=negbin link=log;
Run;

Title "Remove trf_cntl";
Proc genmod data = work.MNDay;
model Nit_Freq = weather1     rdsurf      light no_lanes    desg_spd    aadt
      rururb      surf_ty1    lanewid     typedesc
 /dist=negbin link=log;
Run;

Title "Remove surf_ty1";
Proc genmod data = work.MNDay;
model Nit_Freq = weather1     rdsurf      light no_lanes    desg_spd    aadt
      rururb      lanewid     typedesc
 /dist=negbin link=log;
Run;

Title "Remove desg_spd";
Proc genmod data = work.MNDay;
model Nit_Freq = weather1     rdsurf      light no_lanes    aadt  rururb
      lanewid     typedesc
 /dist=negbin link=log;
Run;

Title "Remove weather1";
Proc genmod data = work.MNDay;
model Nit_Freq =  rdsurf      light no_lanes    aadt  rururb      lanewid
      typedesc
 /dist=negbin link=log;
Run;
```

California Daytime Model

```
PROC IMPORT OUT= WORK.MNDay DATAFILE= "F:\Mohammed Obeidat New\PhD
Dissertation\Database research\Working on Data\SAS Analysis\California
Data\Files for dessertation\CA Day data.xlsx"
            DBMS=xlsx REPLACE;
        GETNAMES=YES;
```

```
RUN;
Title "First Model";
Proc genmod data = work.MNDay;
model Day_Freq = weather1     rdsurf      light trf_cntl    no_lanes
      desg_spd    aadt  rururb      surf_ty1    lanewid     typedesc
 /dist=negbin link=log;
Run;

Title "Remove surf_ty1";
Proc genmod data = work.MNDay;
model Day_Freq = weather1     rdsurf      light trf_cntl    no_lanes
      desg_spd    aadt  rururb      lanewid     typedesc
 /dist=negbin link=log;
Run;


Title "Remove aadt";
Proc genmod data = work.MNDay;
model Day_Freq = weather1     rdsurf      light trf_cntl    no_lanes
      desg_spd    rururb      lanewid     typedesc
 /dist=negbin link=log;
Run;
```