Civil Engineering Studies
Transportation Engineering Series No. 121
Traffic Operations Lab Series No. 6

UILU-ENG-2003-2001

ISSN-0917-9191

A Comparison between the Turn On and Turn Off Characteristics of Incandescent and LED Traffic Signal Modules

By
Rahim F. Benekohal
Montty Girianna
Madhav V. Chitturi

A study conducted by
Traffic Operations Laboratory
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

Prepared for
Illinois Department of Transportation

December 2003

Technical Report Documentation Page

1. Report No,	2. Government Accession No.	3. Recipient's Catalog No
FHWA-IL/UI-TOL-6		

4. Title and Subtitle	5. Report Date
A Comparison between the Turn On and Turn Off Characteristics of Incandescent and LED Traffic Signal Modules	December 18, 2003
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Rahim F. Benekohal, Montty Girianna and Madhav V. Chitturi	UILU-ENG-2003-2001
9. Performing Organization Name and Address	10. Work Unit (TRAIS)
Department of Civil and Environmental Engineering University of Illinois at Urbana-Champaign 205 N. Mathews Ave. Urbana, Illinois 61801	11. Contract or Grant No.
	13. Type of Report and Period Covered Project Report 2002-2003
12. Sponsoring Agency Name and Address	14. Sponsoring Agency Code
The Illinois Department of Transportation	

15. Supplementary

16. Abstract

Illinois Department of Transportation (IDOT) has been replacing the incandescent traffic signal modules with LED modules at various intersections. Using LED modules from different manufacturers on the same intersection approach may create an unsynchronized turn on and turn off characteristics that may be noticeable to some motorists. The objective of this study was to compare the turn on and turn off characteristics of incandescent and LED modules. Data was collected and analyzed to determine the turn on and turn off characteristics of incandescent and LED (Gelcore and Dialight) traffic signal modules. Several measures to quantify the signal modules' characteristics were introduced. These measures included fade in and fade out times, turn on and turn off delay, overlaps/gaps of colors between consecutive phase intervals. For all colors, the LED lenses had shorter fade in times when compared with the incandescent lens. The fade in time for LED Dialight was shorter than that for LED Gelcore, for all the three colors. For solid green, the LED Dialight lens had the longest fade out time. For yellow and red, the LED Dialight lenses had shorter fade out times when compared to the other two lenses. For solid yellow and red, the incandescent lens had the longest fade out time. Except for LED Dialight solid red, all LED lenses turned on a fraction of second later than the corresponding incandescent lenses. LED Dialight solid red lens turned on earlier than the incandescent solid red lens. Except for LED Gelcore solid green lens all the LED lenses turned off a fraction of second earlier than the corresponding incandescent lenses.

17. Key Words	18. Distribution Statement
Light Emitting Diodes, LED Traffic Signal Modules, Incandescent modules, Turn on and Turn off characteristics, Fade in and Fade out times, Traffic Signal, Driver Perception, Intersection Traffic Lights.	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	23	

`Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Acknowledgment and Disclaimer

This study was conducted by the Traffic Operations Laboratory (TOL) at the University of Illinois at Urbana-Champaign. The Illinois Department of Transportation sponsored the study. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not reflect the official views or policies of the Illinois Department of Transportation. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

1. Introduction

Incandescent and LED light sources are the two light sources used in traffic signals. Though, the incandescent lamps are very inexpensive, their use in the traffic signals is an enormous economic burden owing to their high power consumption and maintenance cost due to the requirement of annual preventive replacement. On the contrary, LED based traffic signal modules, though expensive, offer tremendous savings potential because they consume much less power and do not require the annual preventive replacement. Thus the use of LEDs in traffic signals results not only in energy cost savings, but also helps the environment by using less power for operating the signals.

Illinois Department of Transportation (IDOT) has been replacing the incandescent traffic signal modules with LED modules at various intersections. However, it was reported that motorists perceived unsynchronized turn on and turn off characteristics at a traffic signal that used different types of traffic signal modules, i.e. incandescent and LED modules. The University of Illinois at Urbana-Champaign was commissioned to investigate the turn on and turn off characteristics of incandescent and LED modules.

2. Data collection

A set of incandescent modules (solid red, green, and yellow) with DURA-TEST lamps and two different sets of LED modules manufactured by Gelcore and Dialight were used in this investigation. Table 1 shows the specifications of the traffic signal modules used in the investigation.

Traffic Signal Modules	Brand and Models			
Incandescent				
Red	DURA-TEST, 135 W			
Yellow	DURA-TEST, 135 W			
Green	DURA-TEST, 135 W			
LED GELCORE				
Red	Model: D12RA4 MS: 4	120 Volts, 60 Hz, 9.4 W	9.5 VA	SN: 622700 D/C: 0103
Yellow	Model: D12YA4 MS: 4	120 Volts, 60 Hz, 17.5 W	17.6 VA	SN: 612273 D/C: 0102
Green	Model: D12GA4 MS: 4	120 Volts, 60 Hz, 13 W	13.1 VA	SN: 590650 D/C: 0048
LED DIALIGHT				
Red	Model: 433-1210-033	120 Volts, 60 Hz, 10.5 W	10.8 VA	SN: 12AR040172161
Yellow	Model: 431-3235-001	120 Volts, 60 Hz, 32 W	33 VA	SN: 003610165
Green	Model: 432-2275-001	120 Volts, 60 Hz, 10.7 W	11.5 VA	S/N: 0030-00338

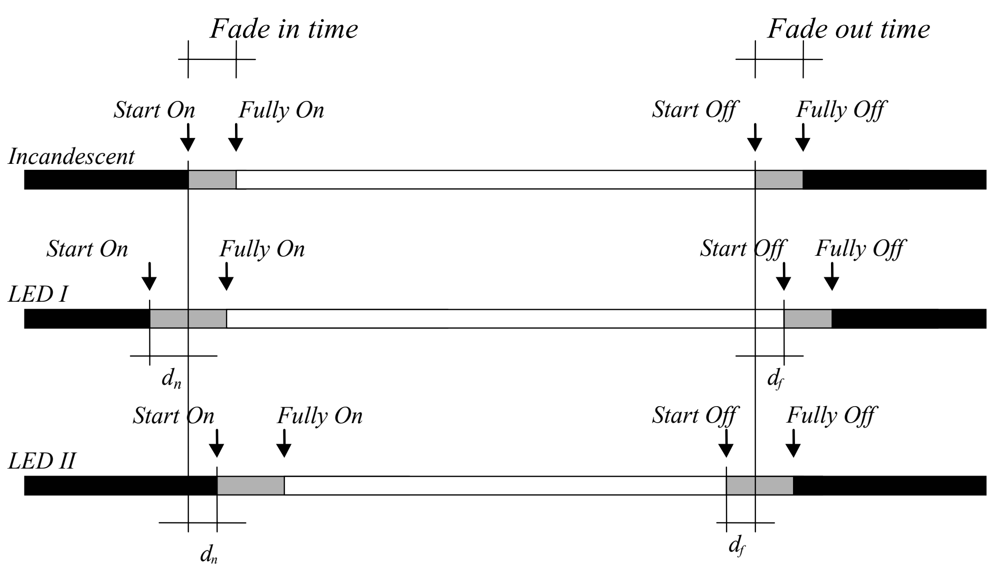
Table 1. Brands and Models of traffic signal modules.

At the Traffic Operations Laboratory of the University of Illinois, a frame was set up with the three signal heads (one incandescent and two LEDs) next to each other and they were programmed to turn on and turn off simultaneously using a NEMA controller. The signal heads were run for 114 cycles and during this time the frame was videotaped. Each cycle was 92 seconds long and therefore approximately three hours of data were recorded. The tapes were then time coded such that each second of elapsed time of image represents 30 image frames. One frame is about 0.03 seconds.

The time-coded tapes were played using a Panasonic AG-2550 VCR at a slow pace so that each frame could be viewed individually. For each lens (for 3 models and 3 colors, i.e., 9 lenses), the times at which the lens starts to turn on, is fully on, starts to turn off, and is fully off were recorded in an Excel Workbook. Therefore, in total (3)(3)(4) = 36 data points were recorded for each cycle. For 114 cycles, (114)(36) = 4,104 data points were recorded. All the measures used to characterize the turn on and turn off capabilities of the traffic signal modules are defined in the following section.

3. Definitions

Figure 1 shows the definitions and terms used in determining the turn on and turn off characteristics of traffic signal modules. Dark bars indicate that the lenses are off, and clear bars indicate that the lenses are on. "Fade In" time is the time required for a lens to reach its full brightness ("Fully On") and is measured from the time the lens starts glowing ("Start On"). The "Fade In" time is indicated as the gray bar in the figures between the points labeled as "Start On" and "Fully On". "Fade Out" time is the time required for a lens to reach complete darkness ("Fully Off") and is measured from the time the light starts to dim ("Start Off"). "Turn On" delay, d_n, is the difference between "Start On" times of LED lenses and incandescent lens. "Turn Off" delay, d_f, is the difference between "Start Off" times of LED lenses and incandescent lens.



d_n="Turn On" delay; d_f="Turn Off" delay

Figure 1. Definitions and terms used to determine turn on and turn off characteristics.

Gaps or overlaps between two consecutive signal phases are measured using four reference points. These four reference points are beginning of fade out (start off), end of fade out times (fully off), beginning of fade in (start on), and end of fade in (fully on) times. A reference point of fade out time will be used with a reference point of fade in time. This yields four different cases (as shown in Table 2). Schematics of these four cases are presented in Figure 2. The time difference (Δ) between the reference point for lens 1 and lens 2 is computed as Δ=(reference point for lens 1) – (reference point for lens 2). When Δ is positive, there is an overlap of two different color lens indicators (2 colors are shown at the same time). When Δ is negative, there is a gap between two different color lens indicators (black out time with no color showing).

		LED 1, lens 2	
		Start on	Fully on
LED 1, lens 1	Start off	Case 1	Case 2
	Fully off	Case 3	Case 4

Table 2. Reference points for lenses being "on" or "off"

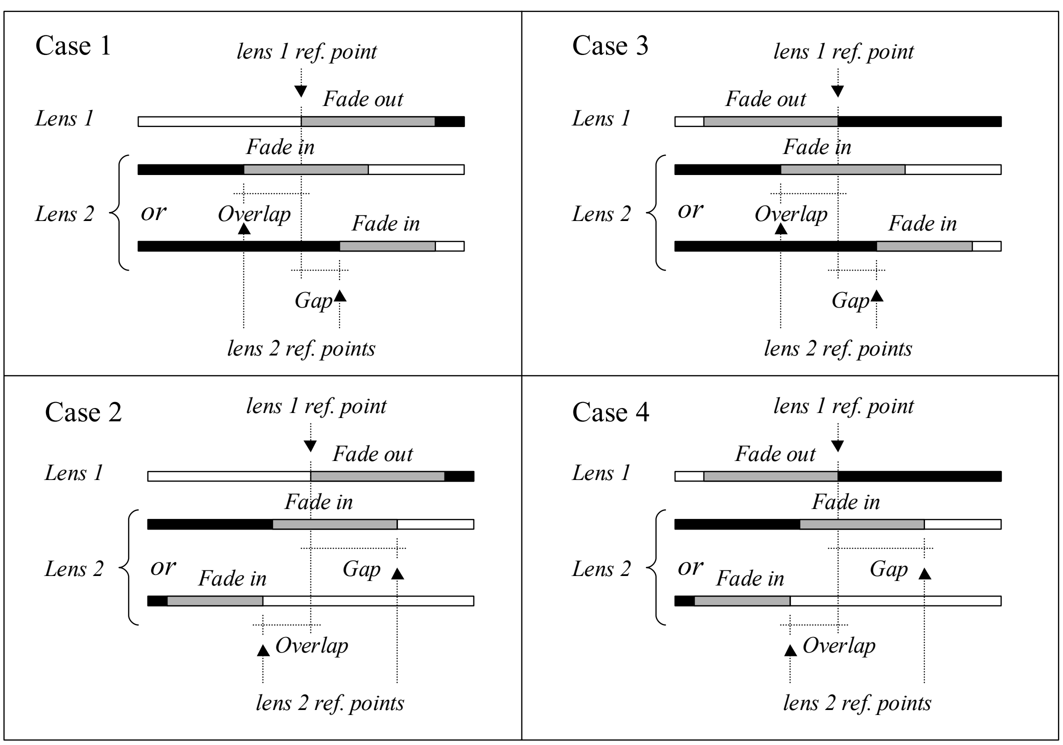


Figure 2. Overlaps and gaps for Cases 1 to 4

4. Fade In Time

Fade in time is the time required for a lens to reach its full brightness and is measured from the time it starts glowing. Different lenses produced by different vendors have different fade in times. Table 3 summarizes the fade in times for the three types of traffic light modules. The fade in time is measured in terms of the number of frames. One frame is 1/30 of a second. Figures 3 (a) to (c) show the fade in time in seconds for all lenses during the investigation.

To verify that a fade in time is statistically different from zero, *t*–test was performed and the value of the *t*-statistic is shown in Table 3. The critical *t*-value corresponding to 95% confidence level is 1.9812. It can be seen that the *t*-statistics computed for all the lenses exceed the critical value. This strongly indicates that the fade-in times for all the lenses are significantly greater than zero.

Colors	Incandescent				LED Gelcore				LED Dialight			
	Min	Average	Max	t-value*	Min	Average	Max	t-value*	Min	Average	Max	t-value*
Red	1	2.13	3	36.88	1	1.19	2	32.14	1	1.02	2	82.39
Yellow	4	5.07	6	83.55	1	1.17	2	33.28	1	1.01	2	115.00
Green	3	4.29	5	89.72	1	1.88	3	38.72	0	1.07	2	35.91

*) t-value (t-critical=1.9812)

Table 3. Fade in times (in unit of frames) for incandescent and LED lenses

Green, yellow, and red solid lenses of LED Dialight had the shortest fade in times. The incandescent lenses had the longest fade in times. The fade in times for Gelcore fell between that of Dialight and the incandescent modules. The incandescent lights used for green, yellow, and red are the same. It is expected that the fade in time of these lights without lenses would be the same. However, with the lenses in front of them, the average fade in time for yellow is longer than green and green is longer than red. These differences are statistically significant at 95% confidence level. The critical *t*-value with the degree of freedom of $2(n-1) = 2(114-1) = 226$ and two-tailed test is 2.414. Table 4 shows the differences in fade in times for different colors and for all signal modules. For

LED Gelcore, the average fade in time for green is larger than either yellow or red and the difference is statistically significant. The fade in time for yellow and red is statistically the same. Unlike other signal modules, the differences in fade in times (for all colors) for LED Dialight are not statistically significant.

Signal Modules	Pair of colors		DIFF	t-value*	Pair of colors		DIFF	t-value*	Pair of colors		DIFF	t-value*
	YELLOW	GREEN			YELLOW	RED			GREEN	RED		
INC. **	5.07	4.29	0.78	10.11	5.07	2.13	2.94	35.07	4.29	2.13	2.16	28.77
LED Gelcore	1.17	1.88	-0.71	-11.88	1.17	1.19	-0.03	-0.52	1.88	1.19	0.68	11.20
LED Dialight	1.01	1.07	-0.06	-1.98	1.01	1.02	-0.01	-0.58	1.07	1.02	0.05	1.63

* df=2(n-1)=1(114-1)=226 and critical t-value=2.414
** INC.=Incandescent

Table 4. Difference in average fade in time (in unit of frames) for different colors of lenses and modules.

Table 5 shows the differences in average fade in time for different signal modules. For any given color of lenses, the fade in time for incandescent is larger than that for LED Gelcore, and the fade in time for LED Gelcore is larger than that for LED Dialight. The differences are statistically significant.

Signal Colors	Pair of modules		DIFF	t-value*	Pair of modules		DIFF	t-value*	Pair of modules		DIFF	t-value*
	INC. **	LED Dialight			INC.**	LED Gelcore			LED Dialight	LED Gelcore		
RED	2.13	1.02	1.11	18.85	2.13	1.19	0.94	13.66	1.02	1.19	-0.18	-4.48
YELLOW	5.07	1.01	4.06	66.24	5.07	1.17	3.90	55.70	1.01	1.17	-0.16	-4.37
GREEN	4.29	1.07	3.22	57.14	4.29	1.88	2.41	35.43	1.07	1.88	-0.81	-14.18

* df=2(n-1)=1(114-1)=226 and critical t-value=2.414

Table 5. Difference in average fade in time (in unit of frames) for different signal modules

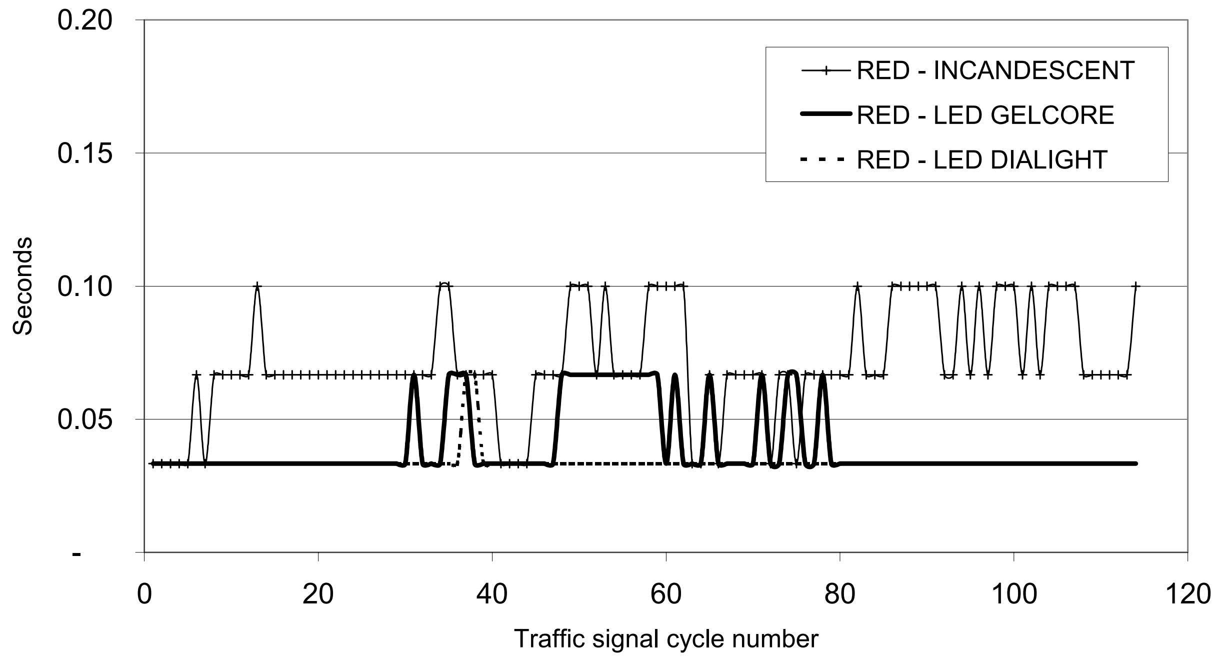


Figure 3a. Fade in time for RED Incandescent and LED lenses

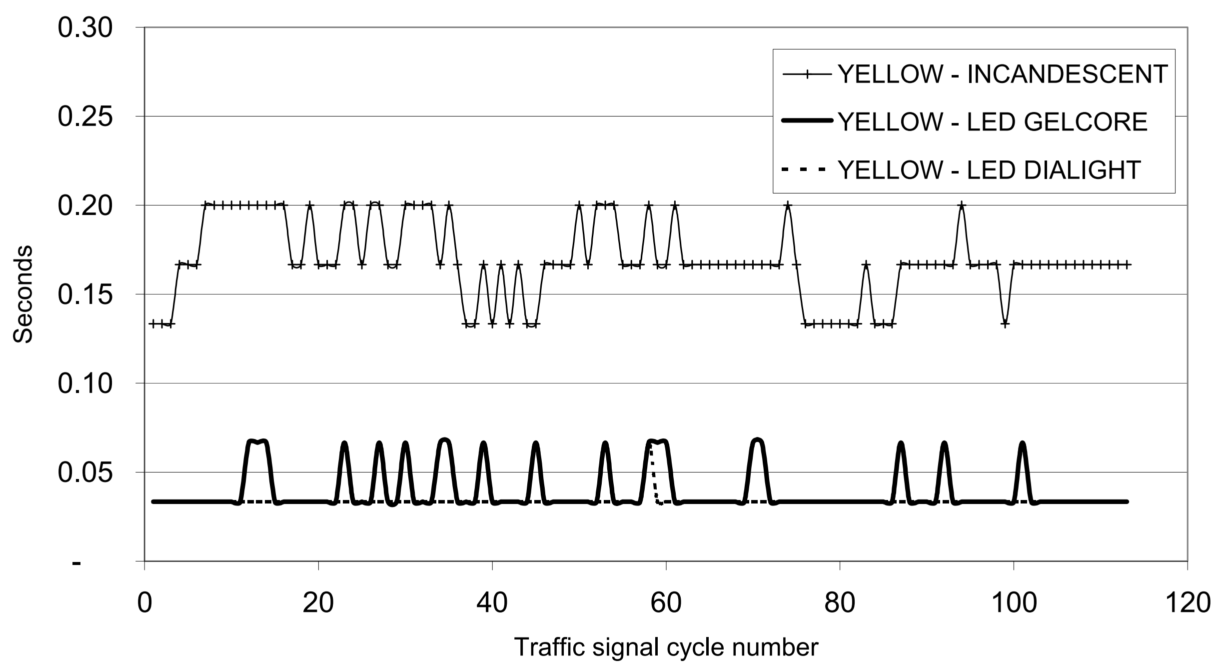


Figure 3b. Fade in time for YELLOW Incandescent and LED lenses

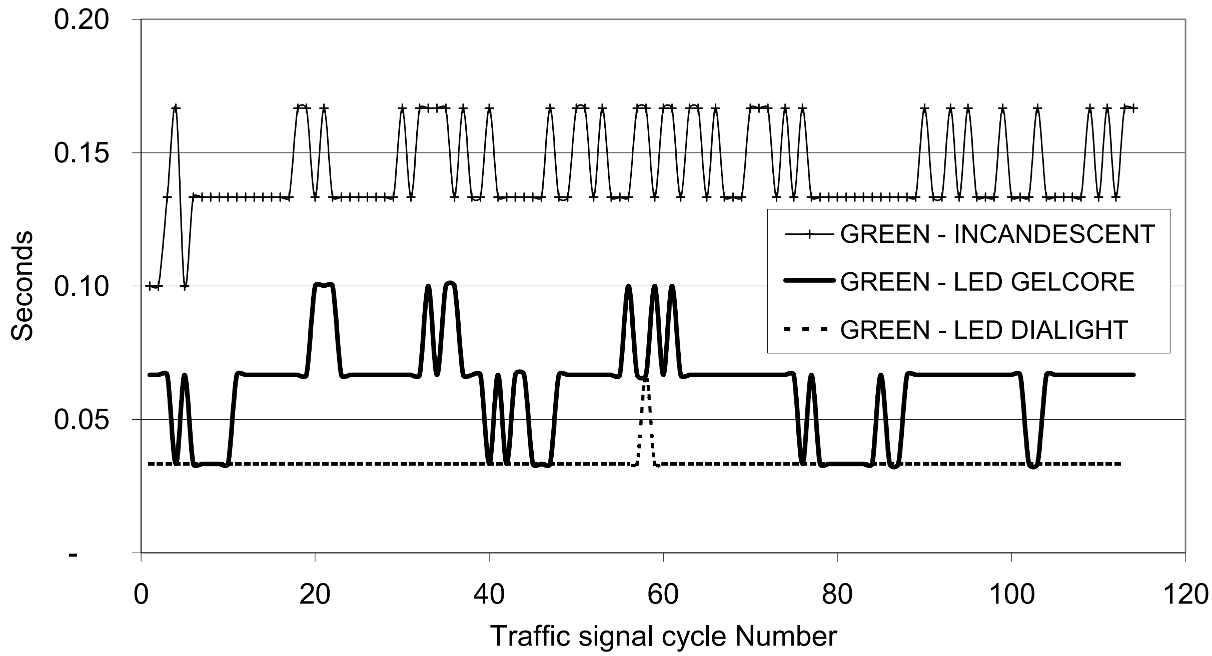


Figure 3c. Fade in time for GREEN Incandescent and LED lenses

5. Fade out time

Fade out time is the time required for a lens to reach complete darkness and is measured from the time it starts to dim. Table 4 summarizes the fade out times for the three types of traffic light modules. Fade out time is measured in terms of the number of frames. Figures 4 (a) to (c) show the fade out time in seconds for all lenses during the investigation.

To verify that a fade in time is statistically different from zero, *t*–test was performed and the value of the *t*-statistic is shown in Table 6. The critical *t*-value corresponding to 95% confidence level is 1.9812. It can be seen that the *t*-statistics computed for all the lenses exceed the critical value. This strongly indicates that the fade out times for all the lenses are significantly greater than zero.

Colors	Incandescent				LED Gelcore				LED Dialight			
	Min	Average	Max	t-value *	Min	Average	Max	t-value *	Min	Average	Max	t-value *
Red	15	18.06	23	120.68	11	12.10	14	137.34	4	6.24	8	53.88
Yellow	13	15.04	18	139.98	5	6.67	9	92.21	6	6.61	8	104.73
Green	10	11.32	14	164.94	5	6.82	8	96.45	13	14.24	16	247.56

*) t-value (t-critical=1.9812)

Table 6. Fade out times (in unit of frames) for incandescent and LED lenses

Table 7 shows the differences in fade out time for different colors of lenses and for a given signal module. For incandescent, the longest fade out time is for red, followed by yellow and green, and the differences are statistically significant. For LED Gelcore, the fade out time for red is the longest. No significant difference is observed between yellow and green, but there is a significant difference between red and either yellow or green. For LED Dialight, the longest fade out time is for green, followed by yellow and red. The differences in fade out time for all colors are statistically significant.

Signal Modules	Pair of colors		DIFF	t-value*	Pair of colors		DIFF	t-value*	Pair of colors		DIFF	t-value*
	YELLOW	GREEN			YELLOW	RED			GREEN	RED		
INC. **	15.04	11.32	3.73	29.24	15.04	18.06	-3.02	-16.38	11.32	18.06	-6.75	-40.97
LED Gelcore	6.67	6.82	-0.16	-1.56	6.67	12.10	-5.43	-47.65	6.82	12.10	-5.27	-46.66
LED Dialight	6.61	14.24	-7.63	-89.41	6.61	6.24	0.37	2.79	14.24	6.24	8.00	61.89

* df=2(n-1)=1(114-1)=226 and critical t-value=2.414
** INC.=Incandescent

Table 7. Difference in average fade out time (in unit of frames) for different colors of lenses and modules.

Table 8 shows the differences in average fade out times for different signal modules and for a given color of lenses. For red lenses, the longest fade out time was observed for incandescent, followed by LED Gelcore and LED Dialight. The differences are statistically significant. For yellow lenses, the fade out time for incandescent is the longest and statistically different from the LED modules, whereas the fade-out times for yellow lenses of the two LED modules are statistically the same. For green lenses, LED

Dialight had the longest fade out time followed by incandescent and LED Gelcore. The differences are statistically significant.

Signal Colors	Pair of modules: INC. **	Pair of modules: LED Dialight	DIFF	t-value*	Pair of modules: INC.**	Pair of modules: LED Gelcore	DIFF	t-value*	Pair of modules: LED Dialight	Pair of modules: LED Gelcore	DIFF	t-value*
RED	18.06	6.24	11.82	62.49	18.06	12.10	5.96	34.35	6.24	12.10	-5.86	-40.29
YELLOW	15.04	6.61	8.44	67.72	15.04	6.67	8.38	64.68	6.61	6.67	-0.06	-0.64
GREEN	11.32	14.24	-2.92	-32.63	11.32	6.82	4.49	45.57	14.24	6.82	7.41	81.29

* df=2(n-1)=1(114-1)=226 and critical t-value=2.414
** INC.=Incandescent

Table 8. Difference in average fade out time (in unit of frames) for different signal modules.

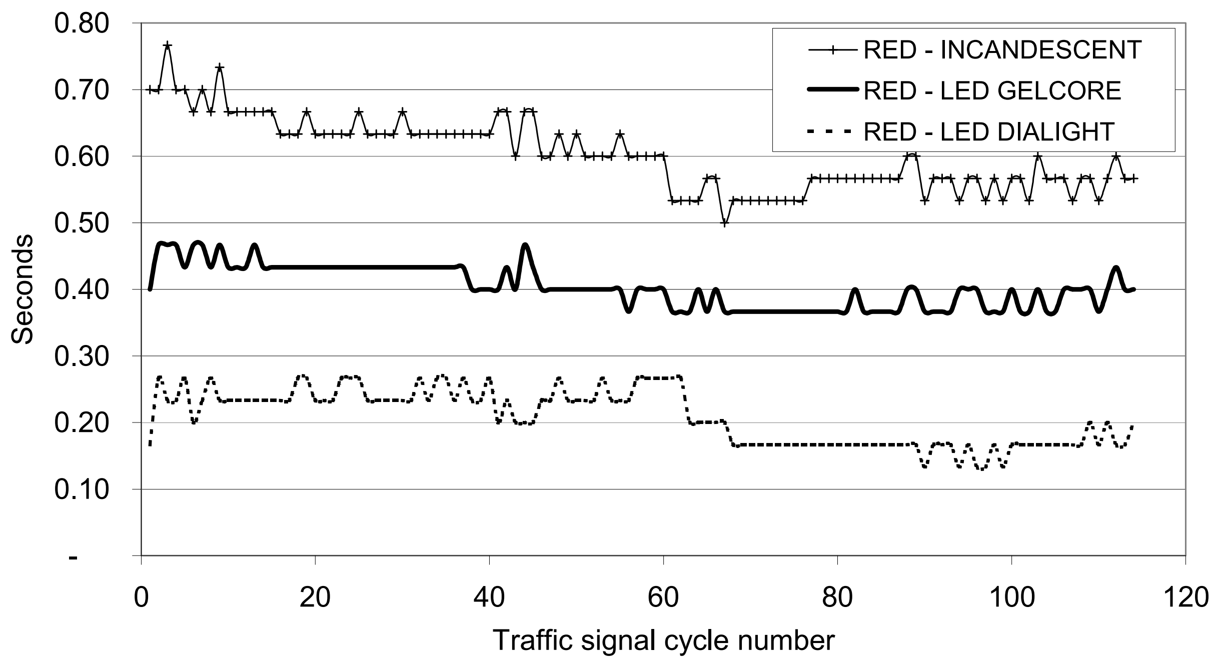


Figure 4a. Fade out time for RED Incandescent and LED lenses

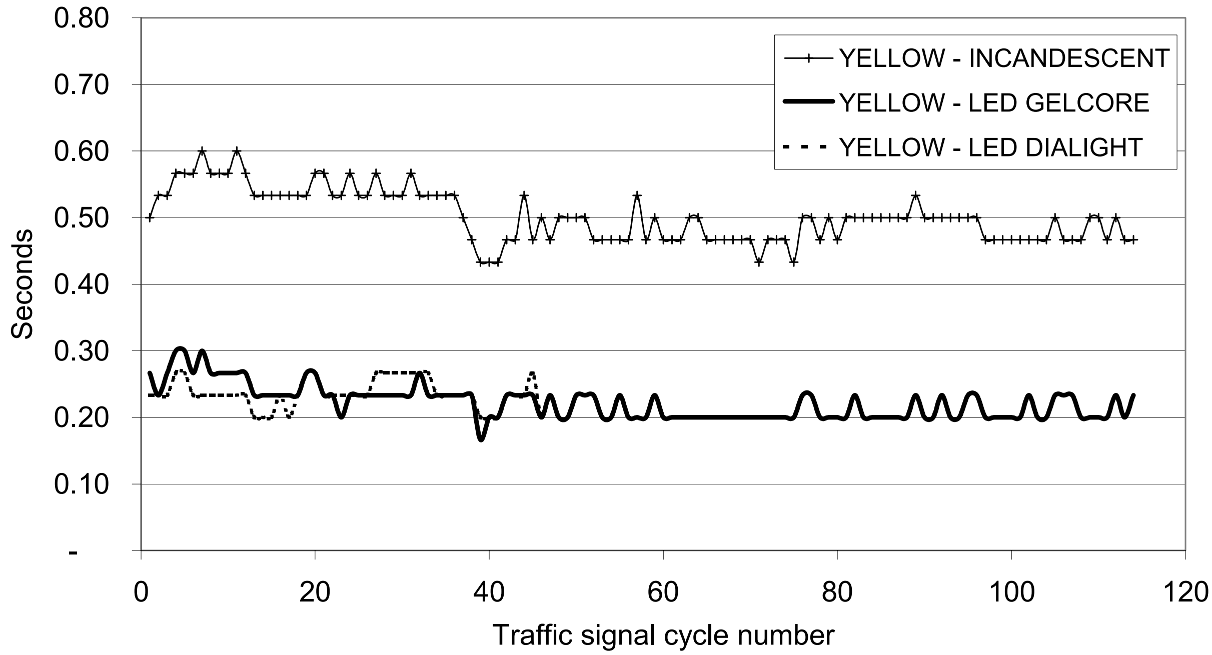


Figure 4b. Fade out time for YELLOW Incandescent and LED lenses

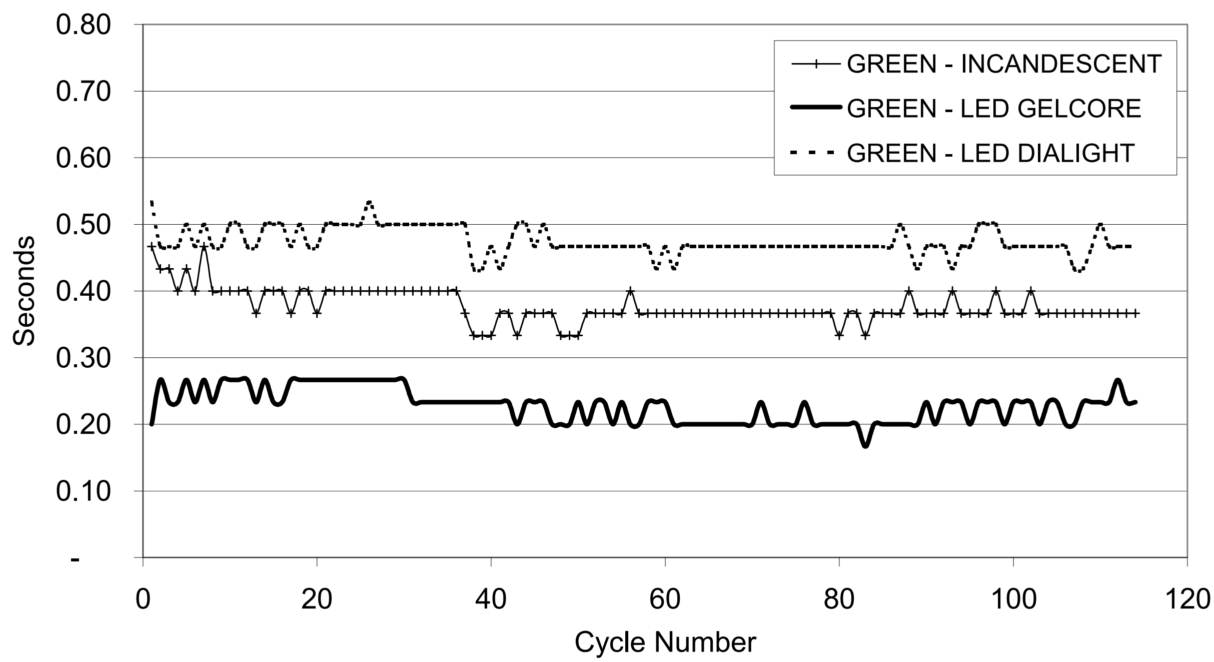


Figure 4c. Fade out time for GREEN Incandescent and LED lenses

6. "Turn On" Delay

"Turn On" delay, d_n, is a measure used to quantify whether LED lenses start turning on earlier or later than incandescent lens. Thus, the start time for the incandescent lens to glow is considered as the benchmark. A positive value for the measurement indicates that the LED lens turns on later than the incandescent lens. A negative value indicates that the LED lens turns on earlier than the incandescent lens. Table 9 summarizes the "Turn On" delay time for the LED lenses relative to the incandescent lens, and Figures 5a, 5b, and 5c show the delay for LEDs during the study period. From Table 9, it is clear that, with the exception of solid red LED Dialight, the delay for all LED lenses is positive; in other words, the LED lenses turned on some time after the incandescent lens turned on. For all colors, LED Gelcore had a higher delay than LED Dialight. For solid red of LED Dialight, the delay was negative indicating that the LED Dialight turned on earlier than the incandescent lens, i.e., a fraction of a frame (0.62 frames or 0.02 seconds). All "Turn On" delays are statistically significant.

Colors	LED Gelcore				LED Dialight			
	Min	Average	Max	t-value*	Min	Average	Max	t-value*
Red	0	1.39	3	27.46	-1	-0.62	0	-13.66
Yellow	1	2.08	4	58.46	0	1.09	2	34.08
Green	3	4.48	6	86.66	1	1.07	2	44.54

*) t-value (t-critical=1.9812)

Table 9. "Turn On" delay (in units of frames) for LED lenses relative to Incandescent lenses

As shown in Table 10, for any given color of lenses, the difference in "Turn On" delays for the two LED modules are statistically significant. The delay is larger for LED Gelcore than that for LED Dialight.

Signal Colors	Pair of modules		DIFF	t-value*
	LED Gelcore	LED Dialight		
RED	1.39	-0.62	2.02	29.56
YELLOW	2.08	1.09	0.99	20.74
GREEN	4.48	1.07	3.41	59.83

* df=2(n-1)=1(114-1)=226 and critical t-value=2.414

Table 10. Difference in "Turn On" delay for different LED modules

Table 11 shows the difference in "Turn On" delay for any pair of colors for a given signal module. For LED Gelcore, the longest delay is for green, followed by yellow and red. The differences are statistically significant. For LED Dialight, the longest delay is for yellow and green, and the difference between the two delays is statistically insignificant. The delay for red is negative (earlier than incandescent) and it is statistically different than either yellow or green.

Signal Modules	Pair of colors		DIFF	t-value*	Pair of colors		DIFF	t-value*	Pair of colors		DIFF	t-value*
	YELLOW	GREEN			YELLOW	RED			GREEN	RED		
LED Gelcore	2.08	4.48	-2.40	-38.29	2.08	1.39	0.68	11.03	4.48	1.39	3.09	42.59
LED Dialight	1.09	1.07	0.02	0.44	1.09	-0.62	1.71	30.73	1.07	-0.62	1.69	32.85

* df=2(n-1)=1(114-1)=226 and critical t-value=2.414

Table 11. Difference in "Turn On" delay for different colors of lenses

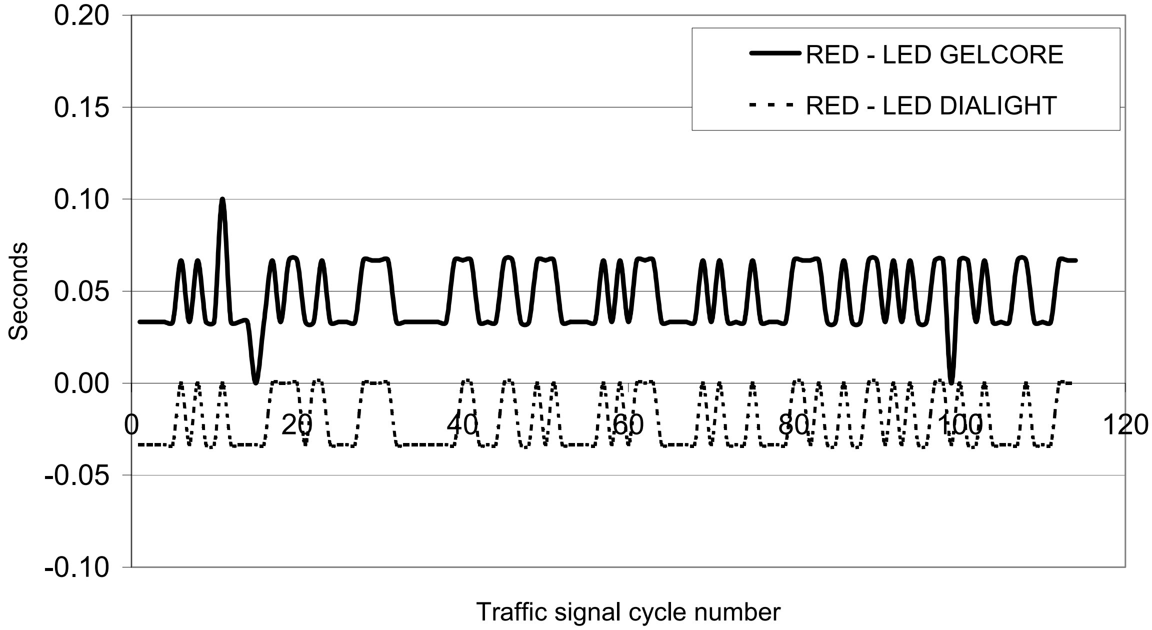


Figure 5a. “Turn On” delay for RED LED lenses relative to RED Incandescent lens.

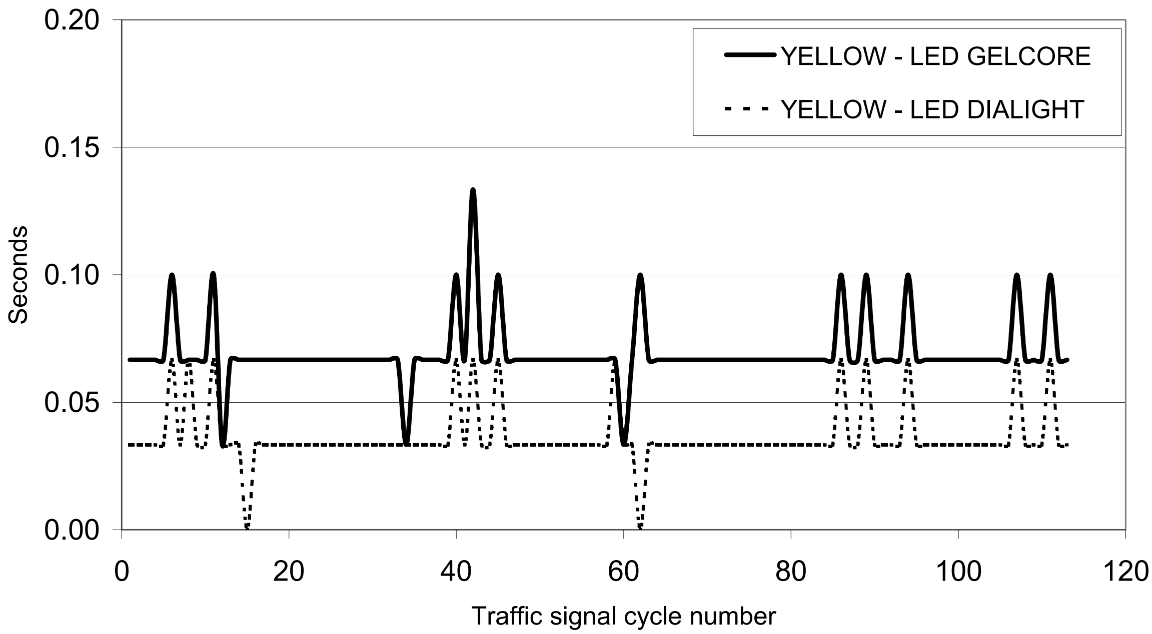


Figure 5b. “Turn On” delay for YELLOW LED lenses relative to YELLOW Incandescent lens.

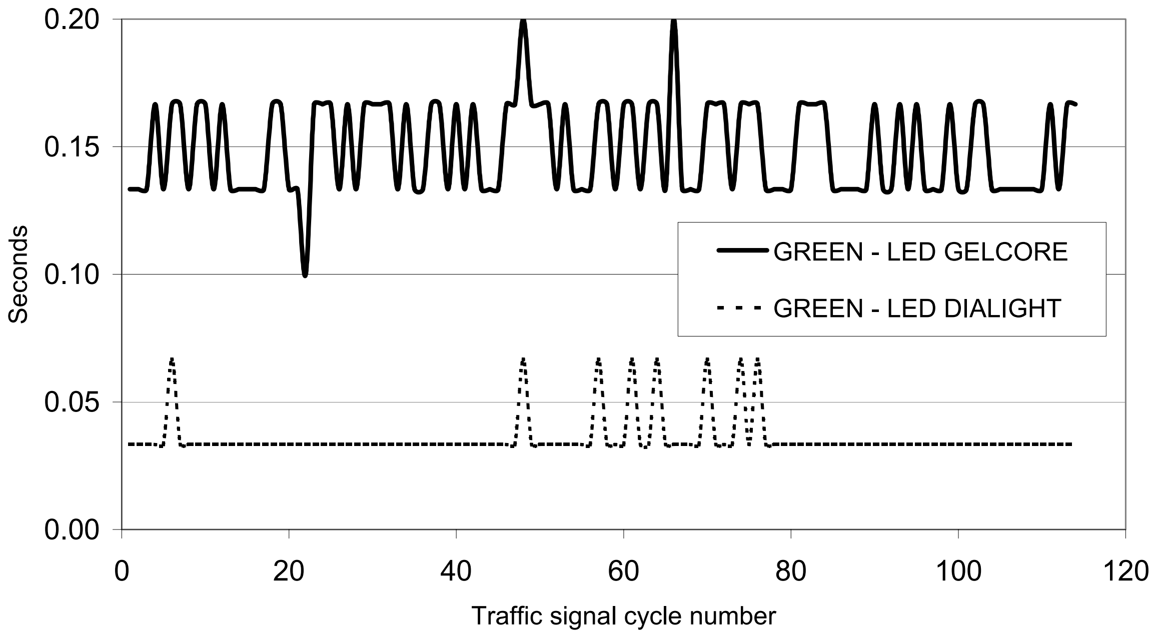


Figure 5c. "Turn On" delay for GREEN LED lenses relative to GREEN Incandescent lens.

7. "Turn Off" Delay

"Turn Off" delay is a measure used to quantify whether LED lenses start to turn off earlier or later than the incandescent lens. Thus, the time at which the incandescent lens starts to dim is considered as the benchmark. A positive value for this measurement indicates that the LED lens starts turning off some time later than the incandescent lens. A negative value indicates that the LED lens starts turning off earlier than the incandescent lens. Table 12 summarizes the "Turn Off" delay time for the LED lenses relative to the incandescent lens, and Figures 6a, 6b, and 6c show the delays for LED lenses during the study period. From Table 12, it is clear that, with the exception of LED Gelcore solid green, the delay for all LED lenses, on average, is negative. In other words, the LED lenses turn off earlier than the incandescent modules. For solid red and yellow, LED Dialight turns off earlier than LED Gelcore.

Colors	LED Gelcore				LED Dialight			
	Min	Average	Max	t-value *	Min	Average	Max	t-value *
Red	-4	-0.48	1	-5.46	-4	-0.95	1	-9.10
Yellow	-3	-0.09	0	-2.41	-3	-0.22	1	-3.86
Green	-1	0.52	2	9.23	-2	-0.17	1	-3.59

*) t-value (t-critical=1.9812)

Table 12 “Turn Off” delay for LED lenses relative to incandescent lens.

As shown in Table 13, for any given color of lenses, the difference in “Turn Off” delays for the two LED modules are statistically significant. For any signal color, LED Dialight lenses start turning off earlier than LED Gelcore lenses.

Signal Colors	Pair of modules		DIFF	t-value*
	LED Gelcore	LED Dialight		
RED	-0.48	-0.95	0.46	6.81
YELLOW	-0.09	-0.22	0.13	2.75
GREEN	0.52	-0.17	0.68	12.00

* df=2(n-1)=1(114-1)=226 and critical t-value=2.414

Table 13. Difference in “Turn Off” delay for different LED lenses

Table 14 shows the difference in “Turn Off” delay for all pairs of colors for a given signal module. For LED Gelcore, the longest delay is for green, followed by yellow and red. The differences are statistically significant. Similarly, for LED Dialight, the longest delay is for green, followed by yellow and red. However, the difference in delay between yellow and green is not significant. The delay of red is significantly different from either yellow or green.

Signal Modules	Pair of colors		DIFF	t-value*	Pair of colors		DIFF	t-value*	Pair of colors		DIFF	t-value*
	YELLOW	GREEN			YELLOW	RED			GREEN	RED		
LED Gelcore	-0.09	0.52	-0.61	-9.64	-0.09	-0.48	0.39	6.37	0.52	-0.48	1.00	13.79
LED Dialight	-0.22	-0.17	-0.05	-1.32	-0.22	-0.95	0.73	13.08	-0.17	-0.95	0.78	15.15

* df=2(n-1)=1(114-1)=226 and critical t-value=2.414

Table 14. Difference in “Turn Off” delay for different colors of lenses

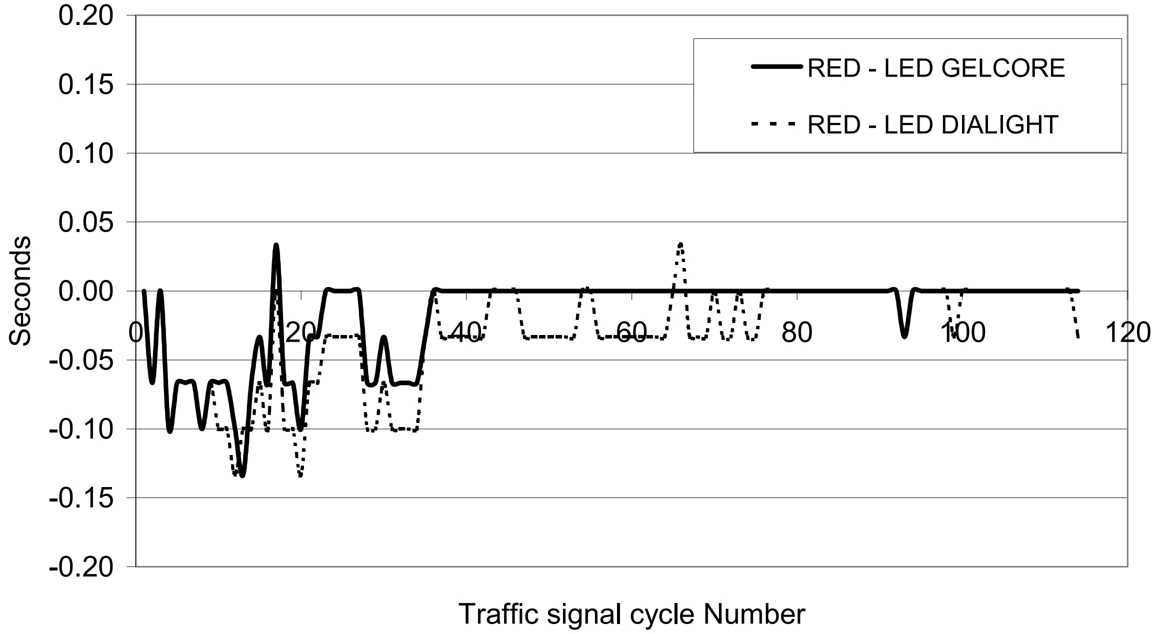


Figure 6 (a) "Turn Off" Delay for RED LED lenses relative to RED Incandescent lens.

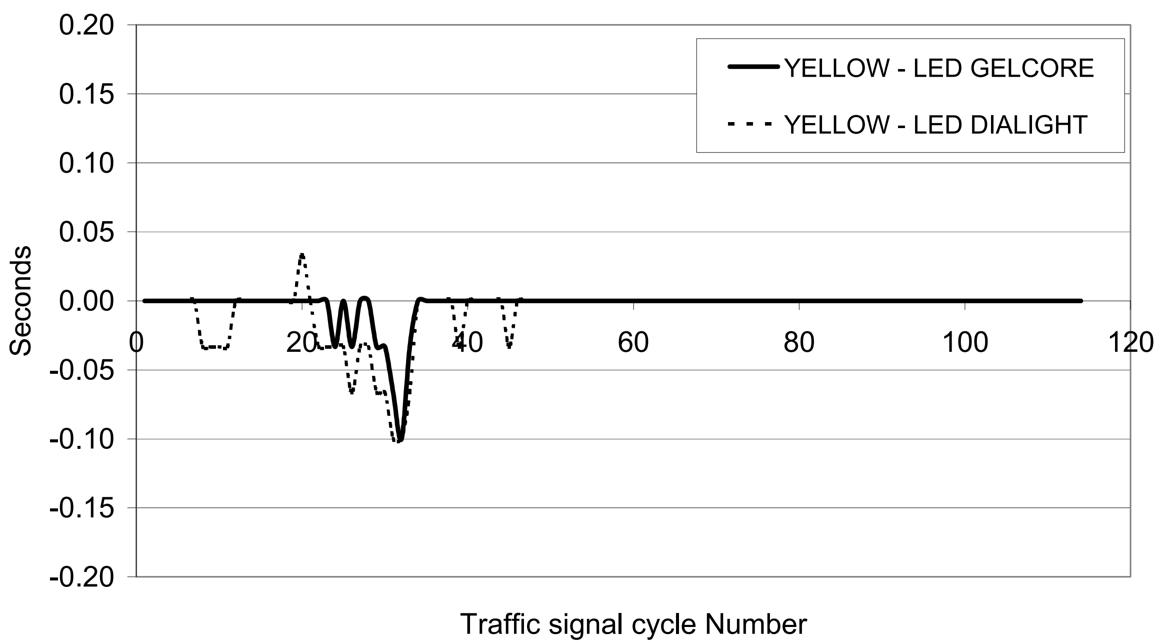


Figure 6 (b) "Turn Off" Delay for YELLOW LED lenses relative to YELLOW Incandescent lens.

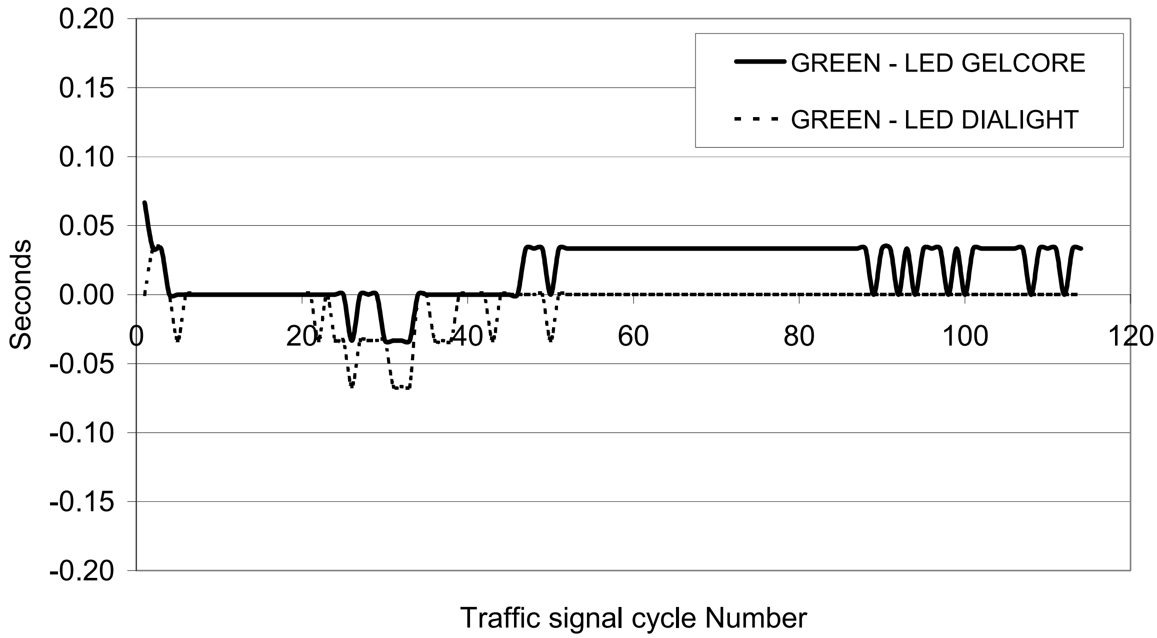


Figure 6 (c) "Turn Off" Delay for GREEN LED lenses relative to GREEN Incandescent lens.

Overlaps and Gaps

8.1. Green to Yellow

Tables 15a and 15 b show the overlaps/gaps, Δ, between consecutive signal phases, green and yellow, . The first two columns of the tables reveal the possible combinations of signal modules. There are nine sets of module combinations. Recall that the reference point for both Cases 1 and 2 is the "Start Off" time for green phase (lens 1, see Figure 2). The difference between the two cases is the reference point for yellow phase (lens 2). Case 1 uses "Start On" time, while Case 2 uses "Fully On" time for yellow phase as the second reference point. Cases 3 and 4 use the "Fully Off" time for green phase (lens no 1). The reference point for lens no 2 is "Start On" (Case 3) and "Fully On" (Case 4) for yellow phase. Gaps result in negative values for Δ and overlaps result in positive values for Δ.. From Table 15a we can conclude that the Gaps are statistically significant for all combinations of signal modules. For Case 1, the longest gap occurs when LED Dialight and LED Gelcore modules are used for green and yellow, respectively, whereas the shortest gap occurs when LED Gelcore modules are used for green with yellow incandescent. Gaps measured using the procedure defined as Case 2 are longer than that measured using Case 1 because for all the lenses the fade in time is greater than zero. The longest gap occurs when LED Dialight modules are used for green with yellow incandescent, while the shortest is when LED Gelcore modules are used for green together with yellow LED Dialight modules.

Signal Module Combination		Case 1: Green-Yellow overlaps/gaps from Start Off Green to Start On Yellow				Case 2: Green-Yellow overlaps/gaps from Start Off Green to Fully On Yellow			
Green	Yellow	Min	Average	Max	t-value *	Min	Average	Max	t-value *
Incandescent	Incandescent	-2	-0.57	1	-9.76	-7	-5.64	-3	-72.37
Incandescent	LED Gelcore	-4	-2.65	-1	-46.41	-5	-3.82	-2	-61.79
Incandescent	LED Dialight	-3	-1.66	0	-29.15	-4	-2.67	-1	-45.98
LED Gelcore	Incandescent	-2	-0.05	1	-1.03	-7	-5.12	-3	-57.49
LED Gelcore	LED Gelcore	-4	-2.13	-1	-38.73	-5	-3.30	-2	-51.98
LED Gelcore	LED Dialight	-3	-1.14	1	-20.53	-4	-2.15	0	-38.35
LED Dialight	Incandescent	-2	-0.74	1	-16.37	-7	-5.81	-3	-72.89
LED Dialight	LED Gelcore	-4	-2.82	-2	-69.52	-5	-3.98	-3	-88.71
LED Dialight	LED Dialight	-3	-1.82	0	-45.75	-4	-2.83	-1	-68.82

* Critical t-value = 1.9812

Table 15a. Overlaps/gaps between two consecutive signal phases for Cases 1 and 2: Green to Yellow

When Δ is measured using procedures described in Cases 3 and 4 overlaps are observed. As shown in Table 15b, overlaps are statistically significant for all combinations of modules. With Case 3, the longest overlap occurs when LED Dialight modules are used for green with yellow incandescent, whereas the shortest overlap occurs when LED Gelcore modules are used for both green and yellow. With Case 4, the longest overlap occurs when LED Dialight modules are used for both green and yellow. The combination of LED Gelcore modules for green and yellow incandescent provides the shortest overlap.

Signal Module Combination		Case 3: Green-Yellow overlaps/gaps from Fully Off Green to Start On Yellow				Case 4: Green-Yellow overlaps/gaps from Fully Off Green to Fully On Yellow			
Green	Yellow	Min	Average	Max	t-value *	Min	Average	Max	t-value *
Incandescent	Incandescent	9	10.75	13	117.56	4	5.68	9	60.07
Incandescent	LED Gelcore	7	8.67	11	92.40	6	7.50	10	78.20
Incandescent	LED Dialight	8	9.66	12	104.68	7	8.65	11	92.77
LED Gelcore	Incandescent	5	6.77	9	102.65	0	1.70	4	20.84
LED Gelcore	LED Gelcore	3	4.69	7	67.51	2	3.53	6	50.66
LED Gelcore	LED Dialight	4	5.68	8	85.73	3	4.68	7	70.29
LED Dialight	Incandescent	12	13.50	15	211.47	7	8.43	11	102.03
LED Dialight	LED Gelcore	10	11.42	13	173.55	9	10.25	12	150.73
LED Dialight	LED Dialight	11	12.41	14	185.59	10	11.40	13	167.88

* Critical t-value = 1.9812

Table 15b. Overlaps/gaps between two consecutive signal phases for Cases 3 and 4: Green to Yellow

8.2. Yellow to Red

Similar to the case for green to yellow, Δs for yellow to red measured using procedures defined in Cases 1 and 2 are negative (except for one case), indicating gaps as shown in Tables 16a. For Case 1, the longest gap occurs when LED Dialight and LED Gelcore modules are used for yellow and red, respectively, and the gap is statistically significant. Gaps are statistically significant for the majority of signal module combination except for a case when either incandescent or LED Gelcore modules for yellow is used with LED Dialight modules for red. For these signal module combinations, gaps are not significant. Gaps measured using the procedure defined in Case 2 are longer than that measured using Case 1, because for all the lenses the fade in time is greater than zero. With this procedure, all gaps are statistically significant. The longest gap occurs when LED Dialight modules are used for yellow with LED Gelcore modules for red, while the shortest is when yellow incandescent is used together with red LED Dialight modules.

Signal Module Combination		Case 1: Yellow-Red overlaps/gaps from Start Off Yellowto Start On Red				Case 2: Yellow-Red overlaps/gaps from Start Off Yellow to Fully On Red			
Yellow	Red	Min	Average	Max	t-value *	Min	Average	Max	t-value *
Incandescent	Incandescent	-2	-0.55	2	-8.68	-4	-2.68	0	-30.99
Incandescent	LED Gelcore	-4	-1.95	1	-32.01	-5	-3.14	0	-42.08
Incandescent	LED Dialight	-2	0.07	3	1.24	-3	-0.95	2	-16.27
LED Gelcore	Incandescent	-2	-0.64	1	-13.21	-4	-2.77	-1	-37.06
LED Gelcore	LED Gelcore	-4	-2.04	-1	-45.42	-5	-3.23	-2	-51.78
LED Gelcore	LED Dialight	-2	-0.02	1	-0.45	-3	-1.04	0	-25.13
LED Dialight	Incandescent	-1	-0.77	0	-19.56	-4	-2.90	-1	-43.29
LED Dialight	LED Gelcore	-3	-2.17	-1	-52.63	-5	-3.36	-2	-58.66
LED Dialight	LED Dialight	-1	-0.15	0	-4.45	-2	-1.17	-1	-33.28

* Critical t-value = 1.9812

Table 16a. Overlaps/gaps between two consecutive signal phases for Cases 1 and 2: Yellow to Red

When Δ is measured using procedures described in Cases 3 and 4 overlaps are observed. As shown in Table 16b, overlaps are statistically significant for all combination of modules. Larger overlaps occur when yellow incandescent is used for any combination of signal modules, and the longest overlaps occur when the incandescent is used with red LED Dialight modules for both Cases 3 and 4. In addition, for both Cases, the shortest overlap occurs when yellow LED Dialight modules are used for with red LED Gelcore modules.

Signal Module Combination		Case 3: Yellow-Red overlaps/gaps from Fully Off Yellowto Start On Red				Case 4: Yellow-Red overlaps/gaps from Fully Off Yellow to Fully On Red			
Yellow	Red	Min	Average	Max	t-value *	Min	Average	Max	t-value *
Incandescent	Incandescent	12	14.49	19	106.95	10	12.36	17	80.42
Incandescent	LED Gelcore	10	13.10	17	95.96	8	11.90	16	80.18
Incandescent	LED Dialight	12	15.11	19	113.73	11	14.10	18	105.05
LED Gelcore	Incandescent	5	6.03	9	73.36	2	3.89	7	35.54
LED Gelcore	LED Gelcore	3	4.63	7	54.65	1	3.44	6	34.49
LED Gelcore	LED Dialight	5	6.65	9	81.39	4	5.63	8	68.71
LED Dialight	Incandescent	5	5.83	7	95.73	2	3.70	6	42.04
LED Dialight	LED Gelcore	3	4.44	6	72.66	1	3.25	5	42.50
LED Dialight	LED Dialight	5	6.46	8	112.69	4	5.44	7	95.17

* Critical t-value = 1.9812

Table 16b. Overlaps/gaps between two consecutive signal phases for Cases 3 and 4: Yellow to Red

9. Conclusion and Recommendations

Data was collected and analyzed to determine the turn on and turn off characteristics of incandescent and LED (Gelcore and Dialight) traffic signal modules. The analysis covered 114 cycles of signal timings, or approximately a period of three hours. Several measures to quantify the signal modules' characteristics were introduced. These measures included fade in and fade out times, turn on and turn off delay overlaps/gaps of colors between consecutive phase intervals.

For all colors, the LED lenses had shorter fade in times when compared with the incandescent lens. The fade in time for LED Dialight was shorter than that for LED Gelcore, for all the three colors. For solid green, the LED Dialight lens had the longest fade out time. For yellow and red, the LED Dialight lenses had shorter fade out times when compared to the other two lenses. For solid yellow and red, the incandescent lens had the longest fade out time. Except for LED Dialight solid red, all LED lenses turned on a fraction of second later than the corresponding incandescent lenses. LED Dialight solid red lens turned on earlier than the incandescent solid red lens. Except for LED Gelcore solid green lens all the LED lenses turned off a fraction of second earlier than the corresponding incandescent lenses.

While reducing the data from the video tapes, it was observed that when the traffic signal changed from one color to another, overlaps or gaps occurred. Overlaps/gaps between two consecutive intervals varied for different combinations of traffic signal modules. For analyzing the overlaps/gaps, four cases were evaluated considering different reference points as described in the report.

Two situations which could jeopardize the traffic safety are when the driver sees :

a) Two signals on simultaneously at the intersection. This translates into an overlap when measured using the procedure defined in case 2, i.e., the second signal is fully on even while the first one has yet to start turning off.

b) No signal at the intersection. This translates to a gap when measured using the procedure defined in case 3, i.e., the second signal is yet to start even though the first one has turned completely dark.

For both of the changes analyzed (green to yellow and yellow to red) no overlaps were observed when the procedure defined in case 2 was used and no gaps were observed when the procedure defined in case 3 was used. This clearly indicates that none of the combinations of the traffic signal lenses could result in multiple signals glowing or none of the signals glowing when used at an intersection.

Some readers may be concerned about the gaps observed when measured using procedures defined in Cases 1 and 2 and overlaps observed when measured using cases 3 and 4. To address these concerns, the investigators viewed the video tapes at regular speed and observed that in none of these cases, the viewers could see multiple signals glowing simultaneously or none of the signals glowing.