# TRANSPORATION POOLED FUND PROGRAM
# QUARTERLY PROGRESS REPORT

Lead Agency (University or Contractor):__Kansas DOT____________________________________

**INSTRUCTIONS:**
*Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the current status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.*

| | | |
|---|---|---|
| **Transportation Pooled Fund Project Number**<br>**TPF-5(351)** | | **Transportation Pooled Fund Program - Report Period:**<br>☐ Quarter 1 (January 1 – March 31)<br>☐ Quarter 2 (April 1 – June 30)<br>☐ Quarter 3 (July 1 – September 30)<br>X Quarter 4 (October 4 – December 31) |
| **Project Title: Self De-Icing LED Signals** | | |
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| **Lead Agency Project ID:**<br>**RE-0721-01** | **Other Project ID (i.e., contract #):** | **Project Start Date:**<br>August 15, 2016 |
| **Original Project End Date:**<br>**August 2019** | **Current Project End Date:**<br>**August 2019** | **Number of Extensions:**<br>0 |

Project schedule status:

X On schedule ☐ On revised schedule ☐ Ahead of schedule ☐ Behind schedule

Overall Project Statistics:

| Total Project Budget | Total Cost to Date for Project | Total Percentage of Work Completed |
|---|---|---|
| $240,000 original, $320,000 with addendum | $196,489 | 65% |

***Quarterly*** Project Statistics:

| Total Project Expenses This Quarter | Total Amount of Funds Expended This Quarter | Percentage of Work Completed This Quarter |
|---|---|---|
| $52,179 | $52,179 | 10% |

**Project Description**:

This pooled fund project will develop and demonstrate new self de-icing LED signals for highway signalized intersections and railroad signaling applications to solve a well-known problem of the existing LED signal light whose lens is too cool to melt snow and de-ice in wintery conditions. The self de-icing LED signals will adopt one or both of two novel architectures (Figure 1), including (a) "Heated Lens Lighting Arrangement" that uses a single high-power LED and (b) "Heat Arrangement of LED Arrays in Low Profile" that deploys multiple LEDs. The heat generated by the LED(s) is harvested by the passive heat exchanger and stored to heat the lens for melting snow and de-icing in wintery conditions.

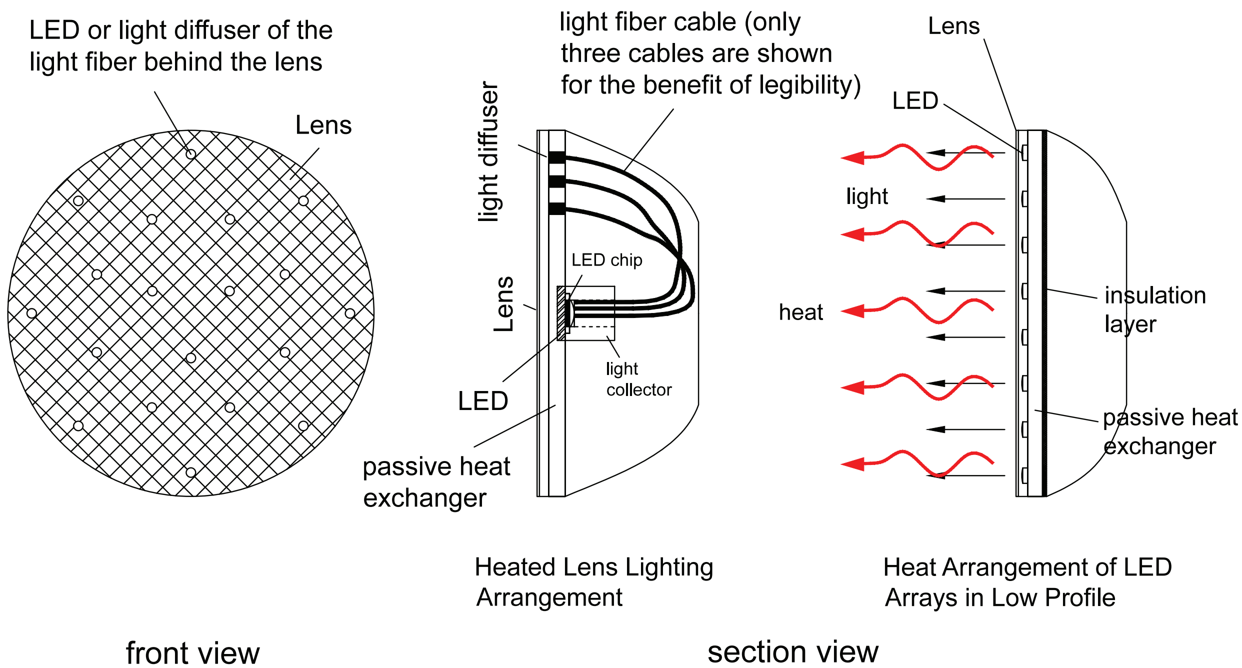



**Figure 1** The concept of the self de-icing LED signal light, which adopts new architecture of "Heated Lens Lighting Arrangement" or "Heat Arrangement of LED Arrays in Low Profile"

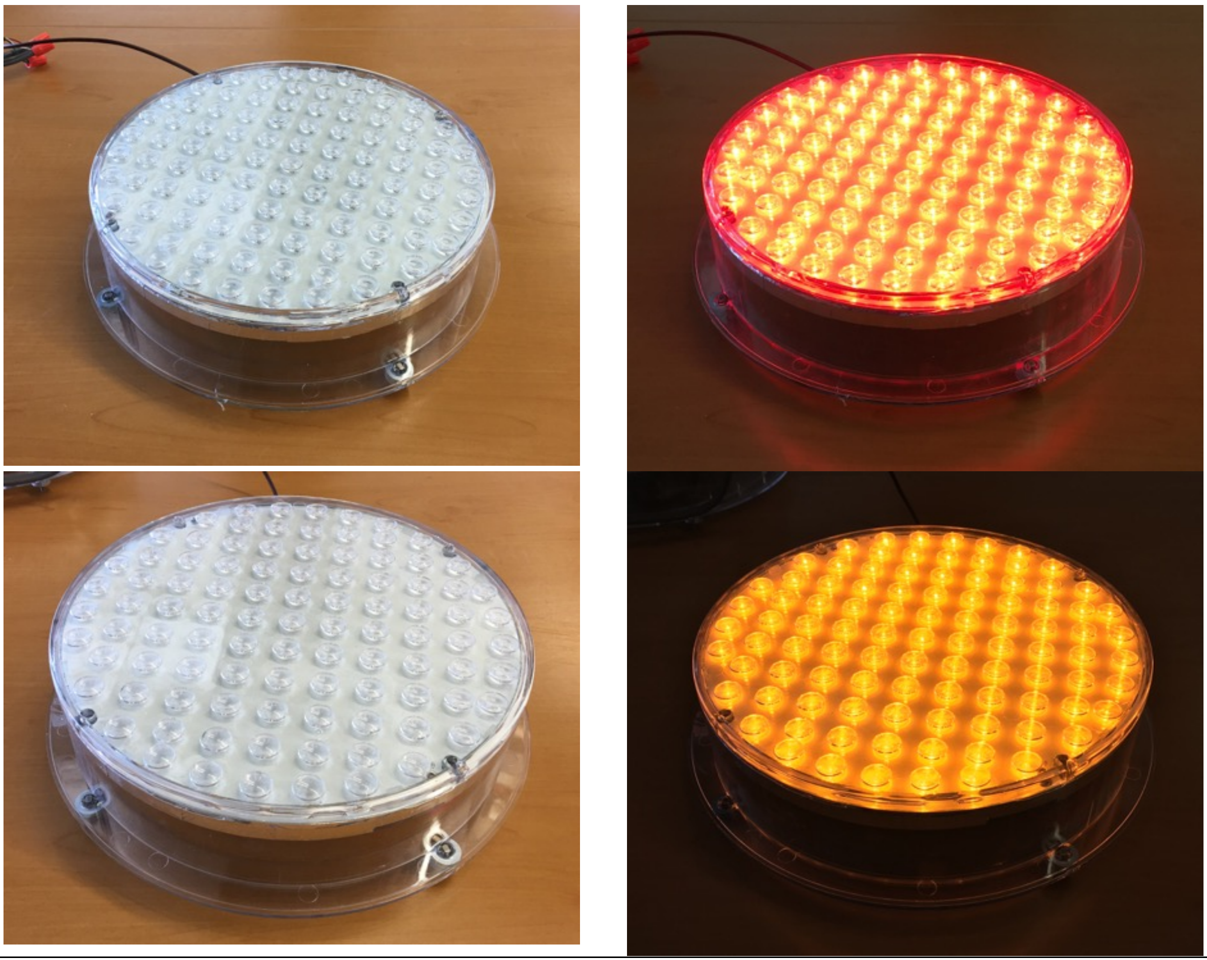
Fully working prototypes of the self-de-icing LED signals have been developed and tested in the laboratory. They have been tested in closed-course settings on the roof of an engineering building followed by field tests on highway intersection and railroad wayside or at-grade crossing signal lights. Each participating agency is required to provide support of three years of funding ($20,000/year, totaling $60,000) and will be guaranteed a field test site in each state for testing the fully working prototypes catering to their specific needs of the new type of signals. The research team will work with each participating agency to identify the desired test site on highway intersections or rail track sections and the desired technical specifications for testing the prototypes.

The investigative approach for the proposed project is divided into the three stages. Work in Stage 1 focuses on laboratory development and tests. Work in Stage 2 focuses on testing the three prototypes in a closed-course setting on the roof of the University of Kansas engineering complex and powered by the signal controller cabinet. Work in the third and final stage involves field testing of the developed prototypes on identified highway signalized intersections and rail track sections. On-site demonstration of the prototype signals will also be held for project partners and state DOTs to initiate the implementation process. A final report will provide all relevant data and results along with plans for implementation of the self-de-icing LED signals in affected states.

**Progress this Quarter (includes meetings, work plan status, contract status, significant progress, etc.):**

During the third quarter (Sept 1, 2018 – Dec 31, 2018) of the project period, we have the following accomplishments.

We have improved the prototypes to the fourth generation (**Figure 1**) with updated LED drivers, plastic housing and new mounting gears, and continued the roof tests of the real-time performance and reliability of the new prototypes in cold snowy winter (**Figure 2**).



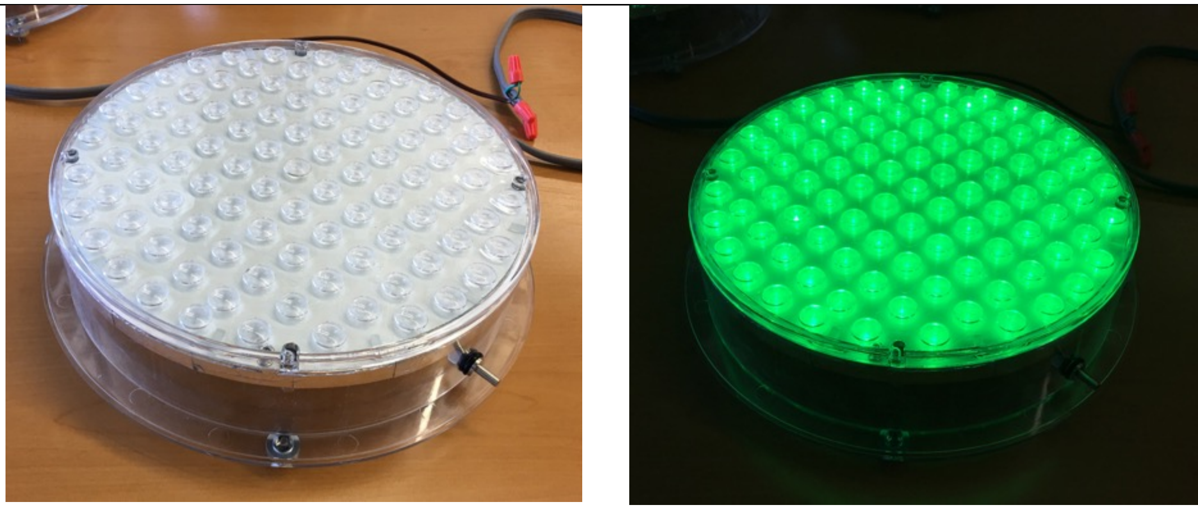


**Figure 1** The fourth generation of signal lights with improvements.

**Figure 2** shows the ongoing roof tests of the fully working prototypes in real-time snowy winter. All signal lights were powered by the signal controller cabinet with real signaling time cycles (in a cycle length of 90 seconds, Red signal light ON for 50 seconds, Green signal light ON for 35 seconds, and Yellow signal light ON for 5 seconds. The signaling time cycles are adjustable, might be adjusted in the upcoming winter season for testing different cycles. A data logger mounted on the tripod pole was connected to a total of 12 temperature sensors mounted on each of the surfaces of the signal lights (4 sensors on each signal light lens), and one more ambient temperature sensor attached on the pole. The temperature data were recorded every 10 seconds continuously over the entire test period, which will be continuously conducted over both winter and summer seasons in 2019.

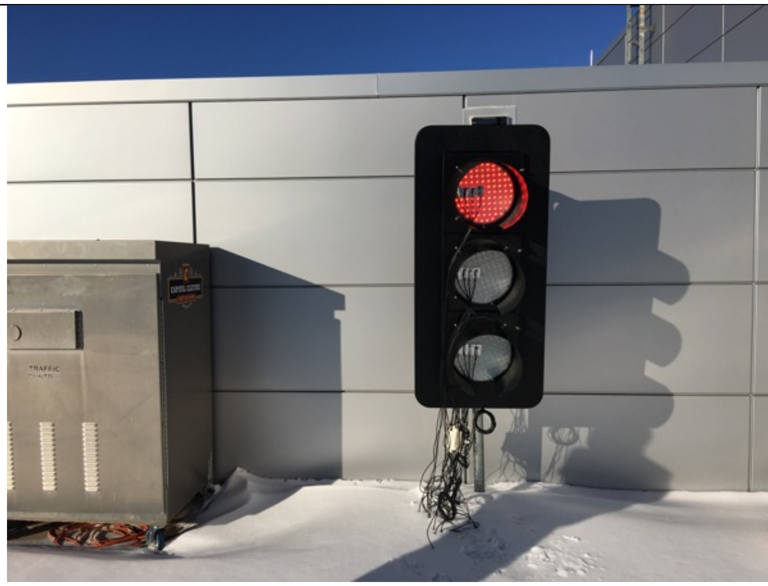


**Figure 2** In real-time snowy winter, the closed-course performance and reliability tests of the fully workin prototypes mounted on the roof of M2SEC building. The roof tests will be continuously conducted in 2019 w necessary real-time adjustments.

**Figure 3** shows the roof test results recorded between Dec 14 through Dec 17 in the real-time wintery conditions. The surface temperature of each signal light jumped when the air temperature was dropped to 4 deg Celsius (39.2 deg Fahrenheit), because the remote ambient temperature sensor attached to each signal light switched the signal light from derated output to full power output. Based on the laboratory measurement, the actual electric current of the prototype signals, at derated / full power output, were shown below.

- Yellow/green LED driver: 0.422A (derated) /0.844 A (full output) for prototype signal #1, 0.402A/0.837A for signal #2, 0.404A/0.838A for signal #3

- Red LED driver: 0.618A (derated)/1.115A (full output) for prototype signal #4, 0.598A (derated)/1.110A (full output) for prototype signal #5, 0.543A (derated)/1.108A (full output) for prototype signal #6

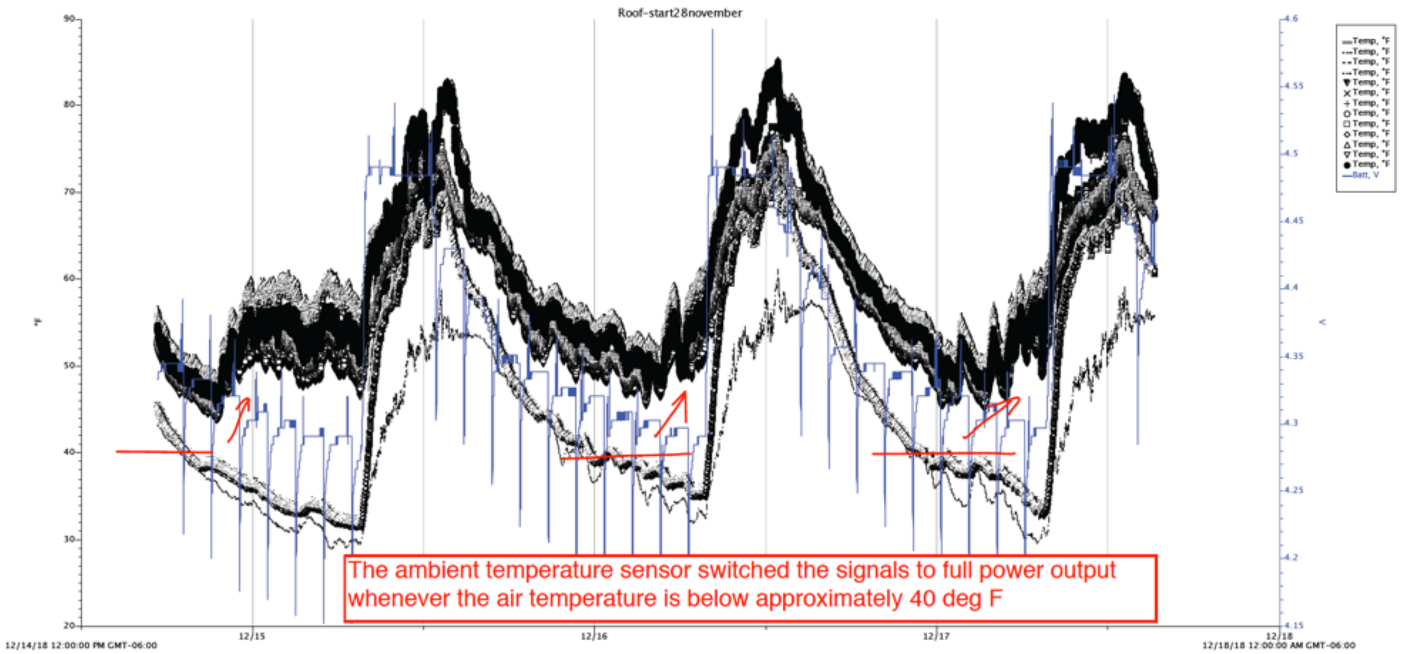



**Figure 3** The roof test data recorded in the snowy winter conditions, showing surface temperature jumped when the ambient air temperature was below 4 deg Celsius (39.2 deg Fahrenheit) as designed.

We also conducted thorough tests of those prototype signals in the laboratory for their heating performance to double check the LED driver's performance and reliability, including the switching ambient air temperature sensor attached to the signals. **Figure 4** shows the testing in the cold room which has well controlled ambient temperature and humidity. However, it was found that the switching temperature was not always at 4 deg Celsius (39.2 deg Fahrenheit) as designed. The actual switching temperature of the sensor was minimum 2.6 deg Celsius, maximum 3.4 deg Celsius, with large deviation. This is not acceptable.  In addition, the wiring of the ambient air temperature sensor to the PCB board has some problems, which prevents installation of the sensor without cutting the wires, as shown in **Figure 5**. As a results, we have requested the LED driver company to make improvements.

**Figure 4** The tests of the fourth generation of prototype signals in the cold room, to double check the switching performance of the ambient air temperature sensor attached to each signal.

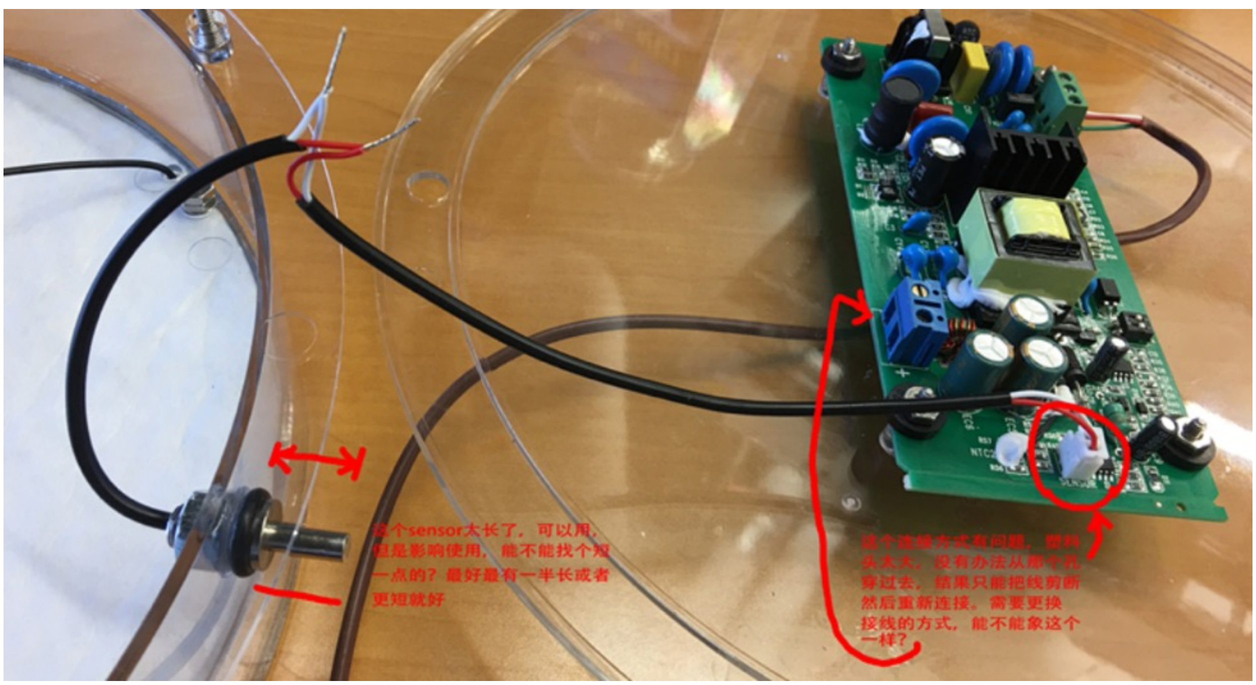



**Figure 5** The switching temperature sensor attached to each signal has some problems of wiring, need improvement.

We also tested the performance of the prototypes in chest freezer under extremely low temperature, like we did before, to compare the thermal performance of the fourth generation to the previous generations. The test results are shown in **Table 1**. The test results show that the fourth generation of signals powered by the new LED drivers have appropriate thermal performance similar to previous generations. However, it is necessary to look into the insulation performance of the housing and installation to seek further improvement if possible.

**Table 1** Thermal performance of the fourth generation signals compared to previous generations.

| | | | | | |
|---|---|---|---|---|---|
| Test conditions | Freezer, 3 signals tested together | | | | |
| Type 2 LED signals | old LED driver | Type 2 insulation | | | |
| Ambient Temp | ambient | 19.6 | Deg F | current | |
| Surface temp | green | 79.1 | Deg F | 0.841 A | old LED driver |
| | Yellow | 68.5 | Deg F | 0.842 A | old LED driver |
| | Red | 60.3 | Deg F | 0.823 A | old LED driver |
| Temp difference | green | 59.5 | Deg F | | |
| | Yellow | 48.9 | Deg F | | |
| | Red | 40.7 | Deg F | | |

| | | | | | |
|---|---|---|---|---|---|
| Test conditions | Freezer, 3 signals tested together | | | | |
| Type 2 LED signals | new LED driver | Type 2 insulation | | | |
| Ambient Temp | Ambient | 21.5 | Deg F | current | |
| Surface temp | green | 76.5 | Deg F | 0.837 A | new LED driver |
| | Yellow | 76.9 | Deg F | 0.838 A | new LED driver |
| | Red | 72.8 | Deg F | 1.115 A | new LED driver |
| Temp difference | green | 55 | Deg F | | |
| | Yellow | 55.4 | Deg F | | |
| | Red | 51.3 | Deg F | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Test conditions | Freezer, 3 singals tested together | | | | | |
| Type 1 LED signals | new LED driver | type 1 insulation | | | | |
| Ambient Temp | Ambient | 21.3 | Deg F | | | |
| Surface temp | green | 63.8 | Deg F | 0.844 A | new LED driver | |
| | Yellow | 82.5 | Deg F | 1.108 A | new LED driver | |
| | Red | 72.5 | Deg F | 1.110 A | new LED driver | |
| Temp difference | green | 42.5 | Deg F | | | |
| | Yellow | 61.2 | Deg F | | | |
| | Red | 51.2 | Deg F | | | |

| | | | | | |
|---|---|---|---|---|---|
| Test conditions | Freezer, 1 signal tested each time | | | | |
| OLD LED signals | old LED driver | old insulation | | current | |
| Temp difference | green | 55.67 | Deg F | 0.842 A | old LED driver |
| | Yellow | 53.62 | Deg F | 0.843 A | old LED driver |
| | RED | 39.17 | Deg F | 0.840 A | old LED driver |

| | | | | |
|---|---|---|---|---|
| Test conditions | Freezer, 1 signal tested alone | | | |
| OLD LED signals | new LED driver | old insulation | | |
| Temp difference | green | 56.3 | Deg F | 0.844 A |
| | Yellow | 71 | Deg F | 1.110 A |
| | RED | 48.5 | Deg F | 1.110 A |

| | | | | | |
|---|---|---|---|---|---|
| Test conditions | Freezer, 1 signal tested each time | | | | |
| Type 1 LED signals | new LED driver | type 1 insulation | | current | |
| Temp difference | green | 55.85 | Deg F | 0.844 A | old LED driver |
| | Yellow | 67.61 | Deg F | 1.109 A | old LED driver |
| | RED | 51.02 | Deg F | 1.110 A | old LED driver |

Next, we measured the lighting performance of the fourth generation of the prototype signals at both derated or dimmed and full power output modes when the ambient air temperature is above or below 4 deg Celsius (39.2 deg Fahrenheit). **Tables 3-8** summarize the measurement results, all passed the code requirements (**Table 2**).

**Table 2** Lighting performance required by codes and standards.

Peak minimum maintained luminous intensity values, at $\theta_{Vert} = -2.5$ deg and $\theta_{Horiz} = 0$ deg [$\mathbf{I}_{(-2.5,\,0)}$], by size and color of the module are:

| Color | $\mathbf{I}_{(-2.5,\,0)}$ 200mm | 300mm |
|---|---|---|
| Red | 165 cd | 365 cd |
| Yellow | 410 cd | 910 cd |
| Green | 215 cd | 475 cd |

Table 1 provides the minimum maintained luminous intensity values for the VTCSH LED Circular Signal, for the range from 12.5 degrees above to 22.5 degrees below the horizontal plane, and from 27.5 degrees left to 27.5 degrees right of the vertical plane, at 5 degree increments.

Minimum Maintained Luminous Intensity Values—VTCSH LED Circular Signal

| Vertical Angle | Horizontal Angle | Luminous Intensity (candela) 200mm (8-inch) Red | Yellow | Green | 300 mm (12-inch) Red | Yellow | Green |
|---|---|---|---|---|---|---|---|
| +12.5 | 2.5 | 17 | 41 | 22 | 37 | 91 | 48 |
| | 7.5 | 13 | 33 | 17 | 29 | 73 | 38 |
| +7.5 | 2.5 | 31 | 78 | 41 | 69 | 173 | 90 |
| | 7.5 | 25 | 62 | 32 | 55 | 137 | 71 |
| | 12.5 | 18 | 45 | 24 | 40 | 100 | 52 |
| +2.5 | 2.5 | 68 | 168 | 88 | 150 | 373 | 195 |
| | 7.5 | 56 | 139 | 73 | 124 | 309 | 162 |
| | 12.5 | 38 | 94 | 49 | 84 | 209 | 109 |
| | 17.5 | 21 | 53 | 28 | 47 | 118 | 62 |
| | 22.5 | 12 | 29 | 15 | 26 | 64 | 33 |
| -2.5 | 2.5 | 162 | 402 | 211 | 358 | 892 | 466 |
| | 7.5 | 132 | 328 | 172 | 292 | 728 | 380 |
| | 12.5 | 91 | 226 | 118 | 201 | 501 | 261 |
| | 17.5 | 53 | 131 | 69 | 117 | 291 | 152 |
| | 22.5 | 28 | 70 | 37 | 62 | 155 | 81 |
| | 27.5 | 15 | 37 | 19 | 33 | 82 | 43 |
| -7.5 | 2.5 | 127 | 316 | 166 | 281 | 701 | 366 |
| | 7.5 | 106 | 262 | 138 | 234 | 582 | 304 |
| | 12.5 | 71 | 176 | 92 | 157 | 391 | 204 |
| | 17.5 | 41 | 103 | 54 | 91 | 228 | 119 |
| | 22.5 | 21 | 53 | 28 | 47 | 118 | 62 |
| | 27.5 | 12 | 29 | 15 | 26 | 64 | 33 |
| -12.5 | 2.5 | 50 | 123 | 65 | 110 | 273 | 143 |
| | 7.5 | 40 | 98 | 52 | 88 | 218 | 114 |
| | 12.5 | 28 | 70 | 37 | 62 | 155 | 81 |
| | 17.5 | 17 | 41 | 22 | 37 | 91 | 48 |
| | 22.5 | 8 | 21 | 11 | 18 | 46 | 24 |
| | 27.5 | 5 | 12 | 6 | 11 | 27 | 14 |
| -17.5 | 2.5 | 23 | 57 | 30 | 51 | 127 | 67 |
| | 7.5 | 18 | 45 | 24 | 40 | 100 | 52 |
| | 12.5 | 13 | 33 | 17 | 29 | 73 | 38 |
| | 17.5 | 7 | 16 | 9 | 15 | 36 | 19 |
| | 22.5 | 3 | 8 | 4 | 7 | 18 | 10 |
| -22.5 | 2.5 | 17 | 41 | 22 | 37 | 91 | 48 |
| | 7.5 | 13 | 33 | 17 | 29 | 73 | 38 |
| | 12.5 | 10 | 25 | 13 | 22 | 55 | 29 |
| | 17.5 | 5 | 12 | 6 | 11 | 27 | 14 |
| -27.5 | 2.5 | 12 | 29 | 15 | 26 | 64 | 33 |
| | 7.5 | 8 | 21 | 11 | 18 | 46 | 24 |

Note 1: Luminous intensity values for equivalent left and right horizontal angles are the same.
Note 2: Tabulated values of luminous intensity are rounded to the nearest whole value.

**Table 3** Lighting performance of **derated/dimmed RED** signal light of the fourth generation

| signal light color | red | Wattage | dimmed | | | |
|---|---|---|---|---|---|---|
| tilting angle | Illuminance in lux | | | Average (lx) | distance(m) | **intensity (cd)** |
| 0 | 190.9 | 190.8 | 190.9 | 190.9 | 2.236 | **954.3** |
| 0.5 | 194 | 193.9 | 194.1 | 194.0 | 2.236 | **969.9** |
| 1 | 196.3 | 196.4 | 196.2 | 196.3 | 2.236 | **981.4** |
| 1.5 | 199.6 | 199.4 | 199.4 | 199.5 | 2.236 | **997.3** |
| 2 | 202.5 | 202.6 | 202.5 | 202.5 | 2.236 | **1012.6** |
| 2.5 | 205.8 | 205.9 | 205.7 | 205.8 | 2.236 | **1028.9** |
| 3 | 209.8 | 209.7 | 209.7 | 209.7 | 2.236 | **1048.6** |
| 3.5 | 213.2 | 213.4 | 213.1 | 213.2 | 2.236 | **1066.1** |
| 4 | 217.4 | 217.3 | 217.3 | 217.3 | 2.236 | **1086.6** |
| 4.5 | 220 | 220 | 220 | 220.0 | 2.236 | **1099.9** |
| 5 | 222 | 221.8 | 221.9 | 221.9 | 2.236 | **1109.4** |
| 6 | 223.8 | 224 | 223.6 | 223.8 | 2.236 | **1118.9** |
| 7 | 224.6 | 224.4 | 224.2 | 224.4 | 2.236 | **1121.9** |
| 8 | 221.4 | 221.6 | 221.3 | 221.4 | 2.236 | **1107.1** |
| 9 | 217.6 | 217.8 | 217.7 | 217.7 | 2.236 | **1088.4** |
| 10 | 214.8 | 214.9 | 214.6 | 214.8 | 2.236 | **1073.8** |
| 20 | 189.3 | 189.6 | 189.4 | 189.4 | 2.236 | **947.1** |
| 30 | 75.2 | 75.1 | 75.2 | 75.2 | 2.236 | **375.8** |
| 40 | 17.19 | 17.17 | 17.18 | 17.2 | 2.236 | **85.9** |
| 50 | 13.46 | 13.44 | 13.42 | 13.4 | 2.236 | **67.2** |
| 60 | 21.66 | 21.65 | 21.67 | 21.7 | 2.236 | **108.3** |
| 70 | 10.42 | 10.37 | 10.36 | 10.4 | 2.236 | **51.9** |

**Table 4** Lighting performance of **derated/dimmed YELLOW** signal light of the fourth generation

| signal light color | yellow | Wattage | dimmed | | | |
|---|---|---|---|---|---|---|
| tilting angle | Illuminance in lux | | | Average (lx) | distance(m) | **intensity (cd)** |
| 0 | 425 | 425 | 425 | 425.0 | 2.236 | **2124.87** |
| 0.5 | 425 | 426 | 425 | 425.3 | 2.236 | **2126.54** |
| 1 | 427 | 426 | 426 | 426.3 | 2.236 | **2131.54** |
| 1.5 | 427 | 427 | 427 | 427.0 | 2.236 | **2134.87** |
| 2 | 428 | 428 | 427 | 427.7 | 2.236 | **2138.20** |
| 2.5 | 427 | 427 | 428 | 427.3 | 2.236 | **2136.54** |
| 3 | 427 | 427 | 427 | 427.0 | 2.236 | **2134.87** |
| 3.5 | 426 | 426 | 426 | 426.0 | 2.236 | **2129.87** |
| 4 | 425 | 425 | 425 | 425.0 | 2.236 | **2124.87** |
| 4.5 | 423 | 424 | 423 | 423.3 | 2.236 | **2116.54** |
| 5 | 422 | 422 | 422 | 422.0 | 2.236 | **2109.87** |
| 6 | 418 | 418 | 418 | 418.0 | 2.236 | **2089.87** |
| 7 | 414 | 414 | 414 | 414.0 | 2.236 | **2069.87** |
| 8 | 408 | 408 | 407 | 407.7 | 2.236 | **2038.21** |
| 9 | 402 | 402 | 402 | 402.0 | 2.236 | **2009.88** |
| 10 | 397 | 397 | 397 | 397.0 | 2.236 | **1984.88** |
| 20 | 340 | 341 | 341 | 340.7 | 2.236 | **1703.23** |
| 30 | 109 | 109 | 109 | 109.0 | 2.236 | **544.97** |
| 40 | 30.3 | 30.4 | 30.6 | 30.4 | 2.236 | **152.16** |
| 50 | 24.19 | 24.18 | 24.18 | 24.2 | 2.236 | **120.91** |
| 60 | 31.9 | 31.9 | 31.9 | 31.9 | 2.236 | **159.49** |
| 70 | 30.5 | 30.5 | 30.5 | 30.5 | 2.236 | **152.49** |

**Table 5** Lighting performance of **derated/dimmed GREEN** signal light of the fourth generation

| signal light color | Green | Wattage | dimmed | | | |
|---|---|---|---|---|---|---|
| tilting angle | Illuminance in lux | | | average (lx) | distance(m) | **intensity (cd)** |
| 0 | 344 | 344 | 344 | 344.0 | 2.236 | **1719.9** |
| 0.5 | 348 | 348 | 348 | 348.0 | 2.236 | **1739.9** |
| 1 | 350 | 351 | 350 | 350.3 | 2.236 | **1751.6** |
| 1.5 | 351 | 351 | 351 | 351.0 | 2.236 | **1754.9** |
| 2 | 351 | 351 | 351 | 351.0 | 2.236 | **1754.9** |
| 2.5 | 350 | 350 | 350 | 350.0 | 2.236 | **1749.9** |
| 3 | 347 | 347 | 347 | 347.0 | 2.236 | **1734.9** |
| 3.5 | 344 | 344 | 344 | 344.0 | 2.236 | **1719.9** |
| 4 | 342 | 342 | 342 | 342.0 | 2.236 | **1709.9** |
| 4.5 | 338 | 338 | 338 | 338.0 | 2.236 | **1689.9** |
| 5 | 335 | 335 | 334 | 334.7 | 2.236 | **1673.2** |
| 6 | 325 | 325 | 325 | 325.0 | 2.236 | **1624.9** |
| 7 | 318 | 318 | 318 | 318.0 | 2.236 | **1589.9** |
| 8 | 313 | 313 | 313 | 313.0 | 2.236 | **1564.9** |
| 9 | 307 | 307 | 307 | 307.0 | 2.236 | **1534.9** |
| 10 | 303 | 303 | 303 | 303.0 | 2.236 | **1514.9** |
| 20 | 281.5 | 281.6 | 281.4 | 281.5 | 2.236 | **1407.4** |
| 30 | 115.6 | 115.9 | 116 | 115.8 | 2.236 | **579.1** |
| 40 | 34.1 | 34.1 | 34.1 | 34.1 | 2.236 | **170.5** |
| 50 | 27.7 | 27.7 | 27.7 | 27.7 | 2.236 | **138.5** |
| 60 | 36.8 | 36.7 | 36.7 | 36.7 | 2.236 | **183.7** |
| 70 | 26.3 | 26.3 | 26.3 | 26.3 | 2.236 | **131.5** |

**Table 6** Lighting performance of **FULLY powered RED** signal light of the fourth generation

| signal light color | red | Wattage | full | | | |
|---|---|---|---|---|---|---|
| tilting angle | Illuminance in lux | | | average(lx) | distance(m) | **intensity (cd)** |
| 0 | 377 | 377 | 377 | 377.0 | 2.236 | **1884.9** |
| 0.5 | 374 | 374 | 374 | 374.0 | 2.236 | **1869.9** |
| 1 | 368 | 368 | 368 | 368.0 | 2.236 | **1839.9** |
| 1.5 | 362 | 362 | 362 | 362.0 | 2.236 | **1809.9** |
| 2 | 355 | 355 | 355 | 355.0 | 2.236 | **1774.9** |
| 2.5 | 352 | 352 | 352 | 352.0 | 2.236 | **1759.9** |
| 3 | 347 | 347 | 347 | 347.0 | 2.236 | **1734.9** |
| 3.5 | 344 | 344 | 344 | 344.0 | 2.236 | **1719.9** |
| 4 | 341 | 341 | 341 | 341.0 | 2.236 | **1704.9** |
| 4.5 | 338 | 338 | 338 | 338.0 | 2.236 | **1689.9** |
| 5 | 336 | 336 | 336 | 336.0 | 2.236 | **1679.9** |
| 6 | 329 | 329 | 329 | 329.0 | 2.236 | **1644.9** |
| 7 | 323 | 323 | 323 | 323.0 | 2.236 | **1614.9** |
| 8 | 317 | 317 | 317 | 317.0 | 2.236 | **1584.9** |
| 9 | 312 | 312 | 312 | 312.0 | 2.236 | **1559.9** |
| 10 | 307 | 308 | 307 | 307.3 | 2.236 | **1536.6** |
| 20 | 290.6 | 290.5 | 290.3 | 290.5 | 2.236 | **1452.2** |
| 30 | 52.8 | 52.8 | 52.8 | 52.8 | 2.236 | **264.0** |
| 40 | 27.95 | 27.96 | 27.95 | 28.0 | 2.236 | **139.8** |
| 50 | 22.08 | 22.05 | 22.03 | 22.1 | 2.236 | **110.3** |
| 60 | 34.4 | 34.3 | 34.3 | 34.3 | 2.236 | **171.7** |
| 70 | 16.17 | 16.16 | 16.15 | 16.2 | 2.236 | **80.8** |

**Table 7** Lighting performance of **FULLY powered Yellow** signal light of the fourth generation

| signal light color | yellow | Wattage | full | | | |
|---|---|---|---|---|---|---|
| tilting angle | Illuminance in lux | | | average (lx) | distance (m) | **intensity (cd)** |
| 0 | 825 | 825 | 825 | 825.0 | 2.236 | **4124.7** |
| 0.5 | 829 | 829 | 829 | 829.0 | 2.236 | **4144.7** |
| 1 | 833 | 833 | 833 | 833.0 | 2.236 | **4164.7** |
| 1.5 | 835 | 835 | 835 | 835.0 | 2.236 | **4174.7** |
| 2 | 837 | 837 | 837 | 837.0 | 2.236 | **4184.7** |
| 2.5 | 838 | 838 | 838 | 838.0 | 2.236 | **4189.7** |
| 3 | 839 | 839 | 839 | 839.0 | 2.236 | **4194.7** |
| 3.5 | 839 | 839 | 839 | 839.0 | 2.236 | **4194.7** |
| 4 | 838 | 839 | 838 | 838.3 | 2.236 | **4191.4** |
| 4.5 | 837 | 837 | 837 | 837.0 | 2.236 | **4184.7** |
| 5 | 837 | 837 | 837 | 837.0 | 2.236 | **4184.7** |
| 6 | 831 | 831 | 831 | 831.0 | 2.236 | **4154.7** |
| 7 | 821 | 821 | 821 | 821.0 | 2.236 | **4104.8** |
| 8 | 812 | 811 | 811 | 811.3 | 2.236 | **4056.4** |
| 9 | 801 | 802 | 801 | 801.3 | 2.236 | **4006.4** |
| 10 | 789 | 788 | 788 | 788.3 | 2.236 | **3941.4** |
| 20 | 675 | 675 | 675 | 675.0 | 2.236 | **3374.8** |
| 30 | 175.6 | 175.7 | 175.7 | 175.7 | 2.236 | **878.3** |
| 40 | 59.5 | 59.5 | 59.4 | 59.5 | 2.236 | **297.3** |
| 50 | 47.1 | 47 | 47.1 | 47.1 | 2.236 | **235.3** |
| 60 | 64.9 | 64.8 | 64.8 | 64.8 | 2.236 | **324.1** |
| 70 | 61.6 | 61.7 | 61.6 | 61.6 | 2.236 | **308.1** |

**Table 8** Lighting performance of **FULLY powered Green** signal light of the fourth generation

| signal light color | green | Wattage | full | | | |
|---|---|---|---|---|---|---|
| tilting angle | Illuminance in lux | | | average (lx) | distance (m) | **intensity (cd)** |
| 0 | 562 | 562 | 561 | 561.7 | 2.236 | **2808.2** |
| 0.5 | 564 | 564 | 564 | 564.0 | 2.236 | **2819.8** |
| 1 | 564 | 564 | 564 | 564.0 | 2.236 | **2819.8** |
| 1.5 | 561 | 561 | 561 | 561.0 | 2.236 | **2804.8** |
| 2 | 555 | 555 | 555 | 555.0 | 2.236 | **2774.8** |
| 2.5 | 551 | 551 | 551 | 551.0 | 2.236 | **2754.8** |
| 3 | 548 | 548 | 548 | 548.0 | 2.236 | **2739.8** |
| 3.5 | 541 | 541 | 541 | 541.0 | 2.236 | **2704.8** |
| 4 | 533 | 533 | 534 | 533.3 | 2.236 | **2666.5** |
| 4.5 | 526 | 526 | 526 | 526.0 | 2.236 | **2629.8** |
| 5 | 521 | 521 | 521 | 521.0 | 2.236 | **2604.8** |
| 6 | 509 | 510 | 510 | 509.7 | 2.236 | **2548.2** |
| 7 | 498 | 498 | 498 | 498.0 | 2.236 | **2489.8** |
| 8 | 492 | 492 | 492 | 492.0 | 2.236 | **2459.9** |
| 9 | 481 | 481 | 481 | 481.0 | 2.236 | **2404.9** |
| 10 | 473 | 473 | 473 | 473.0 | 2.236 | **2364.9** |
| 20 | 443 | 443 | 443 | 443.0 | 2.236 | **2214.9** |
| 30 | 182.7 | 183 | 182.6 | 182.8 | 2.236 | **913.8** |
| 40 | 54 | 54 | 54 | 54.0 | 2.236 | **270.0** |
| 50 | 43.3 | 43.3 | 43.3 | 43.3 | 2.236 | **216.5** |
| 60 | 56.9 | 56.9 | 56.8 | 56.9 | 2.236 | **284.3** |
| 70 | 41.3 | 41.2 | 41.2 | 41.2 | 2.236 | **206.2** |

Based on the changes in need of the LED drivers and the appropriate thermal and lighting performance, we need to adjust the plastic housing design to change the sizes of some mounting holes, and also enlarge four mounting rods to make the future installation more secured.

**Anticipated work next quarter**:

Starting from Oct 1, 2018 till December 31, 2018, we are planning to conduct the following tasks.

1. Assemble all improved prototypes to be tested in the field sites.

2. When the improved prototypes ready for field tests, we will start identify field test sites and test specifications at each site with the aid of sponsor states.

3. Travel to the field for field installation and field test over a whole year with remote monitoring of the field tests.

4. Continue roof testing of the prototypes in the closed-setting for continuous improvements.

**Significant Results:**

As of Dec 31, 2018, we have achieved the following significant results.

- This project was launched in Aug 2016 with six participating states (Kansas, California, Michigan, New Jersey, Wisconsin, and Pennsylvania) and an initial budget of $240,000. Maryland is expected to officially join the study by the end of this year with additional contribution of three years funding.

- An expert panel meeting was held in early March. Discussions were held on desired specifications of the prototype signals and possible field test sites as well as the field evaluation of the prototypes.

- Necessary equipment, components and insulation materials are being procured to develop and build the fully working prototypes of the finalized design and test for their thermal and lighting performance. We will continue to order LED drivers, electricity monitors, waterproof security video cameras, other mounting accessories and materials, etc., for monitoring the performance of the prototypes in the field tests in the upcoming winter season.

- Appropriate color LED modules, which are not available in the market, were designed in-house and custom-made with the aid of the industrial partner.

- Three preliminary prototype signals (Red, Yellow, and Green) of Type 1 have been developed in house, each deploying 26 custom-made color LEDs mounted in an array via “Heat Arrangement of LED Arrays in Low Profile”. They are under laboratory testing for improvements.

- Tested the lighting and thermal performance of the preliminary prototypes of the Type 1 signal lights

(Figure 1). Based on the test results, new design with a lot of changes and improvements has been finalized for final products.

- Finalized the design of Type 1 self de-icing LED signals using 96 custom-made mediate-power color LEDs mounted in an array via "Heat Arrangement of LED Arrays in Low Profile". Designed in house and custom-made our own color LED modules (for each color R, G, Y) for making the fully working prototype signals of the first type with the aid of our industrial partner.

- Worked with the factories to optimize the mounting method of the custom-made LED modules on the 3-5 mm thick aluminum MPCB back plate serving as the passive heat exchangers of aluminum alloy for assembly.

- Custom-made three prototypes of the LED signals of Type 1 using 96 custom-made mediate-power color LEDs mounted in an array via "Heat Arrangement of LED Arrays in Low Profile", with regular paint coating, and finished laboratory testing for improvements and optimizations to finalize the design.

- Improved and custom-made three new signal light engines using 96 medium-power LEDs (0.25 Watt each) mounted in an array via "Heat Arrangement of LED Arrays in Low Profile" but with Tin coating (Figure 3) and tested them to improve the heating performance (to make faster heat transfer).

- Finalized the design of the signal lens that adopts a whole piece design with smooth and flat outside surface and integrated with 96 additional custom-made Fresnel lenses sitting inside the signal lens over each LED on the inside surface to focus the light serving as a collimator lens. Based on the testing results, the signal light engines with TIN coating may have superior thermal performance, however, further testing in the laboratory and field is necessary to validate the final choice.

- Identified and started custom-making the Fresnel Lens from HongXuan Optoelectronic company with diameter 15 mm and focal length 6 mm (model # HX-F015006).

- Developed the new whole-piece signal housing, new Fresnel lenses, LED drivers, and other accessories for the Type 1 self de-icing LED signal lights, with the aid of the industrial partner.

- Found and selected a qualified plastic molding company to custom make the three parts of the plastic housing of fully working prototypes of Type 1 signals that deploy 96 mediate-power LEDs via the architecture of "Heat Arrangement of LED Arrays in Low Profile". The new housing will be used for the new LED signal lights.

- The non-provisional patent application for the invention of Type 2 self de-icing signal light was officially approved by the USPTO and issued on Dec 26, 2017, patent No. US 9,851,086 B2.

- Started custom-making and modeling of the signal housing. Three samples were delivered for examinations and laboratory tests for necessary calibrations and further improvements.

- Started custom-making the LED drivers with desired specifications based on our test results. Seven LED drivers were delivered for sample testing.

- The custom-made signal housing is ready for production of products with possible minor adjustments for field tests in different states. Six improved samples have been delivered and thoroughly tested in laboratory and closed-setting tests on the roof.

- New type of screws for uses in the signal housing are self-designed and will be custom-made with Fastenal company.

- A company is custom making two improved and finalized types of LED driver, one for YELLOW and GREEN signal lights (output 0.8 A, maximum 30 Watts), the other for RED signal light (output 1.1 A, maximum 30 Watts). The new LED drivers have temperature Sensor control, when the temperature is above 4 degree Celsius, the LED driver output will be derated (For Yellow + Green LED lights, output current 0.5 A, approximately 17- 18 Watts; For Red LED light, output current min 0.6 A, approximately 15-16 Watts.) When the temperature sensor is turned off or failed for any reasons, the power output will be restored to 100% as default.

- The self-deicing signal lights have higher light output than the codes and standards required in all viewing angles from 0 deg to 70 deg as measured, even at the derated power output.

- We have been conducting a closed-course performance and reliability tests of the fully working prototypes mounted on the roof of the University of Kansas engineering complex - M2SEC building, in preparation for field tests.

- Seven states have officially participated in this project, including Kansas, California, Michigan, New Jersey, Wisconsin, Pennsylvania and Maryland to provide support.

- A project addendum is proposed to conduct two additional field tests, one in Wisconsin and another one in a test site among Maryland, Pennsylvania, and New Jersey. A budget of $80,000 for the addendum is proposed to be spent starting on 5/18/2018 until the end of the project

- We have been continuously testing the closed-course performance and reliability of the prototypes previously mounted on the roof of M2SEC building (**Figure 1**). All signal lights were powered by the signal controller cabinet with real signaling time cycles (in a cycle length of 90 seconds, Red signal light ON for 50 seconds, Green signal light ON for 35 seconds, and Yellow signal light ON for 5 seconds. The temperature data were recorded every 10 seconds continuously over the entire test period, which will be continuously conducted over both winter and summer seasons in 2019.

- We have designed and custom made new types of screws (**Figure 3**, the bottom pictures) to improve the connection strength of the screws integrated with the plastic housing. This type of screws are finalized products to be used in all finalized plastic housing.

- We have designed and custom made two types of LED drivers, as shown in **Figure 4**, including one type of custom-made LED driver for **red signal light** (input: 100-240 VAC, output: 0.6-1.1 A, max 30 W), and a second type custom made LED driver for **green/yellow signal light** (input: 100-240 VAC, output: 0.5-0.8 A, max 30 W). Both types of LED drivers are now integrated with a remote temperature sensor (**see Figure 4**) for controlling the power output in light of the ambient air temperature. An on/off switch is designed for temperature controls in winter and summer modes which could override the operation of the temperature sensor.

- We have accordingly improved and finalized the plastic housing of the fully working prototype signals of Type 1 with changes/improvements listed below, with assist of the plastic molding company — Eco Molding. Eco Molding company has custom made seven samples (**Figure 5**) of the finalized new plastic housing for validations tests before actual product production.

- We have produced 60 pcs of the finalized LED engines with the aid of the industrial partner (**Figure 6 a**), ready for the upcoming field tests.

- We have also updated and custom made 60 pcs of glass disc (**Figure 6b**) which have four small mounting holes removed on the edge (the original glass disc had 8 mounting holes).

- We also custom made plastic mounting bars (**Figure 6b**) for mounting the glass disc to the LED light engine.

- We are working on getting improvement on custom-made Fresnal lens model number HX-F0150115 (diameter 15 mm, thickness 2.0 mm, focal length 11.5 mm) to increase tolerance of the thickness (approximately 1.8 – 2.1 mm) while reducing the unit cost.

- We are in preparation for field tests. Three fully functional prototypes of the fourth generation were mounted on a signal pole on the roof of an engineering building, powered by a traffic control cabinet for closed-course performance and reliability tests.

- Three more fully functional prototypes of the fourth generation were also tested in a well-controlled cold room for the performance of the ambient temperature sensor connected to the LED driver for switching full/derated power output. Based on the test results, we are adjusting the power output of the LED drivers. We are also making minor adjustments of the signal housing for quick assembly of the real products. Results have been used to evaluate the readiness of the prototypes for field tests starting in next quarter.

**Circumstance affecting project or budget. (Please describe any challenges encountered or anticipated that might affect the completion of the project within the time, scope and fiscal constraints set forth in the agreement, along with recommended solutions to those problems).**

None.