Effective Light Source for Illuminating Overhead Guide Signs and Improving Roadway Safety

by Mohammed S. Obeidat, and Malgorzata J. Rys

Driver safety is considered an important issue to departments of transportation. One way to increase highway safety is to improve the visibility of overhead guide signs for drivers. Visibility improving methods include the use of sign illumination or retroreflective sheeting materials. This paper focuses on sign illumination by comparing five light sources including high pressure sodium (HPS), metal halide (MH), mercury vapor (MV), induction lighting, and light emitting diode (LED). A laboratory experiment was conducted to compare effective light distribution of each light source and a cost analysis was performed to compare initial, maintenance, and operating cost components of the light sources. Results of the light distribution experiment indicated that HPS was the optimum light source followed by MH, induction lighting, MV, and LED. Induction lighting is a promising lighting technology which features good efficiency and long life. According to cost analysis, induction lighting was the most effective source, followed by the LED, HPS, MV, and MH. Of the five light sources considered, induction lighting provided the best overall performance when considering initial cost, operating cost, expected maintenance, and sign illuminance. Environmentally, LED does not contain mercury, and for those agencies that prefer using sources that are friendlier with the environment, the LED can be their best choice.

INTRODUCTION

Motor vehicles are important modes of transportation worldwide. To safely operate a motor vehicle, however, 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 and Broberg 2012). Based on road statistics, the most important driving skills include the acquisition and processing of information and the ability to make appropriate decisions when needed (Dewar and Olson 2007).

One primary mission of the Federal Highway Administration (FHWA) in the U.S. is to increase roadway safety. According to the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS), 32,719 people were killed in motor vehicle traffic crashes in the U.S. in 2013 (NHTSA 2014). 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).

Guide signs in U.S. are typically green and are located along a roadway to notify drivers of destinations and exit information. Overhead guide signs, which are essential for driver guidance, have the primary objective of providing drivers with information regarding destinations.

As required in the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD), overhead guide signs must be illuminated or manufactured from retroreflective sheeting materials (FHWA 2009). Departments of transportation (DOTs) in the U.S. must consider whether to add light sources to overhead guide signs currently installed on highways, or add modern retroreflective sheeting material to these signs, to improve sign visibility for drivers during nighttime, thereby possibly reducing potential accidents due to driver confusion.

This paper consists of three phases to evaluate light sources used to illuminate overhead guide signs: laboratory experiment to compare five light sources, cost analysis of the tested light sources, and testing light sources for toxic materials contents. The laboratory experiment was conducted to compare light distribution of five light sources. These light sources include metal halide (MH), mercury vapor (MV), high pressure sodium (HPS), induction lighting, and light emitting diode (LED) that produces white color. A cost analysis was also performed to compare the five light sources based on initial maintenance and operating costs during the lifespan of each light source. Because of the presence of toxic materials in the studied light sources such as lead and mercury, except for the LED, which is free of lead and mercury, environmental-related issues were considered as additional decision criterion when comparing light sources. The objective of this paper was to determine the most effective light source to be used by DOTs to improve overhead guide sign visibility during nighttime. Determination was made based on three decision criteria: light distribution, average annual cost, and environmental-related issues of light sources. Light distribution refers to the values of the luminous intensities radiated in all relevant directions by the luminaire. Luminaire refers to a complete electric light unit. In this paper, the luminous intensities that fall on a sign will be considered to evaluate the light distribution of different light sources.

LITERATURE REVEW

Drivers of all ages often experience more difficulty driving at night compared with daytime driving. Visibility issues include driver's visual acuity, contrast sensitivity, distance judgment, and color discrimination (Lagergren 1987). Roadway lighting is a basic public amenity that contributes to a safer environment for drivers and pedestrians. Efficient roadway lighting can improve personal security, traffic flow operations, and safety because drivers can more clearly recognize street conditions and geometry of the roadway (Medina et al. 2013).

Guide signs must be visible and clear for intended drivers in order to allow for suitable driving response time. 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). Desirable attributes for guide signs include high visibility and legibility during day and night. Legibility is defined as "the readability of a particular writing style, or font" (Amparano and Morena 2006).

Traveling on U.S. roadways can be confusing and challenging for drivers if driving routes are not easily understood or clearly marked, especially when the driver is unfamiliar with the driving location (Amparano and Morena 2006). Travelling can be challenging for older drivers, age 65 and older, especially those older drivers who have cognitive or physical disabilities (Amparano and Morena 2006). However, various engineering improvements, such as sign placement, legibility of sign lettering, sign illumination, retroreflectivity, and sign size, can increase the probability that a driver will detect signs and comprehend sign messages.

Overhead guide signs can be illuminated from the back, known as back-illuminated, or by utilizing external light sources to illuminate the sign face (Bullough et al. 2008). External light sources are light fixtures designed to illuminate overhead guide signs by transforming electrical power into a visible light. Another way of illuminating overhead guide signs is by using luminous sources or elements, such as LED, to produce required sign characters (Bullough et al. 2008).

Retroreflective sheeting materials can also be used to enhance overhead guide sign visibility for drivers. Obeidat et al. (2014) performed a study to find DOTs' policies for increasing the visibility of overhead guide sign on highways. They found that the most commonly used retroreflective sheeting material by states for overhead guide sign legend is Diamond Grade (type IX followed by type XI), and High Intensity (types III and IV) for sign background. Obeidat et al. (2015) in another study compared three retroreflective sheeting used by DOTs for overhead guide sign: Engineering Grade (type I), High Intensity (type IV), and Diamond Grade (type XI). The comparison was based on results of a field experiment involving human participants and a cost analysis. They recommended DOTs use high intensity (type IV) retroreflective sheeting for guide signs since it increases visibility and consequently increases safety.

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. This is true for certain locations in the field of view and for certain light levels (Bullough 2012a). One wavelength of light represents the distance between two consecutive corresponding points of one wave. Wave in physics is defined as any regularly recurring event. *Waves* are characterized by wavelength, frequency, and the speed at which they move. Several light sources used for roadway illuminating devices are available in the market. These light sources are classified into conventional or traditional lighting and new light source generation. Conventional lighting includes incandescent lamps and electric discharge lamps, and new light source generation includes induction lighting and LED.

Conventional Light Sources

In incandescent lamps, an electrical current passes through a wire and the wire heats to a certain level, causing the wire to glow and emit light (Lopez 2003). According to Lopez (2003), tungsten halogen and common incandescent are two prominent types of incandescent lamps. Tungsten halogen (quartz iodide) is not used for roadway lighting (Lopez 2003). The common incandescent lamps consist of a tungsten filament enclosed in a glass envelope that is attached to a metal base. The bulb is evacuated first (all gases and other materials are removed) and then inert gas (usually nitrogen or argon) is introduced into the bulb to increase bulb life and efficiency. The common incandescent lamp has low initial and operating costs, but it also has low efficacy (lumens per watt) and a short lifespan ranging between 1,000-2,000 hours (BITS 2012). One disadvantage of incandescent lamps is that they contain some toxic materials such as lead and mercury, which makes them non-environmentally friendly (California Department of Toxic Substances Control 2010).

According to Lopez (2003), five common types of electric discharge light sources are: fluorescent, induction fluorescent, MV, HPS, low pressure sodium (LPS), and MH (Lopez 2003).

Based on Lopez (2003), fluorescent lamps contain mercury to produce a mercury arc which operates at low vapor pressure to produce ultraviolet light. The mercury arc in fluorescent lamps is produced when an electric current excites the mercury vapor, which works at low pressure to produce ultraviolet light. The ultraviolet light strikes a phosphor coating the bulb, which causes visible light to be emitted. Fluorescent light sources have a moderate initial cost, long lifespan, and high efficacy (30-70 lumens/watt). However, since fluorescent lamps contain mercury, they are not environmentally friendly.

Induction fluorescent lamps have the same principle as fluorescent lamps except that they do not have a tubular shape (Lopez 2003). Some types of induction fluorescent lamps have a high efficacy (up to 75 lumens/watt) with extremely long lifespan (up to 100,000 hours). Induction fluorescent is suitable for low-mounting heights. However, induction fluorescent is non-environmentally friendly because it contains toxic materials such as lead and mercury (California Department of Toxic Substances Control 2010).

MV light sources contain a quartz arc tube with a mercury arc which produces visible light and ultraviolet light. The glass envelope of the MV light sources helps filter some of the far ultraviolet light (Lopez 2003). Two types of MV are available in the market: clear light and phosphor-coated light. MV light sources that include phosphor-coated light are used for sign lighting. Advantages of MV light include relatively long lifespan and high efficacy (30-65 lumens/watt). One disadvantage of MV is the presence of mercury, consequently causing the MV light source to be non-environmentally friendly. The MV is no longer available in the U.S. market because of the Energy Independence and Security Act (EISA) of 2007.

In the HPS light source, light is produced by an arc in a ceramic tube containing sodium and other elements to improve color rendition (Lopez 2003). Advantages of HPS light include relatively low initial cost, long useful life, high efficacy (45-150 lumens/watt), and the ability to maintain relatively high light output throughout the lifespan (Bullough 2012b). One disadvantage is that most HPS light sources contain toxic materials, such as mercury, which makes those HPS types non-environmentally friendly (Recycle SD Inc. 2014).

In the LPS light source, light is produced by an arc tube (gas discharge tube) in a long glass envelope that only contains sodium in order to produce a yellow light with poor color rendering (Lopez 2003). Advantages of LPS include moderately long lifespan and high efficacy (145-185 lumens/watt). Most of LPS light sources are non-environmentally friendly because they contain mercury (Recycle SD Inc. 2014).

MH light source is similar to the MV light source, but in addition to mercury, it contains various metal halides which provide excellent color rendering, resulting in white light (Lopez 2003). MH light sources have been available for several decades, and recent technology has increased efficacy of MH sources, increased the useful life, and improved lumen maintenance (Bullough 2012b). Lumen maintenance refers to the comparison between the amount of light produced from a light source when it is brand new to the amount produced after using the light source for a period of time. New MH light sources that have ceramic arc tubes and modern source starting methods have increased efficiency, lifespan, and lumen maintenance. One disadvantage of MH is the presence of mercury, rendering it non-environmentally friendly.

New Generation of Light Sources

Unlike conventional fluorescent lamps that have electrodes at either end of the lamp tube, induction lighting uses radio frequencies to stimulate lamp material to produce light (Bullough 2012b). Induction lamps, however, use radio frequency or microwaves to create induced electrical fields which excite gases to produce light. Induction lamps manifest the same color as conventional fluorescents and share their diffuse appearance, but induction lamps do not require the longer tubular shape of most fluorescent sources. Diffused light is non-directional light, where the light has an even intensity. Induction lighting is a lighting technology with efficacy and lifespan advantages over conventional lighting (Deco Lighting 2010).

Induction light source manufacturers claim that induction light sources have rapid start-up and operates at peak efficiency with minimal warm-up time. Disadvantages of induction lighting include limited directionality of light beams and inability to focus compared with LEDs, hazardous lead, and mercury, which require special handling for disposal, inability to function efficiently in cold environments, production of ultraviolet (UV) radiation which harms products such as retroreflective sheeting, and delayed adoption of induction-based roadway lighting systems, which is already in its peak of improvement because of rapidly improving LED technology (Deco Lighting 2010 and GRAH Lighting 2014).

Recent technologies and advances in solid-state lighting have resulted in an LED light source that produces white light. This light is produced by short wavelength LEDs that create blue light which, when combined with phosphor, converts the blue light into yellow light, resulting in a white mixture (Bullough 2012b). LED-based roadway lighting products offer several advantages over traditional lighting technologies. Modern LED light sources used for street and sign lighting are also free of mercury and are compliant with Restriction of Hazardous Substances (RoHS) (Tri-State LED 2012). However, a study performed by Lim et al. (2010) showed that some LEDs contain other toxic materials such as lead, arsenic, and phosphorus, which make them not environmental friendly. Based on Lim et al. (2010), LEDs that produce white light color are free of mercury, lead, arsenic, barium, gadolinium, indium, tungsten, and yttrium. The unique environmental advantage of all LED types, no matter the produced light color, is that they do not contain mercury (Lim et al. 2010).

The LED light source for roadway lighting also meets the American Association of State Highway and Transportation Officials' (AASHTO) requirements published in 2005 with approximately 7% reduction in energy use. 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 2012b).

Advantages of LEDs include low energy consumption, long lifespan, high color quality, improved performance in Mesopic vision conditions (Mesopic vision is defined as the light levels at which cones and rods contribute to human vision [Avrenli et al. 2012], where in the human retina there are two types of photoreceptors: rods and cones), instant lighting, small compact size, directional light, light pollution reduction, environmentally friendly characteristics, dimming capabilities, free of mercury and vibration, and breakage resistance. However, LED disadvantages include high maintenance cost, less luminous efficacy than conventional light sources, heat conversion rate (LEDs have a higher rate of electric power to heat conversion), issues in obtaining white light, and problems associated with the LED module arrays such as increasing failure chance of a component when the number of used LED chips (a semiconductor chip) increase, individual LEDs overdriving in the array when LEDs start to fail (when an LED fails, the remaining LEDs will be driven harder, therefore, the temperature will be increased and the life of the system will be reduced), and leading to multiple shadows (Avrenli et al. 2012). 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). Additional details of LED's advantages and disadvantages can be found in Avrenli et al. 2012.

Light Sources Comparison

Table 1 shows a comparison summary of the light sources included in the literature review section, and can be used to illuminate overhead guide signs on roadways.

Table 1: Light Sources Comparison

Light Source	Lighting Category	Efficacy (lumens/watt)	Lifespan	Toxic Materials Contents
Common incandescent	Conventional	Low	Short	Lead and mercury
fluorescent lamps	Conventional	High	Moderate	Mercury
Induction fluorescent	Conventional	High	Long	lead and mercury
MV	Conventional	High	Long	Mercury
HPS	Conventional	High	Long	Mercury
LPS	Conventional	High	Long	Mercury
MH	Conventional	High	Long	Mercury
Induction lighting	New generation	High	Very long	Lead and mercury
LED	New generation	High	Very long	None

METHODOLOGY

The first phase of this research was the light distribution experiment. A laboratory experiment was conducted to evaluate light distribution of five light sources used for overhead guide sign illumination. The purpose of the experiment was to determine optimal light distribution for each of the five light sources and identify which light source provides the most efficient illuminance on the sign. The optimal light distribution of a luminaire is the best distribution of light intensity on a sign. The studied light sources and their fixtures' specifications are shown in Table 2. The LED type that was used in this experiment was producing white color and designed for sign's lighting.

Table 2: Light Sources and Fixtures Specifications

Light Source	Fixture specifications
The 250 watt MH	Consists of aluminum reflector that contours the light source to distribute light through a borosilicate glass refractor. Borosilicate glass is a low-melting glass produced from a mixture of boric oxide and silica. For maximum efficiency and uniformity, precisely cut prisms direct the light onto the billboard.
The 250 watt MV	Consists of aluminum reflector that contours the light source to distribute the light through clear and tempered glass which is resistant to heat and shock, along with convex-shaped glass lens made from borosilicate.
The 250 watt HPS	Consists of die-cast aluminum housing with electro-coat paint finish. It has clear thermal and impact resistant tempered glass, and convex borosilicate glass lens.
The 85 watt induction lighting	Consists of hydro-formed aluminum reflector that contours the light source to distribute light through a borosilicate glass refractor. For maximum efficiency and uniformity, precisely cut prisms direct the light onto the billboard.
The 62 watt LED	Consists of three adjustable arrays, each containing eight LEDs. The fixture is associated with all-weather marine aluminum, glass diffuser, and stainless steel fastener. Adjustable arrays mean that the rod where the LEDs are attached can be adjusted or rotated.

The second phase of the paper was to conduct a cost analysis for the five light sources, including initial cost, operating cost, and maintenance cost. In the last phase, the presence of toxic materials in the light source and its energy consumption were considered as environmental issues. Finally, results of the light distribution experiment are corroborated with results of the cost analysis and environmental-related issues to determine the most cost-effective light source to illuminate overhead guide signs to increase illuminance on the sign, which contributes to better sign visibility for drivers and consequently better roadway safety.

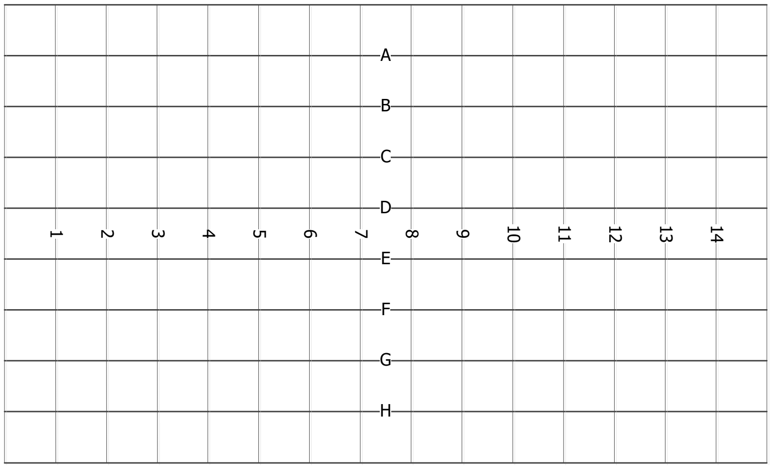
LIGHT DISTRIBUTION EXPERIMENT

Setup and Procedure

The current experiment was conducted in the workshop of the Industrial and Manufacturing Systems Engineering Department at Kansas State University, Manhattan, Kansas. Black cardboard covered all windows, and the emergency light in the room was turned off to ensure complete darkness. A white sheet of paper, 15 ft. wide and 9 ft. high, mounted to the wall represented an overhead guide sign of similar size. The Kansas Department of Transportation (KDOT) had established a standard horizontal distance between the light source unit and sign to be 5-6.5 ft. In this experiment, the light source unit was centered in front of the sign on the floor at a horizontal distance of 5 ft. from the white sheet on the wall to the nearest edge of the light source.

A grid of 1-ft. increments was marked on the sheet of paper, as shown in Figure 1. At a height of 8 ft. from the top of the opposing light source on the floor, the horizontal line on the paper was named row "A" and the line at a height of 1 ft. 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 1: Grid on White Paper



A Minolta illuminance meter measured illuminance in lux (which is the International System [S.I.] unit of illuminance) at each grid line intersection (row-column intersection) beginning at the top row (row A), left side of the white sheet of paper (column 1), to the bottom right side. Three illuminance measurement readings were taken at each intersection and the average was calculated at each intersection point after removing any outlier. The unit of measurement for illuminance is lux, and each lux is equivalent to lumen/meter^2. Illuminance can also be measured by foot-candle, which is lumen/foot^2. When running the experiment, each light source was given a suitable warming period by being turned on at least 45 minutes before commencing illuminance readings to ensure that the light source would run at maximum luminance output. In addition, the Minolta illuminance meter was calibrated before beginning each experimental run.

For the 250 watt MH light source, the unit was placed in front of the white paper at four angles 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. Similarly, for the 250 watt MV light, the unit was placed in front of the white paper at angles 0^o, 5^o up, 5^o down, and 10^o down. For the 250 watt HPS light source, the light source unit was set in front of the paper at 0^o angle only because the output illuminance was very high. For the 250-watt induction light, the angles were 0^o, 5^o down, 10^o down, and 15^o down. Finally, for the 62 watt LED light source, the light source unit was placed in front of the white paper at a 0^o angle because the design of this LED includes independent and adjustable LED arrays (or LED module arrays). The purpose of studying various angles was to identify at what position the light source provides higher illuminance on the sign.

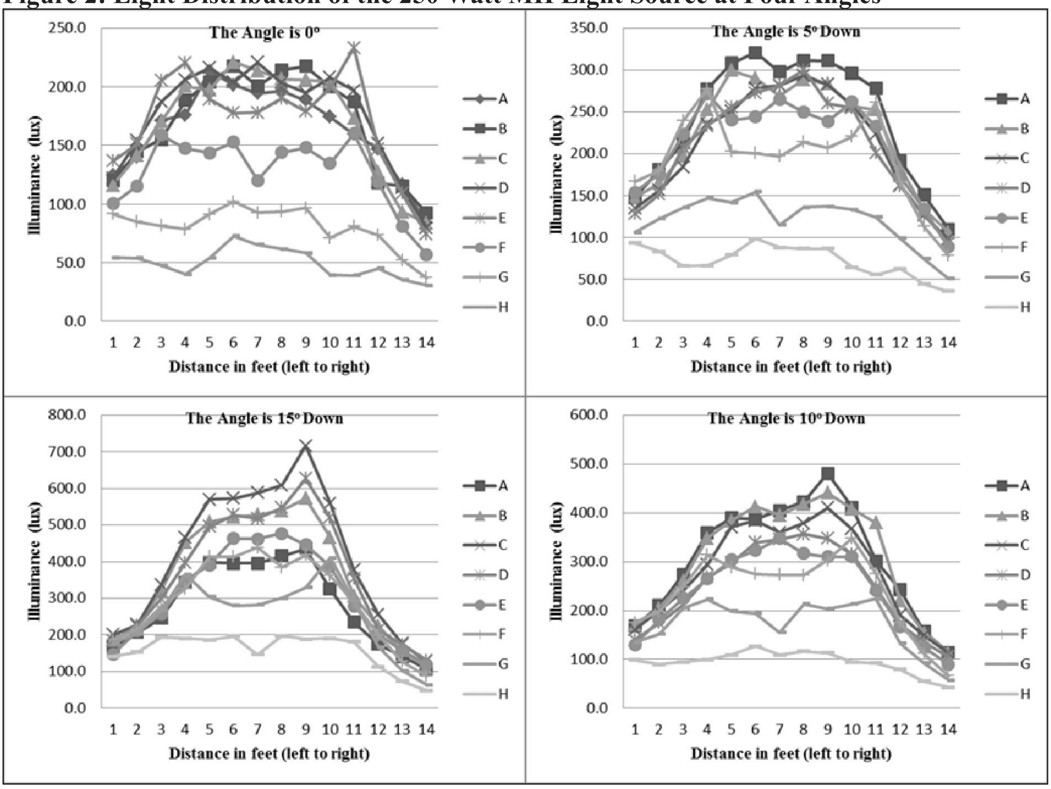
RESULTS AND DISCUSSION

Since some light sources were tested at more than one angle, illuminance values at each row-column intersection of the white paper were compared for each light source in order to determine the angle at which light distribution produced maximum illuminance values. This section of the paper compares light distribution for each light source at various angles and compares optimum light distribution for each light source at the selected angle with other sources' optimum light distribution, to determine which source provided optimum light distribution and increased illuminance on the sign that contributes to better visibility for drivers and higher safety during nighttime.

Finding Optimum Light Distribution for Each Light Source

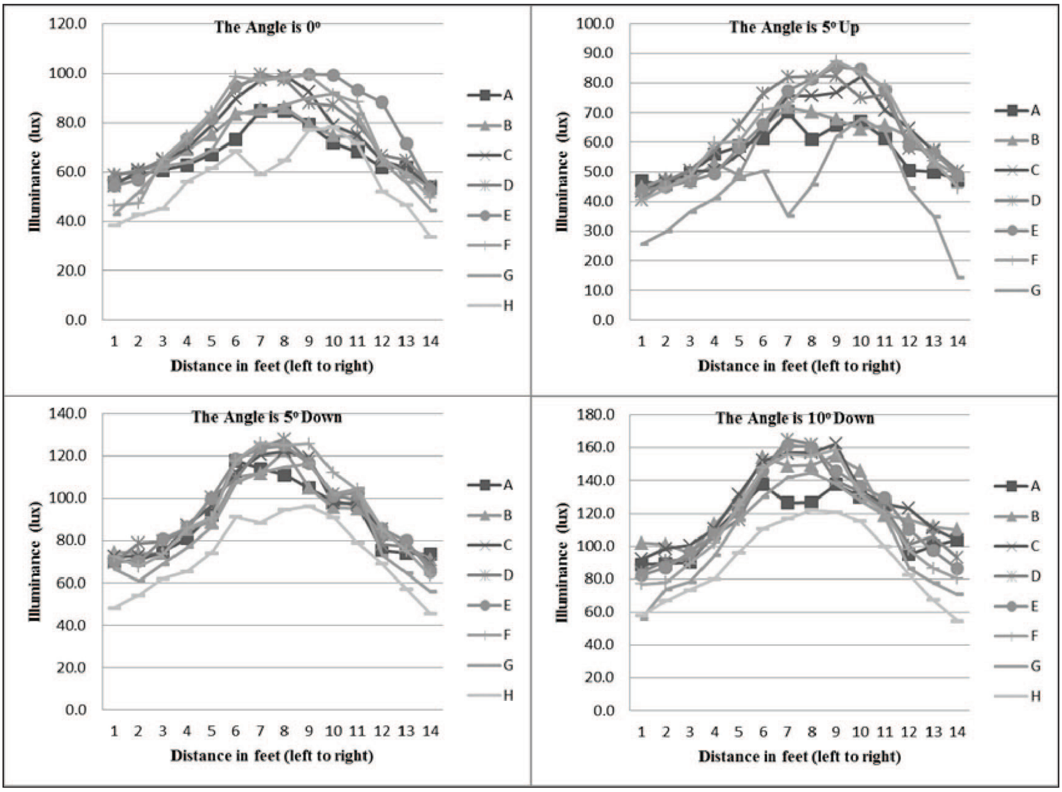
The MH Light Source. Light distribution of the 250 watt MH light source at four angles is shown in Figure 2. Based on results in that figure, the optimum light distribution of the 250 watt MH light source was when the angle between the bottom of the light source unit and the floor was 15^o down. Light distribution at 15^o down appeared to be uniform and illuminance values range between 200-600 lux, approximately. These illuminance values are comparatively high and might cause light pollution, and may not provide high visibility to drivers. Light pollution is defined as brightening of the night sky from street lights and other light sources, which inhibits the observation of stars and planets and has a disruptive effect on natural cycles.

Figure 2: Light Distribution of the 250 Watt MH Light Source at Four Angles



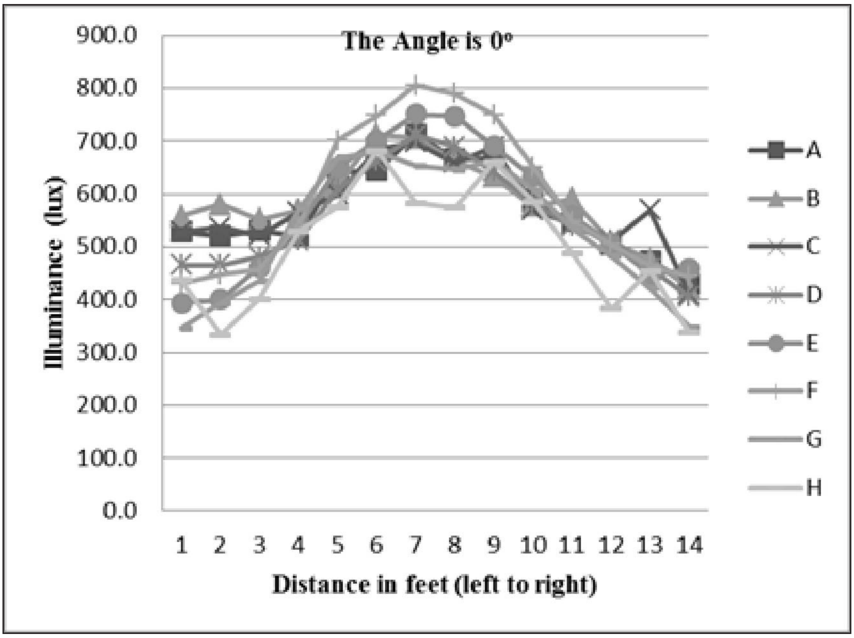
MV Light Source. Light distribution of the 250 watt MH light source at four angles is shown in Figure 3. Based on results shown in that figure, the optimum light distribution of the 250 watt MV light source was when the angle between the bottom of the light source unit and the floor was 10^{o} down. Light distribution at 10^{o} down appeared to be uniform, and illuminance values range between 70-160 lux, approximately.

Figure 3: Light Distribution of the 250 Watt MV Light Source at Four Angles



HPS Light Source. Light distribution of the 250 watt HPS light source at 0^{o} angle is shown in Figure 4. Light distribution for HPS at 0^{o} angle was considered the optimum because measured illuminance values were very high, consequently allowing motorists to see the guide sign because of increased illuminance on the sign. Light distribution appeared to be uniform and illuminance values range between 400-800 lux, approximately. These illuminance values are comparatively very high, and might cause a light pollution.

Figure 4: Light Distribution of 250 Watt HPS Light Source at 0^{o} Angle



Induction Light Source. Light distribution of the 85-watt induction lighting at different angles is shown in Figure 5. Based on results shown in that figure, the optimum light distribution of the 85-watt induction light source occurred when the angle between the bottom of the light source unit and the floor was 15^{o} down. Light distribution appears to be uniform at 15^{o} down and illuminance values range between 110-300 lux, approximately.

LED Light Source. The 62W LED light source was placed in front of the white paper at 0^{o} angle because the design of this LED includes independent and adjustable LED arrays. By rotating these arrays, LED light can be focused toward any direction on the sign. The manager of this LED manufacturer asserted that this LED was ready for installation because the LED array angles were appropriately fixed to focus light along a sign similar to the white paper in the experiment. Light distribution of the 62 watt LED light source at 0^{o} angles is shown in Figure 6. The optimum light distribution of the 62W LED light source occurred when the angle between the bottom of the light source unit and the floor was 0^{o}. Light distribution appeared to be uniform and illuminance values range approximately between 20-165 lux. Light distribution of the 62 watt LED light source demonstrated low illuminance values.

Figure 5: Light Distribution of the 85 Watt Induction Light Source at Four Angles

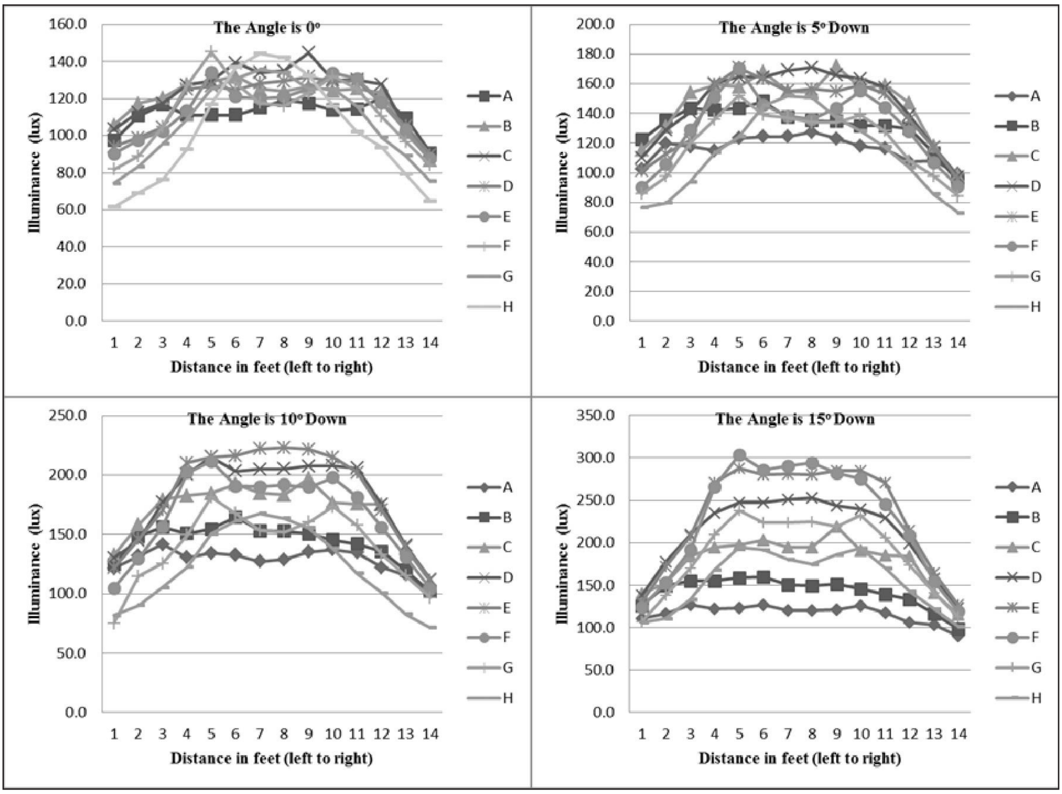
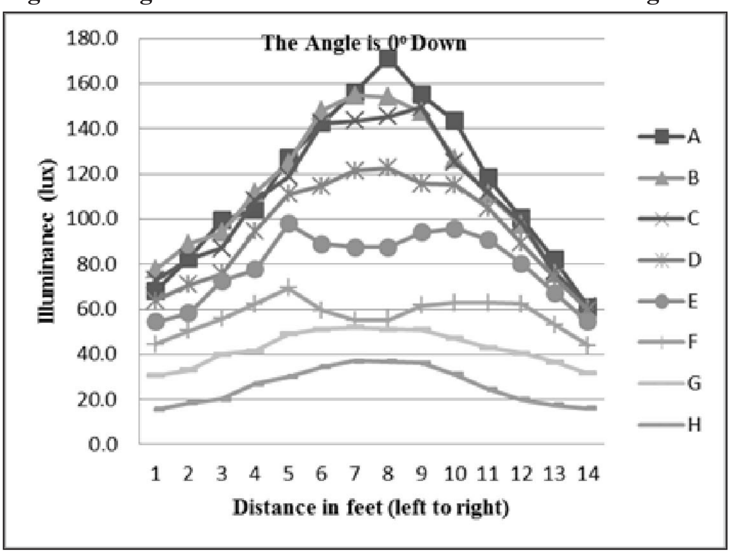


Figure 6: Light Distribution of the 62 Watt LED at 0° Angle



Comparison of Optimum Light Distributions of Five Light Sources

To determine which light source was most advantageous to illuminate overhead guide signs, the optimum light distribution at each row of the white sheet of paper was compared for the five light sources. Figure 7 shows light distribution at each row on the sheet of paper (A to H) for the sources. Again, row "A" is 8 ft. in height from the light source top surface, and row "H" is 1 ft. in height.

For each row, the 250 watt HPS light source provided highest illuminance values, meaning that it provides overhead guide signs with highest illuminance. The 250 watt MH light source provided the next highest illuminance values, followed by the 85 watt induction lighting, the 250 watt MV, and the 62 watt LED. However, higher illuminance does not mean better visibility. At some point, the visual performance reaches a plateau as a function of light level, and higher levels of light do not meaningfully increase visibility. Based on the previous fact, we excluded both the 250 watt HPS and the 250 watt MH since they produced high illuminance values. The MV is no longer available in the U.S. market because of the EISA of 2007; however, some other countries still use this source. As a result, the 85 watt induction provided the average illuminance values and it could be the best light source to increase visibility and safety.

LIGHT SOURCES COST ANALYSIS

Various companies were contacted to ask the prices and the costs associated with the 250 watt MH, 250 watt MV, 250 watt HPS, 85 watt induction, and 62 watt LED light sources studied for light distribution. Four companies provided information regarding the cost and lifespan of the five light sources studied in 2013. Cost calculations were based on light source use for an average of 11 hours per night (average daily operating hours), and the price of electricity was assumed to be $0.08 per kWh. The selection of 11 hours as an average daily operating hours was an approximation from researchers who performed this study, and the selection of the electricity price to be $0.08 per kWh was suggested by a KDOT engineer in charge of signage lighting. Labor and equipment costs were not included. Replacing ballast was not included in calculations since adding it will not affect comparison.

In this section, a detailed comparison between the five light sources is presented. A 50-year comparison period was selected for cost comparison in order to include maintenance factors for the light sources over time. Cost analysis shown in Table 3 includes initial, operating, and maintenance cost components of each light source. Data of initial light source cost and lifespan in hours for each source were obtained from the manufacturers.

Figure 7. Comparison of Optimum Light Distribution at Each Row on the White Paper

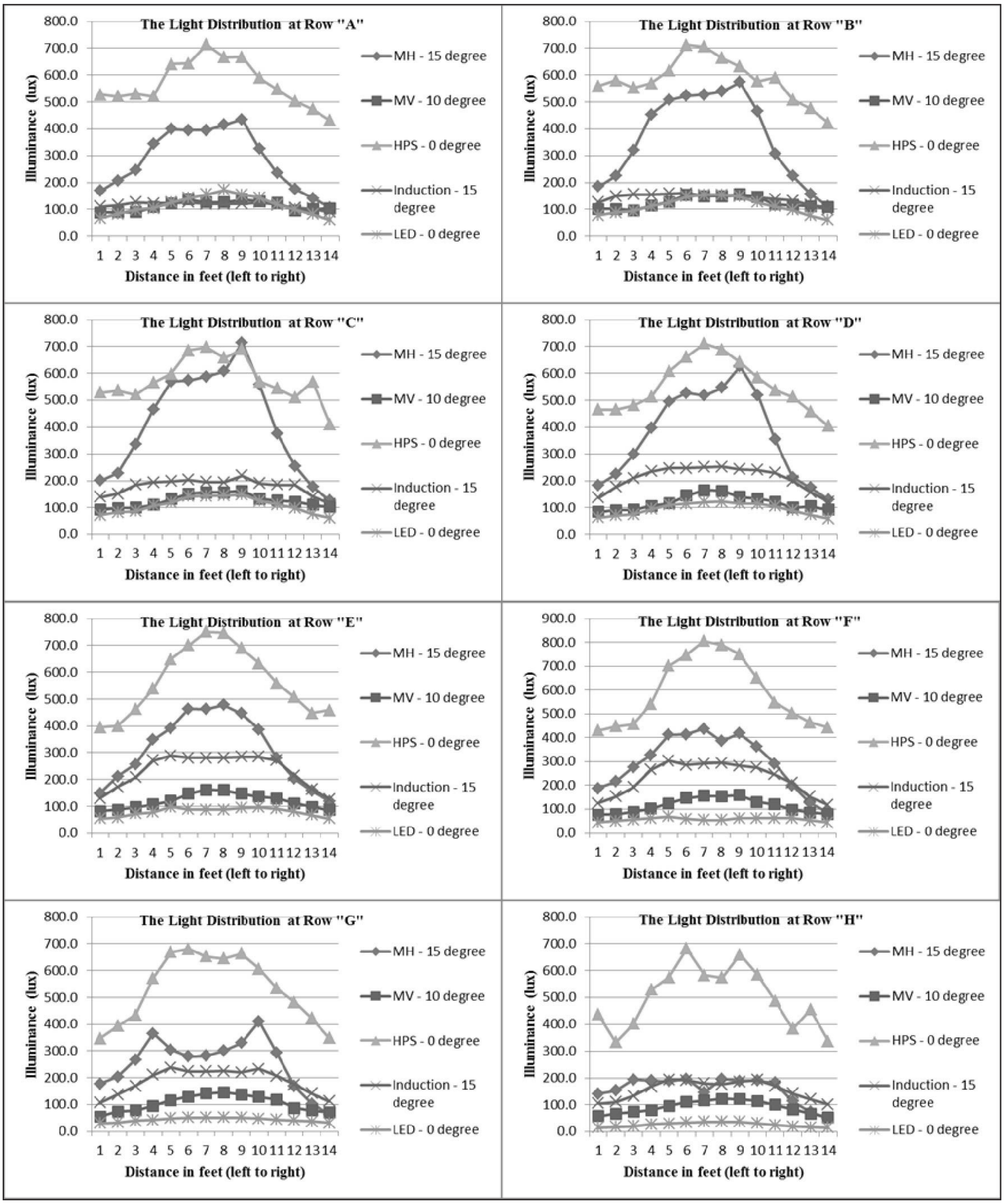


Table 3: Light Sources Cost Comparison

	Details	62 watt LED	85 watt induction	250 watt MH	250 watt HPS	250 watt MV
1	Initial cost ($)	600	678.3	678.3	678.3	678.3
2	Life (hours)	50,000	50,000	30,000	30,000	30,000
3	Life (years)	≅ 12.5	≅ 12.5	≅ 7.5	≅ 7.5	≅ 7.5
4	Daily power consumption (kW)	0.682	0.935	2.75	2.75	2.75
5	Annual power consumption (kW/year)	248.93	341.3	1,003.75	1,003.75	1,003.75
6	Life power consumption (kW)	3,100	4,250	7,500	7,500	7,500
7	Number of maintenance in 50 years	3	3	5.67	5.67	5.67
8	Total power consumption (kW/50 years)	12,446.5	17,065	50,187.5	50,187.5	50,187.5
9	Maintenance required	Replace unit	Replace lamp	Replace lamp	Replace lamp	Replace lamp
10	Maintenance cost ($/each time required)	600	75	30	16	25
11	Total maintenance cost ($/50 years)	1,800	225	170.1	90.72	141.75
12	Daily operating cost ($)	0.05456	0.0748	0.22	0.22	0.22
13	Annual operating cost ($)	19.914	27.302	80.30	80.30	80.30
14	Life operating cost ($)	248	340	600	600	600
15	Total operating cost ($/50 years)	995.7	1,365.1	4,015	4,015	4,015
16	Total cost ($/50 years)	3,395.7	2,268.4	4,863.4	4,784.02	4,835.05
17	Average annual cost ($)	67.91	45.37	97.27	95.68	96.70

For calculations in Table 3, life in years was calculated by dividing the light source life in hours by average daily operating hours (11 hours) and then dividing by 365 (days per year). For example, the 62 watt LED life is approximately 12.5 years (50,000 hours/ [11 hours per day × 365 days per year]). Daily power consumption was calculated by multiplying wattage consumed per hour for each light source by daily operating hours. For example, daily power consumption for the 62 watt LED is 0.682 kW (0.062 kW × 11 hours). Annual power consumption was calculated by multiplying daily power consumption by 365 (days per year). For example, yearly power consumption for the 62 watt LED is 248.93 kW (0.682 kW × 365 days). Life power consumption was calculated by multiplying yearly power consumption for each light source by its life in hours, dividing by average operating hours per day, and then dividing by 365 days per year. For example, power consumption during the life of the 62 watt LED is 3,100 kW (248.93 kW × 50,000 hours / [11 hours × 365 days]).

The amount of required maintenance during a 50-year period was calculated by dividing the 50-year period by the lifespan in years for each light source and subtracting one. One was subtracted because the assumption was made that at the time of installation, no maintenance is required and the light source was ready for use. For example, for the 62 watt LED during the 50-year period, three times the maintenance is required ([50 years/12.5 years]-1). Required maintenance is different based on light source type. For the 62 watt LED, required maintenance means replacing the entire light source fixture. For other light source types, however, lamp replacement is the primary required maintenance along with replacing ballast. LED maintenance cost is equal to the initial installation cost with the assumption that the cost remains constant over time. For example, three maintenance times are required for the 62 watt LED during 50 years, for a total maintenance cost of $1,800 (3 times × $600).

Total power consumption in 50 years was calculated by multiplying power consumption per year times 50. For example, power consumption for the 62 watt LED per 50 years is 12,446.5 kW (248.93 kW × 50 years). Daily operating cost was calculated by multiplying daily power consumption for each light source by the electricity price ($0.08 per kWh). For example, for the 62 watt LED, daily operating cost is $0.05456 (0.682 kW × $0.08). Annual operating cost was calculated by multiplying daily operating cost by 365 days per year. For example, for the 62 watt LED, annual operating cost is $19.914 ($0.05456 × 365 days). Life operating cost was calculated by multiplying annual operating cost by the light source's lifespan in hours, dividing by daily operating hours, and then dividing by 365 days per year. For example, life operating cost for the 62 watt LED is $248 ($19.914 × 50,000 hours/ [11 hours × 365 days]).

The total cost for each light source over 50 years was calculated by adding the initial cost of the light source, operating cost over 50 years, and maintenance cost over 50 years. For example, total cost for the 62 watt LED is $3,395.7 ($600 + $995.7+ $1,800). The average annual cost of a light source was calculated by dividing the total cost during 50 years by 50. For example, the average annual cost for the 62 watt LED is $67.91 ($3,395.7/50 years).

Based on the average annual cost of each light source as shown in Table 3, the 85 watt induction light was found to be the most cost-effective light source, followed by the 62 watt LED, 250 watt HPS, 250 watt MV, and 250 watt MH.

Based on annual power consumption for each light source, the 62 watt LED was found to be most effective for power consumption because it consumes the least amount of power, and the induction lighting was the next in energy consumption. In regards to environmental issues related to the presence of toxic materials in the light source, all light sources except the LED contained some amounts of lead or mercury or both, except for the 62 watt LED used in this experiment, which was the friendliest to the environment. In addition, the 62 watt LED has the minimum power consumption, which itself is a benefit to the environment.

CONCLUSIONS

Five light sources were compared to determine the optimal light source to illuminate overhead guide signs, consequently increasing their visibility and safety. These light sources were the 250 watt MH, 250 watt MV, 250 watt HPS, 85 watt induction, and 62 watt LED. Various decision criteria, including light distribution, average annual cost, and environmental issues, were considered in order to compare light sources.

According to the light distribution experiment, the 250 watt HPS light source had the highest illuminance readings, followed by the 250 watt MH, 85 watt induction lighting, 250 watt MV, and 62 watt LED. Based on the fact that higher illuminance does not mean better visibility, both the 250 watt HPS and the 250 watt MH produced high illuminance values on the sign, which led us to conclude that both of them might not increase visibility. The MV is no longer available in the U.S. market because of the EISA of 2007 law. Based on the light distribution criterion, the 85 watt induction, which provided the average illuminance values, could be the best light source to increase visibility and safety.

Considering the cost analysis for the five light sources, the 85 watt induction light source is the most cost effective because it had minimum average annual cost, followed by the 62 watt LED. Considering environmental issues that are related to the presence of mercury in the light source and electric power consumption, the 62 watt LED was the most environmentally friendly light source because it is free of mercury and consumed the minimum electric power, thereby saving a large amount of electric energy.

Overall, merging the result of the light distribution experiment with the cost analysis, the induction lighting could be the most cost-effective light source that provides sufficient illuminance on the sign and contributes to better sign visibility to the driver, and consequently higher safety. For those agencies that prefer using sources that are friendlier to the environment, the LED could be a good choice.

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Mohammed Said Obeidat *is an assistant professor in the Department of Industrial Engineering at Jordan University of Science and Technology. He obtained his B.S. (2004) and M.S. (2008) degrees from Jordan University of Science and Technology, Irbid, Jordan, and Ph.D. from Kansas State University; all in industrial engineering.*

Margaret J. Rys *is an associate professor in the Department of Industrial and Manufacturing Systems Engineering at Kansas State University. She obtained her integrated B.S./M.S. degree from the Technical University of Wroclaw, Poland, in 1979 and M.S. (1986) and Ph.D. (1989) from Kansas State University; all in industrial engineering. She has over 20 years of experience conducting research and teaching courses in human factors engineering, quality, engineering economy, statistics, and safety. During the past 20 years she has been principal or co-principal investigator on more than 40 projects and authored and co-authored more than 50 journal papers.*