An Evaluation of Linear Length LED Centerline Taxiway Exit Light Systems

Una Blanusa
Seth Young Ph.D., A.A.E., CFI
Shawn Pruchnicki MS ATP CFII
Brian Strzempkowski CFII
Center for Aviation Studies
The Ohio State University
Columbus, Ohio USA

***Abstract* - Airfield lighting, such as runway and taxiway edge and centerline lighting has, traditionally been implemented using incandescent bulbs spaced at set intervals as determined by Federal Aviation Administration (FAA) design standards. The introduction of LED based lights on airfields has allowed for the developments of prototype light systems that have some linear length, rather than be limited to "point" bulb sources. The FAA has been interested in determining if "linear length LED" lights of variable lengths, and laid out in given configurations along a runway or taxiway, may provide greater visibility and thus enhanced airfield orientation to pilots. This study investigated the potential enhancements to airfield visual guidance by deploying an array of Linear Length LED lights to be evaluated by pilots traveling along a runway. Initial results of this investigation validate previous laboratory and simulation studies that reveal that linear length LED lighting configurations do provide statistically significant enhanced visual guidance to pilots, as determined by observed reduced reaction times and greater accuracy of determining airfield orientations by pilot subjects.**

Keywords – LED Lights; Airfield testing; Airport Lighting

I. Introduction and Background

Correct visual perception while on the airfield is important during good visibility but even more so during times of reduced visibility such as rain, fog and dark conditions. Visual information that is provided to any user on the airfield which includes pilots and ground vehicle operators alike, must always be precise, clear, simple and easily discernible. Although approach lights and runway lights guide pilots to the runway environment, once the landing is complete taxiway lighting and the directional information they provide is extremely important for way-finding tasks back to the ramp environment. Information provided in the form of markings and lightings must especially be discernible to pilots who have to make decisions based on the visual cues they receive from these lightings. Although numerous methods have been either conceived or tested, one that has fully made it onto airfields around the world is Light Emitting Diode (LED) lighting systems. This concept has been transferred from non-aviation applications such as household usage to the aviation industry. In terms of visual information and signaling applications, LED's are said to have several advantages over incandescent lights [1] such as:

- Durability and longevity as solid state devices
- Wide range of available colors (including all aviation signal light colors)
- Narrowband wavelength output resulting in saturated color appearance
- Relatively low energy requirements
- Immediate "switch-on" and "switch-off" time

These advantages mean energy savings and increased reliability for airports, which makes them appealing for financial and maintenance reasons. The energy draw on these types of lighting applications is significantly less than incandescent light bulbs. For airfields that have thousands of incandescent bulbs that are illuminated not only at night, but also during inclement weather, operating more energy efficient LED lights can represent a significant cost reduction. Operating lives of these LED bulbs are drastically increased over their incandescent counterparts, which in turn drives down maintenance costs and increases reliability. While LED's have this longer operating life which can be in the tens of thousands of hours, there is no clear definition for the operating life of an airfield luminaire [2]. According to Narendran and Freyssinier incandescent lamps fail catastrophically (for instance, filament breaks) while LED's operating under normal operating conditions mostly suffer from parametric changes (like color shift and light output depreciation). It was also found in the laboratory study [3] that the intensities of the LED-based elevated runway guard lights (ERGL's) could be reduced to approximately one-third than that of the incandescent level while maintaining a similar performance.

According to Bullough [4], LED aviation signal light colors produce equivalent apparent brightness when compared to the incandescent lights, and their intensities never exceed 100%. This would suggest that LED's appear as bright as or brighter than the incandescent signals of the same nominal color. The brightness, color identification and detection of light onset of the LED signals also do not seem to be adversely affected by weather conditions such as fog [5].

Durable and energy efficient lightings may not suffice when it comes to clear visual information. In his paper, Kao says that obscured, ill-defined and unclear information can lead to control confusion and deteriorated performance [6]. According to Kao [6], in terms of highway information system, feedback concepts called for road delineation, with uniformity and spatial continuity for both edge and lane dividers. They report that continuous marking increases positioning accuracy, while dashed and intermittent lines provide only momentary visual information and hence degrades the drivers' performance. According to a report presented by the Oregon Department of Transportation, where lighted guidance tubes (LGT) were tested; it was seen that these LGT's were useful to the motorists and provided them a greater level of comfort while traveling and kept them on alert [7]. All this leads up to airport lighting delineation and its benefits.

Parmalee P.J. [8] talks about linear LED guidance lights being more reliable and providing better directional guidance (rather than positional information like point-source light) to pilots who get a better sense of direction[9]. More recently, studies were conducted at the Lighting Research Center (LRC) where it was established that under simulated laboratory conditions, properly defined linear elements with sufficient length and spacing could provide shorter visual acquisition times than conventional point source lights [9].

Bullough and Skinner [9], conducted a series of studies at the Rensselaer Polytechnic Institute's Lighting Research Center (LRC) (heretofore known as the 2014 LRC Study) where it was established that under simulated laboratory conditions, properly defined linear elements with sufficient length and spacing could provide shorter visual acquisition times than conventional point source lights. In their study, subjects were asked to determine configuration of a computer generated depiction of elevated taxiway edge light fixtures at various light lengths, spacing's, and intersection types (90 degree turns, 30 degree turns, etc.) simulated to depict a light distance of 500 feet away. Variations of this experiment included options for the use of "visual stimuli" depictions on the view to simulate ambient lights and other environmental visual distractions that may be found on actual airfields.

Bullough and Skinner found that LED lights configurations with increased light lengths and reduced spacings between lights did provide shorter visual acquisition times over point based light systems. The authors suggest that real-world applications should be conducted to validate these findings. This study represents some of that effort. Additionally, HIL-Tech [10] talks about the evolution of linear LED lighting LEDline, which was installed at Ted Stevens Anchorage International Airport and the pilots were reported to have said that the LED linear lights were bright and highly visible, even under low visibility conditions.

II. Methodology

In order to validate the findings of the 2014 LRC study the FAA and the LRC partnered to design a full-scale array of linear LED lights to be temporarily located on an active airfield. Subjects would then be asked to view these lighting arrays and determine the configuration of the lights displayed. Unlike the 2014 LRC study that was conducted in a simulated environment, subjects would be asked to make their determination while in a moving aircraft on an active airfield. Similar to the Bullough and Skinner study, the time required for a test subject to determine the lighting configuration was to be recorded, along with additional data that would determine both the confidence and accuracy of the subjects' determinations [9].

The Ohio State University Airport (KOSU) was selected as the airfield to be used for this study. The LED lighting array, set up on and in the surrounding area of runway 9L/27R, a 3000 ft. x 100 ft. general aviation runway with basic runway markings and medium intensity runway edge lighting. Figure 1 provides an aerial illustration of the runway used for this

Figure 1: KOSU Runway 9L/27R

research. The yellow line depicts the route taken by subjects to observe a configuration of lights at the far end of runway 27R, as described below.

The light array was designed to illuminate a green centerline taxiway lead-off light configuration (such configurations are currently in use at many of the larger airports in the United States to provide visual guidance for landing aircraft to determine the location of downstream exit taxiways). Lights on the array were designed with the ability to illuminate in a variety of configurations with variations in light length (point lighting, 2 foot, 8 foot, and 16 foot length), spacing (50 foot, 150 foot spacing between lights), turn angle (90 degree and 30 degree turns) and direction (left and right turns) (See Figures 2 and 3) resulting in 32 different lighting configuration turns (see Figures 2 and 3) resulting in 32 different lighting configurations. Each lighting segment was comprised of two – eight foot sections that contained LED

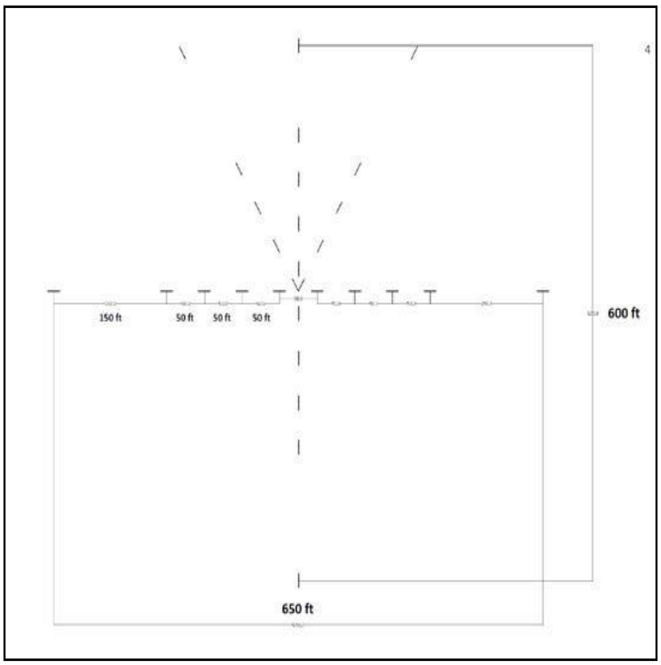


Figure 2: Light Array Configuration

strip lighting. The use of radio frequency (RF) transmitters and a control console running the software program XCTU produced by Digi International, Inc of Minnetonka, Minnesota, the light segments could be controlled remotely in order to display the various configurations.

Experiments were conducted by laying out the lighting array on a series of evenings, after the end of official twilight, during September and October 2015. Weather conditions during each evening were similar with temperatures ranging

Figure 3: Lighting Array Looking downstream from the array

between15 and 25 degrees C, few to scattered clouds, partial to full moon light, and little wind. All airfield lights remained on medium intensity during the experimental periods. In order to simulate real world conditions the aircraft also remained illuminated using taxi, landing navigation and beacon lights.

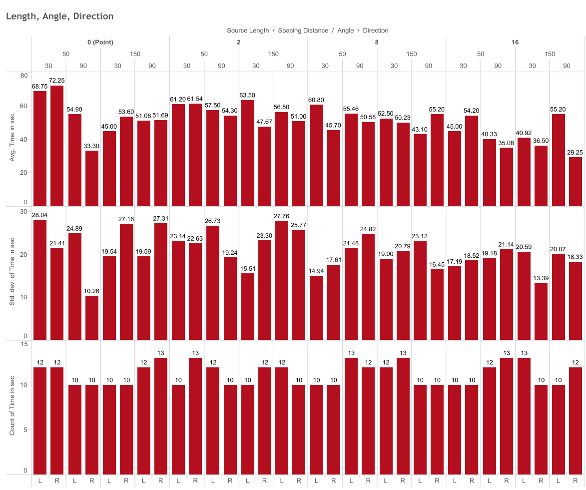
Prior to participating in the study, subjects filled out a questionnaire in order to gather demographic information such as age, gender, flight hours and pilot certification. During this time, subjects were also briefed on the experiment, given a safety briefing and subject consent to participate was obtained. This study was approved by the Ohio State University Institutional Review Board (IRB) prior to the start of these experimental trials.

For each combination of light length, spacing, angle, and direction, reaction time to determine configuration was observed for each participant. Participants, placed in the right seat of a Cessna 172, piloted by an Ohio State University flight instructor, and staffed by a student data recorder in the back seat, were asked to determine a given configuration as they were taxiing towards the configuration along RWY 27R, starting from approximately 2500 feet from the beginning of the light configuration. Reaction time used to determine the given configuration was measured in seconds starting from the beginning of the run after entering RWY 27R to the time the participant verbally stated the lighting configuration. In addition to noting reaction time, it was noted whether or not the participant made an accurate observation of the configuration, i.e. whether the participant was able to identify the correct angle and direction of turn that the lighting configuration displayed. The participant was asked to provide a "confidence" level using 1 to 5 scale in his/her determination. With one being the least confident and 5 being the most confident.

Forty-five participants participated in the experiment. Each participant observed 8 of the 32 possible configurations by making 8 runs along RWY 27R, each run observing a given lighting configuration. The participants resulted in collection of configuration determination reaction times and levels of confidence for a total of 360 observations. Observations were made uniformly across all array configurations. That is, 180 of the 360 configurations were associated with left turns, 180 were associated with right turns, with similar proportion for 50 and 150 foot light spacing's, and 30 degree vs. 90 degree turns.. Each light length (point, 2 ft. 8 ft., and 16 ft.) was observed in 90 of the observations.

Table 1 illustrates the mean, standard deviation, and count of reaction times for each configuration grouped by source light length. From this figure, it becomes more visually clear that there is a decrease in reaction time as light lengths increase. One exception to this pattern is the increased reaction time between Point lighting and 2 ft. length lights. Further analysis is needed, but this may be the result in the point lighting lights having more of a higher, omni-directional profile than the linear LED lights, which are more unidirectional in design.

Table 1 - Raw Data Summary



A. Analysis of Reaction Time based on LED Light Lengths

Table 2 reveals the mean, standard deviation and count for reaction times grouped by source length. Table 3 reveals the T-statistic calculated using the mean and standard error, and Table 4 reveals the calculated P-Values. Table 5 reveals the results of two-tailed Difference of Means T-tests.

III. Data Analysis

The collected data were compiled into spreadsheet and analyzed using *Microsoft Excel* and *Tableau* software. products. Descriptive statistics describing the reaction times and accuracy of lighting array determinations were calculated. Statistical difference of means tests were applied to determine any significant difference in reaction times and levels of accuracy among different array configurations.

As sample sizes for each of the given configurations are low (on the order of 10 observations per configuration), it is difficult to determine with any statistical significance the difference in reaction time for any given configuration. However, as configurations are grouped by light length, spacing, angle or direction, more meaningful results begin to appear.

Table 2: Mean, Standard Deviation and Count (Reaction Time)

Source Length	**Reaction Time Grouped by Source Length**		
	Mean	***Standard Deviation***	***Count***
Point	54.44	25.076	89
2 ft.	56.63	23.131	89
8 ft.	51.77	20.056	90
16ft.	41.47	19.942	90

Table 3: T-Statistic Reaction Time

Source Length	**T-Stat by Source Length**			
	Point	**2 ft.**	**8 ft.**	**16 ft.**
Point	-	-0.60561	0.78616	3.82732
2 ft.		-	1.50118	4.69406
8 ft.			-	3.44527
16ft.				-

Table 4: P-Values (Reaction Time)

Source Length	**P-Values by Source Length**			
	Point	**2 ft.**	**8 ft.**	**16 ft.**
Point	-	0.05449	0.4318	1.30E-04
2 ft.		-	0.1333	2.67E-06
8 ft.			-	3.44527
16ft.				-

Table 5: Statistical Significance (Reaction Time)

Source Length	Statistical Significance by Source Length			
	Point	***2 ft.***	***8 ft.***	***16 ft.***
Point	-	No	No	Yes
2 ft.		-	No	Yes
8 ft.			-	Yes
16ft.				-

This analysis revealed that there is a statistically significant decrease in reaction time (i.e. subjects were able to make a determination sooner, and hence farther away from the lights, in the taxiing process) for 16 ft. linear lights in comparison to the point, 2 ft., or 8 ft. lights. There was no revealed statistical significance in reaction time among any other light lengths. (Note: Previous work by Bullough [9] revealed that during their analysis of reaction time, there was no significant difference between point lighting and 2 ft. length lighting, but there was a statistically significant reaction time between point lighting and 8 ft. lighting. There may be several reasons for the difference between Bullough's results and those found in this study. For one, observations in this study were made from a significantly greater distance (as much as 2000 feet) from the lights, in a moving vehicle, on a real airport environment with other lights, including runway edge lights, in the vicinity. This different experimental condition offers the subject a varied perceptual environment.

B. Analysis of Determination Accuracy based on LED Light Lengths

The mean, standard deviation and count of determination accuracy for each configuration grouped by source light length was calculated. Accuracy was scored as a "1 = accurate" or "0 = inaccurate. As the overall accuracy score increases, the more subjects accurately determined the configuration. Table 6 reveals the mean, standard deviation and count for accuracy reaction time grouped by source length. Table 7 reveals the T-statistic calculated using the mean and standard error, and Table 8 reveals the calculated P values. Table 9 reveals the results of two-tailed Difference of Means T-tests, employed to determine the statistical significance of any differences in determination accuracy between two light lengths.

Table 6: Mean, Standard Deviation and Count (Accuracy Reaction Time)

Source Length	Accuracy Score Grouped by Source Length (0-1 scale)		
	Mean	***Standard Deviation***	***Count***
Point	0.4607	0.50128	89
2 ft.	0.4889	0.50268	89
8 ft.	0.6444	0.48136	90
16ft.	0.7778	0.41807	90

Table 7: T-Statistic (Accuracy Reaction Time)

Source Length	T-Stat by Source Length			
	Point	***2 ft.***	***8 ft.***	***16 ft.***
Point	-	0.374751	2.50032	4.59352
2 ft.		-	2.11341	4.1781
8 ft.			-	1.98496
16ft.				-

Table 8: P-Values (Accuracy Reaction Time)

Source Length	P-Values by Source Length			
	Point	***2 ft.***	***8 ft.***	***16 ft.***
Point	-	0.3539	0.01241	4.36E-06
2 ft.		-	0.03457	1.47E-05
8 ft.			-	4.72E-02
16ft.				-

Table 9: Statistical Significance (Accuracy Reaction Time)

Source Length	Statistical Significance by Source Length			
	Point	***2 ft.***	***8 ft.***	***16 ft.***
Point	-	No	Yes	Yes
2 ft.		-	Yes	Yes
8 ft.			-	Yes
16ft.				-

This analysis revealed that there is a statistically significant increase in determination accuracy for 8ft. and 16ft. length lights over point and 2 ft. length lighting. Furthermore, there is a statistically significant increase in determination accuracy between 16ft. lengths and 8 ft. lengths. There is no statistically significant increase in determination accuracy between point lights and 2ft. length light sources.

C. Analysis of Determination Accuracy based on LED Light Length and Turn Angle

Table 10 reveals the mean, standard deviation and count for 30-degree reaction time, grouped by source length. Table 11 reveals the T-statistic calculated using the mean and standard error, and Table 12 reveals the calculated P-Values. Table 13 reveals the results of two-tailed Difference of Means T-tests, employed to determine the statistical significance of any differences in determination accuracy between two light lengths.

Table 10: Mean, Standard Deviation and Count (30- Degree Reaction Time)

Source Length	**Reaction Time Grouped by Source Length**		
	Mean	***Standard Deviation***	***Count***
Point	59.133	26.143	45
2 ft.	59	21.524	45
8 ft.	53	18.927	45
16ft.	44	18.88	43

Table 11: T-Statistic (30- Degree Reaction Time)

Source Length	**T-Stat by Source Length**			
	Point	***2 ft.***	***8 ft.***	***16 ft.***
Point	-	0.0414511	2.173743532	5.255973882
2 ft.		-	2.126603814	5.209780495
8 ft.			-	3.125868297
16ft.				-

Table 12: P-Values (30- Degree Reaction Time)

Source Length	**P-Values by Source Length**			
	Point	***2 ft.***	***8 ft.***	***16 ft.***
Point	-	0.967123803	0.035147735	4.62016E-06
2 ft.		-	0.039098534	5.37396E-06
8 ft.			-	0.003212526
16ft.				-

Table 13: Statistical Significance (Reaction Time)

Source Length	**Statistical Significance by Source Length**			
	Point	***2 ft.***	***8 ft.***	***16 ft.***
Point	-	No	Yes	Yes
2 ft.		-	Yes	Yes
8 ft.			-	Yes
16ft.				-

This analysis revealed that there is a statistically significant increase in 30-degree reaction time for 8ft. and 16ft. length lights over point and 2 ft. length lighting. This means that people were able to identify 8 ft., and 16 ft., configured at 30 degrees, easier than point based lighting and 2 ft. lights.

Table 14 reveals the mean, standard deviation and count for 90-degree reaction time, grouped by source length. Table 15 reveals the T-statistic calculated using the mean and standard error, and Table 16 reveals the calculated P-Values. Table 17 reveals the results of two-tailed Difference of Means T-tests, employed to determine the statistical significance of any differences in determination accuracy between two light lengths.

Table 14: Mean, Standard Deviation and Count (90- Degree Reaction Time)

Source Length	**Reaction Time Grouped by Source Length**		
	Mean	***Standard Deviation***	***Count***
Point	48.533	22.994	45
2 ft.	49.906	24.255	45
8 ft.	50.422	21.203	45
16ft.	39	21.763	47

Table 15: T-Statistic (90- Degree Reaction Time)

Source Length	T-Stat by Source Length			
	Point	***2 ft.***	***8 ft.***	***16 ft.***
Point	-	0.379732832	0.597652419	3.003087198
2 ft.		-	0.163254975	3.435609879
8 ft.			-	3.598160282
16ft.				-

Table 16: P-Values (90- Degree Reaction Time)

Source Length	P-Values by Source Length			
	Point	***2 ft.***	***8 ft.***	***16 ft.***
Point	-	0.705970477	0.553135575	0.004311744
2 ft.		-	0.871065227	0.001263369
8 ft.			-	0.000780545
16ft.				-

Table 17: Statistical Significance (90- Degree Reaction Time)

Source Length	Statistical Significance by Source Length			
	Point	***2 ft.***	***8 ft.***	***16 ft.***
Point	-	No	No	Yes
2 ft.		-	No	Yes
8 ft.			-	Yes
16ft.				-

This analysis revealed that there is a statistically significant increase in reaction time for 16ft. length lights configured to 90 degree turns over point, 2 ft. length lighting and 8 ft. length lighting. Furthermore, there is a statistically significant increase in determination accuracy between 16ft. lengths and 8 ft. lengths. There is no statistically significant increase in determination accuracy between point lights and 2ft. length light sources, point light and 8 ft. length lighting, and between 2 ft. length light and 8 ft. length light. This means that people are able to see 16 ft. lighting, configured to 90 degree turns, better than point based lighting, 2 ft. lighting and 8 ft. lighting.

These initial analyses of reaction time, determination accuracy, 30-degree reaction time and 90-degree reaction time seem to reveal that 16 ft. linear LED light lengths may present significant benefits over traditional point lights or relatively shorter light lengths.

IV. Conclusion

These initial analyses of reaction time and determination accuracy seem to reveal that 16 ft. linear LED light lengths may present significant benefits over traditional point lights or relatively shorter light lengths. Further data analysis will be conducted to include reaction time for demographic information gathered in the survey. In order to determine statistical significance between different age groups, the different ages will be separated into three groups (under 25, 26-50 and over 50). Then, statistical significance will be determined based on light length, spacing, angle and direction. The same principle will be applied to total flight time. Analysis will be conducted for all possible lighting configuration combinations including but not limited to, directional reaction time (right vs. left) and spacing (50 vs. 150 foot spacing between lights). Additional analysis will be performed on the current data set to further evaluate the participants' confidence, as well as accuracy of determining various lighting configurations. These research efforts are on-going.

Linear LED lighting offers not only an economical advantage but also potentially exciting safety enhancements over traditional incandescent lights. Application of linear LEDs such as studied here appear to offer some perceptual benefits over LED point source lights. Once this relationship is better understood, other uses such as stop bar lights for example can be fully explored.

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