CAN THE INTENSITY OF LED-BASED RUNWAY GUARD LIGHTS BE REDUCED?

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INTRODUCTION

In 2005, the Federal Aviation Administration (FAA) began collaborations with research universities to study the potential for using light-emitting diode (LED) technology in airfield lighting applications. The overarching goal of this research has been to reduce the energy use and maintenance costs associated with incandescent lamps in airfield lighting. One application considered was the elevated runway guard light (ERGL), which helps pilots detect the presence of taxiway-runway intersections. LED-based ERGLs have been developed by manufacturers based on incandescent ERGL specifications (FAA AC 150/5345-46C) [1], but the FAA sought to improve this specification based on the operational and visual performance of LEDs.

At the FAA's request, the Lighting Research Center (LRC) conducted a series of human factors studies, first in the laboratory and then in the field, to understand the influence and interaction of different lighting parameters on the visibility of elevated-type runway guard lights (ERGLs) to pilots. This research would serve to assist in the development of applicable performance standards for LED-based ERGLs.

LABORATORY EVALUATIONS OF SIMULATED ELEVATED RUNWAY GUARD LIGHTS

In 2008, the LRC designed a psychophysical laboratory study to investigate the performance of ERGLs with LEDs compared to traditional incandescent ERGLs using a scale-model airfield, scaled light fixtures, and simulated weather conditions. The goal was to determine first the minimum luminous intensities required by incandescent ERGLs, and second whether LED-based ERGLs could be optimized in terms of flash frequency and duty cycle for better conspicuity than incandescent models while using a lower intensity (light level), and thus less energy.

Equipment

A 40:1 scaled apparatus was used that presented a perspective scene of an airport runway with fixed viewing distance, taxiway width, pilot eye height, ERGL placement and aiming based on FAA recommendations at the time of the study (FAA AC 150/5340-30C) [2]. The light sources in the ERGLs were energized by an LED control module and custom LabView program. All light sources in the perspective scene, even the incandescent sources and additional blue taxiway fixtures, were simulated using LEDs. The wave shape of an oscillating incandescent ERGL was measured and characterized for use in the LabView program.

Various combinations of flash rate and duty cycle (Table 1) were used to determine the most effective combination in terms of decreasing reaction time and increasing noticeability, compared to incandescent ERGLs.

Clear day (Step 1), clear night (Step 1), and foggy day (Step 3) ambient conditions were simulated in the laboratory. An additional apparatus was used to simulate the foggy conditions.

Procedure

Three phases were conducted to determine the minimum luminous intensity and optimum flash frequency and duty cycle for incandescent ERGLs and LED-based ERGLs. Ten naïve (non-

pilot) subjects participated in each phase. The subjects ranged in age from 22 years to 62 years. All subjects demonstrated normal color vision using an Ishihara Color Blindness exam [3].

Phase 1 determined the equivalent minimum luminous intensities for incandescent ERGLs under three ambient conditions. Reaction times and detection accuracy were used as performance measures. The equivalent luminous intensity range used was from about 10 cd to 450 cd for clear day and clear night conditions, and about 600 cd to about 4100 cd for foggy day conditions. A simulated ERGL would flash for 6 seconds on one side of the display. Each ERGL intensity was repeated three times in random order. Subjects used a keyboard to indicate the side they saw flashing. If subjects selected the wrong side or didn't select after 6 seconds, the presentation was noted as a "miss".

Phase 2 determined the most effective combinations of different flash frequencies and duty cycles to a) decrease reaction times (objective measure) and b) increase noticeability (subjective measure) in a side-by-side study using simulated incandescent ERGLs. The equivalent minimum luminous intensity from Phase 1 was used in this phase.

Phase 3 determined the equivalent minimum luminous intensities for LED-based ERGLs using the most effective combinations of flash rate and duty cycle from Phase 2. Reaction times and detection accuracy were used as performance measures.

Table 1.
Flash rate and duty cycle combinations used in Phase 2.

Flash Rate (flashes/min)	Frequency (Hz)	Duty Cycle (% on-time)
30	0.5	10
45	0.75	30
75	1.25	50
105	1.75	70
150	2.5	90

Results

Phase 1: Pieron's Law [4], relating reaction time to a decrease in stimulus intensity, was used to create a best-fitting function for each subject. Reaction time is a function of visual response to the intensity and a combination of motor and cognitive responses intrinsic to each subject. Student's t-tests were used to determine the shortest reaction times that were significantly longer than the reaction times under the highest luminous intensity. "Misses" were observed at luminous intensities equal to the current specifications, and significantly slower reaction times were observed at lower intensity values under some ambient conditions.

Phase 2: The equivalent minimum luminous intensity values used in this phase were 116 cd for clear day and clear night, and 3000 cd for foggy day. Table 2 shows in the reaction time results for all three ambient conditions; Table 3 shows the noticeability results for clear day and foggy day ambient conditions. While different temporal signatures were more effective under different ambient conditions (rank order among combinations varies between conditions), the top four fastest ranked reaction times occurred in the region bounded by a flash frequency range of 1.25 Hz and 2.50 Hz and 30% to 70% on-times. The LED combination of 0.75 Hz and 50% on-

time yielded a faster reaction time than the simulated incandescent ERGL, which was the same temporal signature but a different waveform. These results show that the square waveform of the LEDs themselves makes them more conspicuous, but the ability to tune the temporal signature of the ERGL further improves visibility.

Table 2.
Phase 2a: Mean reaction times (in milliseconds, msec) for each of the LED-based ERGL combinations (flash frequency shown on X-axis of grid [0.5 Hz to 2.5 Hz], duty cycle shown on Y-axis [10% to 90%]). Reference reaction time shown at the top of each ambient condtion is for simulated incandescent ERGL (flash frequency: 0.75 Hz, Duty Cycle: 0.5). Shaded gray squares indicate mean reaction times that are faster than incandescent reaction times. Bolded values are significantly faster than simulated incandescent reaction times.

Clear Day

Reference Reaction Time (msec)	816
	RT < Ref

Reaction Time (msec)

10	814	709	***684***	692	693
30	811	773	***675***	***619***	***605***
50	841	756	699	707	685
70	***684***	***622***	***618***	***651***	***587***
90	854	778	***680***	***620***	723
	0.5	0.75	1.25	1.75	2.5

Flash Frequency

Clear Night

Reference Reaction Time (msec)	733
	RT < Ref

Reaction Time (msec)

10	660	659	620	647	605
30	621	609	***578***	625	601
50	592	604	610	610	636
70	623	***586***	664	***574***	***556***
90	765	***564***	621	603	593
	0.5	0.75	1.25	1.75	2.5

Flash Frequency

Foggy Day

Reference Reaction Time (msec)	642
	RT < Ref

Reaction Time (msec)

10	638	581	***523***	***547***	540
30	588	566	593	565	633
50	***529***	602	573	***556***	***534***
70	571	***513***	***532***	556	570
90	571	***545***	652	582	564
	0.5	0.75	1.25	1.75	2.5

Flash Frequency

Table 3.
Phase 2b: Mean noticability ratings for each of the LED-based ERGL combinations compared to simulated incandescent ERGLs (flash frequency shown on X-axis of grid [0.5 Hz to 2.5 Hz], duty cycle shown on Y-axis [10% to 90%]). By definition, a 0 value was assigned to the incandescent ERGL selection and 1 was assigned to the LED-based ERGL selection. A mean noticability rating of 1 indicates that the subjects always selected the LED-based ERGL combination over the incadescent ERGL.

Reference Noticeability	0
	Notice > Ref

Phase 2B: Day
Mean Noticeability

10		0.80	0.93	0.90	0.93
30		0.93	1.00	1.00	1.00
50		0.97	1.00	1.00	1.00
70		0.93	1.00	0.97	0.93
90		0.87	0.80	0.87	0.80
	0.5	0.75	1.25	1.75	2.5

Flash Frequency

Reference Noticeability	0
	Notice > Ref

Phase 2B: Fog
Mean Noticeability

10	0.7	0.87	1.00	0.97	0.97
30	0.67	0.93	0.87	0.97	1.00
50	0.73	0.93	0.97	1.00	1.00
70	0.8	0.93	1.00	1.00	1.00
90	0.8	0.90	0.93	0.87	1.00
	0.5	0.75	1.25	1.75	2.5

Flash Frequency

Phase 3: Based on the Phase 2 studies, four combinations of simulated LED-based ERGLs were selected (Table 4).

Table 4.
ERGL-LED combinations providing the best reaction times and conspicuity under clear day conditions (Step 1). These temporal signatures were also selected for other ambient conditions (Steps 2 and 3) to maintain the same appearance.

	Frequency (Hz)	Duty Cycle (% on-time)
ERGL-LED 1	1.25	70
ERGL-LED 2	1.25	30
ERGL-LED 3	2.5	70
ERGL-LED 4	2.5	30

The equivalent minimum luminous intensities for each ERGL-LED combination that yielded the fastest reaction times and 100% detection accuracy (no "misses") are shown in Table 5. The minimum luminous intensities shown for Step 2 are based on linear interpolation.

Table 5.
Equivalent minimum luminous intensities for each step and ERGL combination.

Step	ERGL-LED 1	ERGL-LED 2	ERGL-LED 3	ERGL-LED 4	ERGL-Inc.	ERGL-Inc. (existing standard)
Clear Day/Night Step 1 (10% minimum luminous intensity)	93	116	116	70	419	300
Step 2 (30% minimum luminous intensity)	176	245	353	261	1257	900
Foggy Day Step 3 (100% minimum luminous intensity)	466	698	1184	931	4191	3000

FIELD EVALUATION OF VARIOUS ELEVATED RUNWAY GUARD LIGHT CONFIGURATIONS

As a follow-up to the laboratory study, in 2010 a field study was undertaken to investigate the performance of ERGLs in a full-scale, real-world installation. This second stage of research tested at an actual taxiway-runway intersection the most promising combinations of flash rate and duty cycle with the intensity of the LED-based ERGLs reduced to one-third of the incandescent daytime level prescribed by Advisory Circular AC 150/5345-46D [5] (which superseded AC 150/5345-46C [1] in 2009).

Equipment and Location

Two sets of ERGLs were obtained from commercial vendors. One set was a conventional incandescent type and the other set was LED-based. The incandescent set was used without modification, other than to supply the required 6.6 amp current from a driver circuit powered from a 120 VAC generator. The LEDs and optics of the LED ERGLs were retained, but the driver was replaced with a custom driver utilizing a Texas Instruments MSP430 microprocessor paired with driver circuitry. The driver/ERGL pairs were calibrated to provide intensity of 1000 cd in the day setting (corresponding to 1/3 the intensity specified in AC 150/5345-46D [5]) and 100 cd (10% of the daytime level) night setting. The daytime level was chosen in accordance with the laboratory study, which found that intensity could be reduced by approximately 1/3 while still preserving visibility of the light. All waveforms were square in shape.

Table 6.
Flash rate and duty cycle combinations programmed into the custom ERGL driver. All combinations were square wave functions and were programmed to have both daytime (1000 cd) and nighttime levels (100 cd).

Flash Rate (flashes/min)	Frequency (Hz)	Duty Cycle (% on-time)
45	0.75	100
90	1.50	30
		70
135	2.25	30
		70
180	3.00	30
		70

The basic flash rate of 45 flashes per minute (FPM) was selected to comply with the existing incandescent ERGL specification at the time of the study (FAA AC 150/5345-46D) [5]. The remaining flash rates were two, three, and four times this basic rate. The duty cycle (DC) of the 45 FPM configuration was kept at 100% to approximate the temporal profile of the incandescent source (one or the other light was always on). All of the LED configurations tested were square waveform calibrated to operate at 1000 cd (30% of the specified intensity for incandescent ERGLs).

A runway hold short line at Schenectady County Airport (KSCH) in New York state was selected to be the study location and was outfitted with the experimental ERGLs. The location selected was situated in a part of the airport that received little traffic but was large enough to serve moderately sized commercial jet aircraft.

Procedure

Pilots and individuals familiar with airport operations were recruited to participate in the study as subjects. Five of the nine subjects were certificated pilots. Their aeronautical experience is summarized in Table 7.

Table 7.
Summary of experience and ratings of the pilots that participated as subjects in the study.

Pilot Subjects (5 total)			
Ratings		Total Time (hours)	
Private	2	<500	1
Commercial	3	500-1000	2
Instrument	4	>1000	2
CFI/CFII	2		

The study participants were provided with a location to wait from which the ERGL installation could not be seen. The subjects were driven, one at a time, through the installation in the passenger seat of a vehicle with an eye-height comparable to piston single, piston twin, and light jet aircraft. All subjects were driven through a specific configuration before the experimenters changed to the next condition. As soon as the lights were visible to the subjects, they were asked to rate the lights in terms of noticeability, distraction, and brightness. The subjects provided numerical ratings according to prescribed ranges [Noticeability: Very Noticeable (5) – Not Prominent Enough (1); Distraction: Very Distracting (5) – Not Distracting At All (1); Brightness: Too Bright (5) – Too Dim (1)]. The subjects were instructed to rate the ERGLs as though they were actually taxiing an aircraft.

Results

In terms of noticeability, all of the experimental combinations were found to perform comparably to the standard incandescent condition (no statistically reliable differences were found); see Figure 1 and Table 8. The exception to this was 45 FPM/100% DC (the condition meeting the existing incandescent specification), which underperformed the other conditions in terms of noticeability. Configurations using 70% DC were generally rated as less distracting than the same flash rates at 30% DC. On average, 90 FPM/70% DC was rated the highest of the experimental conditions (highest noticeability, lowest distraction). The mean ratings suggest that this condition may offer an advantage over the others, but this study did not have the statistical power to show significance.

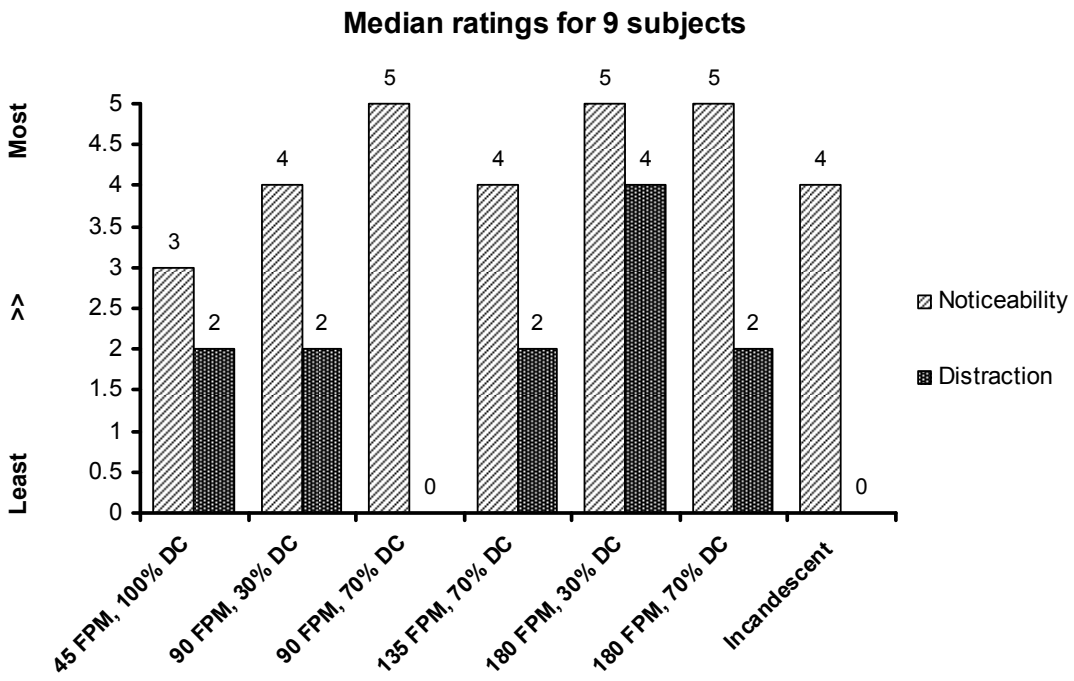

Figure 1. Median noticeability and distraction ratings for selected flash rate/duty cycle combinations.

Table 8.
Noticeability, distraction, and brightness ratings for all conditions utilized in the study.

		Mean Ratings			Median Ratings		
Condition	Description	Notic.	Dist.	Bright.	Notic.	Dist.	Bright.
1	45 FPM , 100% DC	3.22	1.78	2.89	3.00	2.00	3.00
2	90 FPM , 30% DC	3.78	2.11	2.89	4.00	2.00	3.00
3	90 FPM , 70% DC	4.22	1.89	3.11	5.00	1.00	3.00
4[a]	135 FPM , 30% DC	4.00	2.67	3.00	4.00	3.00	3.00
5	135 FPM , 70% DC	4.22	2.22	3.00	4.00	2.00	3.00
6	180 FPM , 30% DC	4.67	3.44	3.17	5.00	4.00	3.00
7	180 FPM , 70% DC	4.56	2.33	3.11	5.00	2.00	3.00
8	Incandescent	3.89	1.56	2.89	4.00	1.00	3.00
C[b]	90 FPM , 70% DC - N	3.17	2.00	2.33	3.50	2.00	2.50

[a]Condition 4 was seen by only 3 subjects before condition C was substituted for it.
[b]Condition C, which corresponds to the nighttime intensity level of 100 cd, was seen by 6 subjects.

CONCLUSIONS

The tunable temporal signature achieved by LED-based ERGLs in the laboratory evaluation study allowed for significantly lower intensities, reducing levels to approximately one-third that of the incandescent level while achieving similar performance. Furthermore, the potentially long life and increased efficacies of LED-based ERGLs show that there may be advantages to using LEDs to replace incandescent ERGLs. However, the specification of an ERGL can be technology neutral. As long as the temporal signatures described above are reproduced, and other technology requirements are met, there is no inherent reason why another lighting technology cannot be specified.

The field evaluation study again showed that the intensity of an LED-based ERGL could be reduced to approximately 30% of a comparable incandescent ERGL while still maintaining comparable performance. The implication of this result is that energy and maintenance savings can be realized without sacrificing safety.

Based on the results of the field evaluation study, 90 FPM/70% DC (primary) and 180 FPM/70% DC were recommended for further study in a semi-permanent installation. Such a study was conducted by researchers at the Daytona campus of Embry-Riddle Aeronautical University. In this last phase of the study, the 90 FPM/70% DC condition was compared to standard incandescent ERGLs by a large number of pilots who were actually involved in taxiing operations to determine how they performed under actual conditions [6,7].

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