INTRODUCTION

LEDs (light-emitting diodes) are becoming more common in safety signals for railroad, highway, automotive, and many other applications. In addition to having a longer life and greater durability than incandescent bulbs, LEDs are much more energy efficient than their incandescent counterparts. LED signals are comprised of an array of individual LEDs, as opposed to the single bulb that illuminates incandescent railroad signals. This characteristic introduces a new failure mode not experienced with incandescent signals. With an incandescent bulb, any failure is a total failure of the signal. LED signals can however have partial failures where only some of the LEDs are lit. These partial failure could be due to vandalism, defective LED elements in the array, or by one or more LED elements simply burning out. This new failure mode raises many questions about the behavior of LED signals. What happens to the light output of the signals during partial failure? What percentage of LEDs must remain lit for the signal to be perceptible? Will the color of the signal remain the same during partial failure? What happens to current consumption and voltage requirements of LED signals in partial failure? Could this change in electrical characteristics be used to detect a level of failure of a signal?

The use of LED signals in railroad applications, specifically wayside signals and highway/railway crossing signals, is the focus of this study. Crossing signals occur in several flashing pairs. This redundancy makes the failure of an individual signal less catastrophic. Wayside signals indicate track conditions to the train engineer. Safety concerns arise if a wayside signal fails, or if a less restrictive color or aspect (such as flashing) is shown. Proper operation of these signals is critical to the safe and efficient operation of trains.

A brief literature review describes the photometric requirements for effective signaling of train engineers and automobile drivers. In the next section, the design of a computer-controlled goniometer (a device used to change the angular position of a test signal) is presented along with instrumentation used in the laboratory tests. Data gathered includes light intensity (measured in candela), signal voltage and current. A limited amount of chromaticity/color data will also be presented. Nine different LED signals (six 12 inch red crossing signals and three 8 inch wayside signals) have been tested over a range of voltages and with and different partial failures. Results from a single incandescent signal will also be given. Detailed light intensity maps from each of these lab tests are shown in the voluminous appendix.

Results from field tests conducted with four of the 12 inch red LED crossing signals are presented along with a description of the field test hardware and setup. This report ends with conclusions from the project.

BACKGROUND

Literature Review

LEDs are commonly used as indicator lights in electronic devices such as televisions and computers. They can efficiently produce light with low current and voltage, have a nearly instantaneous rise and fall time, have a much longer life than incandescent bulbs, and are more robust than incandescent filaments in terms of withstanding shock and vibration. Photons are emitted from an LED when current flows through a p-n junction. Doping materials such as aluminum, gallium, indium, nitrogen, phosphorus, arsenic, and antimony form this p-n junction. The wavelength of the photon emitted from the p-n junction is dependent on the materials used to make the LED. For example, aluminum indium gallium phosphate (AlInGaP) is used to produce red light at a wavelength of 622 nm (Christiansen, 1997).

A driver's proper response to a traffic signal requires seeing that the signal is lit and then reacting to its color. The conspicuity of the signal, or its ability to attract the attention of the driver, depends greatly on the brightness, or luminous intensity, of the signal. Other factors, such as the flash rate used with railway crossing signals, also contribute to the conspicuity of a signal. These other factors are not considered in this report. The luminous intensity and chromaticity of LED signals are the focus of this work.

Luminous intensity, a measure of the brightness of visible light, is measured in candela. By definition, a candela is a lumen per steradian. A lumen is a measure of the power of visible light, weighted to match the response of the human eye. A steradian is solid angle that covers the surface area of a sphere that is equal to the square of the radius of the sphere. A sphere of radius "r" has a surface area of $4\pi r^2$. Therefore, a sphere has 4π steradians of solid angle. The luminous intensity of a theoretical point light source is independent of distance. For example, if a light bulb produces one candela of light, then that means that one lumen per steradian is emitted by the bulb. So at one foot away from the bulb, one lumen passes through an area of one square foot. Similarly, one lumen passes through a hundred square foot area at a distance of ten feet. A steradian is a dimensionless number, independent of distance. Therefore, the luminous intensity of a theoretical point light source is the same, regardless of distance from the source (Ryer, 1997).

A hypothetical average normal observer, as defined by the International Commission on Illumination in 1931, is used to define the color of light. A standard hypothetical observer is required because different people's eyes perceive color differently. The chromaticity of a color, expressed in terms of this standard observer, is given by the numbers x, y, z (called trichromatic coefficients or trilinear coordinates), which may be considered as roughly expressing the respective red, green, and blue contents of the color. Since the sum of x, y, and z always equals one, the chromaticity is adequately specified by giving only x and y (ITE, Chapter 2, 1998).

Green and Milanovic produced a report entitled "LED Technology for Improved Conspicuity of Signal Lights at Road/Railway Grade Crossings" for Transport Canada (TC). This comprehensive study covered many aspects of highway/railway grade crossings, such as the history of crossing signal specifications, the history of LED technology, and human factors involved in signal perception. The purpose of their study was to produce a standard for highway/railway crossing signals in Canada. Green and Milanovic have presented an excellent background history of signal specifications in this report. The following is a synopsis of that history.

Light intensity requirements for traffic signals and highway/railway grade crossing signals have been stated in terms of viewing distance and luminous intensity at various viewing angles. In 1966, the American Association of Railroads (AAR) specified that crossing signals be clearly visible to a normal viewer in bright sunlight conditions. Viewing distance, not luminous intensity, was the criterion by which the signal was measured. With a 30-15 lens, the specification called for a range of 1,500 feet from on-axis to 10° left and right. The range was 500 feet for 15° off-axis. Ranges for vertical displacement were not specified (Green and Milanovic, 2001).

In 1968, a study was conducted on signals that met the 1966 AAR standard. This led to a luminous intensity-based standard for crossing signals. The vertical axis remained unspecified, but the horizontal axes at 0°, 5°, 10°, and 15° had luminous intensity requirements of 1,100, 350, 200, and 100 candela for a 30-15 lens (Green and Milanovic, 2001).

The next change occurred in 1991. This time, the vertical axis was specified, and the luminous intensity values increased across the horizontal axis. Table 1 shows the 1991 AAR specification for the 30-15 lens (Green and Milanovic, 2001).

Table 1. AAR 1991, Luminous Intensity Requirements for a 30-15 Lens.

Luminous Intensity (candela)		Horizontal Axis			
		0°L/R	5° L/R	10° L/R	15° L/R
Vertical Axis	0°D	1,600	1,000	500	200
	5°D	35			
	10°D	25			
	15°D	15			

In 1996, the AAR included a standard for LED crossing signals. The requirements were significantly lowered to accommodate the limitations of LED technology of the time. The 1996 AAR LED crossing signal standard is shown in Table 2 (Green and Milanovic, 2001).

Table 2. AAR 1996, Luminous Intensity Requirements for 30-15 Lens.

Luminous Intensity (candela)		Horizontal Axis						
		0°D	5°L/R	10°L/R	15°L/R	20°L/R	25°L/R	30°L/R
Vertical Axis	0°D	160	128	51	13	5	3	3
	5°D	128						
	10°D	51						
	15°D	13						
	20°D	5						
	30°D	3						

In 1999, the American Railway Engineering and Maintenance-of-Way Association (AREMA) became responsible for setting standards for railway signals. Visibility requirements were given in distance, and the same standard applied to both LED and incandescent signals. The viewing distance requirements were the same as the 1966 AAR standard for the 30-15 lens. However, the 1999 AREMA standard also specified a beam pattern in terms of percentage of on-axis luminous intensity. The beam pattern for an incandescent signal with a 30-15 lens is shown in Table 3 (Green and Milanovic, 2001).

Table 3. Percentage of On-Axis Luminous Intensity for 30-15 Lens.

Percentage of On-Axis Luminous Intensity		Horizontal Axis 0°L/R	5°L/R	10°L/R	15°L/R
Vertical Axis	0°D	100%	63%	31%	13%
	5°D	2%			
	10°D	2%			
	15°D	1%			

Current AREMA standards do have lumen requirements for incandescent bulbs, and chromaticity and transmittance requirements for lenses. The lumen requirements for an incandescent lamp operating at voltages of 10, 11, and 12 volts are 234, 129, and 96 lumens, as given by section 14.2.1 of the standard. Section 7.1.10 requires a minimum transmittance of 0.127 for a red highway/railway grade crossing lens (AREMA, 2001).

The most recent draft of the AREMA standard also includes vertical axis requirements for beam pattern. Section 3.2.35 of the manual describes an intensity profile for highway/railway grade crossing signals. This profile is described on the horizontal and vertical axes of the signal, without giving requirements for deflections from both axes. Requirements for different lens types are specified. Because luminous intensity is not specified in this standard, the profile requirements shown in Tables 4 and 5 are given in terms of percentage of maximum intensity (AREMA, 2001).

Table 4. AREMA's Required Percentage of Maximum Intensity on the Horizontal Axis.

	Horizontal Axis Deflection							
Roundel-Type	0° L/R	5° L/R	10° L/R	15° L/R	20° L/R	25° L/R	30° L/R	35° L/R
30-15	100	63	31	13				
20-32	100	63	31	13				
70	100	67	33	21	13	2	1	1
LED	100	80	33	8	3	2	2	2

Table 5. AREMA's Required Percentage of Maximum Intensity on the Vertical Axis.

	Vertical Axis Deflection				
Roundel-Type	5°D	10°D	15°D	20°D	30°D
30-15	2	2	1		
20-32	3	2	1	1	0.3
LED	80	33	8	3	2

For laboratory testing of an LED signal, luminous intensity and chromaticity, rather than viewing range, are the desired measurements. Two standards are used for comparison in this research. Chapter 2a of the *Equipment and Material Standards of the Institute of Transportation Engineers (ITE)*, "Vehicle Traffic Control Signal Heads (VTCSH)," is a standard for road traffic signals. This standard specifies mechanical, electrical, color, luminous intensity, and other requirements for traffic signals (ITE, Chapter 2, 1998).

Section 11 of the VTCSH gives the luminance requirements of a traffic signal. Section 11.02 describes the apparatus needed for testing a signal. A goniometer positions the signal to various viewing angles encountered in traffic situations. A photometer, calibrated to the human eye response curve of the CIE standard observer, measures luminous intensity. A regulated power supply and test lamps are also called for in this section. Section 11.03 describes the alignment of the test signal. The specifications require that the center of the signal be aligned with the horizontal and vertical axes of the goniometer, and that the light sensor be perpendicular to the aiming axis of the goniometer. The fourth rule in this section specifies a tolerance of ±0.25°. Section 11.04 specifies the intensity requirements of a signal at 44 separate test points. The standard states that all measurements at the test points be at least 80% of the desired intensity value. Further, no more than eight test points are allowed to drop below 90% of the desired intensity value. The luminous intensity values, in candela, for a red 12-inch signal are given in Table 6 (ITE, Chapter 2, 1998).

Table 6. ITE Incandescent Signal Luminous Intensity Requirements.

Luminous Intensity (candela)		Horizontal Angle (Left and Right)					
		2.5°	7.5°	12.5°	17.5°	22.5°	27.5°
Vertical Angle (Down)	2.5°	399	295	166	90	-	-
	7.5°	266	238	171	105	45	19
	12.5°	59	57	52	40	26	19
	17.5°	26	26	26	26	24	19

For LED signals, the luminous intensity requirements are reduced from the requirements stated above. The LED signal requirements, which are about 85% of the incandescent signal requirements, are shown in Table 7 (ITE, Chapter 2a, 1998).

Table 7. ITE LED Signal Luminous Intensity Requirements.

Candlepower Values (candela)		Horizontal Angle (Left and Right) 2.5°	7.5°	12.5°	17.5°	22.5°	27.5°
Vertical Angle (Down)	2.5°	339	251	141	77	-	-
	7.5°	226	202	145	89	38	16
	12.5°	50	48	44	34	22	16
	17.5°	22	22	22	22	20	16

The color requirements of a traffic signal are given in section 8 of chapter 2. The chromaticity requirements are the same for both incandescent and LED signals. The standard states that color shall be expressed in terms of a CIE normal average observer. The ITE standard specifies that the lens color for red, yellow, and green fall within certain color coordinates. For a red lens, the y value (green component) should be less than 0.308, but greater than 0.998-x. For a yellow lens, the y value should be less than 0.452, but greater than 0.411 and greater than 0.995-x. These locations are shown in Figure 1 (ITE, Chapter 2, 1998).

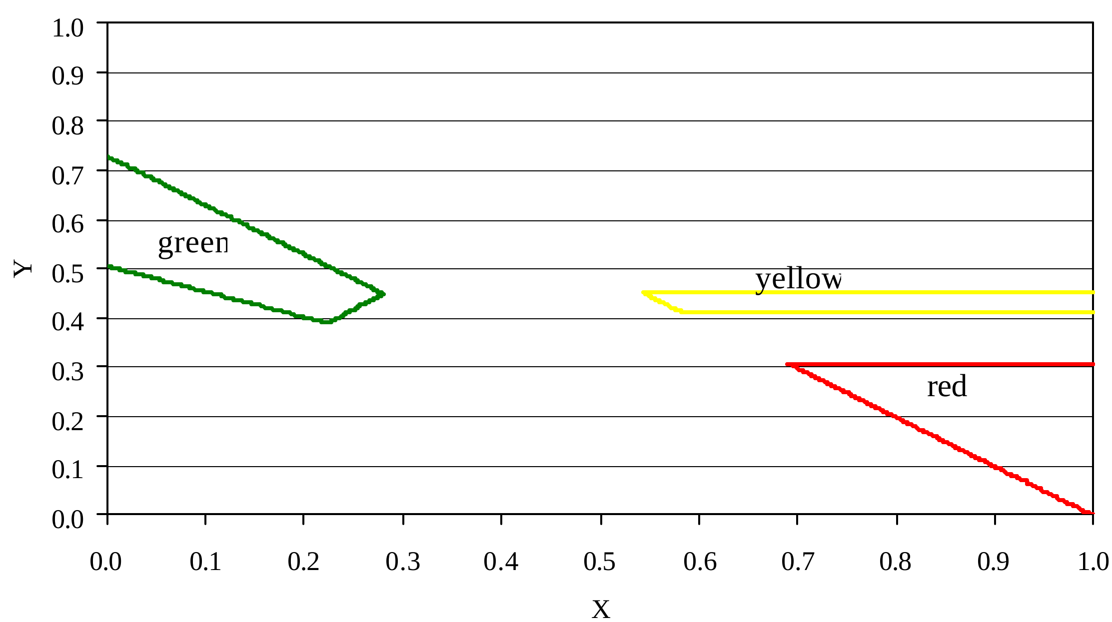

Figure 1. ITE Chromaticity Requirements.

Another standard used for comparison purposes in this research is the proposed "Transport Canada Standard for LED Signal Modules at Highway/Railway Grade Crossings." Many aspects of the TC standard were based on the ITE standard, because having a crossing signal with the same characteristics as a traffic signal should help automobile drivers recognize and respond to the signal. The chromaticity requirement section of the proposed TC standard refers to the ITE standard. The luminous intensity requirements for different viewing angles are given in a format similar to the ITE standard. These values are shown in Table 8 (TC, 2002).

Table 8. TC LED Luminous Intensity Requirements.

Luminous Intensity (candela)		Horizontal Angle (Left and Right) 0°	5°	10°	15°	20°	25°	30°
Vertical Angle (Down)	0°	400	375	300	200	100	50	15
	5°	350	325	250	150	75	40	15
	10°	130	125	110	85	60	35	15
	15°	45	40	35	30	25	20	15
	20°	15	15	15	15	15	15	10

These requirements differ from the ITE requirements in several ways. First, this standard has an on-axis measurement, while the ITE standard does not. Both standards require measurements in five-degree increments with respect to the horizontal and vertical axes. Also, the TC requirements are absolute minimums, whereas the ITE standard allows a certain number of measurements to fall slightly below requirements. The profiles for the TC and ITE specifications for LED signals are compared in Figure 2. The TC requirements exceed the ITE requirements across the range. The profiles are very similar, with the TC profile being slightly wider and deeper.

Many LED signal manufacturers are able to meet or exceed these standards. Some provide information about the dominant wavelength and peak luminous intensity (Dialight, n.d.). Others provide beam profiles for different LED signal products in addition to luminous intensity and chromaticity (Gelcore, 2001).

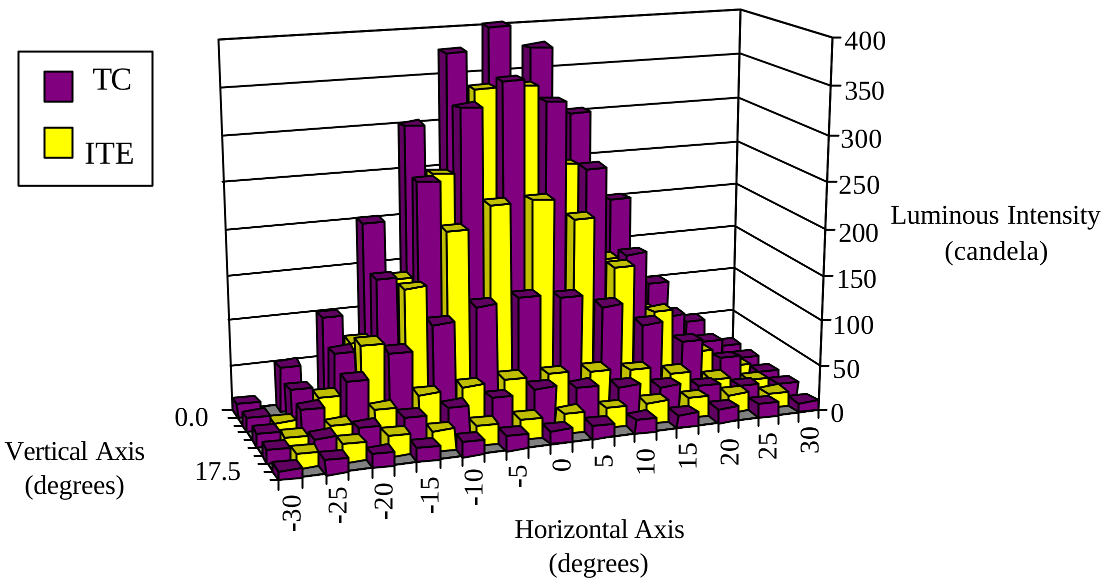

Figure 1. Comparison of ITE and TC Specifications for LED Signals.

The two main differences between traffic signals and crossing signals are operating power and alignment. Traffic signals operate off of a 120V AC line from the electrical grid. A 150-watt bulb is used in standard incandescent traffic signals. However, due to the dangerous potential of train accidents, grade crossings and wayside signals need to be able to run off of batteries in case of a power outage. Standard bulbs for railway applications are 18-watt bulbs, which require a much smaller battery bank than a 150-watt bulb would require. Because of the reduced amount of operating power, the light produced by these bulbs must be precisely focused to be effective. In the case of wayside signals, the path of a train is well-defined by the tracks, and proper alignment is a straightforward process. For grade crossings, there can be many angles of approach for cars, thus requiring more effort in alignment. Rigid mounting of the signal is required to maintain alignment (Green and Milanovic, 2001).

LED technology has improved exponentially over the years. Red LEDs commercially available today have efficiencies of 15-20 lumens/watt, as compared to the most efficient LED of 1970, which had an efficiency of 1 lumen/watt. Incandescent lamps also produce about 15-20 lumens/watt of white light. However, a red filter reduces the light output by about two-thirds. Therefore, an LED is about three times more efficient at producing red light as an incandescent lamp with a red filter. Furthermore, the LED efficiencies continue to improve, approaching efficiencies of 45 lumens/watt in laboratories in 2001 (Green and Milanovic, 2001).

LEDs also perform well under shock and vibration, since they are a solid-state technology. Light degradation over time is also excellent, with LEDs producing over 90% relative light output after 10,000 hours. The report notes that the reliability of drive circuitry is more likely to be the cause of failure of an LED signal. The drive circuitry has a reliability of about 90% after five years of operation (Green and Milanovic, 2001).

The California Department of Transportation conducted a study to determine the functional equivalence of LED signals to incandescent signals for traffic applications. This study employed a "usability factor" to make a relative comparison of different light sources. Tests were conducted by setting an incandescent reference signal at a set luminance. The brightness of the test signal was adjustable. The images of the signals were superimposed, and the images appeared alternately to the human test subject at a rate of 16 Hz. The test subject adjusted the brightness of the test lamp until the perceptible difference in signal brightness was at a minimum. This brightness setting was recorded seven times each for six subjects. The luminance of the reference signal was divided by the average of the medians of each test set. This ratio was the "usability factor." Tests were conducted with subjects looking directly at the signal, viewing it, and looking at it with a +1 diopter lens to simulate 20/40 vision. This study concluded that a red LED round signal is not significantly different than a red incandescent round signal. The "usability factor" was close to unity, meaning the perceived brightness and measured brightness were essentially the same (Caltrans, n.d.).

Manufacturer Contacts

Several LED manufacturers and/or distributors have been contacted during the course of this project. A total of six 12 inch red LED crossing signals were obtained and tested. Three 8 inch LED wayside signals (red, green, yellow) have also been obtained and tested. Table 9 lists the companies and types of signals that were tested during this project. Contact has been made with these manufacturers and others to obtain additional LED wayside signals, without success. ALSTOM Transport Information Solutions expressed initial interest in supporting the project. Dialight was in the final stages of field testing a new design for their wayside signals during 2002-2003. Unfortunately, no additional LED wayside signals were obtained from either manufacturer.

Table 9. Manufacturers and Distributors of LED Railway Signals Used in Project.

Company	Manufacturer or Distributor	Type of LED Signal	Purchased or Donated
Dialight	Manufacturer	12 inch red crossing	Donated
Electro-Techs	Manufacturer	12 inch red crossing	Purchased
GELcore	Manufacturer	8 inch wayside (red, green, yellow)	Donated
General Signals	Manufacturer	12 inch red crossing	Purchased
Ledtronics	Manufacturer	12 inch red crossing	Purchased
Safetran	Distributor	12 inch red crossing	Donated
Western-Cullen Hayes	Distributor	12 inch red crossing	Purchased

Transport Canada

Both Dr. Parker and one of his graduate students (Matthew Chatham) were members of the Transport Canada *Steering Committee on LED Technology for Improved Conspicuity of Signal Lights at Grade Crossings* from August 2001 through April 2002. The committee met with several telephone conference calls as well as two meetings in Victoria, British Columbia. These meeting were conducted at the facilities of Carmanah Technologies, the contractor for the Transport Canada study. Both daytime and nighttime field tests of five different rail crossing safety lights (four LED, one incandescent) were conducted during the September 2001 meeting. The field test procedure used by the Transport Canada committee will be discussed more thoroughly in the Field Testing section of this report. Two of the most significant findings from the TC field tests were:

1. All of the LED signals were significantly more "conspicuous" than the single incandescent signal when viewed from any angle except on-axis, and
2. The TC committee lowered their minimum on-axis rating from 600 to 400 candela.

The draft Canadian standard for the use of LED lights for railway/highway crossings is available on the WWW at http://www.railwaycrossings.com/. This document has a great deal of information and materials relevant to LED signal development. The reference section in particular would be useful to anyone wishing to become more knowledgeable in this field.

Dr. Parker also presented a talk entitled "LED Signal Performance with Non-Illuminated Elements" for the Fourth Annual Workshop on Highway-Railway Grade Crossing Research sponsored by Transport Canada on November 26, 2002.

<u>AREMA</u>

Contact was also made with two AREMA (American Railway Engineers and Maintenance-of-Way Association) committees that have an interest in LED signal technology. Two committee meetings (#36 - Highway-Rail Grade Crossing Warning Systems and #37 - Signal Systems) on February 25-27, 2001 in Jacksonville, FL. A brief presentation on the status of the LED project was made to each committee.

Several issues were discussed at the AREMA meeting that relate to this LED project:

- Chromaticity / color of the wayside signal is an important issue.
- Environmental issues (particularly sunlight reflecting from the lens) are important as they affect how lights appear.
- An on-axis measurement should be added to the ITE-style test used by Transport Canada and in our preliminary results
- Many members thought the ITE-style test numbers from the sides were also important, since they simulate the approach to a signal along a curve.
- A suggestion was made that both styles of wayside signals should be tested: "searchlight" and "traffic," possibly with a lunar white signal added to the bottom.
- There were many comments made about the different types of LED signals, those with power supplies (abbreviated as WPS in this report) and the older style that has no power supply (abbreviated as NPS in this report).

The issue of using LED signals for wayside signals was the topic of discussion at one session of the AREMA 37.2 Sub-committee. Two items of interest to our project were discussed.

- Wayside signals have an 8-16 volt operating range (which we should duplicate in our testing).

- The LED signal must hold enough current at the lowest voltage to maintain the lights-out relay (LOR) -- 0.68 amps is the lowest rating for standard relays by Alstom / Safetran / Union Switch.

The sub-committee spent a great deal of time discussing the effect that losing LED elements would have on the signal operation. The "FRA requirement for 50% output" was mentioned several times. During these discussions three positions became clear:

1. Railways do not want to guarantee that 50% of the original light intensity is maintained (due to the difficulty in measuring light output in the field),
2. Manufacturers do not want to signal the lights-out condition when 50% of the individual LED elements are non-functional (no low-cost way to determine how many LED elements are operational), and
3. Most members of the committee wanted to rely on a current setting to activate the lights-out relay. This was discussed at great length with no definite resolution.