Innovations Deserving
Exploratory Analysis Programs

Rail Safety IDEA Program

Self- Deicing LED Signal for Railroads and Highway Intersections

Final Report for
Rail Safety IDEA Project 29/NCHRP IDEA 190

Prepared by:
Hongyi Cai-University of Kansas
Steven Schrock-University of Kansas
Eric Fitzsimmons-Kansas State University

August 2019

TRANSPORTATION RESEARCH BOARD
The National Academies of
SCIENCES · ENGINEERING · MEDICINE

Innovations Deserving Exploratory Analysis (IDEA) Programs Managed by the Transportation Research Board

This IDEA project was funded by the Rail Safety IDEA Program.

The TRB currently manages the following three IDEA programs:

- The NCHRP IDEA Program, which focuses on advances in the design, construction, and maintenance of highway systems, is funded by American Association of State Highway and Transportation Officials (AASHTO) as part of the National Cooperative Highway Research Program (NCHRP).
- The Rail Safety IDEA Program currently focuses on innovative approaches for improving railroad safety or performance. The program is currently funded by the Federal Railroad Administration (FRA). The program was previously jointly funded by the Federal Motor Carrier Safety Administration (FMCSA) and the FRA.
- The Transit IDEA Program, which supports development and testing of innovative concepts and methods for advancing transit practice, is funded by the Federal Transit Administration (FTA) as part of the Transit Cooperative Research Program (TCRP).

Management of the three IDEA programs is coordinated to promote the development and testing of innovative concepts, methods, and technologies.

For information on the IDEA programs, check the IDEA website (www.trb.org/idea). For questions, contact the IDEA programs office by telephone at (202) 334-3310.

IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

Joint IDEA Project S-29/NCHRP-190

Self-Deicing LED Signal for Railroads and Highway Intersections

IDEA Program Final Report

For the period 11/24/2015 – 08/31/2019

Contract No: SAFETY-29

Prepared for the IDEA Program
Transportation Research Board
National Research Council

Hongyi Cai, Principal Investigator
Department of Civil, Environmental, and Architectural Engineering
The University of Kansas

Steven Schrock, Co-Principal Investigator
Department of Civil, Environmental, and Architectural Engineering
The University of Kansas

Eric Fitzsimmons, Co-Principal Investigator
Department of Civil Engineering
Kansas State University

January 31, 2020

ACKNOWLEDGEMENTS

The development and implementation of the Self-Deicing LED Signals for Railroads and Highway Intersections was also supported by the Kansas Department of Transportation, the California Department of Transportation, the Michigan Department of Transportation, the New Jersey Department of Transportation, the Wisconsin Department of Transportation, the Pennsylvania Department of Transportation, and the Maryland Department of Transportation in a relevant project funded by the Transportation Pooled Fund Program.

RAIL SAFETY IDEA PROGRAM COMMITTEE

CHAIR
CONRAD RUPPERT, JR.
Railway Engineering Educator &Consultant

MEMBERS
TOM BARTLETT
Transportation Product Sales Company
MELVIN CLARK
LTK Engineering Services
MICHAEL FRANKE
Retired Amtrak
BRAD KERCHOF
Norfolk Southern Railway
MARTITA MULLEN
Canadian National Railway
STEPHEN M. POPKIN
Volpe National Transportation Systems Center

FRA LIAISON
TAREK OMAR
Federal Railroad Administration

TRB LIAISON
SCOTT BABCOCK
Transportation Research Board

IDEA PROGRAMS STAFF
GWEN CHISHOLM-SMITH, *Manager, Transit Cooperative Research Program*
VELVET BASEMERA-FITZPATRICK, *Senior Program Officer*
DEMISHA WILLIAMS, *Senior Program Assistant*

EXPERT REVIEW PANEL SAFETY IDEA PROJECT 29
RICHARD CUNARD, *Transportation Research Board*
CONRAD RUPPERT, *University of Illinois at Urbana Champaign*

EXECUTIVE SUMMARY

This project was aimed at developing and demonstrating a new type of self-de-icing LED signals for highway and railroad intersections, as a replacement for the existing LED signal lights that remain too cold on the signal lens to deice or melt snow and could cause accidents in snowy conditions.

The work of this project was divided into three stages. Stage 1 work focused on laboratory development and testing of the new self-de-icing LED signals. The self-de-icing LED signals adopt an innovative system architecture of "Integrated Light and Heat Arrangement of LEDs in Low Profile", which was tested in the laboratory to enhance the lighting and heating performance while reducing costs. Necessary equipment, components and materials were procured to develop and build prototypes. Three types of new light engines (R, Y, G) in low profile, each equipped with 96 medium-power LEDs, were designed in-house and custom-made with assistance from the industrial partner. On top of each LED, a Fresnel lens (diameter: 15 mm, focal length: 11.5 mm, thickness: 1.5-2.0 mm) was mounted with a gap of ¼" for light collimation. New signal housing was custom made by a plastic molding company using UV stabilized polycarbonate materials. Two new LED drivers (one for red light and the other for green/yellow light), which were integrated with a remote temperature sensor for controlling the signal power output in light of the ambient air temperature and an on/off switch for winter and summer modes, were self-designed and custom-made by an electronics company. As a result, the prototype signals (R, Y, G) consist of a new signal housing, three new light engines in different light color (R, Y, G), two custom-made LED drivers integrated with a remote temperature sensor, new signal lens integrated with 96 small Fresnel lenses for light collimation of individual LEDs, and insulation materials as part of the innovative system architecture. Four generations of prototype signals in Red, Yellow, and Green were developed and tested in the laboratory with continuous improvements on their heating and lighting parameters with the desired specifications.

Work in Stage 2 focused on closed-course performance and reliability tests of the fully working prototypes mounted on the roof of the University of Kansas engineering complex, and follow-up improvements on any identified issues. Fully functional prototypes have been under continuous testing on the roof, powered by a real traffic control cabinet. Based on the test results, new plastic housing with desired changes were designed and tested in the laboratory with satisfactory performance. Some issues with the second generation LED drivers were resolved with needed changes, and the ambient temperature sensor of the drivers was improved for switching power output at 4°C with acceptable tolerances. Second generation LED driver samples were tested thoroughly in the cold room and on the roof and, based on the test results, improvements were made for developing the third generation LED drivers. New Fresnel lenses made by another manufacturer with lower price and higher quality control were procured and tested in the laboratory with satisfactory results. A total of 21 new LED drivers of the third generation were tested for their field performance and further improvements needed for the control of the yield rate in production. The industrial partner assisted in the production of finalized LED light engines while several other contracted companies have been producing all other metal, glass, and plastic parts needed for assembling the final porotypes for field tests. The fourth generation prototypes were tested in a controlled cold room for the performance of the ambient temperature sensor connected to the LED driver. The power output of the LED drivers was adjusted. The signal housing was also revised for quick assembly.

Work in the third and final stage involved field testing of the developed prototypes on identified highway signalized intersections and/or rail track sections. New fully functional prototypes for field tests were assembled and continuously tested in the laboratory in preparation for field tests. Also, a field monitoring system consisting of a Raspberry PI computer, three cable cameras, four temperature sensors, USB flash drivers, power supplies, and mounting accessories, was built in-house and continuously tested in the laboratory and on the roof for field installation. The prototypes, once validated in the closed-course setting, were installed on pole-mounted side signals as backup to the existing primary signals and commissioned. Real-time performance for melting snow and deicing was monitored by a field monitoring system for year-around data recording. The first field test site was set up in Kansas at the intersection of County Rd 458 (or 1200 Rd) /US-59. All new equipment including the performance monitoring system for data recording were installed on side signals facing north. More prototypes of the final products are in preparation for other test sites. Seven states (Kansas, California, Michigan, New Jersey, Wisconsin, Pennsylvania, and Maryland) are participating in field testing and evaluation of the prototypes. On-site demonstration of the prototype signals would also be held for project partners and state DOTs to initiate the implementation process.

1. IDEA PRODUCT

This project developed a new type of self-de-icing LED signals (FIGURE 1) for highway signalized intersections and railroad signaling applications, and validated their lighting and heating performances and reliability using closed-course tests on the building roof and then field tests at multiple appropriate test sites of the participating state departments of transportation (Kansas, California, Michigan, New Jersey, Wisconsin, Pennsylvania, and Maryland).

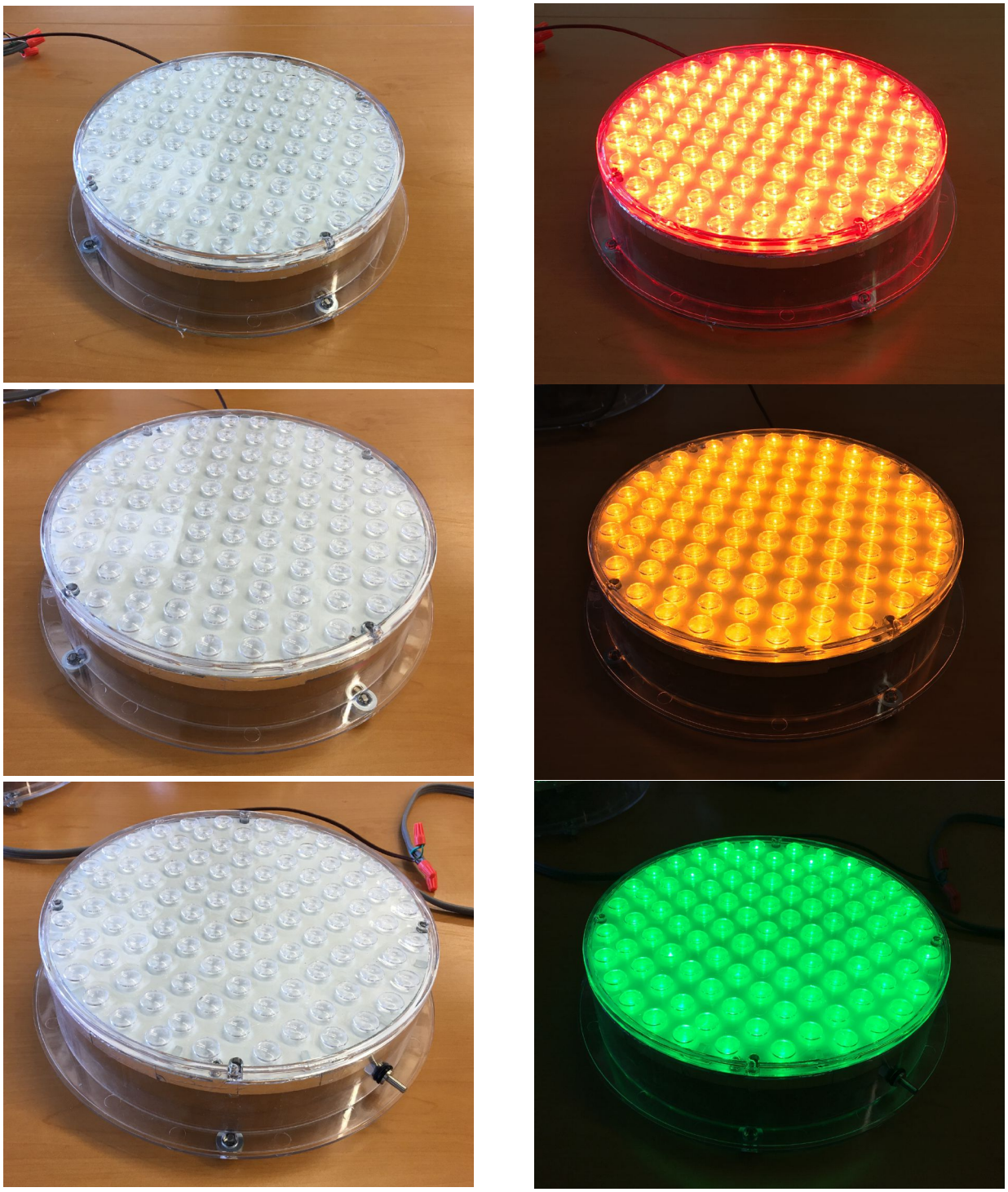


FIGURE 1 Prototypes of the new type of self-de-icing LED signals (Red, Yellow, Green) for highway signalized intersections and railroad signaling applications, and their performance and reliability tests on the roof of the University of Kansas engineering complex, powered by a real traffic control cabinet

The self-de-icing LED signal light was aimed to solve a well-known problem of the existing "cool" LED signal light that does not generate sufficient heat in the forward direction towards the lens of the signal necessary to melt snow and ice in cold wintery conditions (FIGURE 2, FIGURE 3). Snow and ice can easily accumulate on the lens within the signal hood in wintery conditions and block light to the drivers of vehicles or locomotive engineers. This can decrease the performance of signalized intersections and railroads and also result in collisions in inclement weather conditions. This is a problem in the snowy regions in North America for which a viable retrofit has not been developed or tested.

Given that 39 states and over 70% of the population of the United States and the entire country of Canada are located in snowy regions that receive at least five inches of snow each year [1, 2], this problem of snow-clogged "cool" LED signal lights in cold winter is a very typical and expansive problem in which a viable retrofit has not been developed or tested that does not compromise the efficiency, brightness, and operation complexity of the system.

(a) (b) (c) (d)

FIGURE 2 Snow-clogged "cool" LED traffic lights and their cleaning off by hand [3, 4]

(a) (b)

FIGURE 3 Snow-clogged railroad signals, (a) the crossbucks and signal lights taken within two hours of the crossing crash [5], (b) the wayside signals with snow buildup on the lens in Quebec [6]

Current solutions to the snow-clogged signal lights include manual labor of brushing snow off of the signal lens and spraying de-icing chemicals on the lens to prevent the buildup of snow and ice. These manual methods are laborious, adding extra annual maintenance cost. The chemicals also have unknown long-term effectiveness on signal lens and harm to the local environment resulting in periodic spraying at intervals that largely increases the labor costs. Additionally, there are a couple of products designed and developed to prevent snow from collecting by physically allowing air venting through the signal hood and snow cover, including the Fortan "snow sentry" cover and the McCain "snow scoop" visor [7]. Nonetheless, tests of these products have mixed conclusions, which may fail in extreme winter conditions. Alternatively, competitive technologies use additional heat generators on the existing "cool" LED signals, such as resistance wires on the lens (e.g., patent No. US 20070114225A1, 2007), infrared LEDs mounted on the circuit board for radiating additional heat to the lens (e.g., Patent No. US8246205B2, 2012), and a heat generating sheet behind the lens (Patent No. US 20140152471 A1, 2014). However, the heat generators demand additional significant power consumption from the signal controller cabinet, resulting in additional wiring and energy costs, meanwhile a large amount of heat generated by the LEDs is not used and wasted. Resistance wires on the lens may decrease the visibility of the signal light. The self-de-icing LED signals can solve all of those issues and be more reliable and effective under inclement wintery conditions, but not compromise the efficiency, brightness, and/or operational complexity of the system. Compared with the aforementioned technologies, the self-de-icing LED signals have a simple, reliable, and more effective design. The self-de-icing LED signals harvest the otherwise wasted heat generated by the LEDs and do not need additional heat generators (e.g., resistance wires, infrared LEDs, heat generating sheet). The self-de-icing LED signals harvest both the light and the heat generated by the same LEDs, thus, is deemed more energy efficient (no waste of energy) than the existing "cool" LED signals and the proposed LED signals with additional heat generators.

The self-de-icing LED signal lights were designed to be swappable with the existing "cool" LED and incandescent signal lights without needs of extra installations other than "re-lamping". This system will not alter the function and sizes of the existing signal lights. There will also be no need to add additional wiring inside and outside of the existing signal controller cabinets, no need to change anything outside of the signal housing. The self-de-icing LED signal is expected to transform the use and operation of the existing signal lights in snowy regions in North America with significant benefits in safety and performance efficiency and overall user cost savings. Once validated in the field, the self-de-icing LED signal light will be a viable retrofit to the existing "cool" LED signal lights (also the obsolete incandescent signal lights as well) installed at the highway signalized intersections and railroad wayside and at-grade crossings. Additionally, the self-de-icing LED signal light is expected to extend into other rail applications (e.g., commuter or light rail), or in other surface transportation applications including airport taxiway/apron lighting and seaport applications located in cold weather zones. Although the self-de-icing LED signals are targeted for colder weather regions, they can certainly be installed in warmer climate where they may see only a limited number of cold weather days.

2. CONCEPT AND INNOVATION

Approximately 70-80% of the electricity consumed by LEDs is converted to heat rather than light [8]. The self-de-icing LED signal light was designed to harvest both the light and the heat generated by the same LED(s) for lighting and heating the signal lens. The harnessed great deal of LED heat enables the self-de-icing LED signal light with self-efficacy for prevention of the buildup and accumulation of ice, sleet, and snow on the lens of the signals during wintery conditions. There is no need of additional heat generators (e.g., resistance wires or infrared LEDs).

The self-de-icing LED signal light adopts an innovative system architecture of "Integrated Light and Heat Arrangement of LEDs in Low Profile" that was patented (**Patent No. US 10,253,965 B2, US 10,215,441 B2, US 9,851,086 B2**), as illustrated in FIGURE 4 and FIGURE 5.

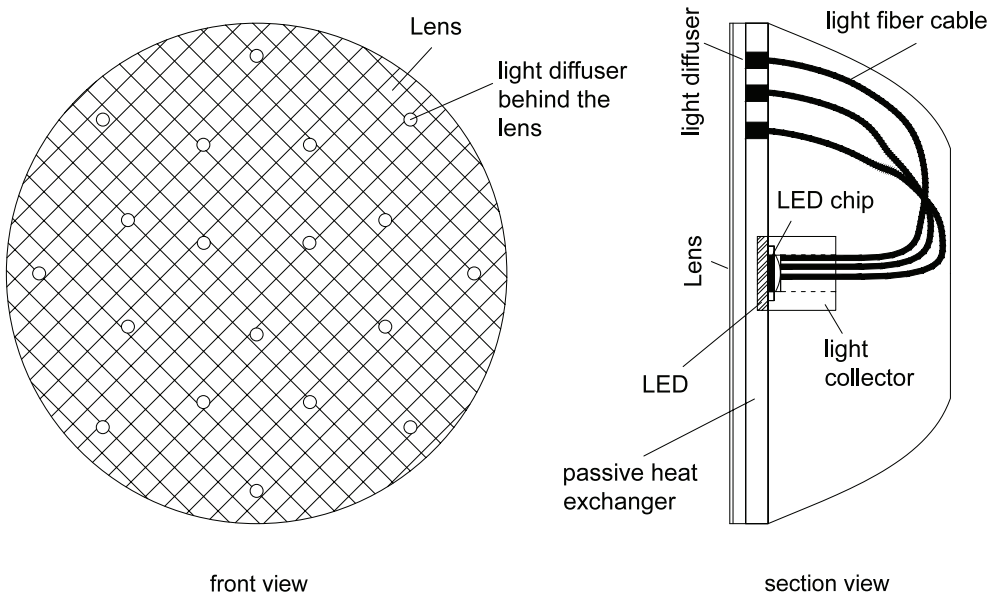


FIGURE 4 The front and section view of the self-de-icing LED signal light that deploys the innovation of "*Heated Lens Lighting Arrangement*" (only three fibers are shown for the benefit of legibility)

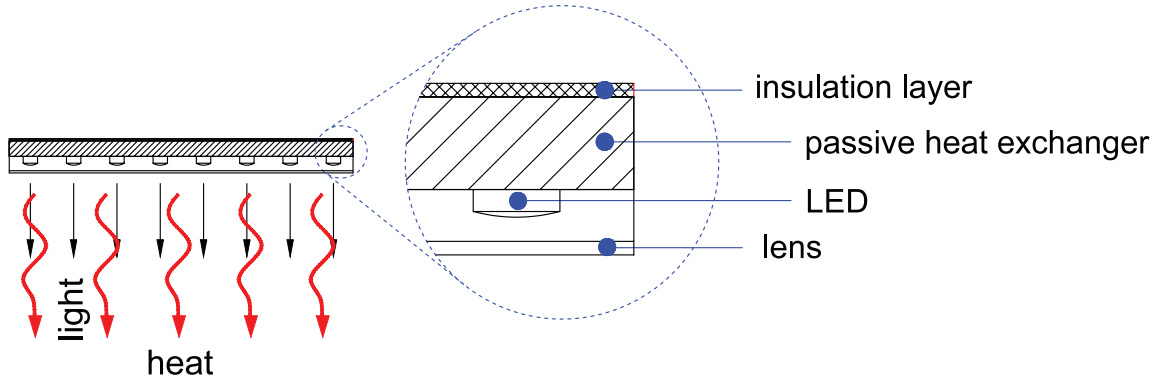


FIGURE 5 A new system architecture of "Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture" to harvest both the light and the heat generated by the same LEDs via a mingled path for lighting and heating uses

As illustrated in FIGURE 4, one side of a passive heat exchanger (an aluminum disk) is mounted closely adjacent or proximate to the lens of the new signal light. A single high-power LED is mounted to the other side of the passive heat exchanger at the center. The heat generated by the LED is conducted by the passive heat exchanger to heat the lens for melting snow and de-icing in wintertime conditions. The light emitted from the LED to the back of the signal housing, which is otherwise trapped inside, is redirected back through the passive heat exchanger to the lens using a bundle of light fiber cables. The fiber cables are bundled at the end and connected to a light collector, which is mounted on top of the LED to collect all light. At the other end, each fiber cable is fitted with a diffusive light emitter, which is mounted through a hole on the front side of the passive heat exchanger. The light diffusers of all fiber cables are evenly distributed behind the lens to generate uniform light distribution across the lens.

As illustrated in FIGURE 5, multiple LEDs are mounted on the passive heat exchanger (e.g., a ¼" thick aluminum disk) and evenly spread. One side of the passive heat exchanger is mounted closely adjacent or proximate to the lens of the light-emitting surface with a small gap (e.g., 1/8"- 1/4") in between. The new system architecture of "Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture" uses a mingled path for lighting and heating towards the same direction — the signal lens, canceling the need of optical fibers shown in FIGURE 4. The heat generated by the LEDs is dissipated by the passive heat exchanger in an optimal manner [9], and directly used for heating the signal lens. As a result of the array of 96 LEDs in low profile and the substantial overlap in the surface area of the passive heat exchanger that is proximate to the lens, the heat is transferred to the lens evenly and to its outer edges, making it a uniform light & heat source for the signals. To minimize the heat transfer toward an unwanted direction, a layer of insulation materials, such as fiberglass, plastic fiber, rubber foam, aerogel, air gap or vacuum gap, is mounted on the back of the passive heat exchanger. Meanwhile, the light output of each LED is maximized toward the desired direction using a Fresnel lens for light collimation.

3. INVESTIGATION

Three stages of work were conducted to develop and validate the self-de-icing signals.

At Stage 1 – Laboratory Development and Tests. The new self-de-icing LED signals were developed and tested in multiple laboratories, including the University of Kansas lighting research laboratory and its dark room, and the Cold Room in the LEEP2 engineering complex. We ordered necessary equipment, components and insulation materials to develop and build the fully working prototypes of the finalized design and test for their thermal and lighting performance. Application of innovative "Integrated Light and Heat Arrangement of LEDs in Low Profile" was adopted for architecture of the new LED signals and tested in the laboratory to enhance the heating and lighting performance while reducing costs. Appropriate color LED modules were designed in-house and custom-made with the aid of the industrial partner (Sunlite Science & Technology). Four generations of prototype signals (Red, Yellow, and Green) were developed and tested in the laboratory for improvements. The fully working prototype signals (R, G, and Y) adopt new light engines in low profile using 96 medium-power LEDs, two new custom-made LED drivers (one for red light, one for green/yellow light) integrated with a remote temperature sensor for controlling the power output in light of the ambient air temperature and an on/off switch for winter and summer modes, new signal housing custom made by a plastic molding company using UV Stabilized Polycarbonate materials in accurate dimensions, and new signal lens integrated with 96 small Fresnel lenses (diameter: 15 mm, focal length: 11.5 mm, thickness: 1.5-2.0 mm) for light collimation of individual LEDs. Laboratory testing of all heating and lighting parameters of the fully working prototypes with the desired specifications was completed. The industrial partner has assisted in the production of finalized LED light engines. Several contracted companies have been producing all other metal, glass, and plastic parts needed for assembling the final porotypes for field tests. Using the fully working prototypes, we have conducted thorough thermal and lighting performance tests in the laboratory. Testing all heating and lighting parameters of the fully working prototypes was completed with the desired specifications in the laboratories.

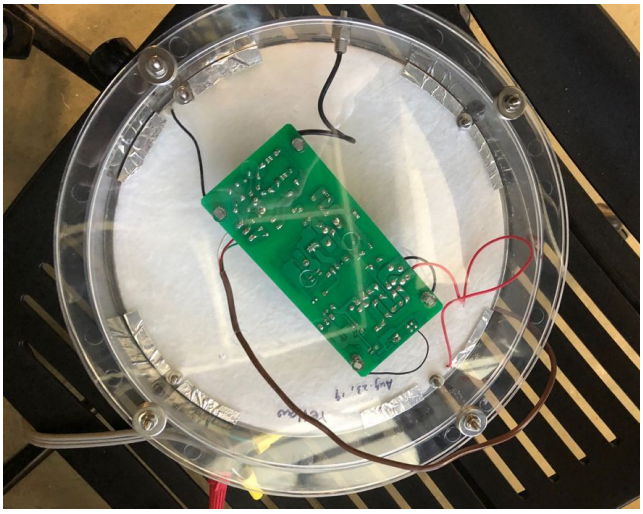
At Stage 2 – Performance and Reliability Tests on the Roof. The fully working prototypes (R, G, and Y) were mounted on the roof of the University of Kansas engineering complex – M2SEC building for closed-course performance and reliability tests, and follow-up improvements on any identified issues. Three prototypes were mounted on a signal pole, powered by a traffic control cabinet in real signaling time cycles for comprehensive heating and lighting performance tests. Based on the test results, new plastic housing with desired changes were designed and tested in the laboratory with satisfactory performance. Some issues with the second generation LED drivers were resolved with needed changes, and the ambient temperature sensor of the drivers was improved for switching power output at 4°C with acceptable tolerances. Second generation LED driver samples were tested thoroughly in the cold room and on the roof and, based on the test results, improvements were made for developing the third generation LED drivers. New Fresnel lenses made by another

manufacturer with lower price and higher quality control were procured and tested in the laboratory with satisfactory results. A total of 21 new LED drivers of the third generation were tested for their field performance and further improvements needed for the control of the yield rate in production. The industrial partner assisted in the production of finalized LED light engines while several other contracted companies have been producing all other metal, glass, and plastic parts needed for assembling the final porotypes for field tests. The fourth generation prototypes were tested in a controlled cold room for the performance of the ambient temperature sensor connected to the LED driver. The power output of the LED drivers was adjusted. The signal housing was also revised for quick assembly.

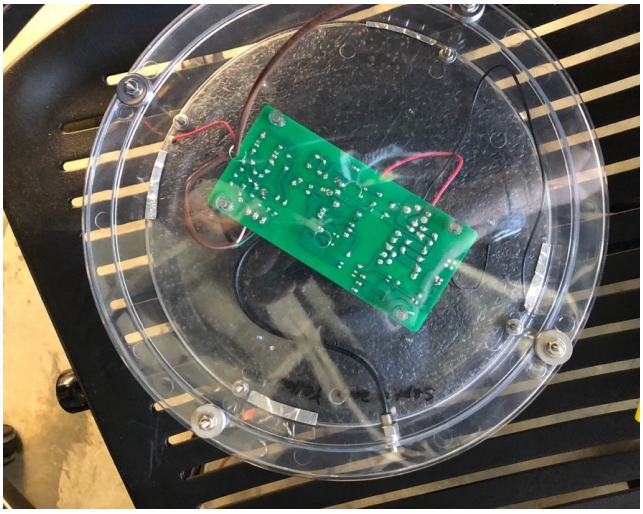
At Stage 3 – Field Tests. Roof validated prototypes were continuously tested in the field on identified highway signalized intersections and/or rail track sections. New fully functional prototypes for field tests were assembled and continuously tested in the laboratory in preparation for field tests. All prototypes in preparation for field tests have been undergone thorough laboratory and roof tests for at least 2-4 weeks before they could be used in the field. Also, a field monitoring system consisting of a Raspberry PI computer, three cable cameras, four temperature sensors, USB flash drivers, power supplies, and mounting accessories, was built in-house and continuously tested in the laboratory and on the roof for field installation. The prototypes, once validated in the closed-course setting, were installed on pole-mounted side signals as backup to the existing primary signals and commissioned. Real-time performance for melting snow and deicing was monitored by a field monitoring system for year-around data recording. The first field test site was set up in Kansas at the intersection of County Rd 458 (or 1200 Rd) /US-59. All new equipment including the performance monitoring system for data recording were installed on side signals facing north. More prototypes of the final products are in preparation for other test sites. Seven states (Kansas, California, Michigan, New Jersey, Wisconsin, Pennsylvania, and Maryland) are participating in field testing and evaluation of the prototypes. On-site demonstration of the prototype signals would also be held for project partners and state DOTs to initiate the implementation process. We have also been talking with Union Pacific (UP) Railroad and Burlington Northern and Santa Fe (BNSF) railroad for their participation in the project for testing railroad signals.

More details are listed as follows for the development and testing of different parts, and different generations of fully working prototypes of the self-de-icing signals.

As shown in FIGURE 6, fully working prototypes of the self-de-icing signal lights for field tests were assembled in their plastic housing. Alternative insulation materials were also tested for equivalent thermal performance but at lower cost of the materials, as shown in FIGURE 6(b). The housing has three parts, as shown in FIGURE 6(c). It was found that the mass production of the signal housings needs adjustment for quality control. The problem was that the lens surface of the product in mass production could be uneven against the design, due to the fast production speed and short time of cooling products. The problem was shown in FIGURE 6 (d). The concave surface of the new housing made the assembly of the final signal light products difficulty, and could easily crack the inside glass disc used to support the 96 Fresnel lenses. As a result, we have requested the housing manufacturer to improve the mass production techniques to solve this problem with a maximum tolerance of uneven lens' surface of 0.5-2 mm in depth. The manufacturer was since then working on a solution to solve the problem of uneven lens' surface during future mass production.



(a)



(b)

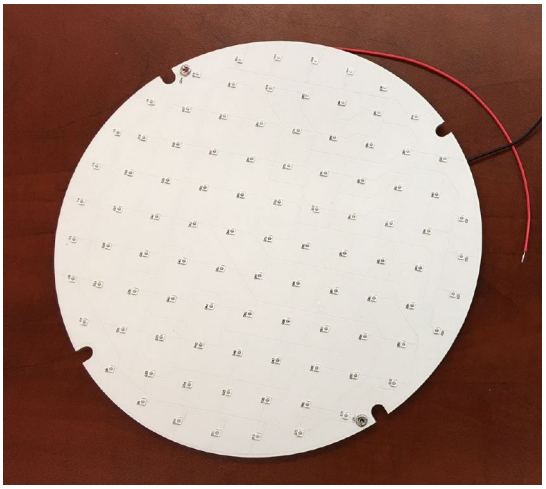
(c)

(d)

(e)

FIGURE 6 Signal housing, (a) the new prototype signal light with the current Aerogel insulation material, (b) the new prototype signal light with alternative insulation materials (shown only one type), (c) the three parts of the housing, (d) self-designed custom made screws for the housing, (e) the concave lens surface of the housing, which has a maximum tolerance of 1.5-2 mm in depth

As shown in FIGURE 7(a), We have produced 60 pcs of the finalized LED engines with the aid of the industrial partner, ready for the upcoming field tests. We have also updated and custom made 90 pcs of glass disc (Figure 7(b)) which have four mounting holes removed on the edge. We also custom made plastic mounting bars (Figure 7(c)) for mounting the glass disc to the LED light engine, in order to secure the 96 pieces of Fresnel lenses (Figure 7 (d)). Another manufacturer for Fresnel lenses was selected for lower unit price with high quality control. Samples of the new Fresnel lenses were tested in the laboratory with satisfactory results. Thus, 5000 pieces of the new Fresnel lenses (**Model #1511**) were ordered and arrived in preparation for upcoming field tests.



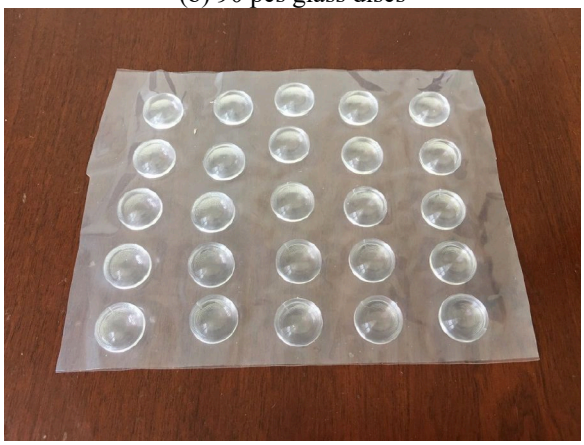
(a) LED engine sample

(a) 60 pcs LED engines of different light colors

(b) Updated glass disc, custom made

(b) 90 pcs glass discs

(c) Glass disc mounting bar, custom made



(d) Fresnel lenses (diameter: 15 mm, focal length: 11.5 mm, thickness: 1.5-2.0 mm)

FIGURE 7 Other custom-made pieces in preparation for field tests, including (a) 60 pieces of LED engines as the final products to be tested in the field, (b) 90 pcs of glass discs for the LED engine assembly, (c) custom-made plastic mounting bars for mounting the glass disc in signal lens, and (d) Fresnel lenses (diameter: 15 mm, focal length: 11.5 mm, thickness: 1.5-2.0 mm) for light collimation of individual LEDs

We worked with the electronics company of the LED drivers and resolved some issues and problems of the custom-made prototype LED drivers, including:

- Decreased the size of the power connector of the temperature sensor, so the sensor no longer has problem to connect through the inside hole of the installation nut and the opening hole on side of the plastic housing.
- Downsized the length of the ambient temperature sensor to 6 mm.
- Changed the power board switch from double switch to more reliable single switch.
- Enlarged the inside size of the installation hole from original **4.5mm x 3.5mm** (LxW) to **6mm x 4.5 mm**.
- Changed the final designed output current of Yellow/Green LED drivers to **0.40 A (derated) /0.84 A(full output).**
- Changed the final designed output current of Red LED drivers to **0.60 A (derated) /1.1 A(full output)**.
- Of the new tested TYPE 2 samples (whose switching temp sensor was set by the factory at 6°C), the ambient temperature sensor's switching temperature, based on our laboratory test results, is actually close to approximately 4° C, as designed.

FIGURE 8 shows the prototypes of two types of LED drivers of the third generation (7 red LED drivers (0.60 A (derated) /1.1 A(full output)) and 14 yellow/green LED drivers (0.40 A (derated) /0.84 A(full output))), which were thoroughly tested and used in the fully working prototypes for the field tests. Their ambient temperature sensor's switching temperature was

set to approximately 4° C. However, further tests in the laboratory and at the first field test site installed in Kansas showed two main issues of the current LED drivers, as listed below with proposed solutions. A fourth generation of the LED drivers are in need to overcome those issues. We are currently working with the vendor to make the fourth generation of LED drivers.

1) light power-up delay (the time delay between power on and signal light on) for about 0.5-1 second, especially for green signal light. ---- **Proposed Solution:** adjustment of MCU chips used in the driver to decrease the delay to only mini-seconds.
2) Unstable output performance of the drivers, due to unsecured soldering of wire connections by hands. ---- **Proposed Solution:** new products will be made on the automatic production line instead of hand-making (all previous samples due to small quantity were made by hands, not by machines). The unreliable soldering connection will be resolved, all new products will be aged by the standard procedure before shipping. This can largely improve the quality and reliability of new drivers, increasing the yield rate in production.

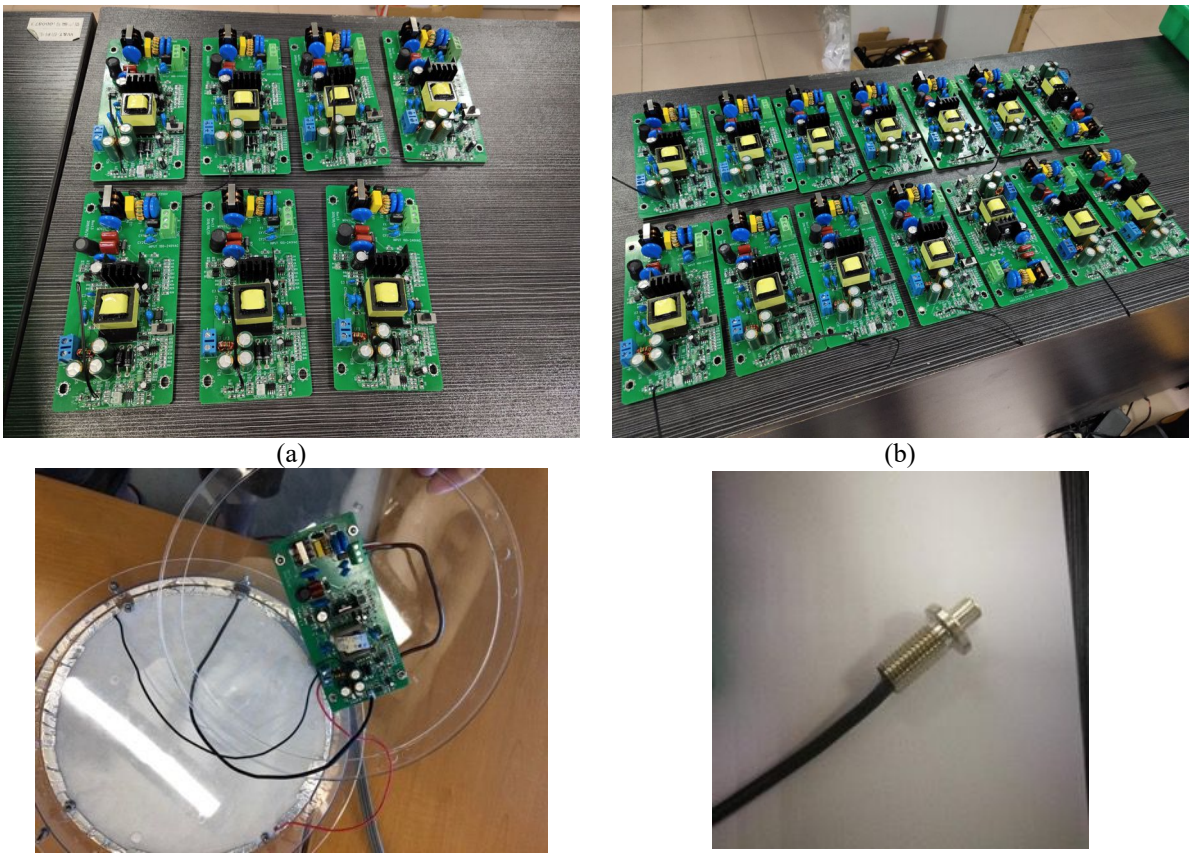
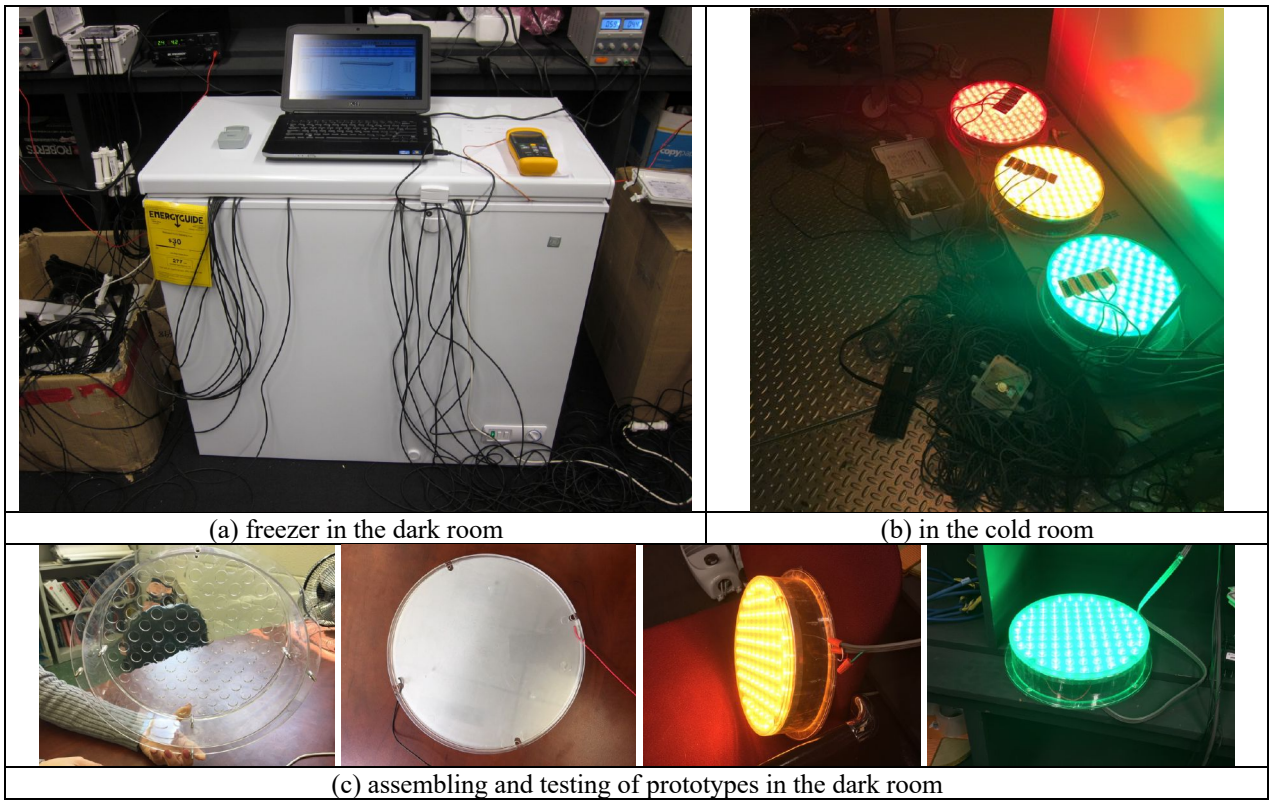


FIGURE 8 The third generation of LED drivers with all improvements, (a) Red LED drivers with designed power output of 0.60 A (derated) /1.1 A(full output), (b) Yellow/Green LED drivers with designed power output of 0.40 A (derated) /0.84 A(full output), (c) the LED driver installed inside the housing integrated with a remote temperature sensor mounted through a hole on the side of the housing for controlling the signal power output in light of the ambient air temperature, (d) the remote temperature sensor

FIGURE 9 shows the testing of three fully functional prototypes (R, G, Y) of the new signals in a freezer located in the Dark Room of the lighting research laboratory, and then in a well-controlled Cold Room (G445-A, M2SEC building) with controllable ambient temperature (0-30 °C with precision of 0.1 °C) and relative humidity (40% to 50%) for testing their thermal performance and identifying the switching temperature of the remote temperature sensor of the LED drivers. In both tests, the signals were continuously powered by DC power sources. TABLE 1 shows the results of a typical test, indicating the temperature difference between the signal lens and the ambient air temperature was 55.0 ° F for green light, 55.4° F for yellow light, and 51.3° F for red light, when the signals were powered continuously.



(a) freezer in the dark room

(b) in the cold room

(c) assembling and testing of prototypes in the dark room

FIGURE 9 Three fully functional prototypes (R, G, Y) of the self-de-icing signals were assembled in the dark room, and then tested first in the freezer location in the dark room and then in the well-controlled Cold Room located in the LEEP2 building for their thermal performance of the signal lens when the signals were powered continuously with DC power sources

TABLE 1 Typical thermal performance of fully functional prototypes (R, G, Y) of the new signals in a freezer when continuously powered by the DC power sources

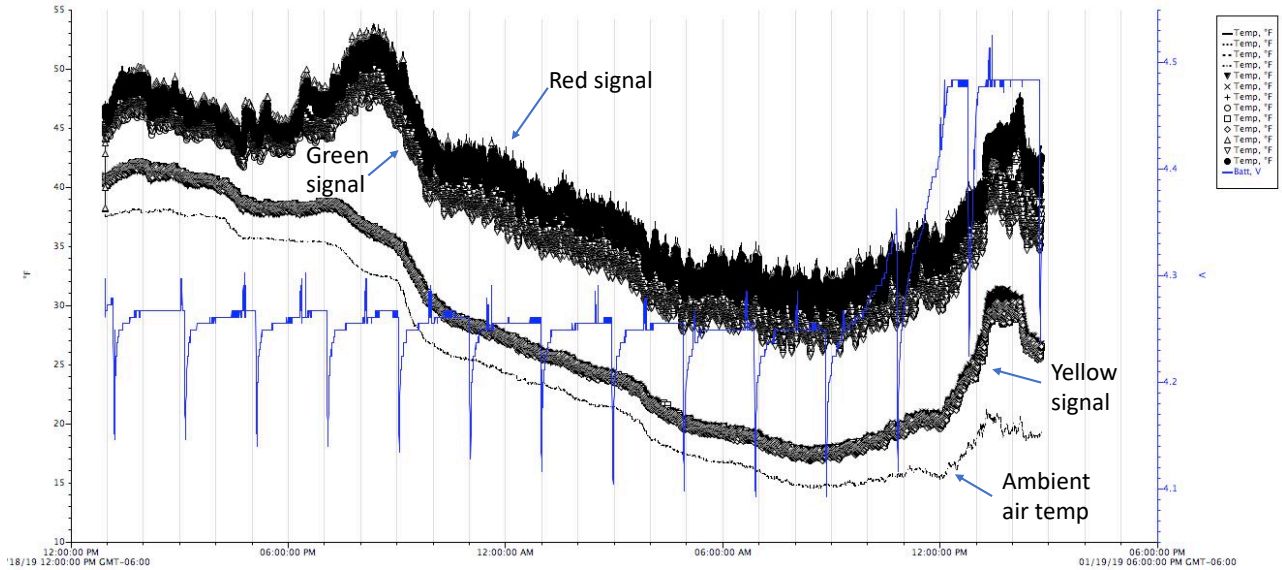
Test conditions	**Freezer, 3 signals tested together**	
Ambient Temp	Ambient	21.5 ° F
Surface Temp	Green light	76.5 ° F
	Yellow light	76.9 ° F
	Red light	72.8 ° F
Temp Difference	Green light	55 ° F
	Yellow light	55.4 ° F
	Red light	51.3 ° F

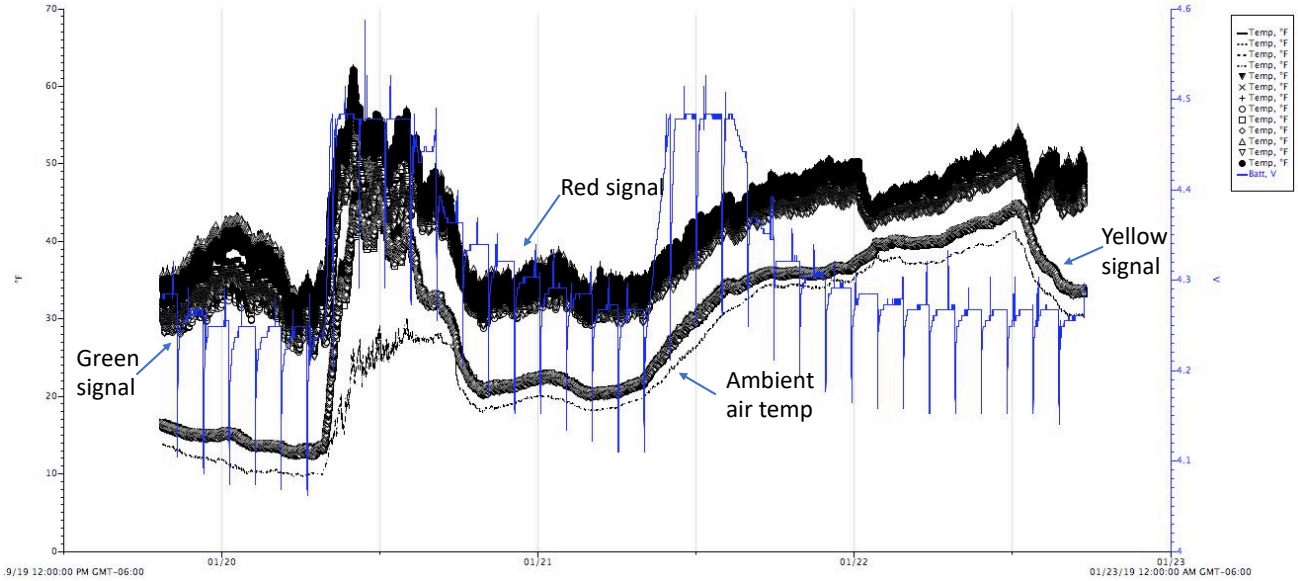
Next, we have being continuously testing the closed-course performance and reliability of the prototypes mounted on the roof of M2SEC building (FIGURE 10). All signal lights were powered by the signal controller cabinet with real signaling time cycles (in a cycle length of 90 seconds, Red signal light 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, could be adjusted for testing different cycles. We also replaced the existing power extension cord connecting the cabinet on the roof to a wall outlet with two 100 ft heavy-duty contractor grade outdoor extension cord, to satisfy the fire code requirements by long-term tests on the roof. 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 both winter and summer seasons. Later the data recording system were replaced with new data monitoring system used in the field tests.

FIGURE 10 The closed-course performance and reliability tests of the fully working prototypes mounted on the roof of M2SEC building, 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 for testing different cycles for different prototypes of different generations or in preparation of fully working prototypes for field tests. The roof tests were continuously conducted since 2018 through multiple snow storms in the past two years.

FIGURE 11 shows some sample data recorded in the roof tests for the performance of the signals lights at three different time periods in the cold wintery environments. The data show that the remote temperature sensor switched power output when the ambient air temperature was below 4 °C (39.2 °F), as follows.

- Yellow/green LED signals:
  - 0.4A/ ~14W (derated), when the ambient air temperature > 4 °C (39.2 °F);
  - 0.84 A /~29W (full output), when the ambient air temperature ≤ 4 °C (39.2 °F)
- Red LED signal:
  - 0.6A/~15W (derated), when the ambient air temperature > 4 °C (39.2 °F);
  - 1.1A/~29W (full output), when the ambient air temperature ≤ 4 °C (39.2 °F)





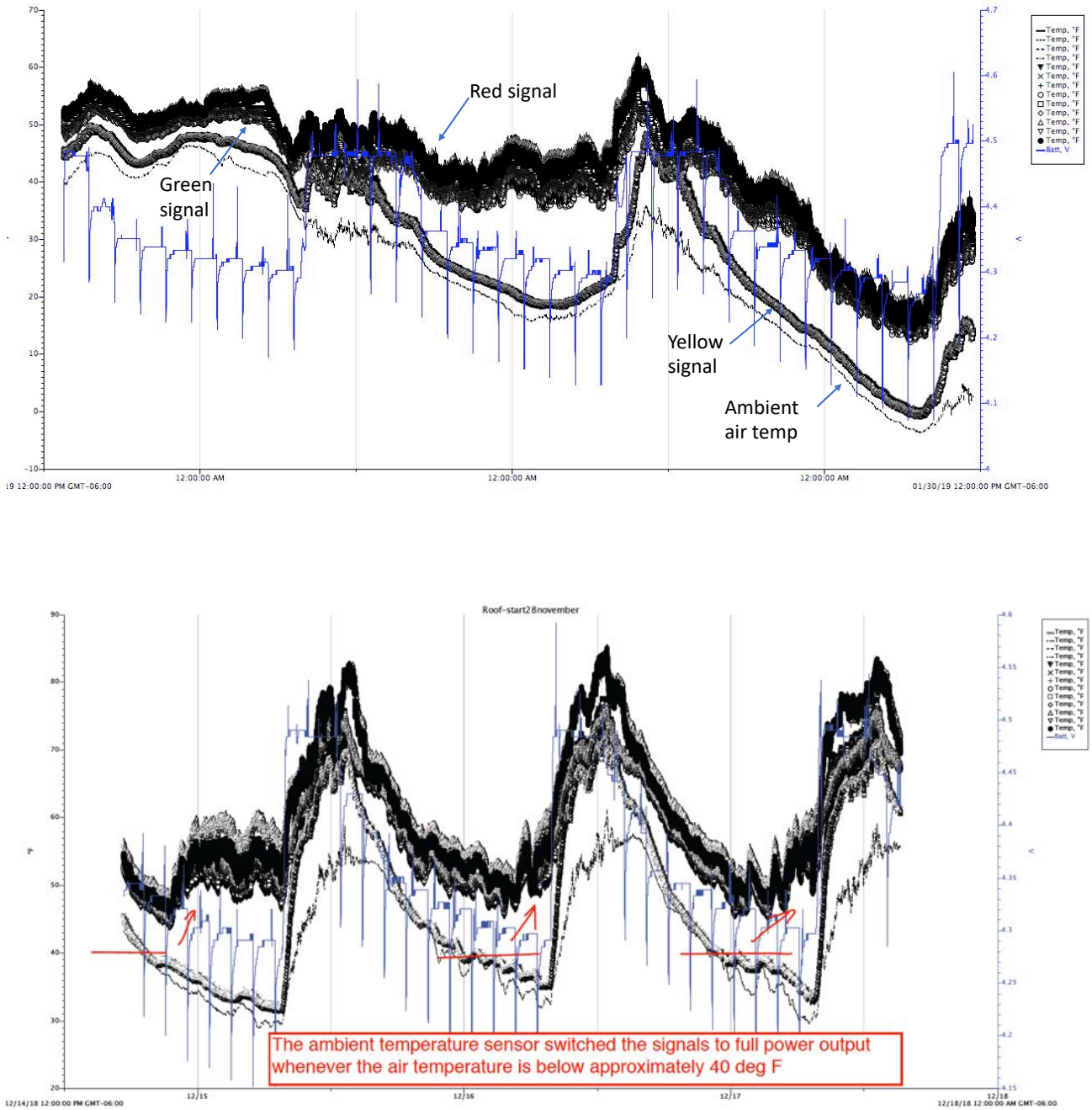


Figure 11 In real-time snowy winter 2019, sample data recorded in the roof tests for the performance of the signals lights at four different time periods. The red and green signals had higher surface temperatures than yellow signal, which was a bit higher than the ambient air temperature due to the short-on time (5 sconds) in each signaling cycle (90 seconds). The data also show that the remote temperature sensor switched power output when the ambient air temperature was below 4 °C (39.2 °F)

We also measured the lighting performance of the fourth generation of the prototype signals at both derated/dimmed mode when the ambient air temperature is above 4 °C (39.2 °F) and full power output mode when the ambient air temperature is below 4 °C (39.2 °F), respectively. TABLE 3 summarizes the measurement results, all passed the code requirements (TABLE 2). The signal lights were brighter when they have full power output.

TABLE 2 Peak minimum maintained luminous intensity values of $I_{(-2.5°, 0°)}$, measured at vertical off-axis viewing angle of θ_{vert} = -2.5° and horizontal off-axis viewing angle θ_{horiz} = 0°, of signal lights with a lens diameter of 12 inches by color of the module as required by the code [10]

Light color	$I_{(-2.5°, 0°)}$ 300 mm (12" in diameter)
Red	365 cd
Yellow	910 cd
Green	475 cd

TABLE 3 Lighting performance of the fourth generation signal lights of different colors with derated/dimmed output and full output, respectively, all passed the code requirements of $I_{(-2.5°, 0°)}$

Tilting angle θ_{vert} (°)	Intensity (cd)					
	Red, Dimmed	Yellow, Dimmed	Green, Dimmed	Red, Full output	Yellow, Full output	Green, Full output
0	954.3	2124.87	1719.9	1884.9	4124.7	2808.2
0.5	969.9	2126.54	1739.9	1869.9	4144.7	2819.8
1	981.4	2131.54	1751.6	1839.9	4164.7	2819.8
1.5	997.3	2134.87	1754.9	1809.9	4174.7	2804.8
2	1012.6	2138.2	1754.9	1774.9	4184.7	2774.8
2.5	**1028.9 > 365**	**2136.54 > 910**	**1749.9 > 475**	**1759.9 > 365**	**4189.7 > 910**	**2754.8 > 475**
3	1048.6	2134.87	1734.9	1734.9	4194.7	2739.8
3.5	1066.1	2129.87	1719.9	1719.9	4194.7	2704.8
4	1086.6	2124.87	1709.9	1704.9	4191.4	2666.5
4.5	1099.9	2116.54	1689.9	1689.9	4184.7	2629.8
5	1109.4	2109.87	1673.2	1679.9	4184.7	2604.8
6	1118.9	2089.87	1624.9	1644.9	4154.7	2548.2
7	1121.9	2069.87	1589.9	1614.9	4104.8	2489.8
8	1107.1	2038.21	1564.9	1584.9	4056.4	2459.9
9	1088.4	2009.88	1534.9	1559.9	4006.4	2404.9
10	1073.8	1984.88	1514.9	1536.6	3941.4	2364.9
20	947.1	1703.23	1407.4	1452.2	3374.8	2214.9
30	375.8	544.97	579.1	264	878.3	913.8
40	85.9	152.16	170.5	139.8	297.3	270
50	67.2	120.91	138.5	110.3	235.3	216.5
60	108.3	159.49	183.7	171.7	324.1	284.3

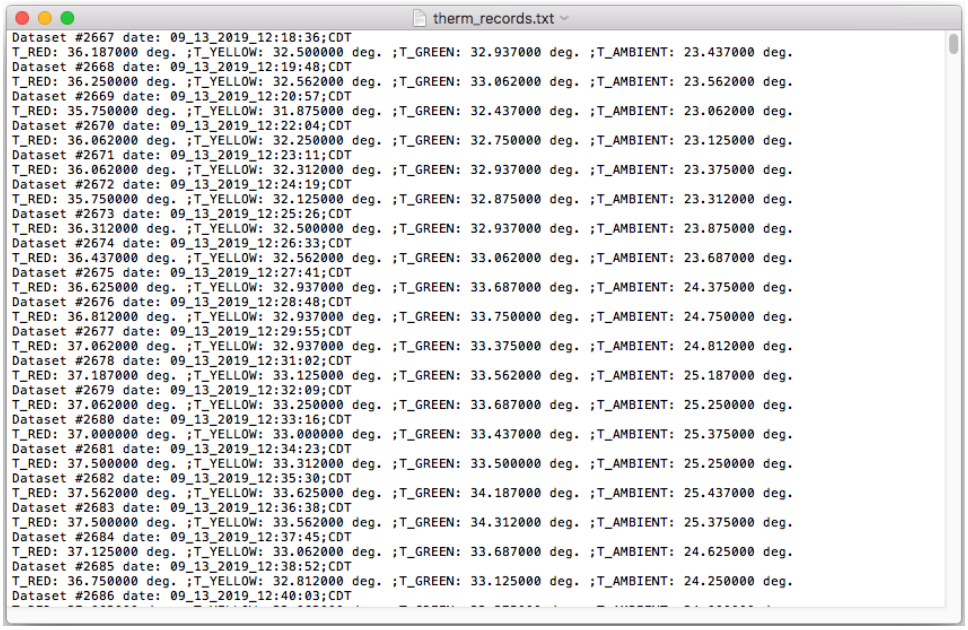
70	51.9	152.49	131.5	80.8	308.1	206.2

Additionally, for monitoring and data recording of the field tests, we developed the new house-built field monitoring system that has been undergone continuously tests on the roof. With a few improvements, the system was proven reliable for data recording. As shown in FIGURE 12, the field monitoring system consists of a Raspberry PI computer, three cable cameras used to monitor three signal lights (Red, Yellow, Green) in each unit, four temperature sensors used to record the lens' surface temperature of the three signal lights (Red, Yellow, Green) and the ambient air temperature, USB flash drivers used to store the year around test data (pictures and temperature dataset), power supplies, and mounting accessories. The field monitoring system was set up to take photos of the lens' surface and record the lens' surface temperature data every 20 seconds in winter seasons (when the ambient temperature is lower than 4 °C (39.2 °F)) and every hour in summer seasons. The temperature sensor is mounted on the lower edge of the signal lens to prevent blocking the driver's view to the signal light. The system would be mounted at every field test site for year-around real-time monitoring and data recording of the new signals. FIGURE 13 shows results of the ongoing roof tests with the field monitoring system, including photos of the lens' surface and temperature data recorded.

FIGURE 12 Field performance monitoring system shown in the roof tests, controlled by a Raspberry PI computer with a USB driver for recording 2-year data, which consists of three cable cameras used to monitor three signal lights (Red, Yellow, Green) in each unit, four temperature sensors used to record the lens' surface temperature of the three signal lights (Red, Yellow, Green) and the ambient air temperature, power supplies, and mounting accessories

therm_records.txt

```
Dataset #3293 date: 09_14_2019_00:00:58;CDT
T_RED: 25.625000 deg. ;T_YELLOW: 20.875000 deg. ;T_GREEN: 23.062000 deg. ;T_AMBIENT: 17.500000 deg.
Dataset #3294 date: 09_14_2019_00:02:06;CDT
T_RED: 25.437000 deg. ;T_YELLOW: 20.687000 deg. ;T_GREEN: 23.000000 deg. ;T_AMBIENT: 17.437000 deg.
Dataset #3295 date: 09_14_2019_00:03:13;CDT
T_RED: 25.500000 deg. ;T_YELLOW: 20.687000 deg. ;T_GREEN: 22.687000 deg. ;T_AMBIENT: 17.437000 deg.
Dataset #3296 date: 09_14_2019_00:04:21;CDT
T_RED: 25.312000 deg. ;T_YELLOW: 20.687000 deg. ;T_GREEN: 22.750000 deg. ;T_AMBIENT: 17.375000 deg.
Dataset #3297 date: 09_14_2019_00:05:28;CDT
T_RED: 25.312000 deg. ;T_YELLOW: 20.812000 deg. ;T_GREEN: 22.937000 deg. ;T_AMBIENT: 17.375000 deg.
Dataset #3298 date: 09_14_2019_00:06:35;CDT
T_RED: 25.312000 deg. ;T_YELLOW: 20.625000 deg. ;T_GREEN: 22.937000 deg. ;T_AMBIENT: 17.312000 deg.
Dataset #3299 date: 09_14_2019_00:07:43;CDT
T_RED: 25.437000 deg. ;T_YELLOW: 20.687000 deg. ;T_GREEN: 22.687000 deg. ;T_AMBIENT: 17.312000 deg.
Dataset #3300 date: 09_14_2019_00:08:50;CDT
T_RED: 25.375000 deg. ;T_YELLOW: 20.750000 deg. ;T_GREEN: 22.812000 deg. ;T_AMBIENT: 17.312000 deg.
Dataset #3301 date: 09_14_2019_00:09:57;CDT
T_RED: 25.125000 deg. ;T_YELLOW: 20.750000 deg. ;T_GREEN: 22.812000 deg. ;T_AMBIENT: 17.250000 deg.
Dataset #3302 date: 09_14_2019_00:11:05;CDT
T_RED: 25.375000 deg. ;T_YELLOW: 20.687000 deg. ;T_GREEN: 22.875000 deg. ;T_AMBIENT: 17.250000 deg.
Dataset #3303 date: 09_14_2019_00:12:12;CDT
T_RED: 25.562000 deg. ;T_YELLOW: 20.687000 deg. ;T_GREEN: 22.750000 deg. ;T_AMBIENT: 17.187000 deg.
Dataset #3304 date: 09_14_2019_00:13:19;CDT
T_RED: 25.437000 deg. ;T_YELLOW: 20.687000 deg. ;T_GREEN: 22.750000 deg. ;T_AMBIENT: 17.125000 deg.
Dataset #3305 date: 09_14_2019_00:14:27;CDT
T_RED: 25.187000 deg. ;T_YELLOW: 20.625000 deg. ;T_GREEN: 22.812000 deg. ;T_AMBIENT: 17.125000 deg.
Dataset #3306 date: 09_14_2019_00:15:34;CDT
T_RED: 25.375000 deg. ;T_YELLOW: 20.625000 deg. ;T_GREEN: 22.750000 deg. ;T_AMBIENT: 17.125000 deg.
Dataset #3307 date: 09_14_2019_00:16:42;CDT
T_RED: 25.375000 deg. ;T_YELLOW: 20.625000 deg. ;T_GREEN: 22.687000 deg. ;T_AMBIENT: 16.937000 deg.
Dataset #3308 date: 09_14_2019_00:17:49;CDT
T_RED: 25.125000 deg. ;T_YELLOW: 20.625000 deg. ;T_GREEN: 22.812000 deg. ;T_AMBIENT: 17.000000 deg.
Dataset #3309 date: 09_14_2019_00:18:56;CDT
T_RED: 25.062000 deg. ;T_YELLOW: 20.500000 deg. ;T_GREEN: 22.812000 deg. ;T_AMBIENT: 16.937000 deg.
Dataset #3310 date: 09_14_2019_00:20:04;CDT
```



therm_records.txt

```
Dataset #2667 date: 09_13_2019_12:18:36;CDT
T_RED: 36.187000 deg. ;T_YELLOW: 32.500000 deg. ;T_GREEN: 32.937000 deg. ;T_AMBIENT: 23.437000 deg.
Dataset #2668 date: 09_13_2019_12:19:48;CDT
T_RED: 36.250000 deg. ;T_YELLOW: 32.562000 deg. ;T_GREEN: 33.062000 deg. ;T_AMBIENT: 23.562000 deg.
Dataset #2669 date: 09_13_2019_12:20:57;CDT
T_RED: 35.750000 deg. ;T_YELLOW: 31.875000 deg. ;T_GREEN: 32.437000 deg. ;T_AMBIENT: 23.062000 deg.
Dataset #2670 date: 09_13_2019_12:22:04;CDT
T_RED: 36.062000 deg. ;T_YELLOW: 32.250000 deg. ;T_GREEN: 32.750000 deg. ;T_AMBIENT: 23.125000 deg.
Dataset #2671 date: 09_13_2019_12:23:11;CDT
T_RED: 36.062000 deg. ;T_YELLOW: 32.312000 deg. ;T_GREEN: 32.937000 deg. ;T_AMBIENT: 23.375000 deg.
Dataset #2672 date: 09_13_2019_12:24:19;CDT
T_RED: 35.750000 deg. ;T_YELLOW: 32.125000 deg. ;T_GREEN: 32.875000 deg. ;T_AMBIENT: 23.312000 deg.
Dataset #2673 date: 09_13_2019_12:25:26;CDT
T_RED: 36.312000 deg. ;T_YELLOW: 32.500000 deg. ;T_GREEN: 32.937000 deg. ;T_AMBIENT: 23.875000 deg.
Dataset #2674 date: 09_13_2019_12:26:33;CDT
T_RED: 36.437000 deg. ;T_YELLOW: 32.562000 deg. ;T_GREEN: 33.062000 deg. ;T_AMBIENT: 23.687000 deg.
Dataset #2675 date: 09_13_2019_12:27:41;CDT
T_RED: 36.625000 deg. ;T_YELLOW: 32.937000 deg. ;T_GREEN: 33.687000 deg. ;T_AMBIENT: 24.375000 deg.
Dataset #2676 date: 09_13_2019_12:28:48;CDT
T_RED: 36.812000 deg. ;T_YELLOW: 32.937000 deg. ;T_GREEN: 33.750000 deg. ;T_AMBIENT: 24.750000 deg.
Dataset #2677 date: 09_13_2019_12:29:55;CDT
T_RED: 37.062000 deg. ;T_YELLOW: 32.937000 deg. ;T_GREEN: 33.375000 deg. ;T_AMBIENT: 24.812000 deg.
Dataset #2678 date: 09_13_2019_12:31:02;CDT
T_RED: 37.187000 deg. ;T_YELLOW: 33.125000 deg. ;T_GREEN: 33.562000 deg. ;T_AMBIENT: 25.187000 deg.
Dataset #2679 date: 09_13_2019_12:32:09;CDT
T_RED: 37.062000 deg. ;T_YELLOW: 33.250000 deg. ;T_GREEN: 33.687000 deg. ;T_AMBIENT: 25.250000 deg.
Dataset #2680 date: 09_13_2019_12:33:16;CDT
T_RED: 37.000000 deg. ;T_YELLOW: 33.000000 deg. ;T_GREEN: 33.437000 deg. ;T_AMBIENT: 25.375000 deg.
Dataset #2681 date: 09_13_2019_12:34:23;CDT
T_RED: 37.500000 deg. ;T_YELLOW: 33.312000 deg. ;T_GREEN: 33.500000 deg. ;T_AMBIENT: 25.250000 deg.
Dataset #2682 date: 09_13_2019_12:35:30;CDT
T_RED: 37.562000 deg. ;T_YELLOW: 33.625000 deg. ;T_GREEN: 34.187000 deg. ;T_AMBIENT: 25.437000 deg.
Dataset #2683 date: 09_13_2019_12:36:38;CDT
T_RED: 37.500000 deg. ;T_YELLOW: 33.562000 deg. ;T_GREEN: 34.312000 deg. ;T_AMBIENT: 25.375000 deg.
Dataset #2684 date: 09_13_2019_12:37:45;CDT
T_RED: 37.125000 deg. ;T_YELLOW: 33.062000 deg. ;T_GREEN: 33.687000 deg. ;T_AMBIENT: 24.625000 deg.
Dataset #2685 date: 09_13_2019_12:38:52;CDT
T_RED: 36.750000 deg. ;T_YELLOW: 32.812000 deg. ;T_GREEN: 33.125000 deg. ;T_AMBIENT: 24.250000 deg.
Dataset #2686 date: 09_13_2019_12:40:03;CDT
```

FIGURE 13 Sample results of the ongoing roof tests with the field monitoring system, including photos of the lens' surface and temperature data recorded every 20 seconds in winter seasons (when the ambient temperature is lower than 4° C) and every hour in summer seasons.

Lastly, as shown in FIGURE 14, the first field test site was set up in Kansas at the intersection of County Rd 458 (or 1200 Rd) /US-59. FIGURE 15 shows the field installation process. Three fully tested prototypes of the self-de-icing signals were installed onsite with the help from the Lawrence city signal light crew. All of the new equipment including the performance monitoring system for data recording were installed on side signals facing north and already survived several snowstorm. The new signals and the monitoring system would be testing onsite continuously for 2 years.

FIGURE 14 The first field test site in Kansas, at the intersection of County Rd 458 (or 1200 Rd) /US-59, where the selected signals are on the side of the road shoulder, facing north

In preparation, existing signals

Replacing with the new self de-icing signals

Replacing with the new signals

Replacing with the new signals

Wiring of the new signals

Wiring of the signals

The installed new signals

A box for mounting the field monitoring system

Preparing for mounting the box on poles

The box mounted on pole with the monitoring system put inside

New green /orange signals are powered on

New red signal light is powered on

FIGURE 15 The field installation process at the first field test site in Kansas, with the help form the Lawrence city signal light crew and the Kansas Department of Transportation

Nonetheless, based on the test results on site, it was found that the new signal lights have a problem of light power-up delay (the time delay between power on and signal light on) for about 0.5 second, especially for green signal light. **Proposed Solution:** adjustment of MCU chips used in the driver to decrease the delay to only mini-seconds. As a result, the third-generation LED drivers need further improvements towards the fourth generation. We are working with the vendor to solve this problem and make the 4th generation drivers. New samples would be tested in laboratory and on roof, to make sure the problem is solved for other test sites. The signal lights on the current Kansas site also have a chance to get replaced if necessary. More prototypes of the final products are in preparation for other test sites in California, Michigan, Wisconsin, Maryland, and New Jersey & Pennsylvania, as shown in FIGURE 16.

State	Test Site
California	1
Kansas	1
Michigan	1
Wisconsin	1
Maryland	1
New Jersey Pennsylvania	1

FIGURE 16 A total of 6 field test sites in Kansas (1), California (1), Michigan (1), Wisconsin (1), Maryland (1), and New Jersey & Pennsylvania (joint 1)

4. PLANS FOR IMPLEMENTATION

Seven states (Kansas, California, Michigan, New Jersey, Wisconsin, Pennsylvania, and Maryland) are participating in field testing and evaluation of the prototypes. Preparations are underway for more field tests in addition to Kansas. New fully functional prototypes for field tests were assembled and have been continuously tested in the laboratory and on the roof in preparation for field tests. We have also been talking with Union Pacific (UP) Railroad and Burlington Northern and Santa Fe (BNSF) railroad for their participation in the project for testing railroad signals in the field. By the end of the field tests, on-site demonstration of the prototype signals would be held for project partners and state DOTs to initiate the implementation process.

In the expected implementation, the self-de-icing LED signal lights will replace the existing "cool" LED and any dated incandescent signal lights installed at the highway signalized intersections and railroad wayside and at-grade crossings. As proven in the first field test, the replacement is easy and simple without needs of extra installations other than "re-lamping". No need to alter the function and sizes of the existing signal lights, no need to increase power consumptions from the existing controller cabinet or add additional wiring inside and outside of the existing signal controller cabinets, no need to change anything outside of the signal housing. The self-de-icing LED signal is expected to transform the use and operation of the existing signal lights in snowy regions in North America with significant benefits in safety and performance efficiency and overall user cost savings. With some modifications to the products developed in this project, future models of the self-de-icing LED signal light can extend into other rail applications (e.g., commuter or light rail), or in other surface transportation applications including airport taxiway/apron lighting and seaport applications located in cold weather zones.

The self-de-icing LED signal light and its innovative system architecture of "Integrated Light and Heat Arrangement of LEDs in Low Profile" have been patented (**Patent No. US 10,253,965 B2, US 10,215,441 B2, US 9,851,086 B2**). We will work with state DOTs and Union Pacific (UP) Railroad and Burlington Northern and Santa Fe (BNSF) railroad and other businesses in private sectors on potential technology transfer and future implementation of the self-de-icing LED signals in practice. Dr. Cai has set up a start-up company SSLaH Tech, Inc. University of Kansas Center for Technology Commercialization (KUCTC) will also assist Dr. Cai in licensing and marketing the new technology. TABLE 4 is the timelines for our planned major activities .

TABLE 4 Timelines for major activities to transfer the technology to practice

Date of Completion	Action	Reason
2019 – 2021	Product Testing in field	Ensure product is capable of patent use
2020 – 2021	Initial Market Testing	Launch prototypes into market in the participating agencies
2020 – 2021	Cost Benefit Analysis	Use market testing research to update more accurate figures
2021 – 2022	Pricing Strategy	Use market testing research to update more accurate figures
2021 – 2022	Licensing Pitch	Concept is proven now time to reach out to potential buyers
2021 – 2023	Leverage IP to other Markets	Expand into other markets

5. CONCLUSIONS

This pooled fund project has developed and demonstrated the 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 adopt one or both of the two novel system architectures including (a) "Heated Lens Lighting Arrangement (**Patent No. US 10,253,965 B2, US 9,851,086 B2**)" that uses a single high-power LED and (b) "*Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture*". (**Patent No. US 10,215,441 B2**) 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.

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 a field test in Kansas on highway intersection. More field testing of the developed prototypes on highway intersection or railroad wayside or at-grade crossing signal lights is planned on identified test sites in California, Michigan, Wisconsin, Maryland, and New Jersey & Pennsylvania. On-site demonstration of the prototype signals would be held for project partners and state DOTs to initiate the implementation process.

As of Dec 31, 2019, we have achieved the following significant results in chronological order.

- Necessary equipment, components and insulation materials were procured. 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 were developed in house, each deploying 96 custom-made mediate-power color LEDs mounted in an array via "Heat Arrangement of LED Arrays in Low Profile", with regular paint coating. They were under laboratory testing for lighting and thermal performance. Based on the test results, we improved the design of Type 1 self-de-icing LED signals.
- We worked with 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. Then we 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 and tested them to improve the heating performance (to make faster heat transfer). Based on the testing results, the signal light engines with TIN coating have similar thermal performance, however, further testing in the laboratory and field was necessary to validate the final choice.
- We finalized the design of the signal housing 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. We 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.
- We designed and custom made two types of LED drivers. An electronics company was selected for 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. An on/off switch was designed for temperature

controls in winter and summer modes which could override the operation of the temperature sensor.

- We identified and started custom-making the Fresnel Lens from an Optoelectronic company with 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. Additional vendors for Fresnel lenses were contacted for lower unit price with higher quality control than the current lens vendor. Based on the lab test results, a total of 5000 PCS of new Fresnel lenses (**Model #1511**) were ordered from the new vendor for field tests.
- We started custom-making and modeling of the signal housing. Three samples were delivered for examinations and laboratory tests for necessary calibrations and further improvements. With minor adjustments for field tests, six improved samples were delivered and thoroughly tested in laboratory and closed-setting tests on the roof. We also started custom-making the LED drivers with desired specifications based on our test results. Seven LED drivers were delivered for sample testing. Next, we 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.
- The non-provisional patent application for the invention of Type 2 self-de-icing signal light "Heated Lens Lighting Arrangement (**Patent No. US 10,253,965 B2, US 9,851,086 B2**)" was officially approved by the USPTO. The self-de-icing LED signals adopt another novel system architectures "*Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture*s" (**Patent No. US 10,215,441 B2**) for Type 1 self-de-icing signal light was also approved by the USPTO.
- We designed and custom made new types of screws 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.
- It was proven that 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 conducted 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. 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 was continuously conducted over both winter and summer seasons in 2019. We have been continuously testing the closed-course performance and reliability of the prototypes since then.
- Seven states officially participated in this project, including Kansas, California, Michigan, New Jersey, Wisconsin, Pennsylvania and Maryland. A project addendum was proposed to conduct two additional field tests, one in Wisconsin and another one in a test site among Maryland, Pennsylvania, and New Jersey.
- We accordingly improved and finalized the plastic housing of the fully working prototype signals of Type 1 with changes/improvements, with assist of the plastic molding company, which custom made seven samples of the finalized new plastic housing for validations tests before actual product production.
- We produced 60 pcs of the finalized LED engines with the aid of the industrial partner, ready for the upcoming field tests.
- We updated and custom made 60 pcs of glass disc 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 for mounting the glass disc to the LED light engine.
- We were 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 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 adjusted the power output of the LED drivers. We also made minor adjustments of the signal housing for quick assembly of the real products. We corrected some problems and resolved issues of the custom-made LED drivers, including (1) decreased the size of the power connector of the temperature sensor, (2) decreased the length to 6 mm, (3) changed to more reliable single switch, (4) enlarged the inside size of the installation hole to 6mm x 4.5 mm, (5) changed the final designed output current of Yellow/Green LED drivers to 0.40 A (derated) /0.84 A(full output), (6) changed the final designed output current of Red LED drivers to 0.60 A (derated) /1.1 A(full output), (7) improvements on temperature measurement accuracy, redesigned logic circuits, and changes of electronic parts used on the LED PCB boards.
- The signal housing of the fourth generation LED signal lights was revised for quick assembly. We received the new prototypes of the housing with desired changes, which were tested in the laboratory with satisfactory performance.
- Other parts like glass mounting discs were been improved in house for enlarging the installation holes to fit the new housing. We custom made 30 more pcs of glass disc which have four larger mounting holes.

- Based on the lab test results on the second generation of LED drivers, a total of 21 new LED drivers of the third generation for the field tests were made and are under testing in the laboratory for their field performance and further improvements needed for the control of the yield rate in production. Based on the test results, the third-generation LED drivers may need further improvements towards the fourth generation, which will resolve two issues: 1) light power-up delay (the time delay between power on and signal light on) for about 0.5-1 second, 2) Unstable output performance of the drivers, due to unsecured soldering of wire connections by hands.
- We developed field monitoring system powered by Raspberry 3 B+ motherboard, fitted with three cable cameras used to monitor three signal lights (Red, Yellow, Green) in each unit, four temperature sensors used to record the lens' surface temperature of the three signal lights (Red, Yellow, Green) and the ambient air temperature, USB flash drivers used to store the year around test data (pictures and temperature dataset), power supplies, and mounting accessories. The system was custom built in house and under testing in the lab and on the roof, which would be mounted at each field test site for year-around real-time monitoring and data recording of the new signals to be tested in the field. The field monitoring system was continuously tested in the laboratory and on the roof for field installation. The system would be mounted at every field test site for year-around real-time monitoring and data recording of the new signals.
- New fully working prototypes of the signal lights for field tests were assembled and are under thorough final tests in the laboratory in preparation for upcoming field tests.
- The first field test site was set up in Kansas at the intersection of County Rd 458 (or 1200 Rd) /US-59. All new equipment including the performance monitoring system for data recording were installed on side signals facing north and already survived the first snowstorm in December.

References

[1] Federal Highway Administration (FHWA). 2013. Road Weather Management Program, Snow and Ice. Available online: http://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm.

[2] U.S. Average Snow State Rank. Available online: http://www.usa.com/rank/us--average-snow--state-rank.htm?hl=&hlst=&wist=&yr=&dis=&sb=DESC&plow=&phigh=&ps=.

[3] Kiska P. 2014. 'Cool' LED traffic lights get snow clogged easily, confused drivers run red lights. Available online: http://www.newsnet5.com/news/local-news/oh-cuyahoga/cool-led-traffic-lights-get-snow-clogged-easily-confused-drivers-run-red-lights.

[4] The Associated Press. 2009. Energy-saving traffic light blamed in crashes. Available online: http://www.nbcnews.com/id/34436730/ns/us_news-life/t/energy-saving-traffic-lights-blamed-crashes/#.VNqJ6ink3EM

[5] Transportation Safety Board of Canada. 2013. Railway Investigation Report R10E0056, Photos 1-3. Available online: http://www.tsb.gc.ca/eng/rapports-reports/rail/2010/r10e0056/r10e0056.asp

[6] Transportation Safety Board of Canada. 2013. Railway Investigation Report R10Q0011, Photo 2. Available online: http://www.tsb.gc.ca/eng/rapports-reports/rail/2010/r10q0011/r10q0011.asp

[7] Institute of Transportation Engineers (ITE). 2010. Traffic Signal LED Module Specification Workshop and Informational Report for Snow Conditions. Available online: http://www.ite.org/standards/led/snowconditions.asp.

[8] DOE. 2008. Updated per multi-year program plan (MYPP), Mar 2008, figure 4-5, pg 58. U.S. Department of Energy, Washington, DC.

[9] Hajmohammadi M. R., Salimpour M. R., Saber M., Campo A. 2013. Detailed analysis for the cooling performance enhancement of a heat source under a thick plate, Energy Conversion and Management, 76: 691–700.

[10] Institute of Transportation Engineers (ITE). 2005. Vehicle Traffic Control Signal Heads: Light Emitting Diode (LED) Circular Signal Supplement.