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Self-de-icing LED Signal

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The University of Kansas

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16 Abstract

This Pooled Fund project was aimed at developing and demonstrating a new type of self-de-icing LED signal for highway intersections as a replacement for existing LED signal lights that remain too cold to prevent snow, sleet, and ice buildup on the lens and could cause accidents in snowy conditions. The self-de-icing LED signals adopt a novel system architecture of "Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture" (Patent No. US 10,215,441 B2) or "Heated Lens Lighting Arrangement" (Patent No. US 10,253,965 B2, US 9,851,086 B2) for integrative solid-state lighting and heating. The heat generated by the LEDs is harvested by the passive heat exchanger and stored there to continuously heat the signal lens in wintery conditions.

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Final Report

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Executive Summary

This Pooled Fund project was aimed at developing and demonstrating a new type of self-de-icing LED signal for highway intersections as a replacement for existing LED signal lights that remain too cold to prevent snow, sleet, and ice buildup on the lens and could cause accidents in snowy conditions. The self-de-icing LED signals adopt a novel system architecture of "Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture" (Patent No. US 10,215,441 B2) or "Heated Lens Lighting Arrangement" (Patent No. US 10,253,965 B2, US 9,851,086 B2) for integrative solid-state lighting and heating. The heat generated by the LEDs is harvested by the passive heat exchanger and stored there to continuously heat the signal lens in wintery conditions.

The work of this project was divided into three stages. Stage 1 work focused on laboratory development and testing. Application of the innovative "Heat Arrangement of LED Arrays in Low Profile" was adopted for the architecture of the new self-de-icing LED signals and tested in the laboratory to enhance the integrative heating and lighting performance while reducing costs. Needed equipment, components, and materials were procured to develop and build the prototypes. A total of five generations of prototype signals (Red, Yellow, and Green) were developed and tested in the laboratory for further improvements. The prototype signals (R, Y, G) consist of (a) new light engines in low profile using 96 medium-power LEDs; (b) an insulation layer put on the back of the light engine as part of the innovative system architecture; (c) two self-designed and custom-made LED drivers (one for red light signal and the other for green/yellow light), each 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; (d) new signal housing custom made by a plastic molding company using UV stabilized polycarbonate materials; and (e) a new signal lens disc integrated with 96 small Fresnel lenses for light collimation of individual LEDs. The new light engines for appropriate color LED modules (R, Y, G) were self-designed and custom made with the aid of the industrial partner (the Sunlite Science & Technology). On top of the light engine, the Fresnel lens disc with 96 lenses (each lens in diameter 15 mm, focal length 11.5 mm or less, thickness 1.5–2.0 mm) was mounted with a gap of ¼" for optimal LED light collimation

and balanced thermal performance. Laboratory testing of all heating and lighting parameters of the prototypes with the desired specifications that meet the ITE codes and standards was completed. The prototypes were also tested in a controlled cold room for the performance of the ambient temperature sensor connected to the LED driver, and the power output of the LED drivers was adjusted accordingly. The signal housing was also continuously revised for quick assembly of final products. Several other contracted companies have been producing all other parts needed for assembling the final prototypes.

Work in Stage 2 focused on closed-course performance and reliability tests of the new signals on the roof of the University of Kansas engineering complex. The fully functional prototypes of different generations were continuously tested on the roof, powered by a real traffic control cabinet, with the 5th generation prototypes still under ongoing testing. Based on the test results, new plastic housing with desired changes was tested in the laboratory and then on the roof with satisfactory performance. The housing was also revised for quick assembly. Second-generation LED driver samples were tested thoroughly in the cold room and on the roof. Issues were resolved with needed changes. The ambient temperature sensor of the drivers was improved for switching power output at 4 °C with acceptable tolerances. A total of 21 new samples of third-generation LED drivers were tested for field performance and further improvements needed for the control of the yield rate in production toward the fourth generation. The new Fresnel lens disc was also continuously improved with a lower unit price and higher quality control. Samples of different generations were tested in the laboratory and on the roof.

Work in the third stage involved field testing at selected highway signalized intersections in different states. Seven states (Kansas, California, Michigan, New Jersey, Wisconsin, Pennsylvania, and Maryland) participated in field testing and evaluation of the prototypes. Fully functional prototypes were assembled and thoroughly tested in the laboratory and on the roof in preparation for field tests. In the field, prototype LED modules (R, G, Y) of the self-de-icing signals were used to replace the existing LED modules installed on pole-mounted side signals on the right shoulder as a backup to the overhead signals. Additionally, a remote monitoring system was built in-house, which consists of a Raspberry PI computer, three cable cameras, four temperature sensors, USB flash drivers, LTE mobile communication device with a monthly data plan, power supplies, and mounting accessories, all put in a weather-proof plastic box, and continuously tested in the laboratory and on the roof for field installation. At each field test site, the system was mounted near the signal head for year-round monitoring and data recording of the real-time performance of the signals (R, G, Y). Real-time performance for melting snow and deicing was monitored by the field monitoring system for year-round data recording. The first field test site was set up in Lawrence, Kansas, at the intersection of County Rd 458 (or 1200 Rd) /US-59 on a side signal head facing north. More prototypes of the final products were prepared for other test sites. Two additional field tests were conducted in Michigan and Wisconsin in November 2021. The realistic field performance of the prototype signals would help project partners and state DOTs evaluate and initiate the implementation process.

Acknowledgments

The development and implementation of the self-de-icing LED Signal was 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 (*Project Number TPF-5(351)*). Additionally, the initial development of the self-de-icing LED signal was supported by the TRB-IDEA program in the Joint IDEA Project S-29/NCHRP-190 for self-deicing LED signals for railroads and highway intersections.

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Chapter 1: Technology and Product Development

This project developed a new type of self-de-icing LED signals (Figure 1) for highway signalized intersections, which adopt a novel system architecture of "Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture" (Patent No. US 10,215,441 B2) or "Heated Lens Lighting Arrangement" (Patent No. US 10,253,965 B2, US 9,851,086 B2) for integrative solid-state lighting and heating. The heat generated by the LEDs is harvested by the passive heat exchanger and stored there to continuously heat the signal lens in wintery conditions. The lighting and heating performances and reliability of the new signals were tested in the laboratory and then validated using closed-course tests on a building roof and field tests at multiple selected test sites of the participating state Departments of Transportation (Kansas, California, Michigan, New Jersey, Wisconsin, Pennsylvania, and Maryland).

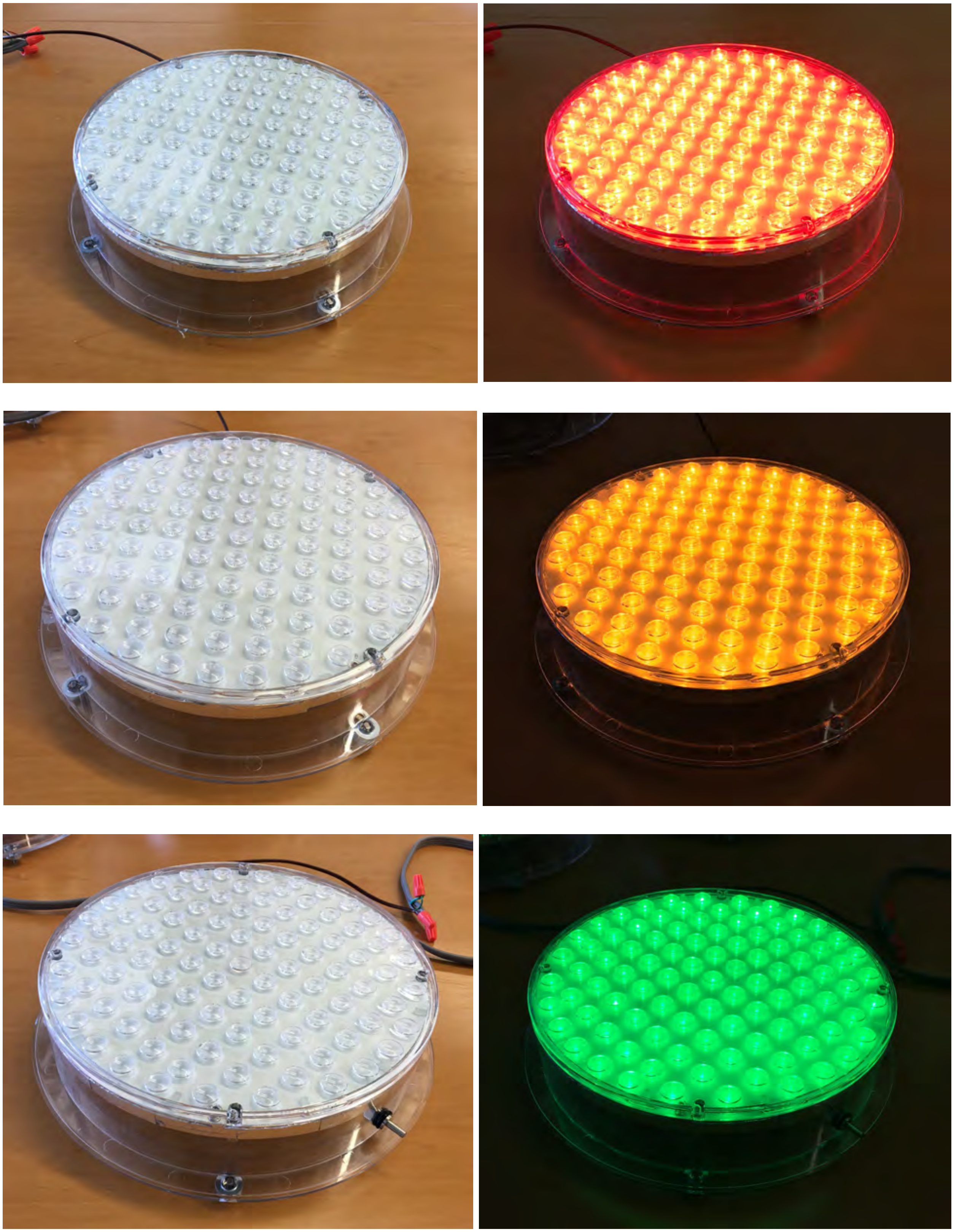


Figure 1: Prototypes of the new type of self-de-icing LED signals (Red, Yellow, Green) for highway signalized intersections

The self-de-icing LED signal light was designed and developed 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. As shown in Figure 2, 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, resulting in collisions in inclement weather conditions. 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.

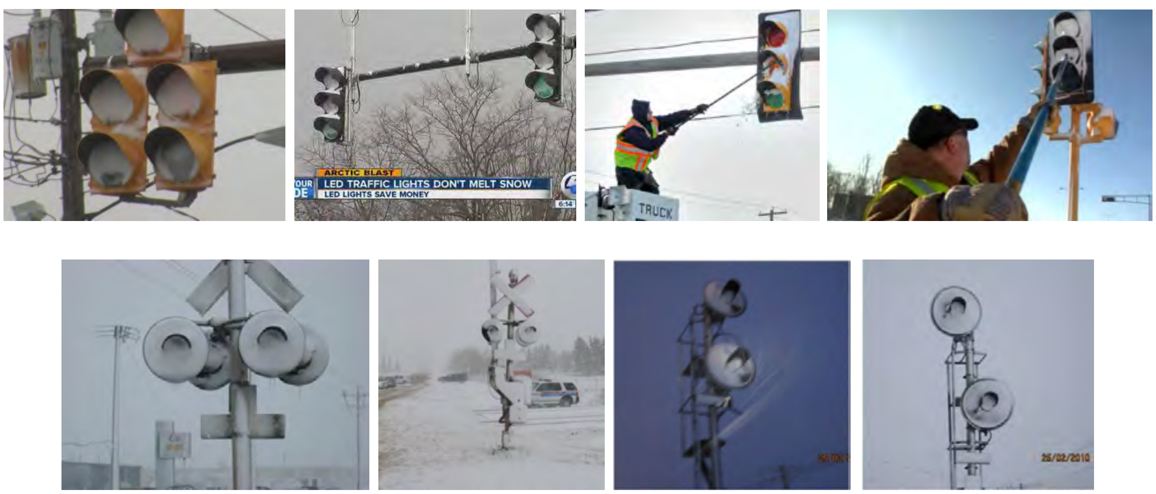


Figure 2: Snow-clogged “cool” LED traffic lights and their cleaning off by hand [3, 4], and snow-clogged railroad signals [5, 6]

Current solutions to the snow-clogged signal lights include manual labor of brushing snow off the signal lens (Figure 2) 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 costs. The chemicals also have unknown long-term effectiveness on signal lenses and harm to the local environment, resulting in periodic spraying at intervals that largely increase 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.

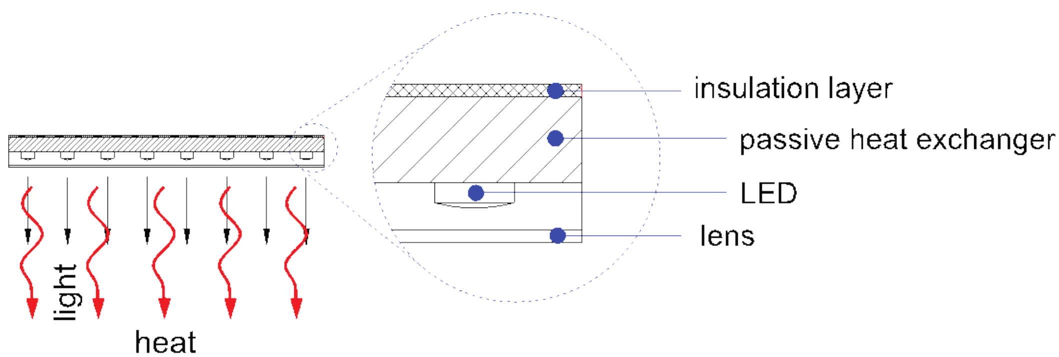
The self-de-icing LED signals can solve all of those issues and be more reliable and effective under inclement wintery conditions, but not compromise the efficiency, brightness, and/or operational complexity of the system. Compared with the aforementioned technologies, the self-de-icing LED signals have 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, they are 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 light modules (R, G, Y) were designed to be swappable with the existing “cool” LED and legacy incandescent signal modules of the same color without the need for extra installations. 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, and 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. As validated in the field, the self-de-icing LED signal light can be a viable retrofit to the existing “cool” LED signal lights (also the obsolete incandescent signal lights as well) installed at the signalized highway intersections.

Additionally, continuous development of more types of the self-de-icing LED signals in the future is expected to extend their applications into railroad wayside and at-grade crossings and 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 climates where they may see only a limited number of cold weather days.

Chapter 2: Concept and Innovation

Approximately 70–80% of the electricity consumed by LEDs is converted to heat rather than light [8]. Designed to harvest both the light and the heat generated by the same LED(s) for lighting and heating the signal lens, 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 10,215,441 B2), as illustrated in Figure 3. The harnessed great deal of LED heat enables the self-de-icing LED signal with self-efficacy for the prevention of the buildup and accumulation of ice, sleet, and snow on the lens of the signals during wintery conditions. There is no need for additional heat generators (e.g., resistance wires or infrared LEDs).



"*Integrated Light and Heat Arrangement of Low Profile LED Fixture*"
(Patent No. US 10,215,441 B2)

Figure 3: The concept of self-de-icing LED signals, which adopt a new system architecture of "Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture" (Patent No. US 10,215,441 B2) for integrative solid-state lighting and heating

As illustrated in Figure 3, multiple LEDs are mounted on a 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. 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 and 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, an air gap, or a 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 disc, with 96 Fresnel lenses mounted above 96 individual LEDs for light collimation.

Additionally, for energy saving, the self-de-icing LED signals are equipped with a remote ambient temperature sensor wired to their LED driver. In cold weather, when the ambient air temperature drops below 4 °C (39.2 °F), the remote temperature sensor switches the driver's power output to full output to prevent snow and ice accumulation on the signal lens. In warm weather, when the ambient air temperature is above 4 °C (39.2 °F) and there is no risk of snow and ice accumulation, the signals will have only derated power output, at about 26-32%[1] of the full power output, for energy saving. Meanwhile, the maintained signal light output meets the code requirements. Table 1 summarizes how the remote temperature sensor of the signals switches their power output in accordance with the ambient air temperature. The derated power output in warm weather will also largely extend the useful life of the product in field implementation.

Table 1: The remote temperature sensor of the signals switches their power output in accordance with the ambient air temperature

Ambient air temperature	> 4 °C (39.2 °F)	≤ 4 °C (39.2 °F)
Red LED signal	**Derated 32%** power output	**full** power output
Yellow LED signals	**Derated 26%** power output	**full** power output
Green LED signals	**Derated 32%** power output	**full** power output

[1] 26-32% is for final product, current prototypes use 48-51%, which will be further lowered for more energy saving.

Chapter 3: Investigation

Three stages of work were conducted to develop and validate the self-de-icing signals, including Stage 1 – Laboratory Development and Tests, Stage 2 – Performance and Reliability Tests on the Roof, and Stage 3 – Field Tests. More detailed work at each stage is introduced below for research and development of the self-de-icing LED technology, parts, and testing of different generations of fully working prototypes of the self-de-icing signals.

3.1 Laboratory Development and Tests

At Stage 1, the new self-de-icing LED signals were developed and tested in the University of Kansas lighting research laboratory and its darkroom, and the Cold Room in the LEEP2 engineering complex. We first ordered necessary equipment, components, and insulation materials available in the market to develop and finalize the design of the self-de-icing signals, with initial concepts tested and validated for optimal thermal and lighting performance. Application of the innovative "Integrated Light and Heat Arrangement of LEDs in Low Profile" (Patent No. US 10,215,441 B2) was adopted for the architecture of the new LED signals and tested in the laboratory to enhance the heating and lighting performance while reducing costs.

A total of five generations of the prototype self-de-icing LED signals were developed and tested comprehensively in the laboratory. The fully working prototype signals (R, G, Y) adopt the 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 with accurate dimensions, and new custom-made Fresnel lens disc with integrated 96 small Fresnel lenses (diameter: 15 mm, focal length: 11.5 mm or less with different generations of the prototypes, thickness: 1.5 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. Other self-designed metal, glass, and plastic parts needed for assembling the final prototypes for field implementation were custom-made by several contracted companies.

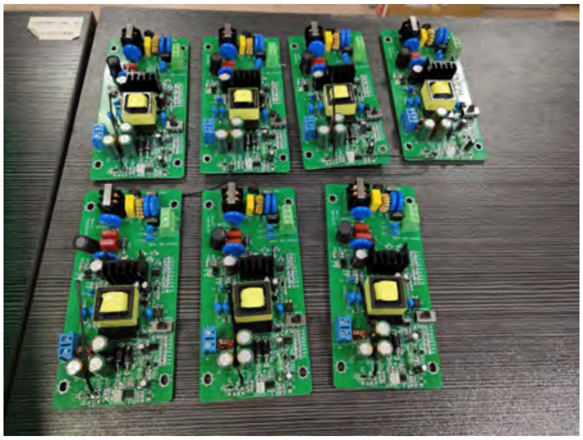
More details are listed as follows for the development and testing of different parts, and different generations of fully working prototypes of the self-de-icing signals.

Firstly, appropriate color LED modules in red, green, and yellow light were designed in-house and custom made with the aid of the industrial partner (Sunlite Science & Technology). As shown in Figure 4, we produced 60 pieces of the finalized LED engines (20 pieces for each color), which were used for making fully working prototypes ready for field tests.

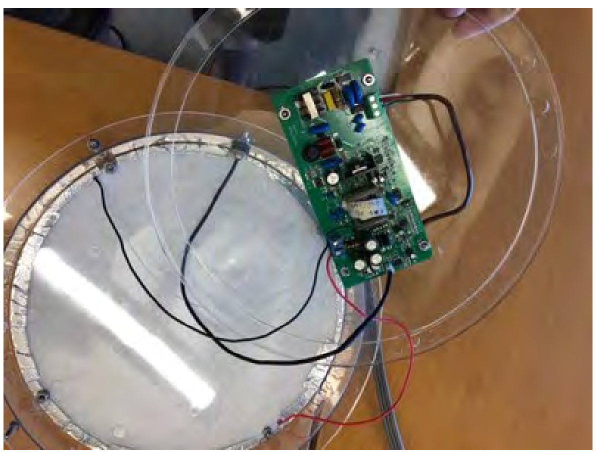
Figure 4: Sixty pieces of self-designed LED light engines, which were custom made with the aid of the industrial partner, including 20 pieces in each color (R, G, Y).

Secondly, we custom made two types of LED drivers for powering the LED engines of the self-de-icing LED signals (R, G, Y), including a red LED driver (0.60 A (derated) /1.1 A (full output)), and a yellow/green LED driver (0.40 A (derated) /0.84 A (full output)). Figure 5 shows the prototype LED drivers of the third generation (seven red LED drivers and 14 yellow/green LED drivers), 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. Those drivers had a few improvements on the 2nd generation, including: (a) decreased size of the power connector of the temperature sensor that no longer has a problem in assembly; (b) reduced length of the ambient temperature sensor to 6 mm; (c) changed power board switch from double switch to more reliable single switch; (d) enlarged installation hole from original 4.5 mm x 3.5 mm to 6 mm x 4.5 mm; (e) changed final output current of the Yellow/Green LED drivers to 0.40 A (derated) /0.84 A (full output); (f) changed final output current of the Red LED drivers to 0.60

A (derated) /1.1 A (full output); and (g) corrected ambient temperature sensor’s switching temperature from the factory default 6 °C to 4 °C as designed.




(a) (b)




(c) (d)

Figure 5: The third generation of LED drivers with all improvements, (a) Red LED drivers with a designed power output of 0.60 A (derated) /1.1 A(full output), (b) Yellow/Green LED drivers with a 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.

However, further tests in the laboratory and at the first field test site in Kansas revealed two major issues of the third generation LED drivers, as listed below with proposed solutions. To overcome those issues, we are 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 seconds, especially for green signal light. Proposed Solution: adjustment of MCU chips used in the driver to decrease the delay to only milliseconds.
2. Unreliable soldering of the wire connections by hand. Proposed Solution: new products will be made on the automatic production line instead of being handmade (all previous samples due to small quantity were made by hand, 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.

Thirdly, as shown in Figure 6a, fully working prototypes of the self-de-icing signal lights for field tests were assembled in their plastic housing. Alternative insulation materials (Figure 6b) were also tested for equivalent thermal performance but at a lower cost of the materials. The housing has three parts, as shown in Figure 6c. We also self-designed and custom made special screws (Figure 6d) used in the housing for mass production. The mass production of the signal housings had continuous adjustment for quality control. One problem (Figure 6e) 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 concave surface of the new housing made the assembly of the final signal products difficult. This problem was solved via improved mass-production techniques with a maximum tolerance of uneven lens surface of 0.5–2 mm in depth.

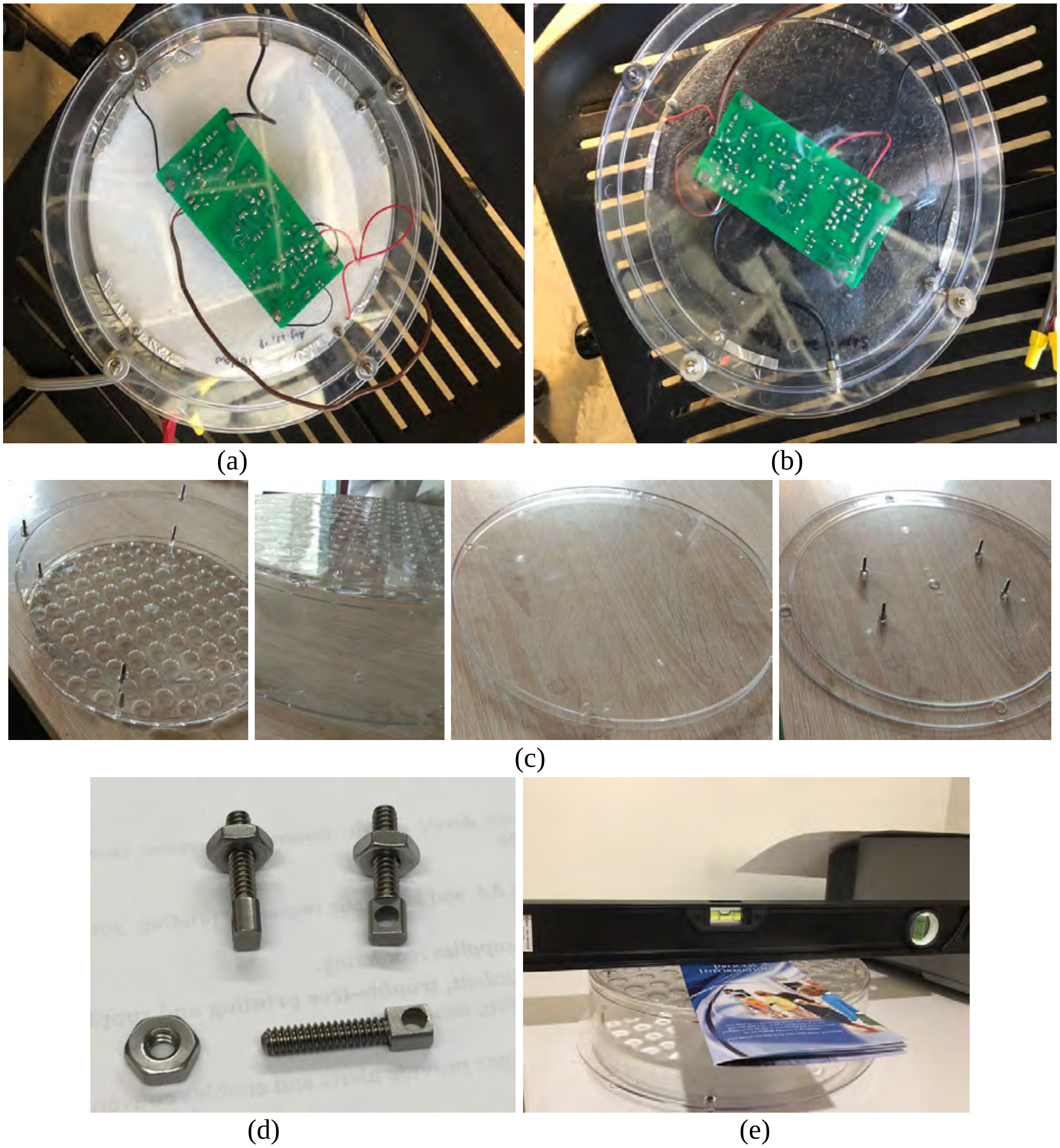


Figure 6: Signal housing, (a) the prototype signal light with Aerogel insulation material, (b) the prototype signal light with alternative insulation materials (shown only one type), (c) the three parts of the housing, (d) self-designed custom-made screws used for the housing, (e) the concave lens surface of the housing, with a maximum tolerance of 0.5–2 mm in depth

Fourthly, we adopted two different solutions to mount and secure the Fresnel lenses for light collimation of individual LEDs. First, in the 1st-4th generation prototypes, we used some custom-made glass disc (Figure 7a, Figure 7b) with four mounting holes on the edge. We also used some custom-made plastic mounting bars (Figure 7c) for mounting the glass disc to the LED light engine, in order to secure the 96 pieces of Fresnel lenses (Model #1511) (Figure 7d). Samples of the new Fresnel lenses mounted in the 4th generation of prototypes were tested in the laboratory with satisfactory results. This solution has accurate control of the focal length of the Fresnel lenses for optimal lighting performance of LEDs, which is changeable in different applications. However, this solution has a problem in mounting due to the undesired concaveness of the housing lens surface that easily cracks the glass disc. Also, because the flat glass disc could not perfectly fit the concave lens surface, over time, the glass disc may no longer hold the individual Fresnel lens in each niche of the housing due to its repeated expansion and contraction in winter and summer seasons.


(a) 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: Custom-made parts and accessories used in the 1st-4th generation prototypes for mounting the Fresnel lenses, including (a) (b) custom-made glass discs, (c) custom-made plastic mounting bars for mounting the glass disc, and (d) individual Fresnel lenses (diameter: 15 mm, focal length: 11.5 mm, thickness: 1.5–2.0 mm) for light collimation of individual LEDs.

Later this solution was discarded and replaced by another solution using a single piece of Fresnel lens disc (Figure 8) which was adopted in the 5th generation product. The new Fresnel lens disc, as a whole piece, has 96 small Fresnel lenses integrated into it, with four linear stiffeners on the back that strengthen the lens disc to be flat, also canceling the mounting bars (Figure 7c). The new Fresnel lens disc was self-designed and custom made in a factory using an injection mold. The lens disc was made of UV stabilized clear PC materials (e.g., Markrolon 2807) with light transmittance of 85–90%, with stable temperature from -30° C (-22° F) to +120° C (+248° F), and UL94 rating for heat/fire resistance. The new lens disc with 96 Fresnel lenses integrated on it is deemed a more cost-effective solution than using separate 96 Fresnel lenses, and also provides an alternative solution to the aforementioned problem of the uneven housing lens (Figure 6e).

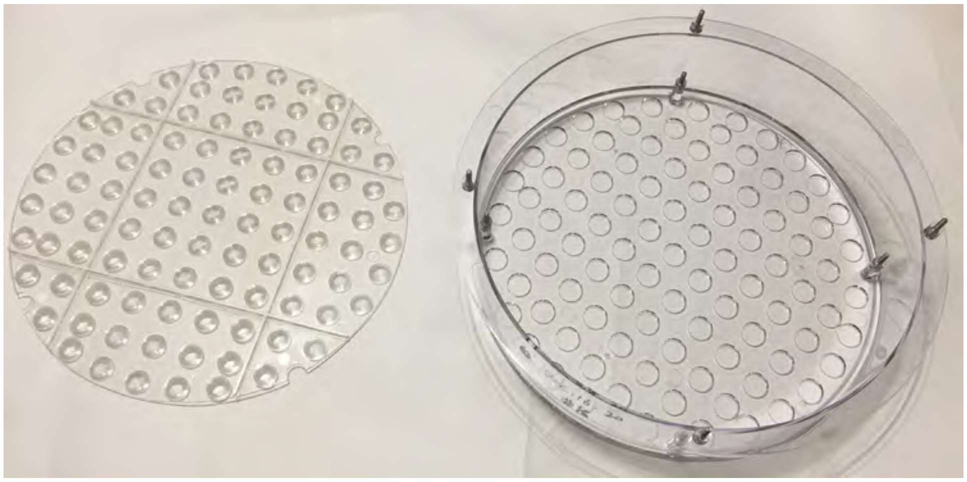
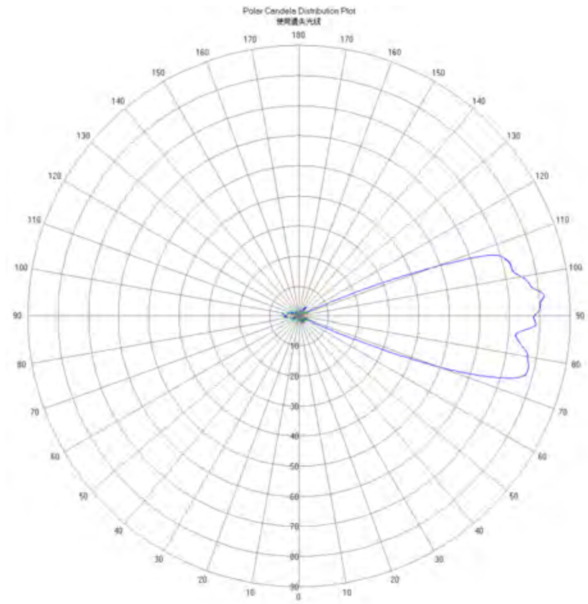


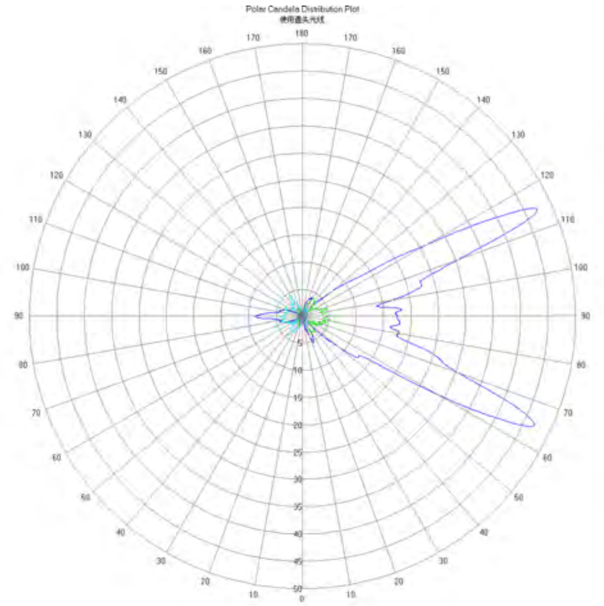
Figure 8: Self-designed and custom-made new Fresnel lens disc with 96 small Fresnel lenses integrated on it, and four linear stiffeners on the back to strengthen the lens disc to be flat.

With continuous improvements, three generations of samples of the new Fresnel lens disc were made and tested in the laboratory for lighting and thermal performance. The lighting performance passed the code requirements, the thermal performance was also good. Note that the first- and second-generation samples had a problem with fitting in the housing base. Among the 96 Fresnel lenses, four of them did not fit in the niches of the housing, slightly offset by 0.5–1.2 mm. Ten more Fresnel lenses were also offset by 0.3 mm, but they could still fit in the niches. The fitting problem was caused by the wrong drawing (not mirrored) used in the molding, which was thus corrected in the third-generation samples. Nonetheless, the signal samples for mass production have unoptimized lighting performance caused by the undesired increase of the focal length to 12.5–13.0 mm (> the designed 11.5 mm) in the manufacturing process. Multiple laboratory tests were conducted to double-check the focus length and help the factory revise the mold for improvement. The measured focal length of the third-generation samples was around 11.9–12.0 mm, still longer than the designed 11.5 mm. As a result, it was found that the peak lighting performance of the third generation was around 15° off-axis, different from 20° of the second generation and 8–9° of the first generation, also different from 1–3° of the individual

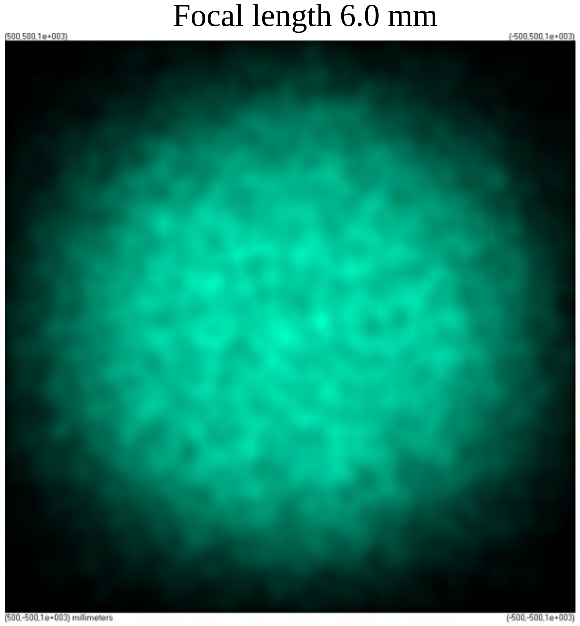
Fresnel lens adopted in the initial solution (Figure 7d). The target light intensity peak value is ideally < 10°. To solve this problem, we are working with the engineers in the factory to revise the mold for making the fourth-generation samples with a target focal length shorter than 11.5 mm. Figure 9 shows the computer simulations on the light output angles and lighting performance of the signal at different focal lengths of the Fresnel lenses. After discussions with the engineers in the factory, it was found that the focal length of the Fresnel lens probably needs to be decreased to 6 mm (from the initial 11.5 mm), to compensate for the increase of focal length in the mass production process.



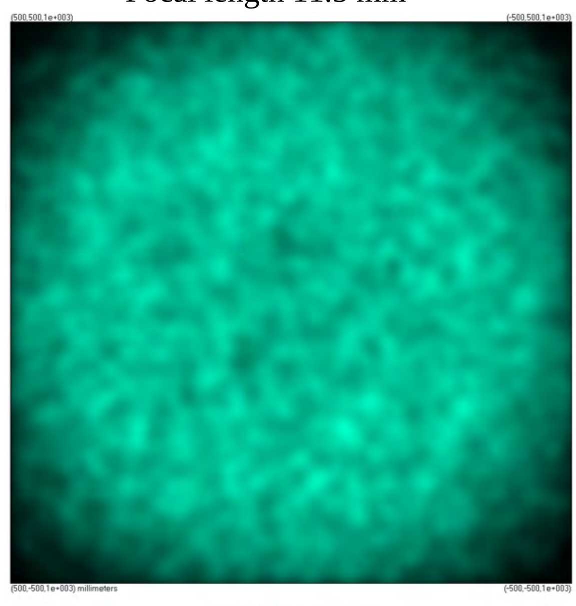
Focal length 6.0 mm



Focal length 11.5 mm



Focal length 6.0 mm



Focal length 11.5 mm

Figure 9: Computer simulations on the light output angles and lighting performance of the signal at different focal lengths of the 96 Fresnel lenses integrated into the disc.

Additionally, we tested the signal lens's surface luminance uniformity based on the code requirements, as shown in Figure 10. It was found that the max/min ratio is in a range of 5.5–8.3 for different colors (R, G, Y), less than the code requirements of max/min ratio of maximum 10. However, for further improvement on the lens surface luminance uniformity, we could modify the

Fresnel lens disc surface treatment with a possible frosted surface in those gaps between lenses from the current transparent surface. Based on the computer simulation, this could increase the uniformity while not significantly affecting the signal light distribution. Yet additional laboratory testing will be needed once the new fourth-generation samples are made and available in the near future.

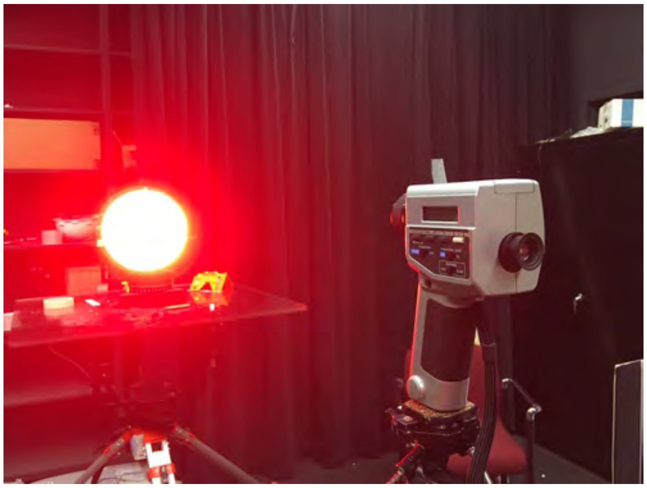
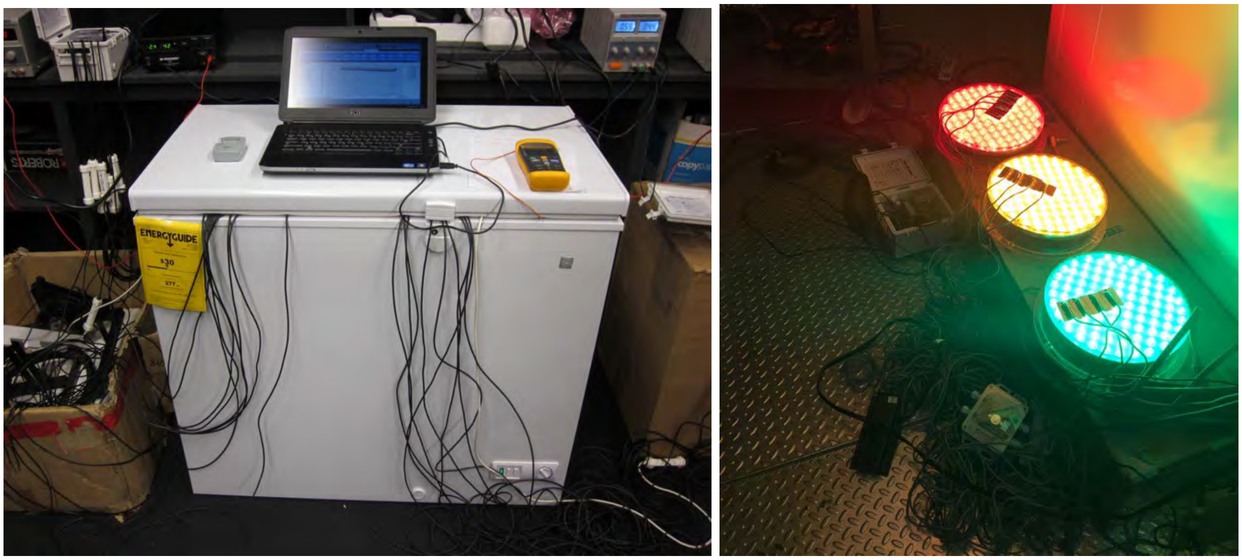


Figure 10: Lab measurement of the signal lens surface luminance using the code recommended measurement method with a luminance meter.

Fifthly, we conducted thorough thermal and lighting tests of all samples in the laboratory for continuous improvements on the product. Testing for all heating and lighting parameters of the fourth- and fifth-generation fully working prototypes was completed with desired specifications. Figure 11 shows the testing of three fully functional prototypes (R, G, Y) of the new signals in a freezer located in the darkroom, and then in a well-controlled Cold Room with controllable ambient air temperature. In those tests, the signals were continuously powered by DC power sources. Table 2 and Figure 12 show the results of a typical test of the 5th generation signals, indicating the temperature difference between the signal lens and the ambient air temperature was all larger than 30 °C for all signals when the signals were powered continuously with full power output (current 0.837 A for green light, 0.838 A for yellow light, and 1.115 A for red light).



(a) in a freezer in the darkroom (b) in the cold room

Figure 11: Prototypes (R, G, Y) of the self-de-icing LED signals were tested in a freezer and the well-controlled Cold Room located for their thermal performance when the signals were powered continuously with DC power sources.

Table 2: Typical thermal performance of a 5th generation prototypes (R, G, Y) of the self-de-icing signals in a freezer when continuously powered by a DC power source with 100% power output

Test conditions	**Freezer, 3 signals tested together**	
Ambient Air Temp	Ambient air	-11.5° C
Lens Surface Temp	Green light (current 0.837 A)	19.2° C
	Yellow light (current 0.838 A)	21.1° C
	Red light (current 1.115 A)	19.8° C
Temp Difference (Δ) above Ambient	Green light (current 0.837 A)	**Δ 30.7° C**
	Yellow light (current 0.838 A)	**Δ 32.6° C**
	Red light (current 1.115 A)	**Δ 31.3° C**

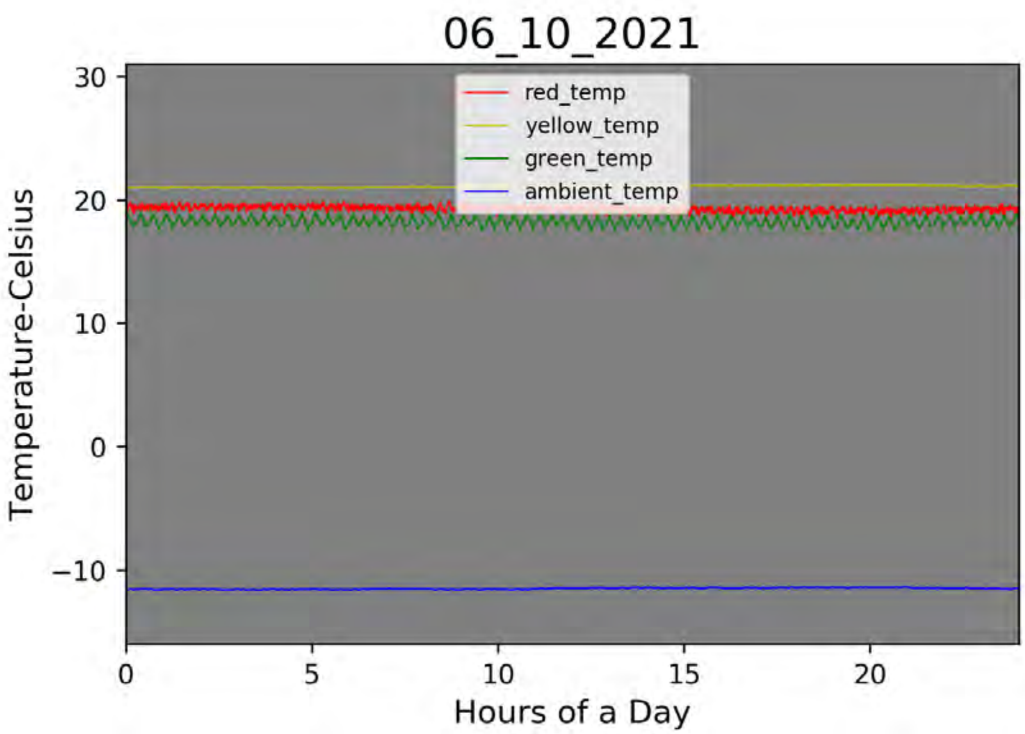


Figure 12: The thermal performance of the 5th generation prototypes of the self-de-icing LED signals tested in a freezer, powered continuously with DC power sources with full power output.

Moreover, we measured the lighting performance of different generations 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 4 and Table 5 summarize the measurement results of the 4th and 5th generation prototypes, all passed the code requirements (Table 3). The signal lights were brighter when they have full power output. It is worth mentioning that the prototype signals still have the potential to further lower their derated power output to save more energy, while still meeting the code requirements for light output.

Table 3: Peak minimum maintained luminous intensity values of $I_{(-2.5°, 0°)}$, measured at a 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 the 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 4: Lighting performance of the 4th 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

Table 5: Lighting performance of the 5th 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	667.5	2088.2	1713.3	1277.2	3900.8	2740.9
0.5	668.1	2089.6	1721.3	1277.9	3903.4	2741.6
1	668.1	2091.6	1728.0	1281.9	3927.6	2747.6
1.5	671.5	2091.6	1733.4	1283.3	3932.3	2791.2
2	676.2	2089.6	1740.8	1288.0	3928.3	2818.1
2.5	**680.9 > 365 (code)**	**2087.6 > 910 (code)**	**1751.5 > 475 (code)**	**1300.0 > 365 (code)**	**3945.7 > 910 (code)**	**2827.5 > 475 (code)**
3	685.6	2088.2	1761.5	1301.4	3925.6	2832.2
3.5	691.6	2091.6	1772.3	1316.8	3932.3	2835.5
4	697.0	2093.6	1785.0	1328.2	3977.9	2838.2
4.5	708.4	2099.6	1801.8	1351.7	3988.6	2900.6
5	721.1	2109.0	1821.2	1394.6	4028.2	2932.1
6	741.9	2129.2	1873.6	1459.7	4173.1	2960.3
7	774.8	2163.4	1954.7	1518.7	4197.3	3127.3
8	821.7	2199.6	2027.2	1618.7	4311.3	3203.1
9	878.1	2208.3	2129.8	1597.2	3953.1	3407.7
10	873.4	2153.3	2127.1	1521.4	3725.0	3382.2
11	822.4	2021.8	1959.4	1338.3	3275.6	3115.2
12	752.6	1778.3	1845.4	1134.3	2667.8	2952.9
13	626.5	1452.3	1768.3	898.2	2048.0	2829.5
14	491.7	1178.6	1630.7	731.2	1744.1	2625.6
15	399.1	923.0	1343.0	668.8	1532.1	2162.0
20	145.6	437.4	463.5	256.2	760.7	737.2
25	102.6	301.2	313.9	188.5	551.4	502.4
30	82.5	232.8	249.5	150.3	416.6	404.5
40	57.7	159.0	173.7	117.4	318.0	276.4
50	53.0	133.5	143.6	77.8	193.9	232.8
60	63.1	155.6	177.1	75.8	185.1	285.1
70	23.5	88.5	113.4	50.3	188.5	180.4
80	8.0	48.3	58.4	21.5	74.5	92.6
90	3.4	20.8	28.2	12.1	59.7	45.6

3.2 Performance and Reliability Tests on the Roof

At Stage 2, the fully working prototypes (R, G, Y) of different generations were mounted on the roof of the University of Kansas engineering complex for closed-course performance and reliability tests, and follow-up improvements on any identified issues. As shown in Figure 13, three prototypes were mounted on a signal pole, powered by a traffic control cabinet in 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, yellow signal light ON for 5 seconds) for comprehensive heating and lighting performance tests. The signaling time cycles are adjustable for testing different cycles.

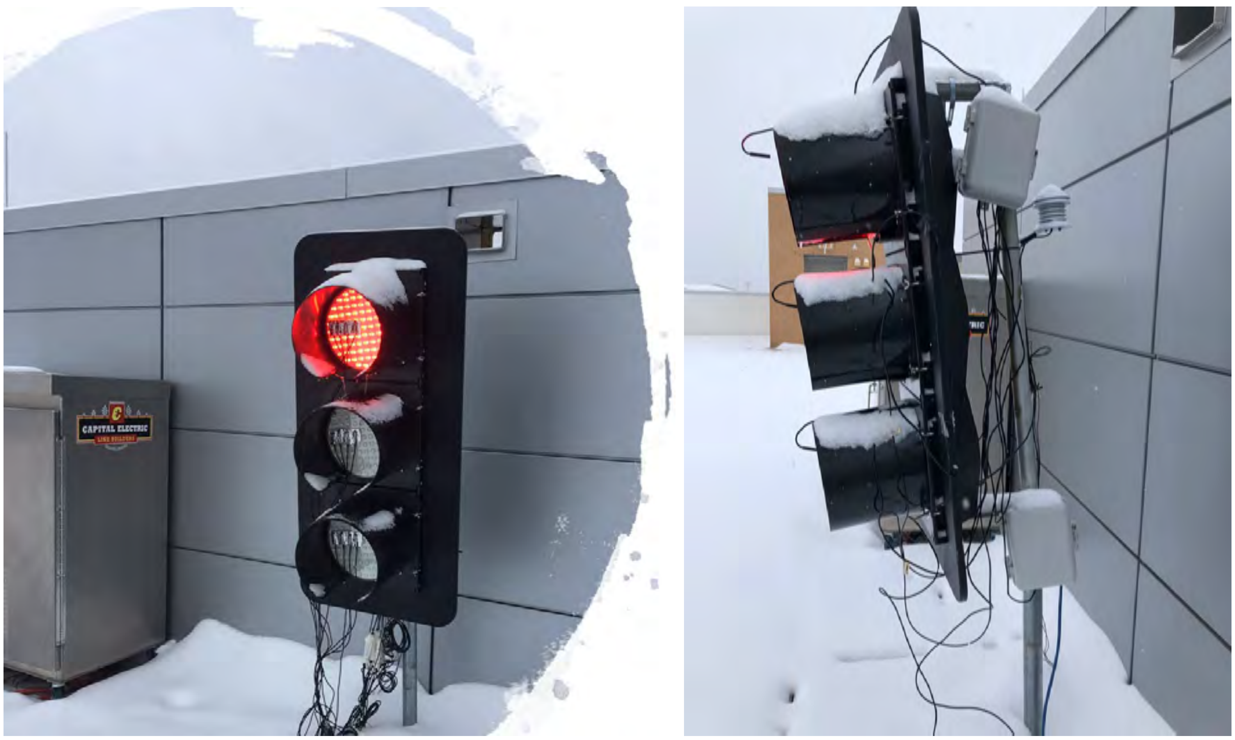


Figure 13: Prototypes of the new type of self-de-icing LED signals (Red, Yellow, Green) for highway signalized intersections, and their performance and reliability tests on the roof of the University of Kansas engineering complex, powered by a real traffic control cabinet.

The roof testing of the closed-course performance and reliability of different generation prototypes have been continuously conducted since 2018 through multiple snowstorms in the past years. For test monitoring and data recording, we developed a house-built field monitoring system that has been undergoing continuous tests on the roof. With a few improvements, the system was proven reliable for data recording. As shown in Figure 14, 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 was mounted on the lower edge of the signal lens to prevent blocking the driver's view of the signal light. After validation on the roof, the system would be mounted at every field test site for year-round real-time monitoring and data recording of the new signals. Figure 15 shows the results of the roof tests with the field monitoring system, including temperature figures, photos of the lens' surface (R, G, Y), and recorded temperature data log, in both winter and summer.

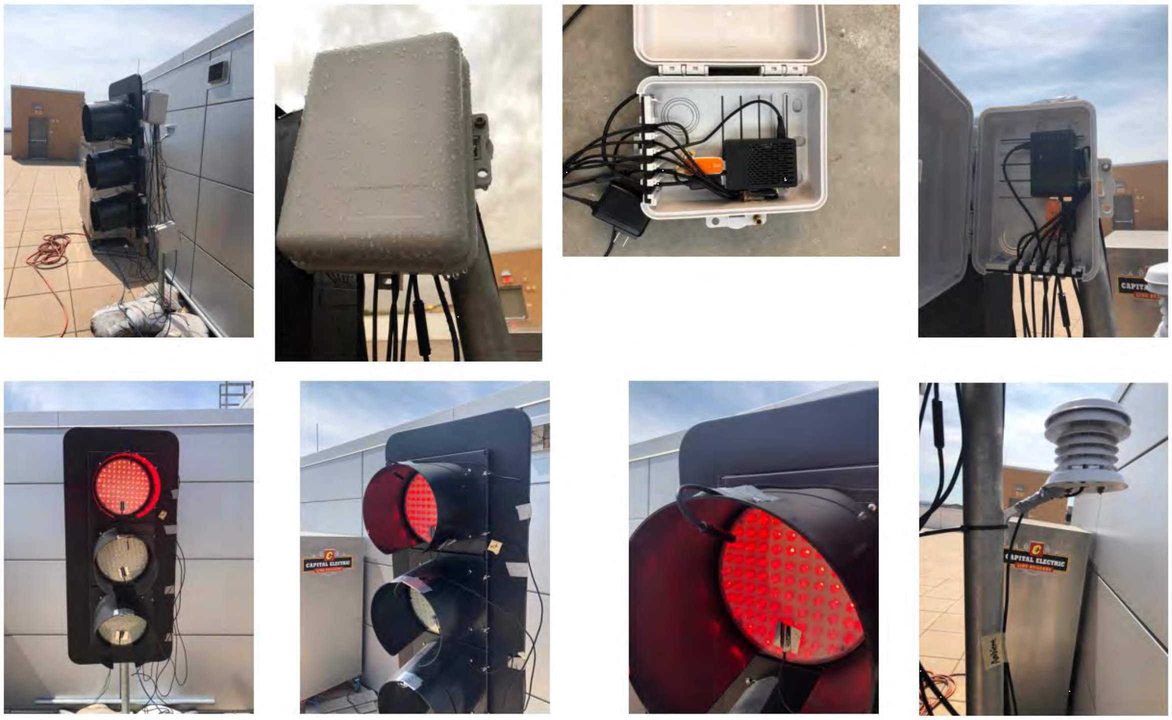
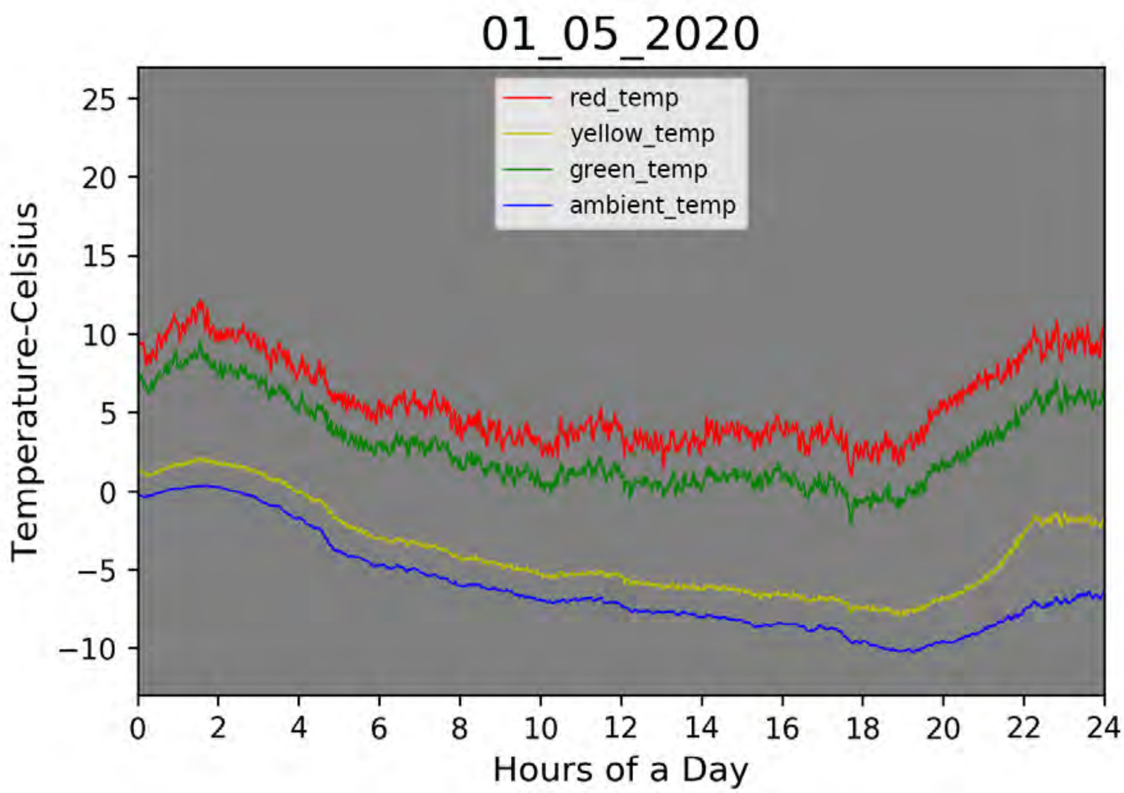


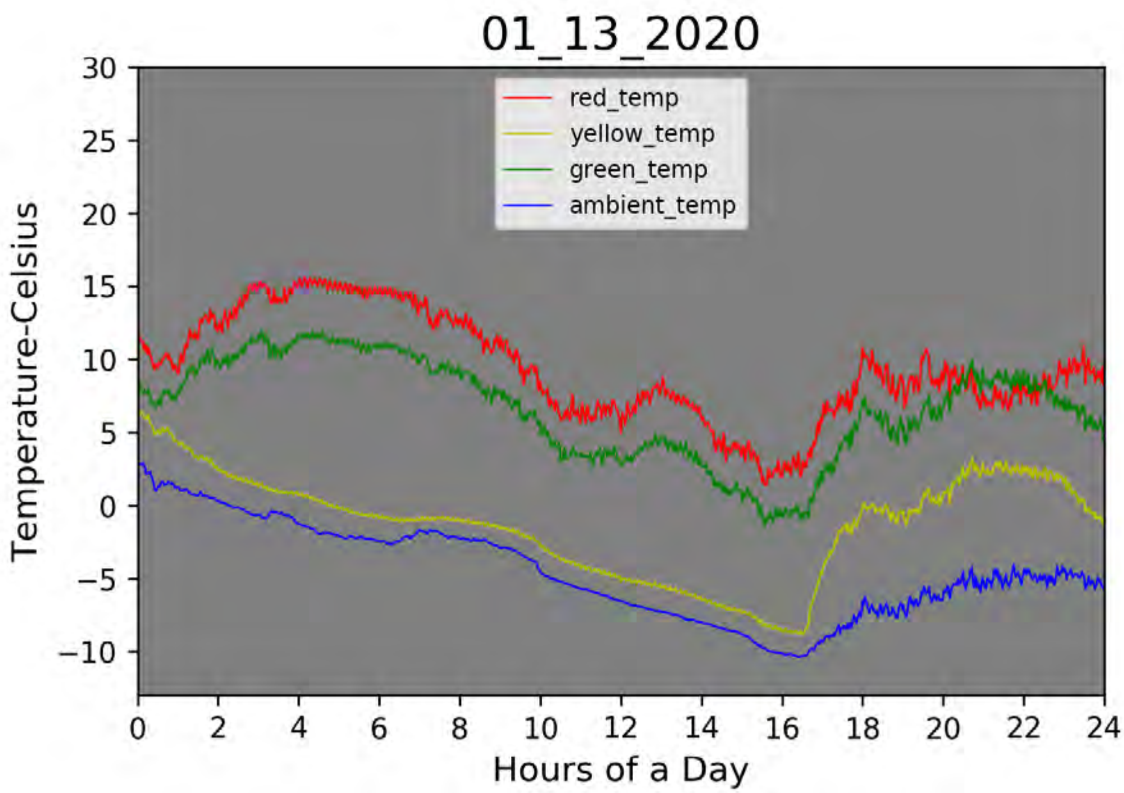
Figure 14: Equipment for testing the closed-course performance and reliability of fully working prototypes mounted on the roof, powered by the signal controller cabinet with real signaling time cycles (in a cycle length of 90 seconds, red signal light ON for 50 seconds, green signal light ON for 35 seconds, and yellow signal light ON for 5 seconds). The field performance monitoring system consists of a Raspberry PI computer with a USB driver for recording year-around data, three cable cameras used to monitor three signal lights (R, G, Y) in each unit, four temperature sensors used to record the lens' surface temperature of the three signal lights and the ambient air temperature, power supplies, and mounting accessories.

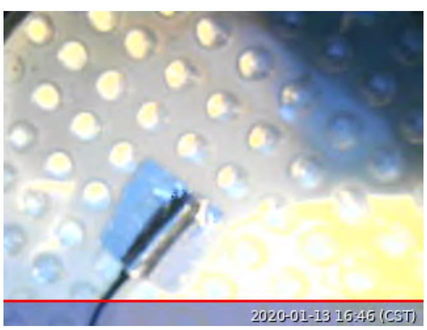
Based on the roof test results, improvements on plastic housing with desired changes were made for quick assembly and tested in the laboratory with satisfactory performance. Other issues with the second-generation LED drivers were resolved with needed changes, and the ambient temperature sensor of the drivers was improved for switching power output at 4 °C with acceptable tolerances. A total of 21 new LED drivers of the third generation were tested for their field performance and further improved for the control of the yield rate in production. Those drivers were then assembled in the 4th and 5th generation fully working prototypes for field tests, whose switching temperature of the ambient temperature sensor was tested and validated around 4 °C.

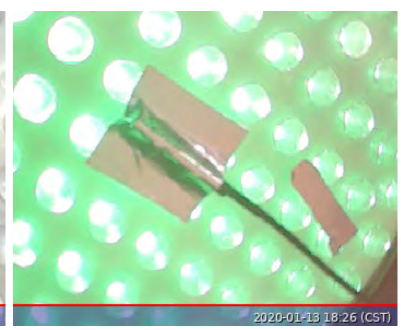


Red Yellow Green

On Jan 5th, 2020

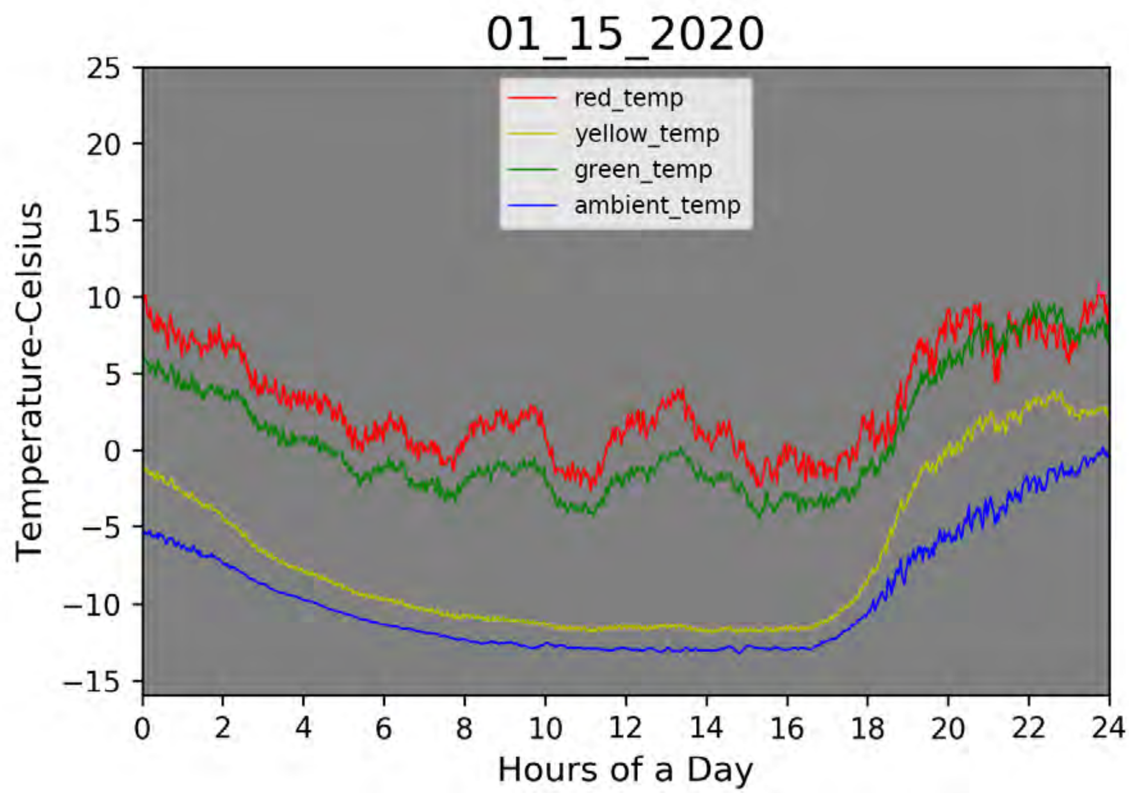






Red Yellow Green

On Jan 13th, 2020



Red Yellow Green

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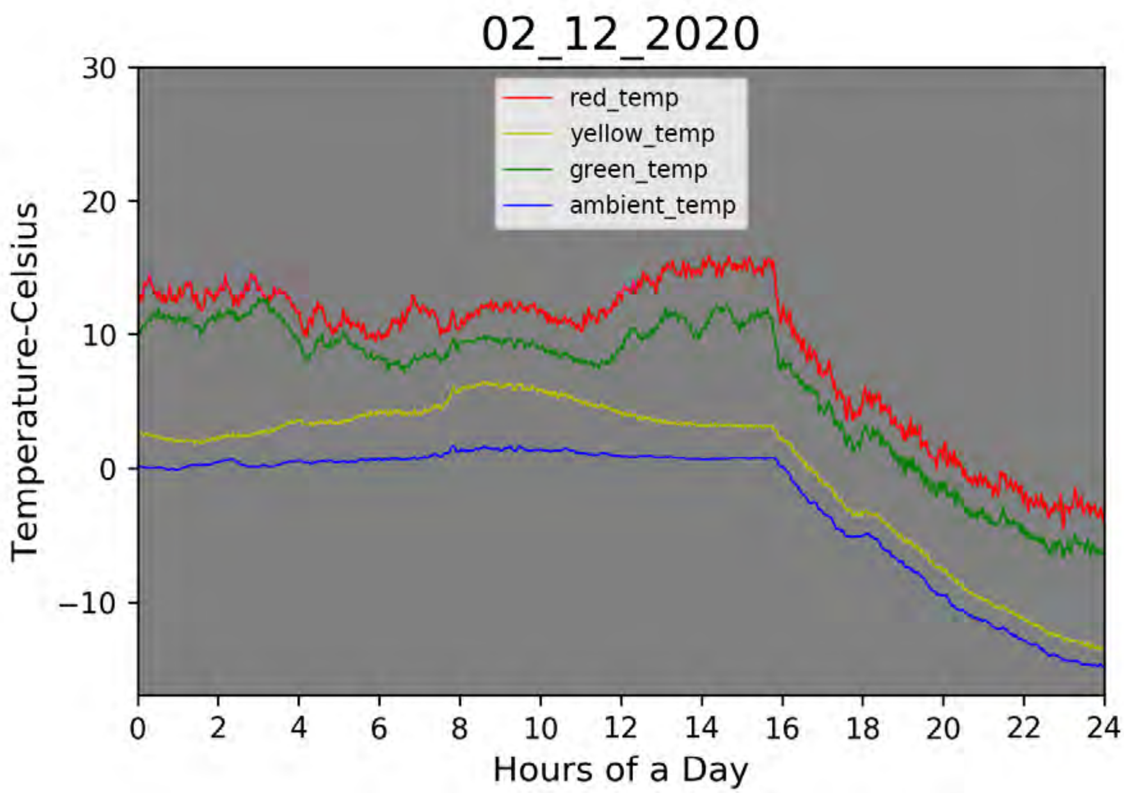
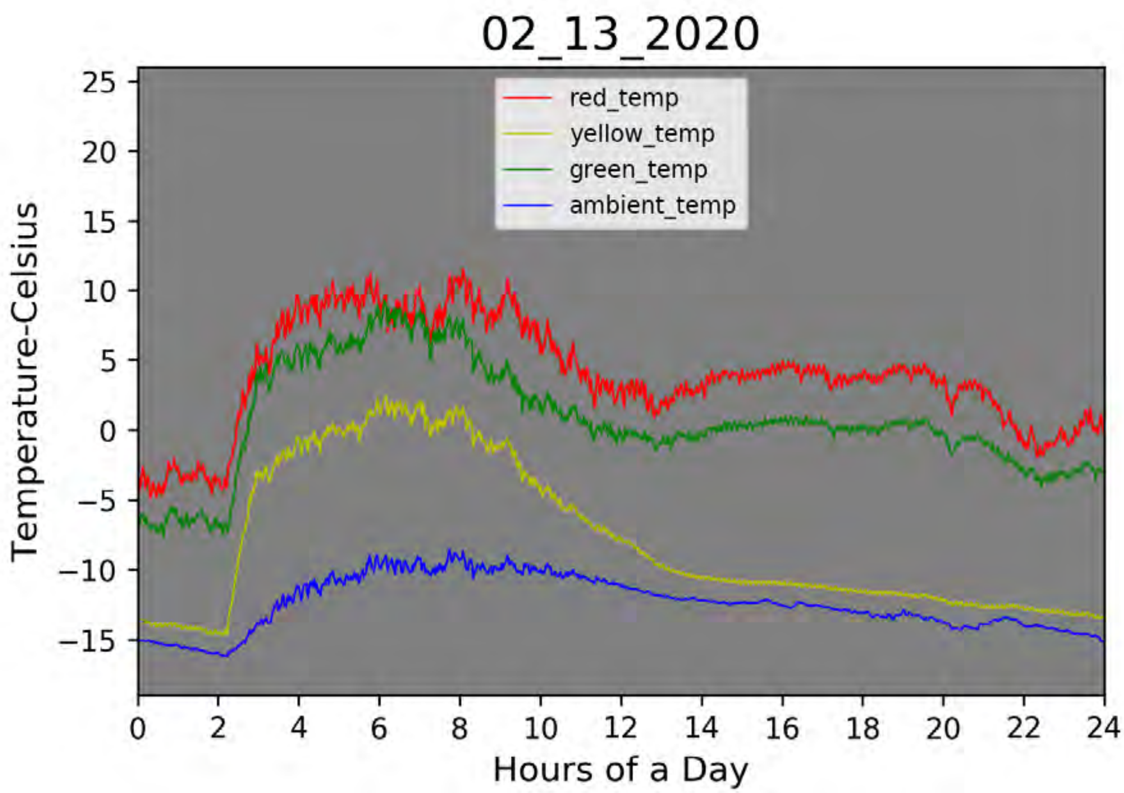


Red

Yellow

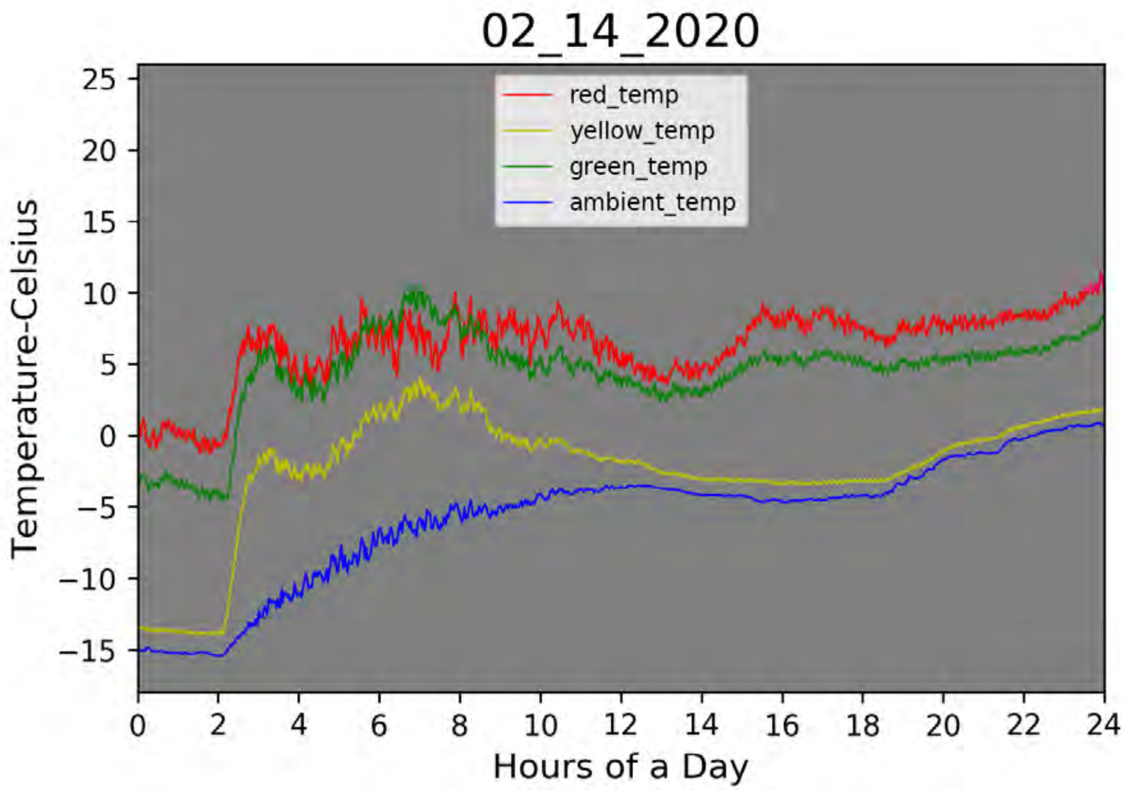
Green

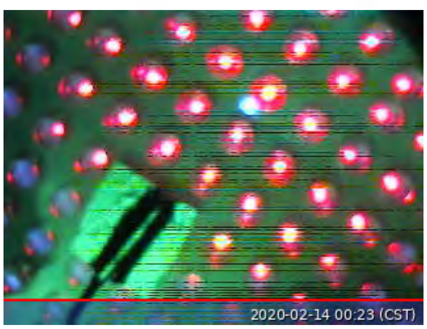
On Feb 12th, 2020



Red Yellow Green

On Feb 13th, 2020



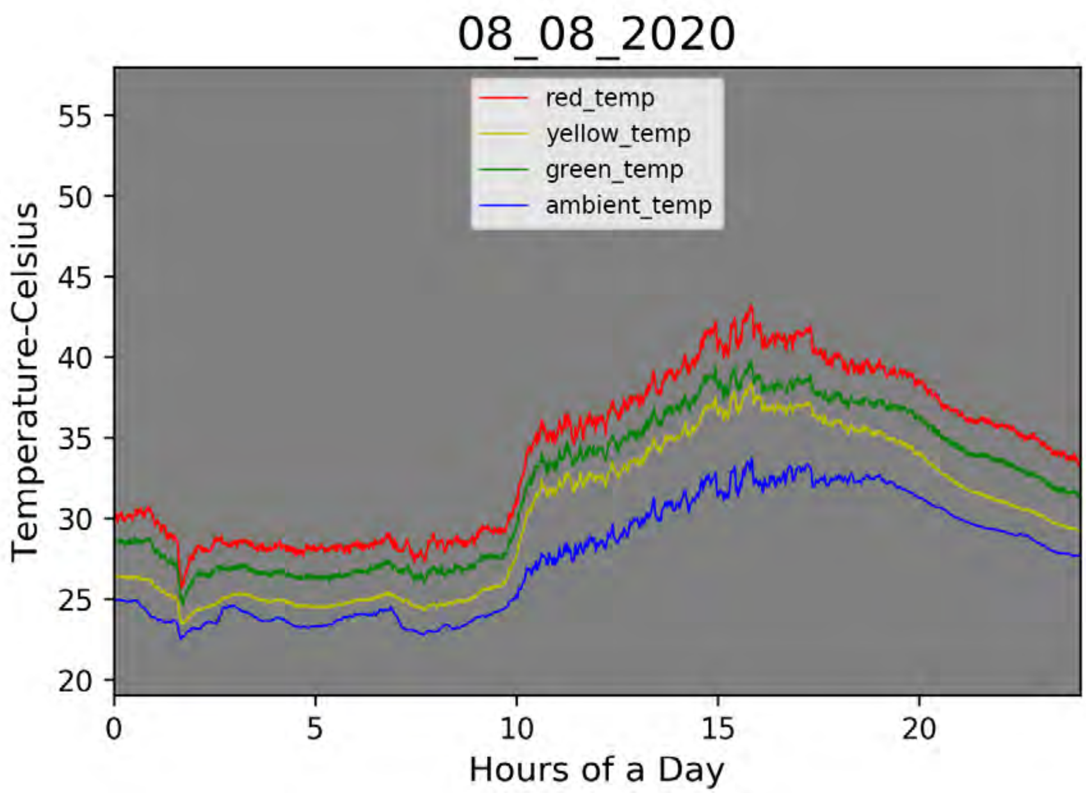


Red

Yellow

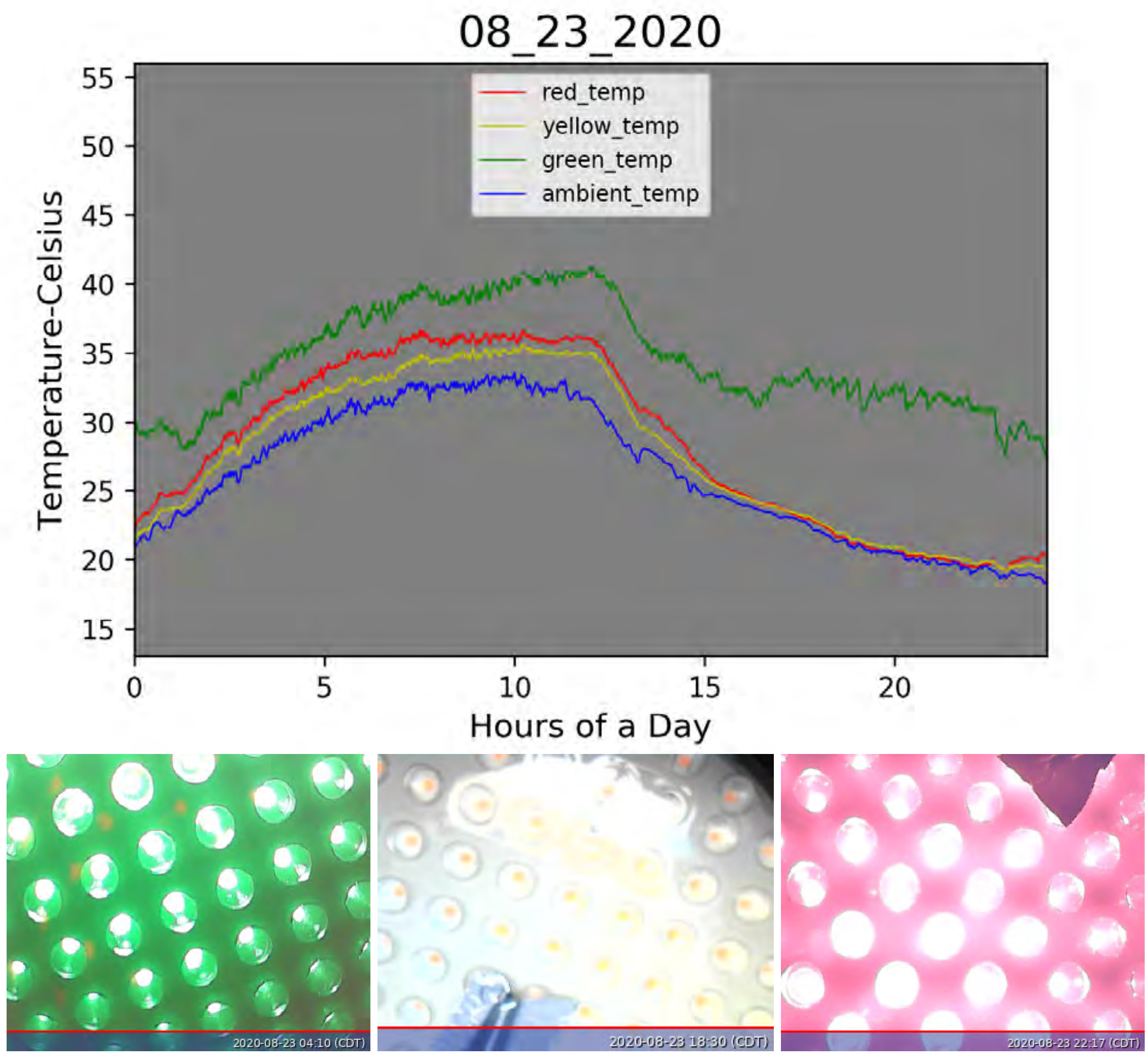
Green

On Feb 14th, 2020



Red Yellow Green

On Aug 8th, 2020



Red Yellow Green

On Aug 23rd, 2020

Figure 15: 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.

3.3 Field Tests

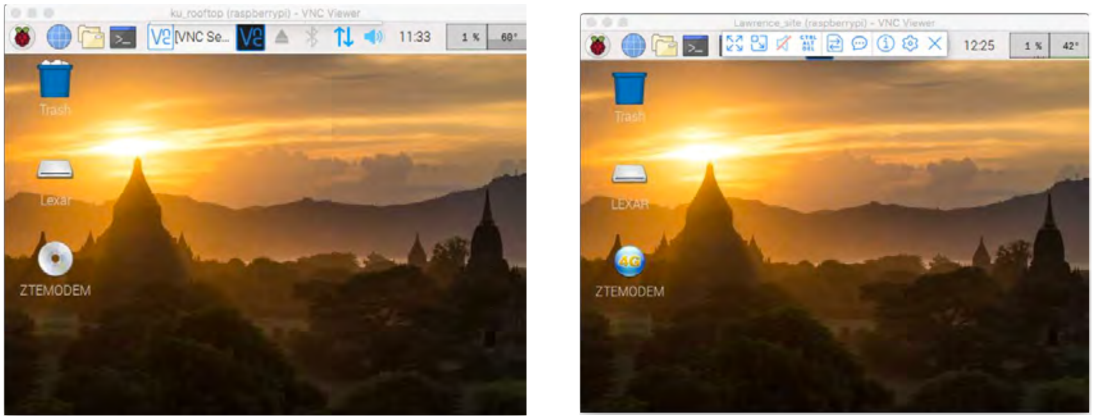
At Stage 3, the 4th and 5th generation fully functional prototypes were implemented in the field and continuously tested at carefully selected highway signalized intersections for at least two years of realistic operation. In preparation for the field tests, the fully functional prototypes were first continuously tested in the laboratory and on the roof for a couple of weeks. The validated prototypes were then taken to the test sites and installed on pole-mounted side signals as a backup to the existing primary signals and commissioned. Each LED module (R, G, Y) would replace the existing signal module in the same color in the same signal head. The real-time performance of the self-de-icing signals in wintery conditions with full power output for melting snow and deicing, as well as their derated performance in warm weather when the ambient temperature is higher than 4 °C, was monitored by a custom-built field remote monitoring system for year-round data recording. Seven states (Kansas, California, Michigan, Wisconsin, New Jersey, Pennsylvania, and Maryland) participated in this project for the field testing and evaluation of the prototypes for potential future implementation. More details are as follows.

3.3.1 Remote Field Monitoring System for Field Tests

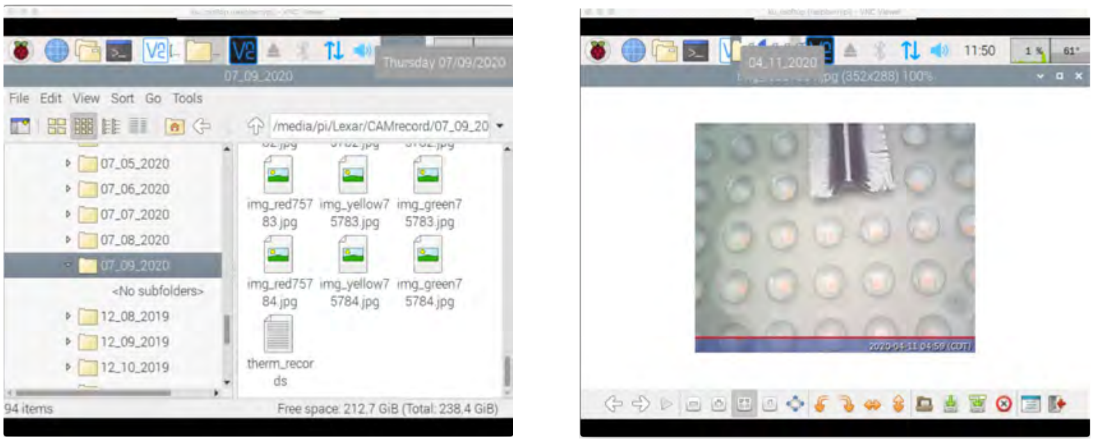
For real-time signal performance monitoring and long-term test data collection at the test sites in different states far away from our laboratory, we developed, and custom built a remote field monitoring system (Figure 16) put in a plastic box to be mounted on the pole behind the signal head. The remote monitoring system consists of a Raspberry PI computer, three cable cameras, four temperature sensors, USB flash drivers used to store the year-round test data (pictures and temperatures), an LTE mobile communication device with a monthly data plan, power supplies, and mounting accessories. As a result, we could remotely access the field test and its stored data on a daily basis for real-time performance monitoring.

The remote field monitoring system will take photos of the lens' surface and record the lens' surface temperature every 20 seconds in winter (when the ambient temperature is lower than 4 °C [39.2 °F]) and every hour in summer. The temperature sensor is mounted on the lower edge of the signal lens to prevent blocking the driver's view of the signal light. The system would be mounted at every field test site for year-round real-time monitoring and data recording of the new signals. Figure 17 shows example screen images of the program and the recessed data collected in the first field test site located in Lawrence, KS.

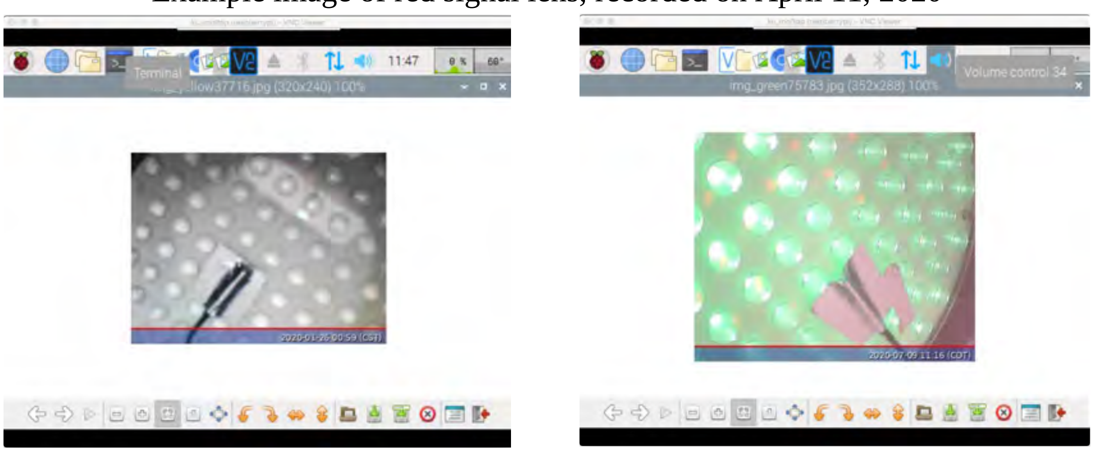
Figure 16: A remote field performance monitoring system, controlled by a Raspberry PI computer with a USB driver for recording data, which consists of three cable cameras used to monitor the lens of the three signal lights (Red, Yellow, Green), four temperature sensors used to record the lens' surface temperature of signal lights and the ambient air temperature, LTE mobile communication device with a monthly data plan, power supplies, and mounting accessories.



The computer interface (on the rooftop)
The computer interface (in Lawrence site)



Folders created on daily basis for storage of the photos and temperature record of each lens
Example image of red signal lens, recorded on April 11, 2020

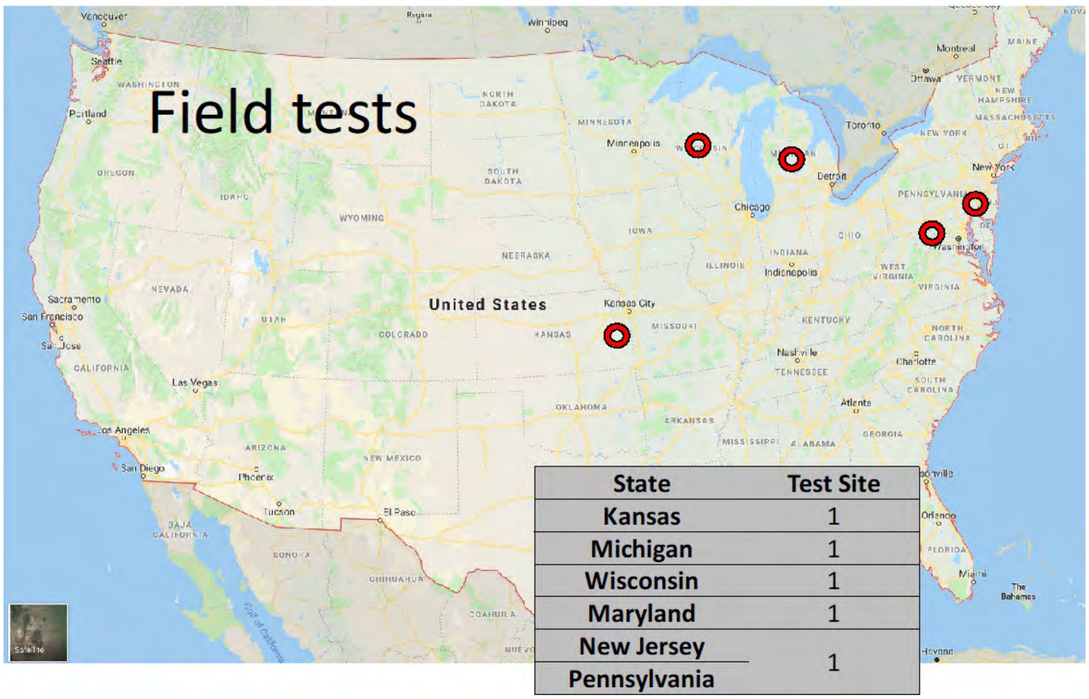


Example image of yellow signal lens, recorded on Jan 26, 2020
Example image of green signal lens, recorded on July 9, 2020

Figure 17: Illustration of the remote monitoring systems installed on the roof test and in the Lawrence field test site. The real-time data were remotely retrieved from the computer of the monitoring system using any computers in the laboratory, out of campus, or on travel.

3.3.2 Field Test Sites and Installation Tasks

As scheduled, a total of five field tests would be conducted in different states in cold zones, as shown in Figure 18, including Kansas (1 test site), Michigan (1 test site), Wisconsin (1 test site), Maryland (1 test site), and New Jersey & Pennsylvania (1 joint test site).



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

Figure 18: Field testing of the self-de-icing signals was scheduled in Kansas (1), Michigan (1), Wisconsin (1), Maryland (1), and New Jersey & Pennsylvania (joint 1).

Each participating state or a city and their signal crew would help select a good test site for installation of the fully functional self-de-icing LED signal prototypes and test them for at least two years in the field after the installation. There are a few recommendations on the selection of a good test site, as follows:

1. The site has a good chance to see a lot of snow and ice in winter. Ideally, the selected signal head is north facing. East and west-facing signals will see a lot of sun and solar heat, which affect the evaluation of the signal's thermal performance, especially in the afternoon, thus, shall be avoided.
2. The intersection has well-balanced traffic by direction so that the signal timing for red and green lights is also balanced.

3. The selected signal head is on the right side of the road shoulder for convenience of access and field installation without blocking the traffic.
4. The test site has good 4G mobile signal coverage for the remote monitoring system.

The field installation would need help from the signal crew and their electrician to conduct two tasks. Installation of the new signals is simply swapping the existing signal modules with the new signal modules of the same color in the same signal head without extra wiring. Additionally, at every field test site, a remote monitoring system put in a weatherproof plastic box would be mounted on the signal pole, at least 10 ft above the ground to prevent vandalism, and hidden on the back of the signal head (Figure 16). The remote monitoring system is wired with temperature sensors and cable cameras that are mounted on the signal lens and visor for year-round real-time monitoring and data recording of the new signals. A dedicated 12 or 14 AWG cable is needed for powering this remote monitoring system with continuous 120 VAC electricity, which will be removed after the field testing is completed. The whole field installation may take 3 hours or less.

3.3.3 Field Test in Lawrence, Kansas, 2019 - Present

On Dec. 4, 2019, the first field test site (Figure 19) was set up in Lawrence, Kansas, at the intersection of County Rd 458 (or 1200 Rd) /US-59 for testing the 4th generation prototypes in a north-facing signal head on the right road shoulder for at least 2 years. Note that this test site has a dominant green light with much longer signal timing than the red and yellow lights. This unbalanced signaling is not optimal and would later be avoided in other test sites.

Figure 20 shows the field installation process of three fully tested 4th generation prototypes and the remote monitoring system put in a plastic box, with the help of the Lawrence city signal crew. Since then, the new signals and the remote monitoring system have been tested onsite continuously for almost 3 years, already surviving several snowstorms in two winters and a hot climate in two summers. For example, Figure 21 shows the performance of the signals in the Lawrence test site that survived the snowstorm in 2020 as well as the hot summer of 2020. From the data, it is clear the green signal had a much longer time of power, resulting in higher lens surface temperature than that on the red and yellow signal lights. The Lawrence field test is still ongoing.

Nonetheless, based on the test results on-site, it was found that the signals equipped with the third-generation drivers have a light power-up delay of about 0.5 seconds, especially for green signal lights. As aforementioned, this problem will be solved with the adjustment of MCU chips used in the 4th generation drivers for mass production to decrease the delay to only milliseconds.

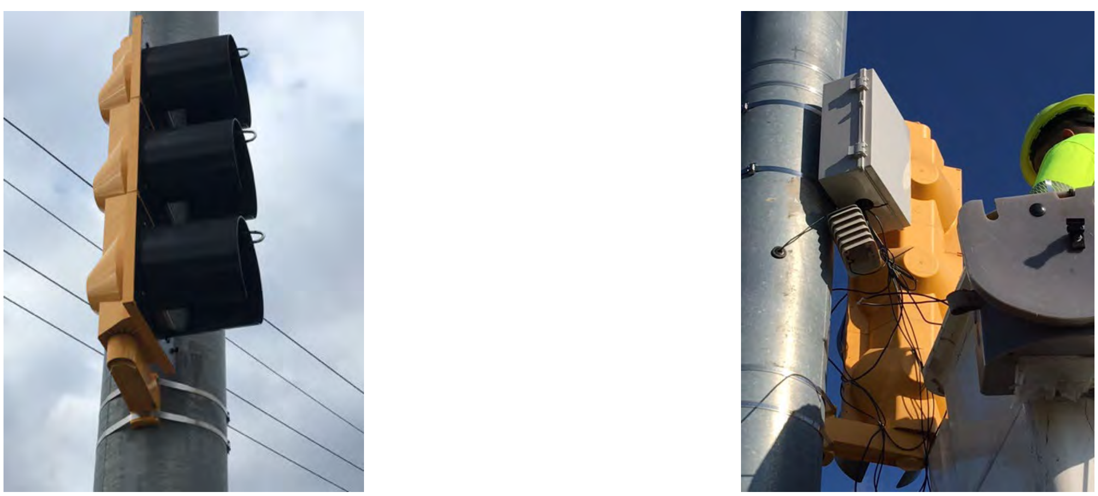
Figure 19: The first field test site in Kansas, at the intersection of County Rd 458 (or 1200 Rd) /US-59, where the selected signal head is on the right side of the road shoulder, facing north.

In preparation, the existing LED signals

Remove the existing LED signals

Replacing the old LED signals with the new self-de-icing signals

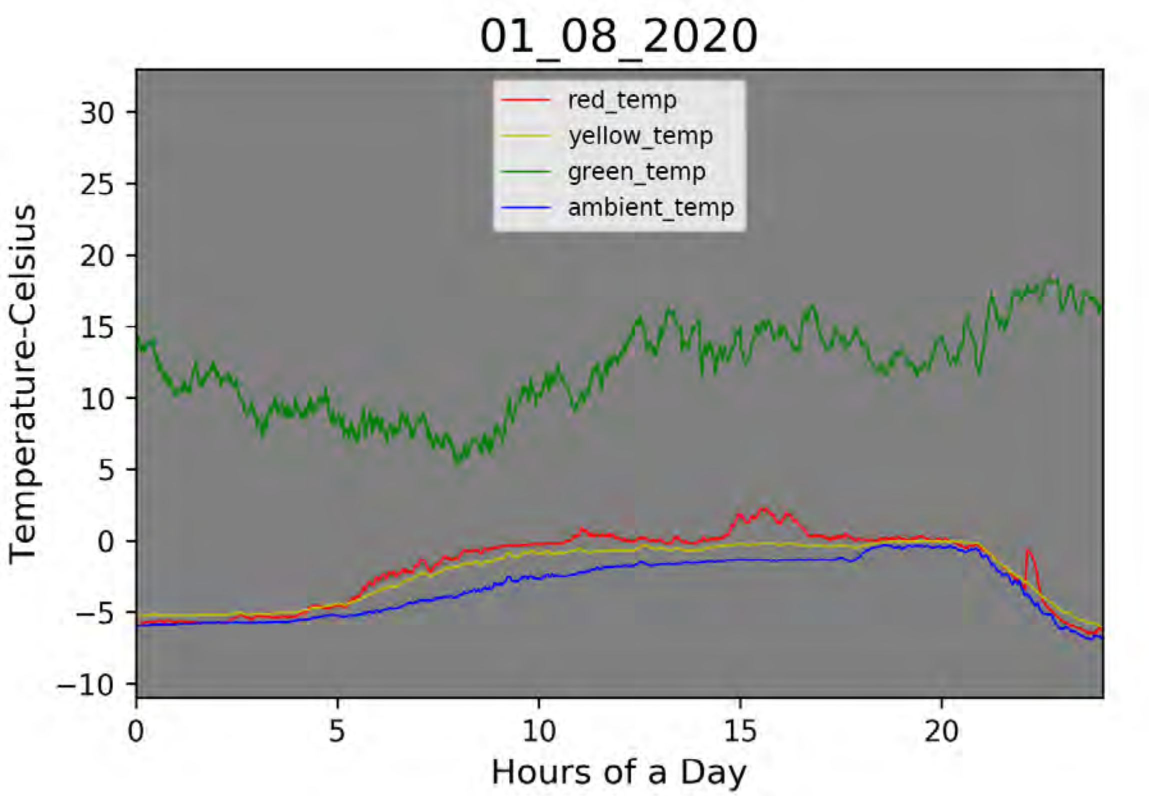
Wiring of the new signals

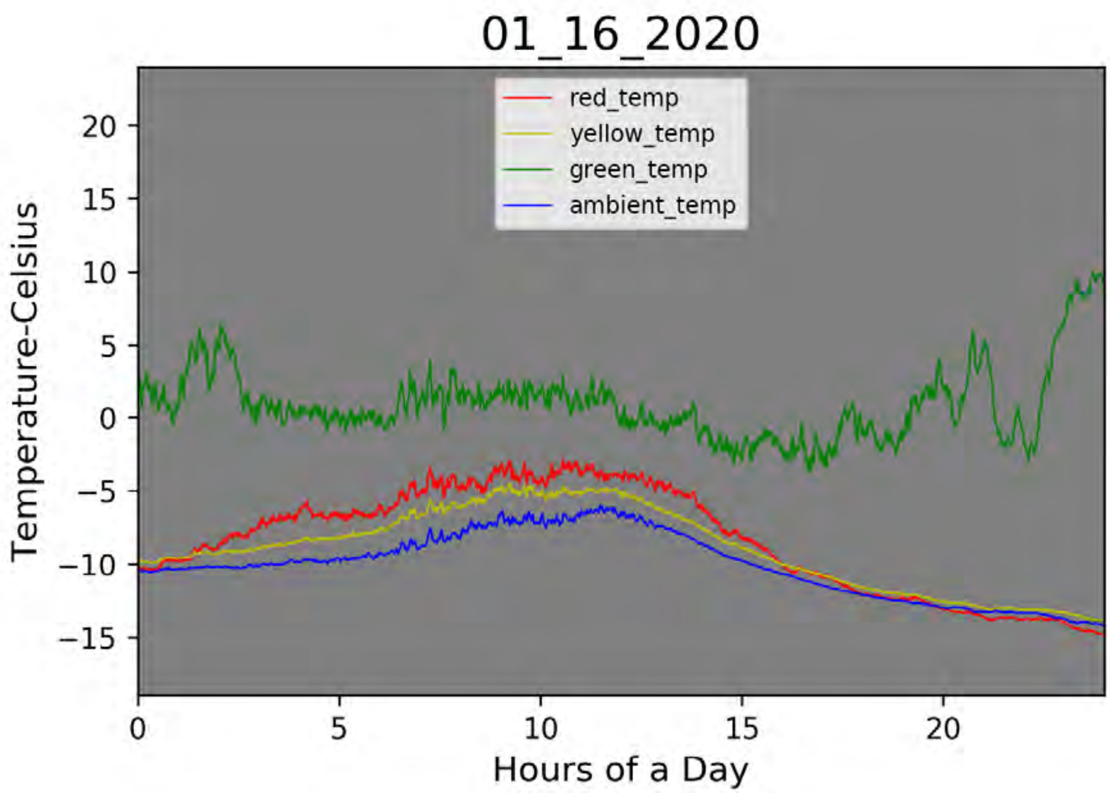


The installed new signals with a plastic weatherproof box for mounting the field monitoring system inside

New green /orange signals are powered on New red signal light is powered on

Figure 20: The field installation process at the first field test site in Kansas, with the help from the Lawrence city signal crew and the Kansas Department of Transportation.

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Hours of a Day


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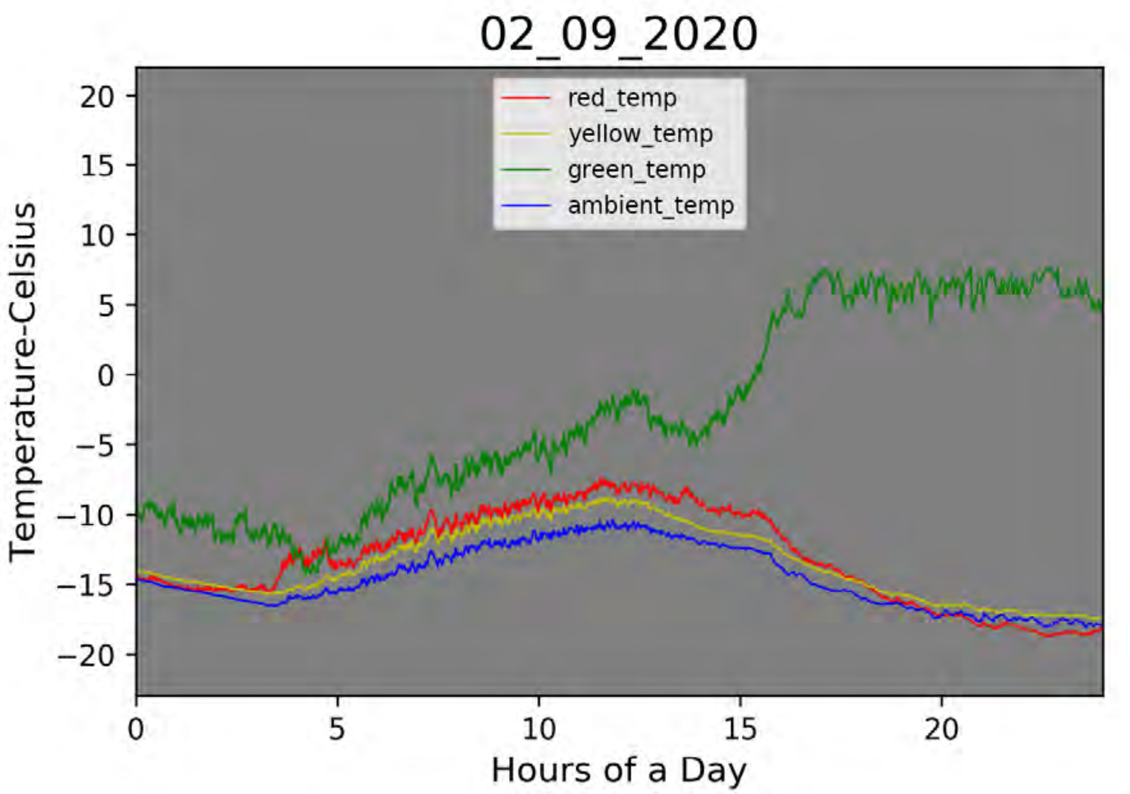
2020-01-16 15:07 (CST)


2020-01-16 03:48 (CST)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10
15
20


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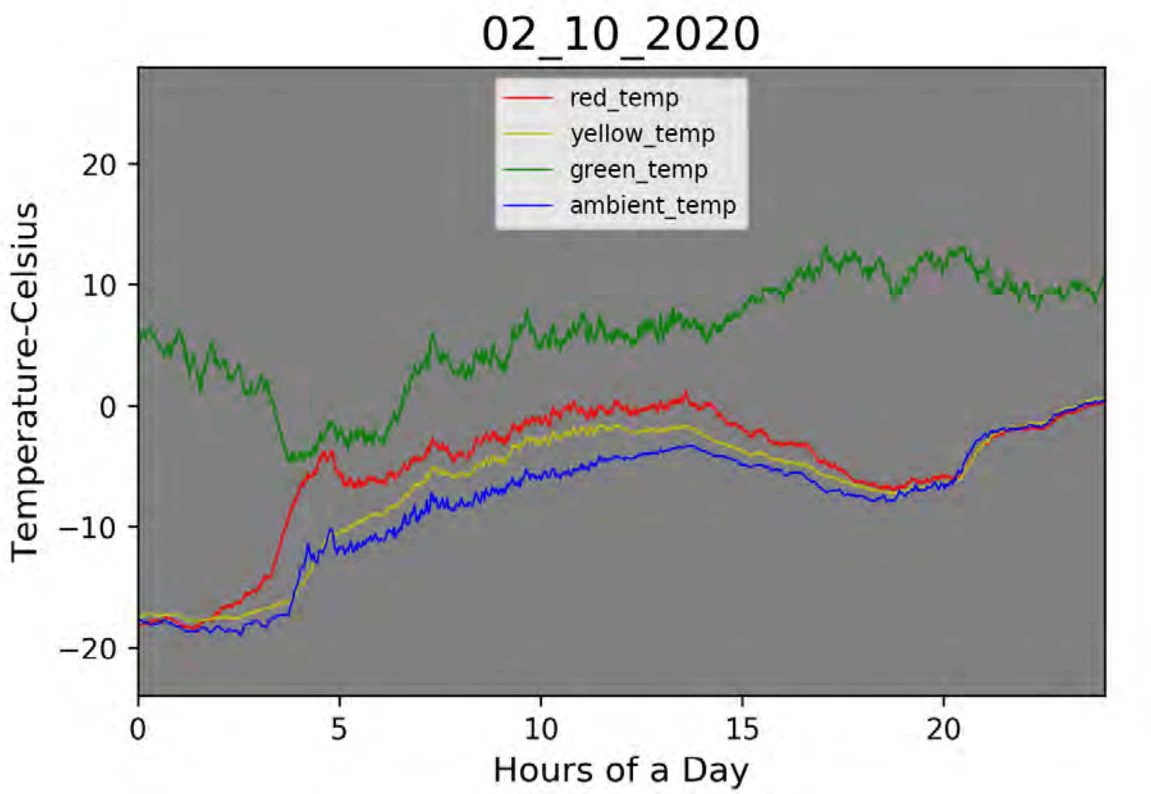
2020-02-09 03:26 (CST)
2020-02-09 03:26 (CST)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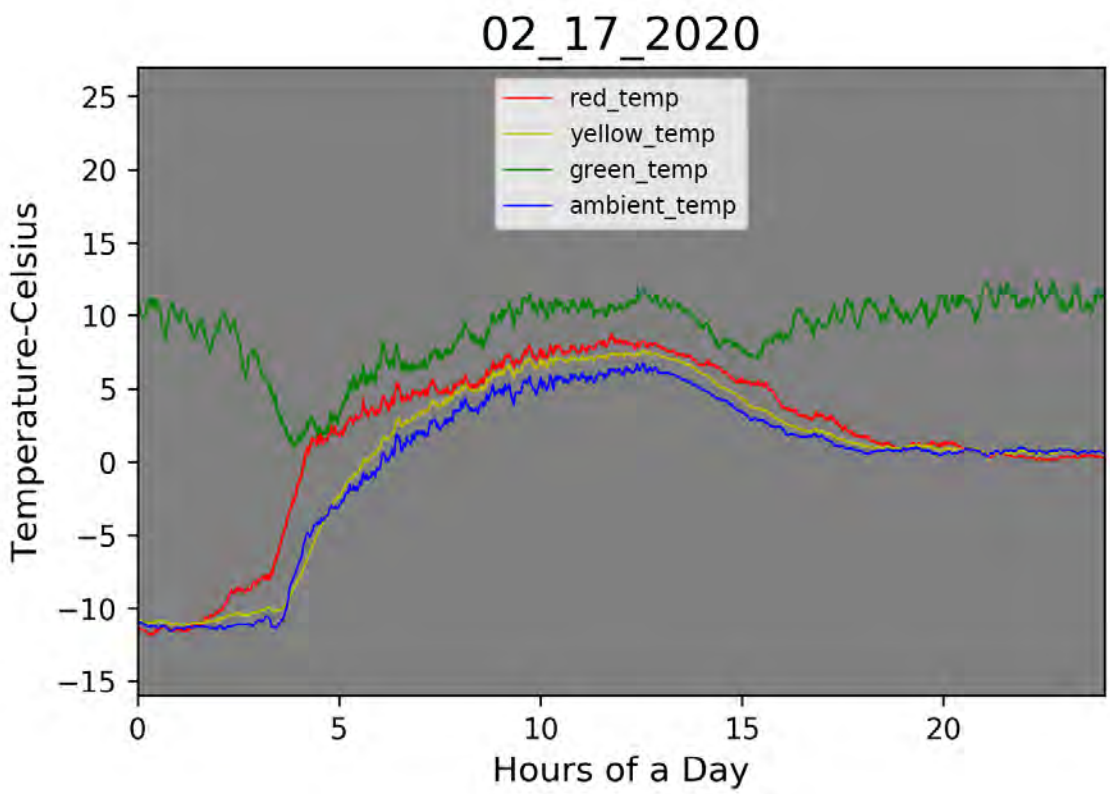
2020-02-10 15:20 (CST)
2020-02-10 13:49 (CST)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Hours of a Day


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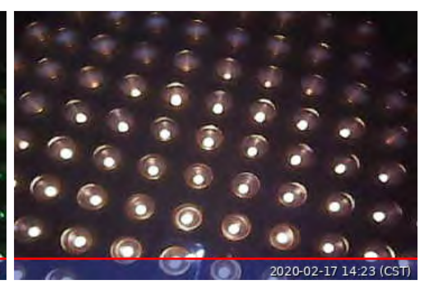
2020-02-17 19:22 (CST)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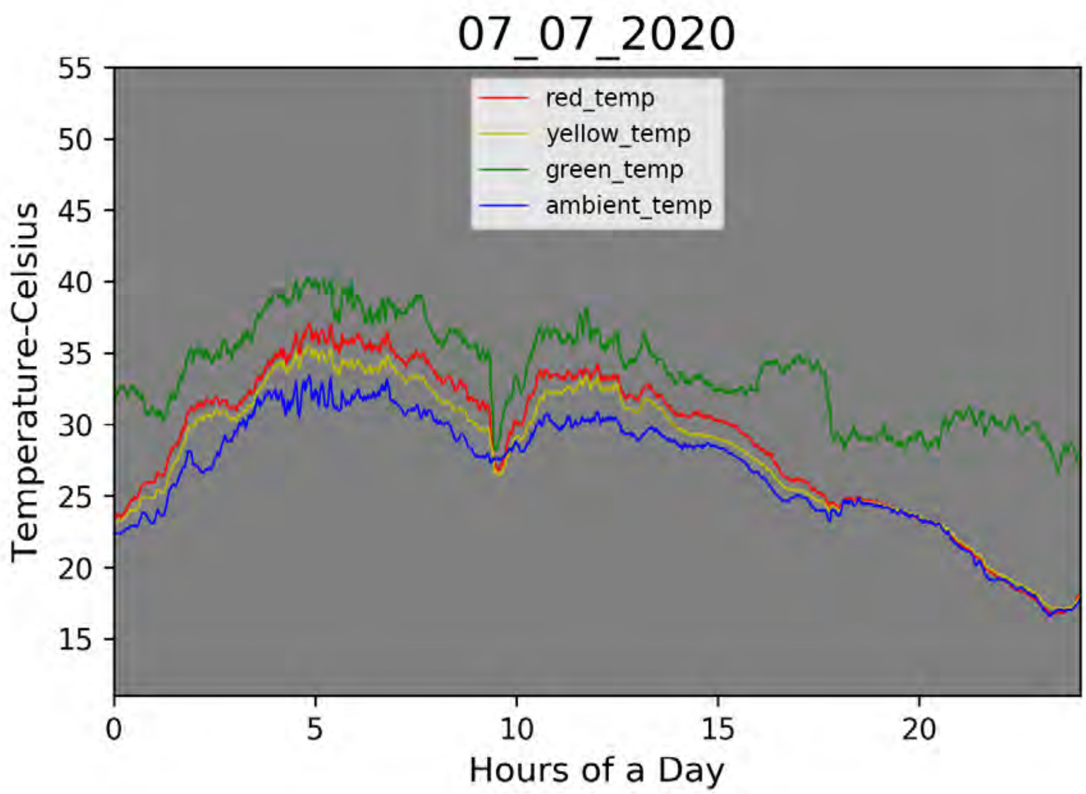
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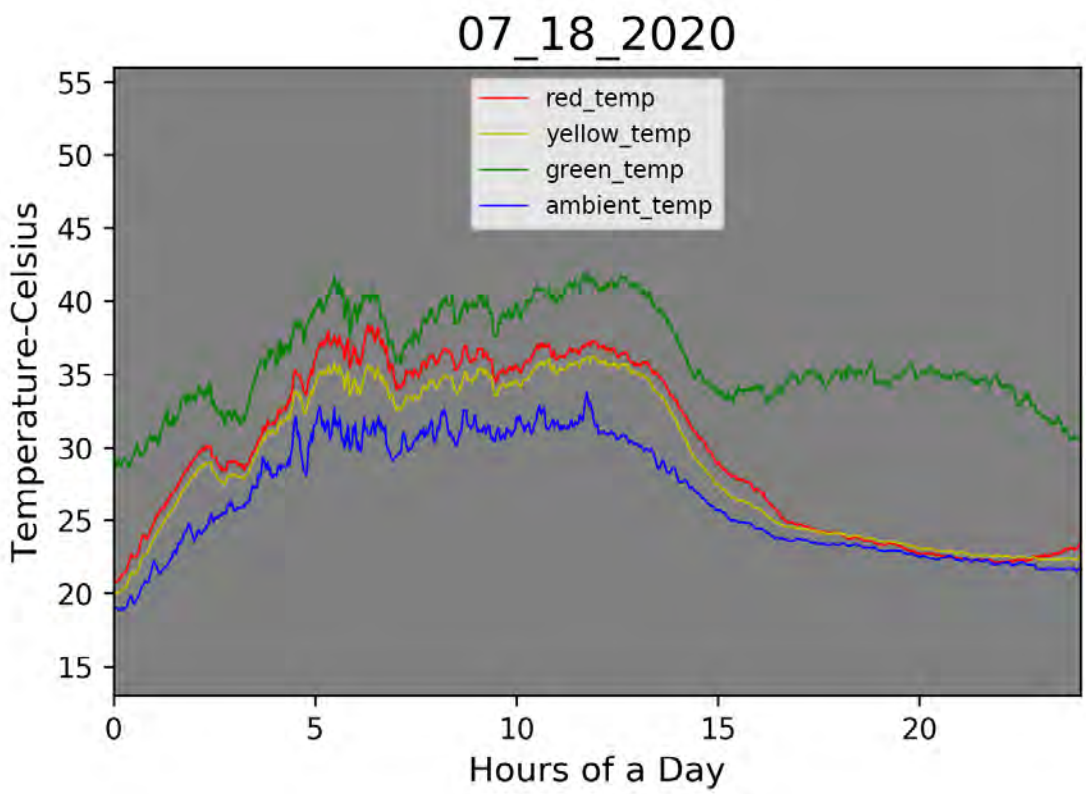
2020-07-07 08:44 (CDT)


2020-07-07 14:01 (CDT)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green_temp
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Temperature-Celsius
Hours of a Day
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2020-07-18 14:06 (CDT)


2020-07-18 14:06 (CDT)


2020-07-18 23:54 (CDT)

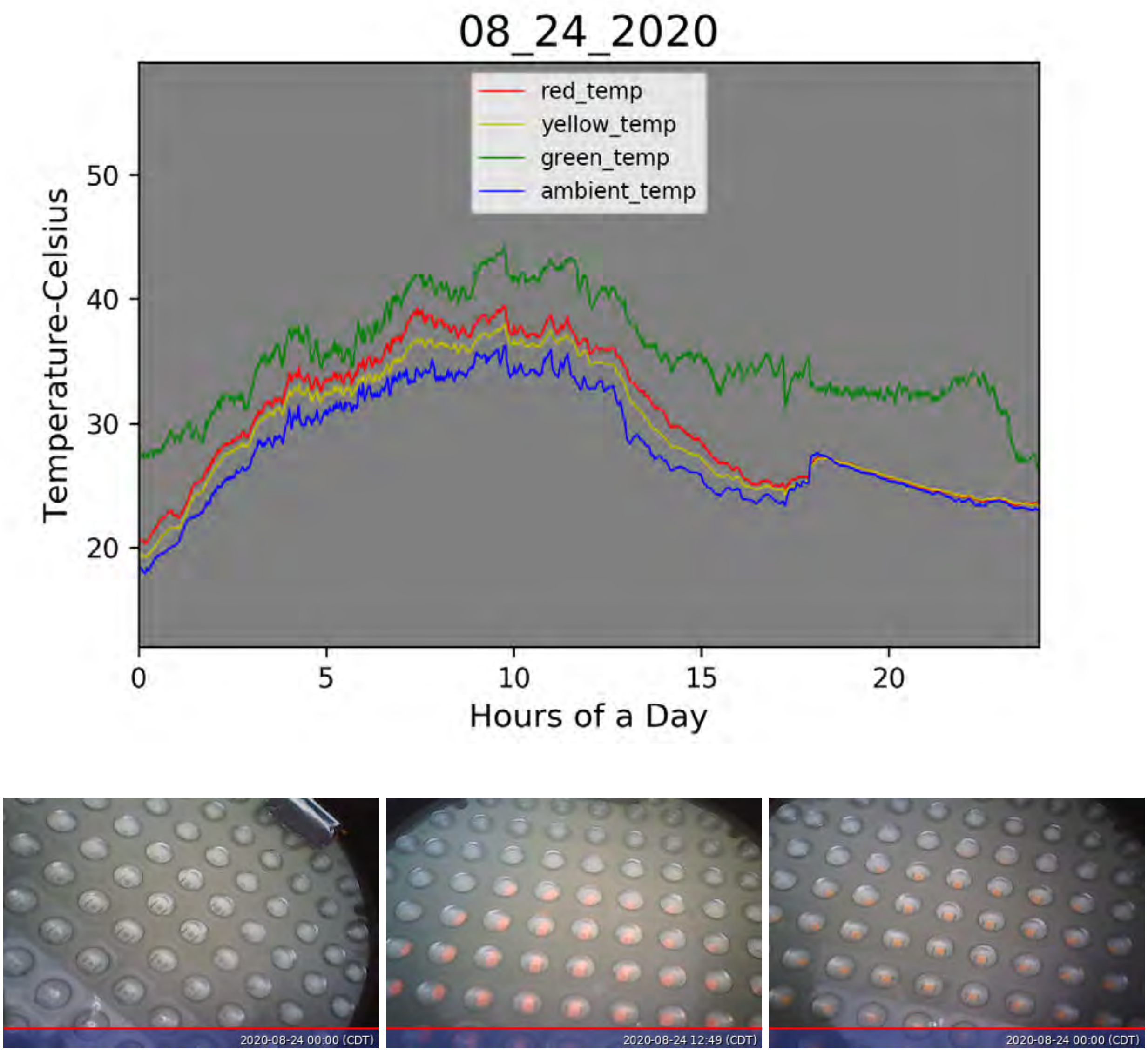


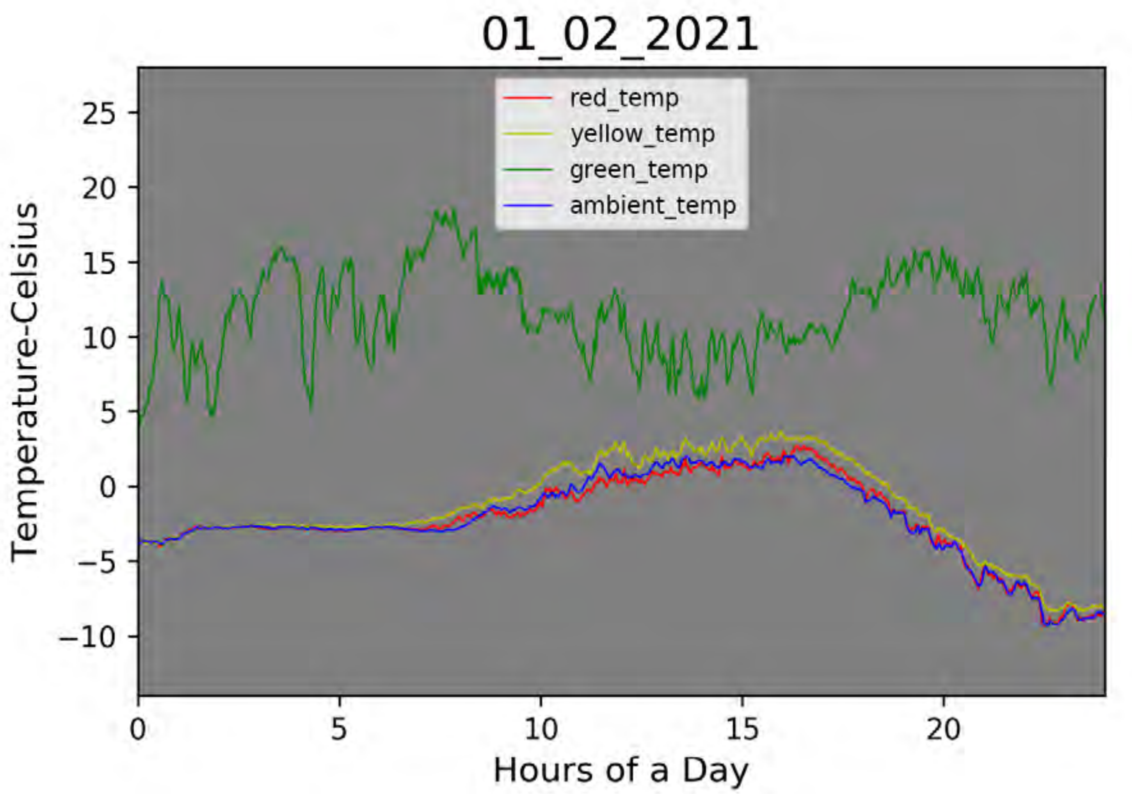
Figure 21: Lawrence field test data during the coldest days in winter 2019-2020 and hottest days in summer 2020 showing the performance of the red, yellow, and green signal lights under different weather conditions. Test results were collected at the intersection of County Rd 458 (or 1200 Rd) /US-59, where the selected signals are on the side of the road shoulder, facing north.

Later, on Feb. 25th, 2021, as shown in Figure 22, we visited the test site again to replace all cable cameras used to record the real-time image of the R/G/Y signal lens, which failed after being exposed to the environment for two years. We also re-mounted the loose temperature sensors on the red and yellow signal lenses, which explained why the recorded lens' surface temperature of the red and yellow signal lights dropped to the ambient temperature in late January and early

February, as shown in Figure 23 on those cold dates. It is also worth mentioning that the ambient temperature sensor was always mounted inside a shade that isolated the sensor from the wind. Therefore, on windy days, as shown in Figure 23, the temperature sensors loosely mounted on the red and yellow signals sometimes could record slightly lower temperatures than the ambient temperature measured inside the shade.

All signal lights have been working normally in the past two years. After the field visit for those corrections, the performance data retrieved from the Lawrence test site showed the self-deicing signals were working properly, especially for the green signal light which had the longest power-on time, as shown in Figure 24. Meanwhile, the ambient temperature was slightly lower than that recorded on the lens of the yellow and red signals with a short power-on time.

Figure 22: We stopped at the Lawrence field test site on Feb 25th, 2021, with the Lawrence signal crew, to fix two problems related to the data collection and performance remote monitoring system (not part of the self-de-icing signal lights). We replaced the problematic cable cameras which failed after being exposed to the environment in the past two years, also fixed the loose mounting of the temperature sensors.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green_temp
ambient_temp
Temperature-Celsius
Hours of a Day
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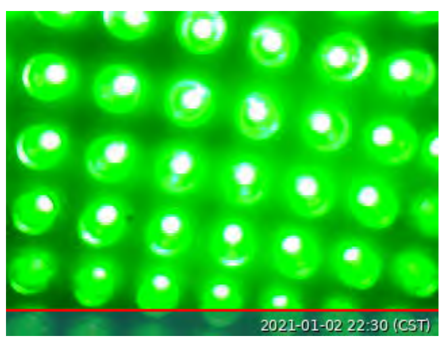
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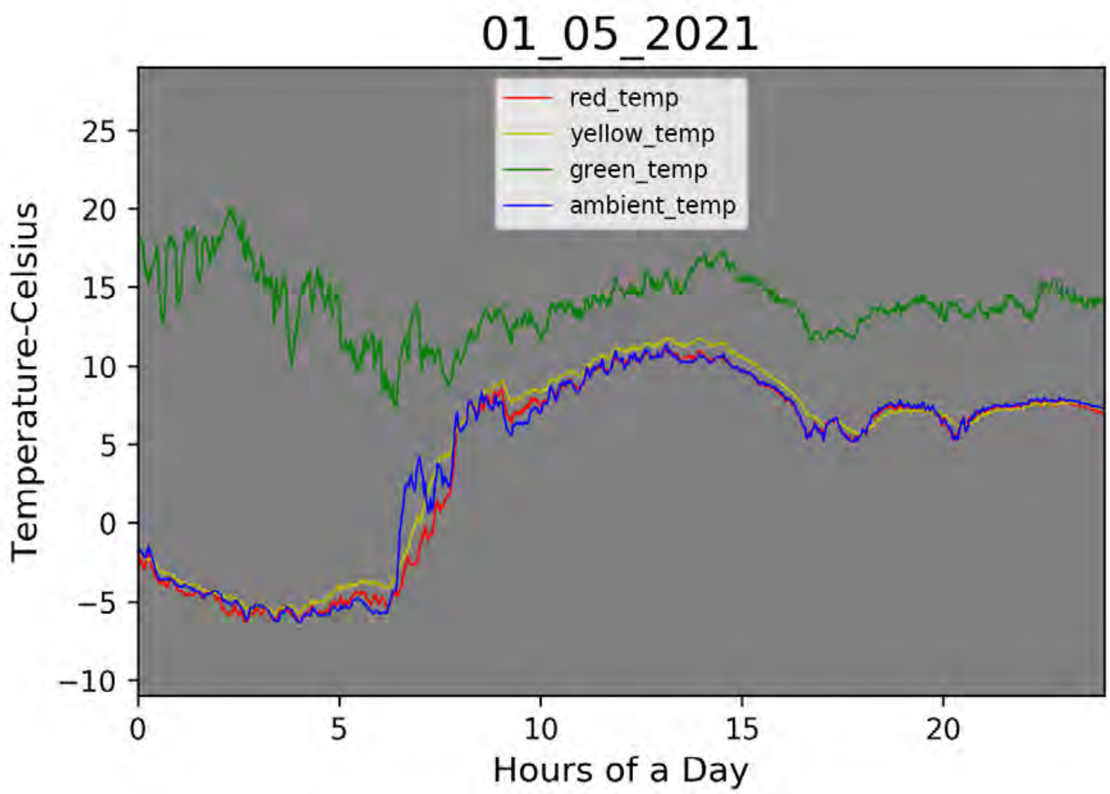
2021-01-02 15:13 (CST)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green_temp
ambient_temp
Temperature-Celsius
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Hours of a Day


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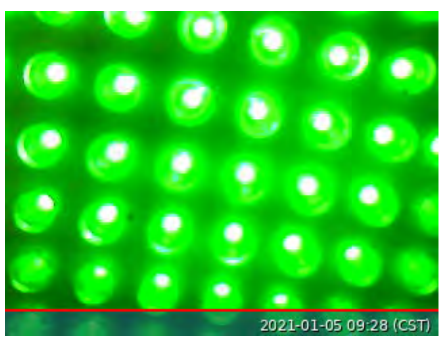
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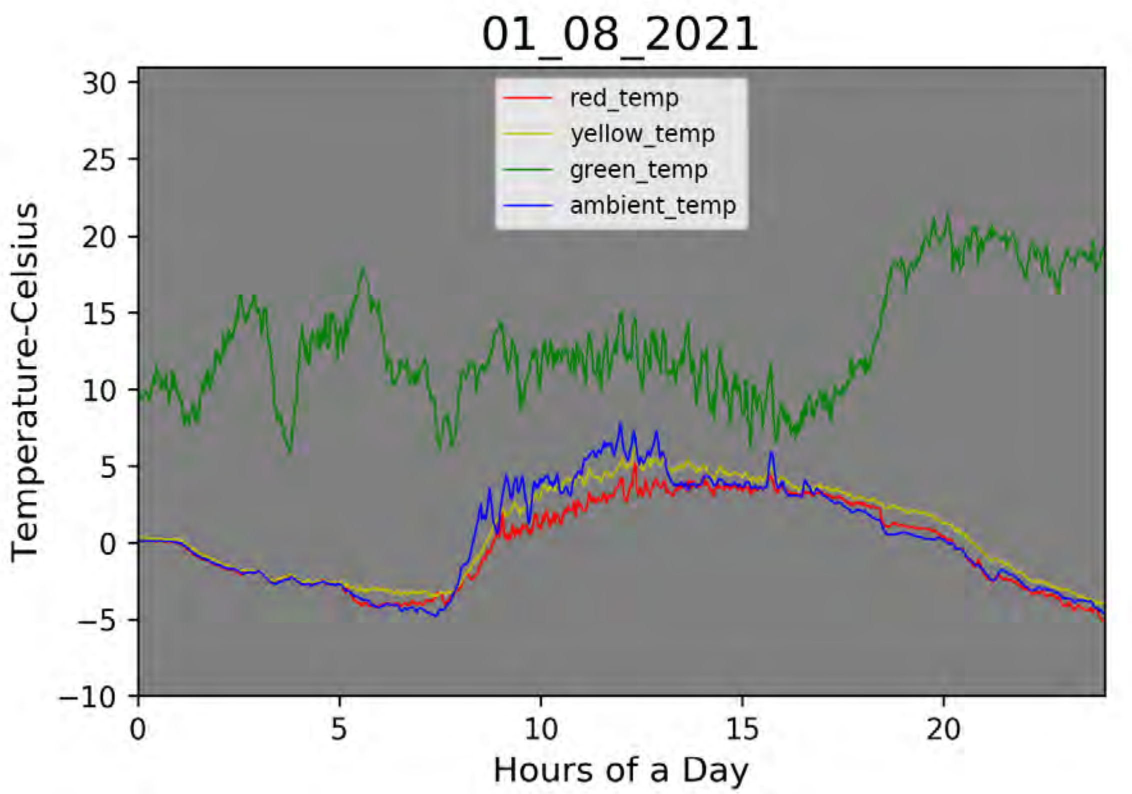
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ambient_temp
Temperature-Celsius
Hours of a Day
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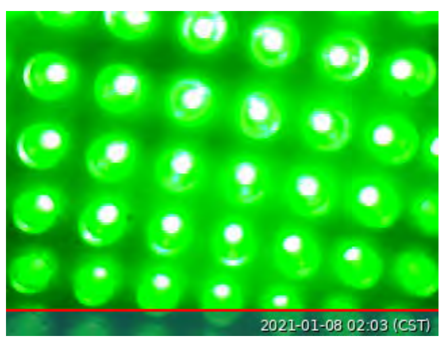
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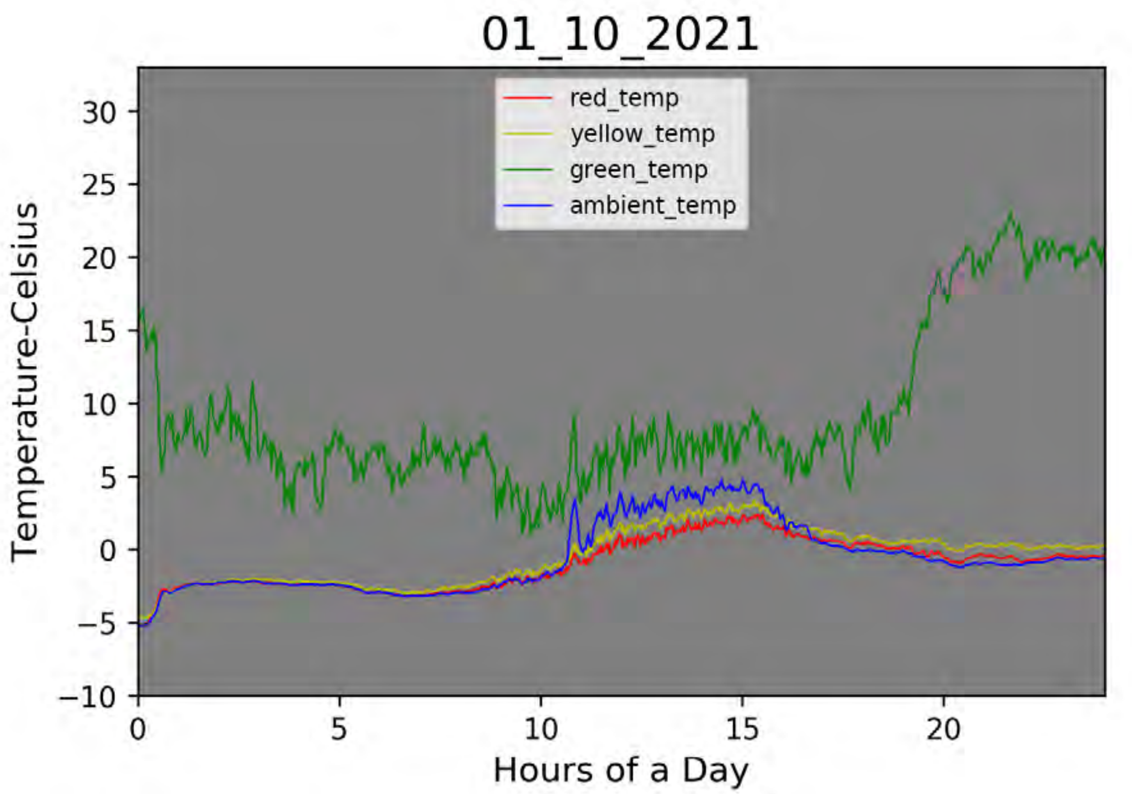
2021-01-08 16:13 (CST)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Hours of a Day


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2021-01-10 15:42 (CST)

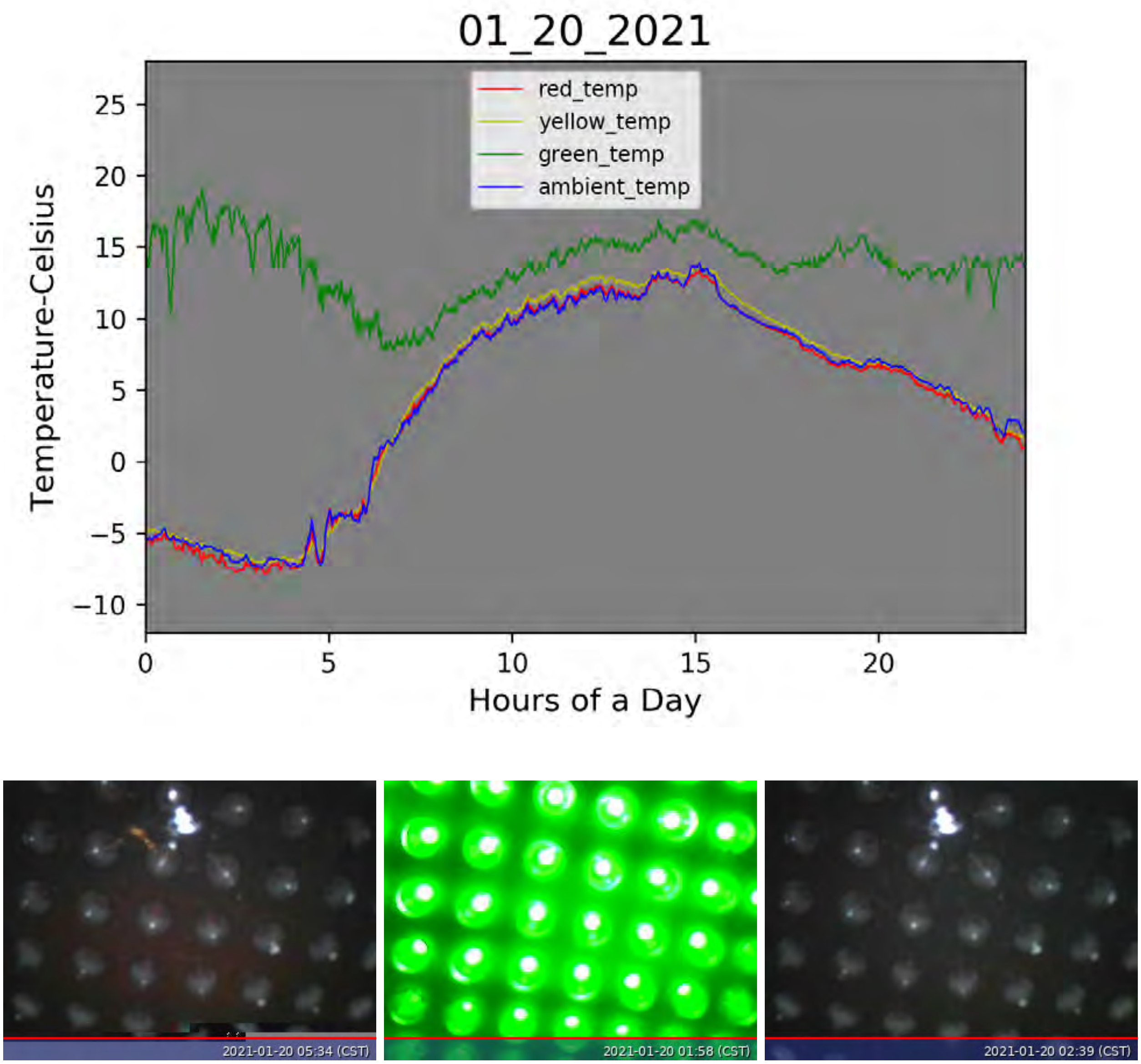
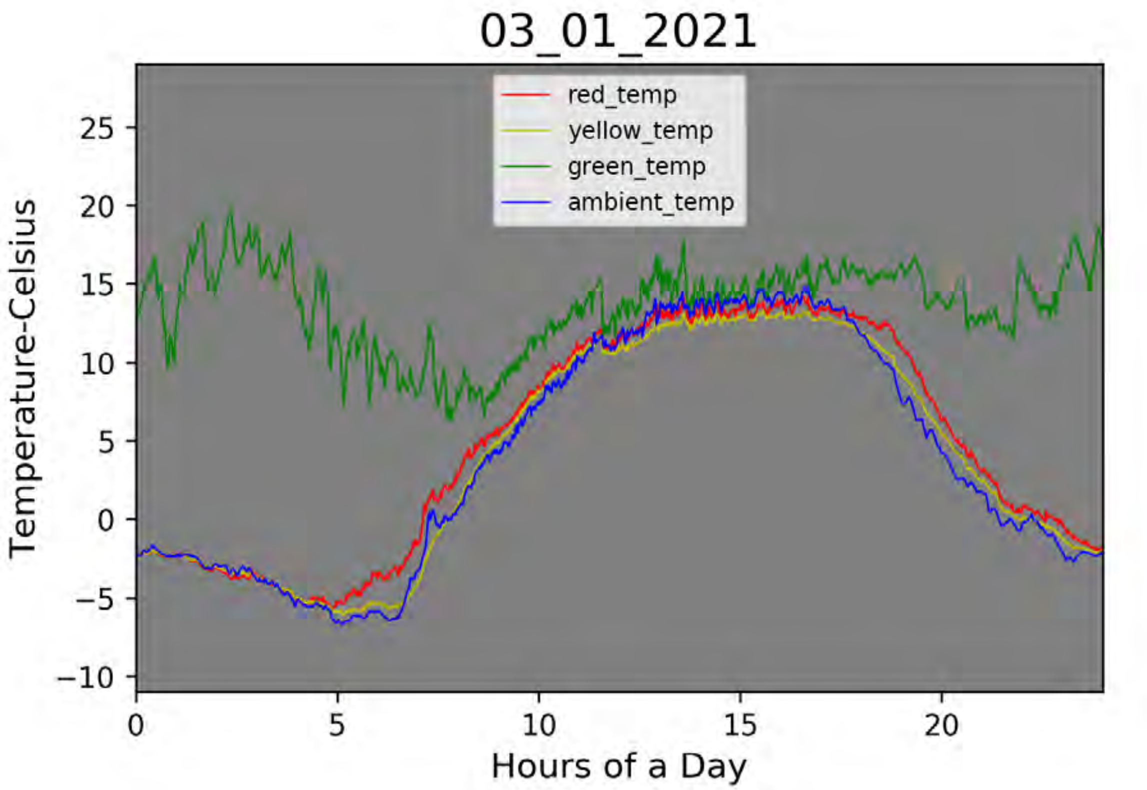


Figure 23: Lawrence field test data during the coldest days in January and February 2021, showing the performance of the red, yellow, and green signal lights under wintery weather conditions. The loose mounting of temperature sensors on the red and yellow signals, after exposure to the environment for 2 years, explained why the recorded lens' surface temperature dropped to the ambient temperature. On windy days, sometimes the yellow and red signal lens with short power-on time had recorded lens's temperature slightly lower than the reading of the ambient temperature sensor mounted inside a shade and thus isolated from the wind.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Hours of a Day
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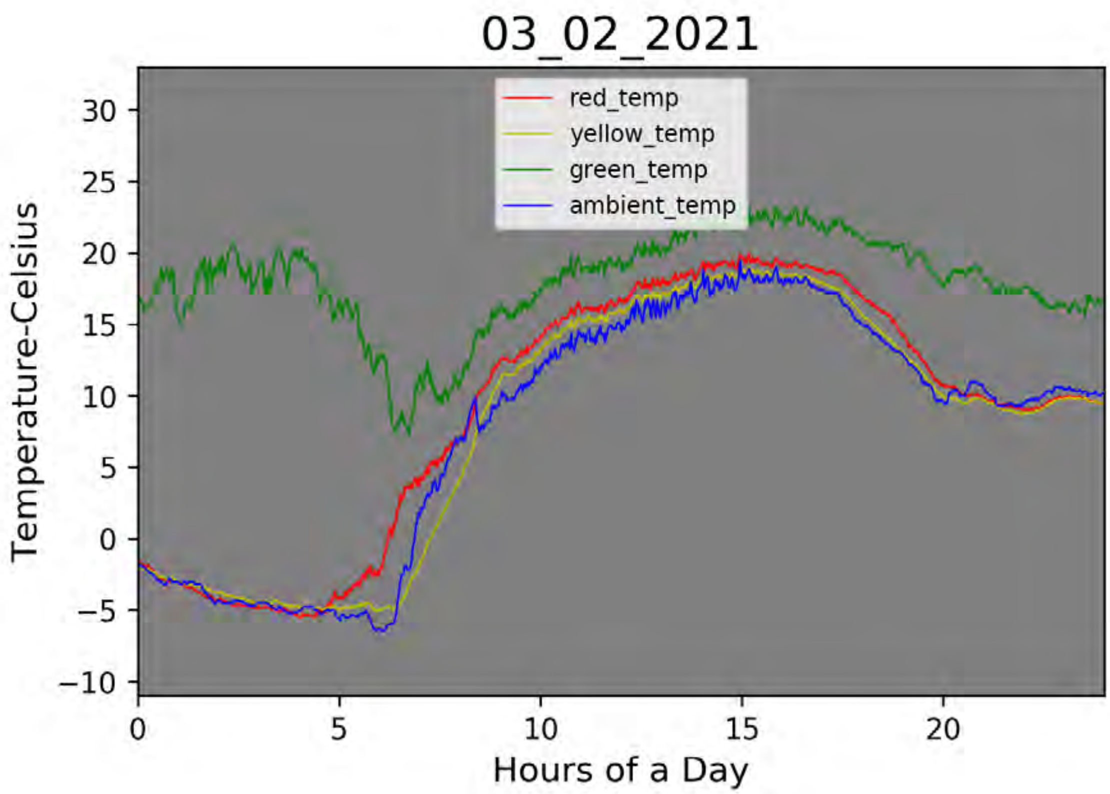
2021-03-01 20:23 (CST)
2021-03-01 05:15 (CST)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2021-03-02 00:23 (CST)
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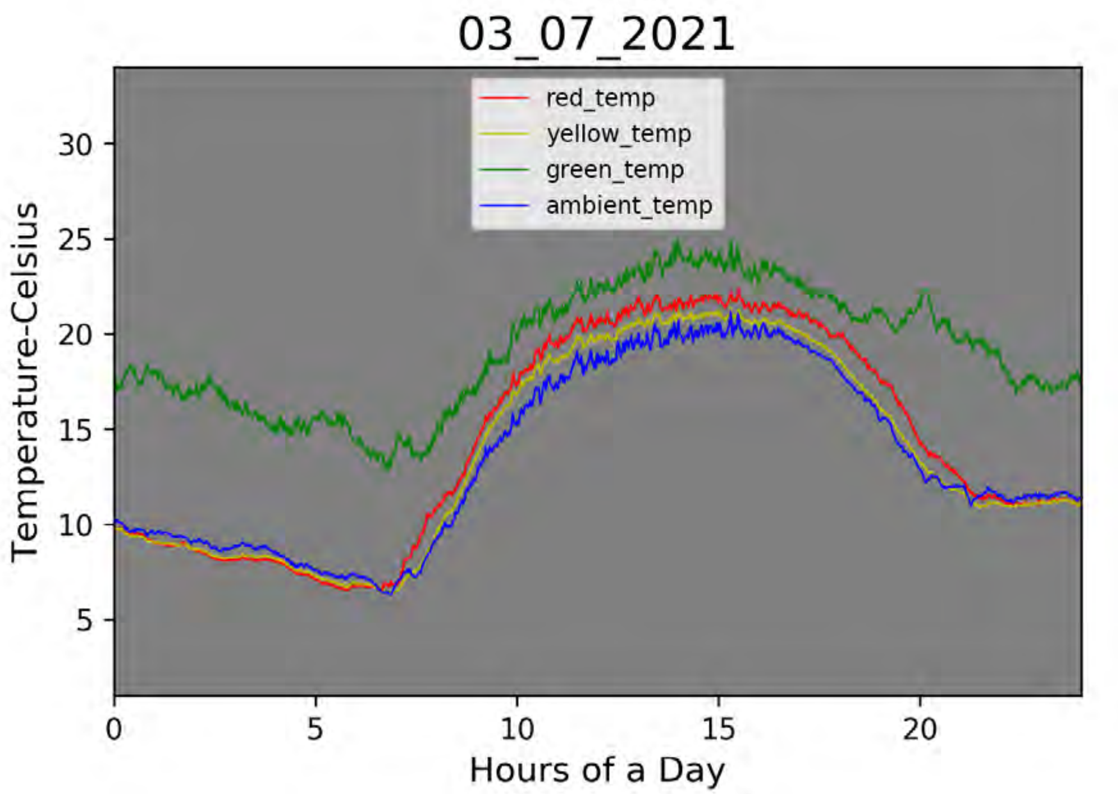
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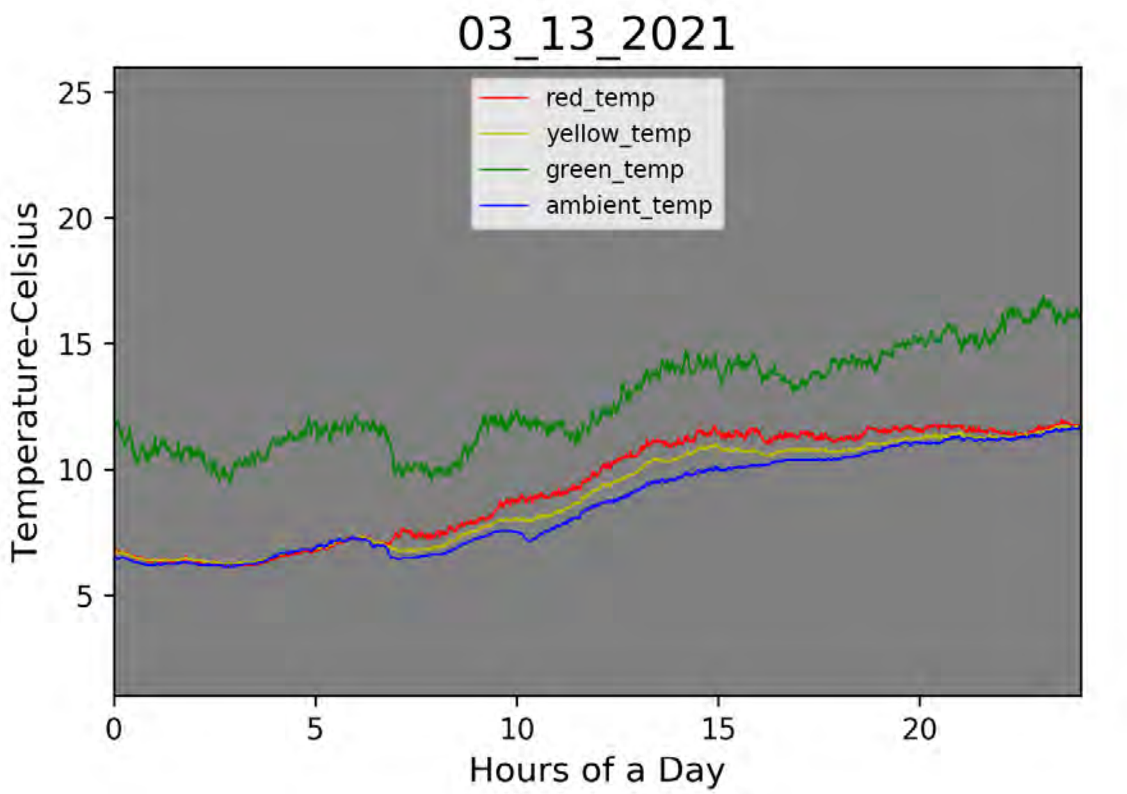
Hours of a Day


2021-03-07 07:08 (CST)


2021-03-07 22:35 (CST)


2021-03-07 22:35 (CST)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Hours of a Day


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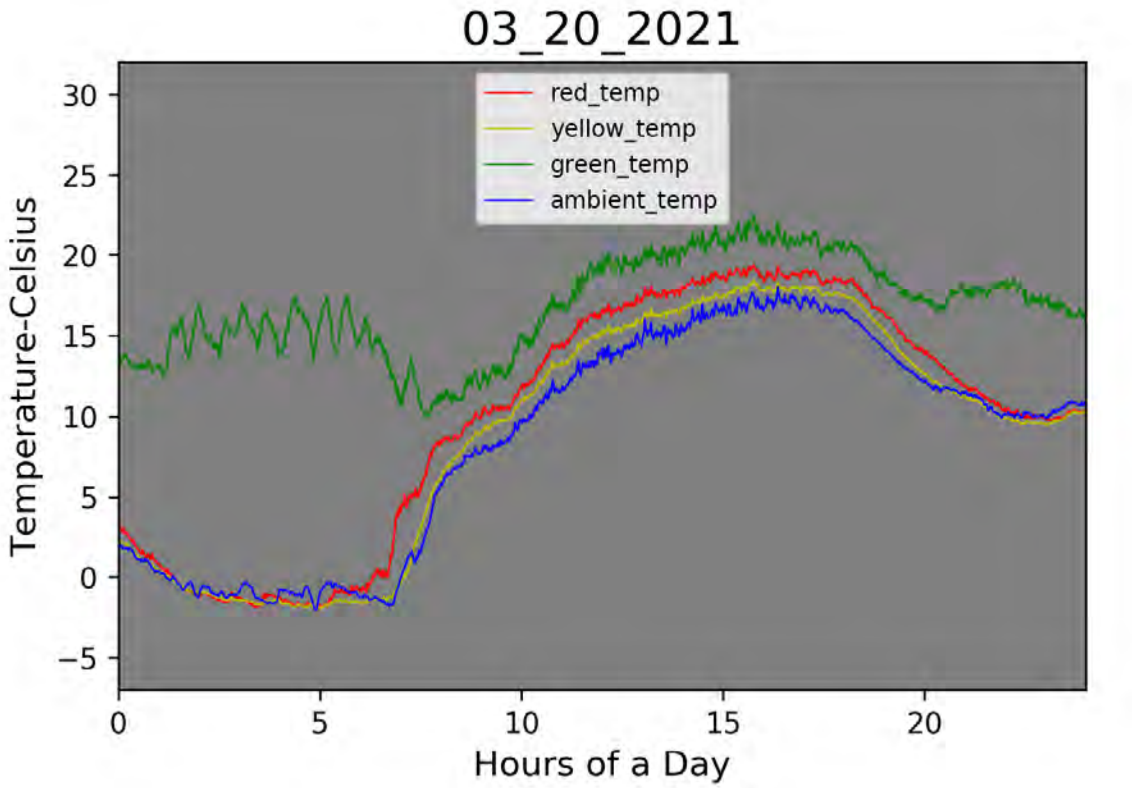
2021-03-13 20:16 (CST)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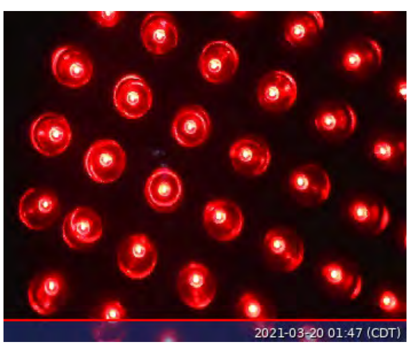
Hours of a Day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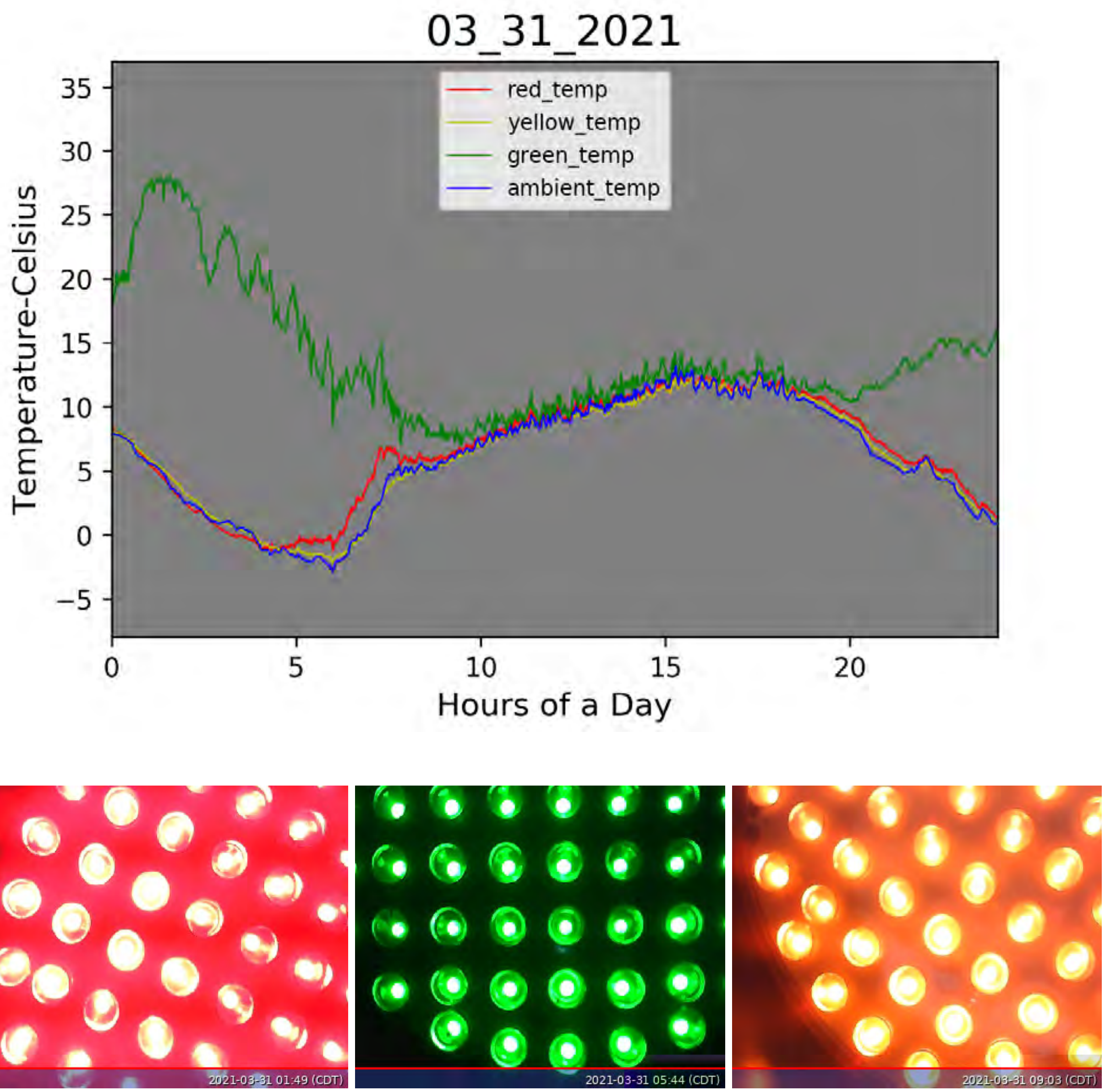
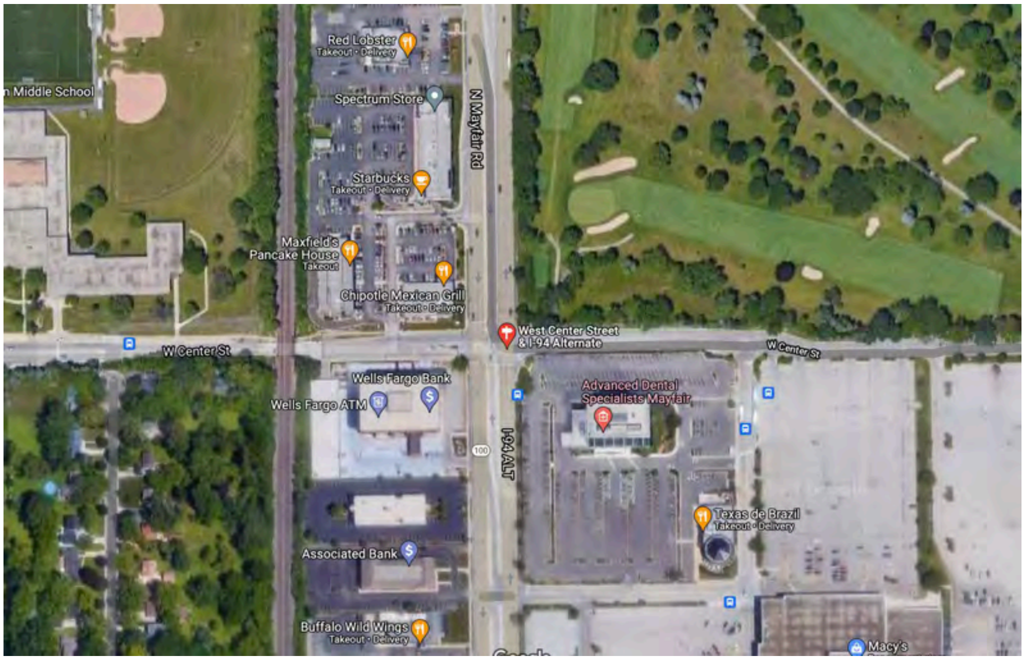


Figure 24: Lawrence field test data collected in March 2021 after the field visit on Feb 25th to fix those two problems of the remote data monitoring system, showing the normal performance of the red, yellow, and green signal lights under spring weather conditions, especially for the green signal light which had the longest power-on time. The ambient temperature was slightly lower than that on the yellow and red signal lens with short power-on time.

3.3.4 Field Tests in Other States, 2021 - Present

We have prepared five complete sets of the fifth-generation prototypes of the self-de-icing signals. Each set comes with a remote field monitoring kit for data collection. All five sets of prototypes and associated remote monitoring kits have been fully tested in the laboratory to be ready for field tests in other states (Michigan, Wisconsin, Maryland, and New Jersey/Pennsylvania). One set of three prototypes (R, G, Y) was shipped to the Maryland Department of Transportation (MDOT) for compatibility tests. We are following up with them on the test results. One issue found in the test is the “dual indication” fault, which we did not encounter in the ongoing field tests in Kansas. There are multiple possible causes for that fault, including possible problematic load switch of the testing facilities. We are working with the signal engineer for troubleshooting and trying to find and solve the problem for Maryland.

Since summer 2020, we have been contacting the Michigan, Wisconsin, Maryland, New Jersey, and Pennsylvania DOTs to select a good field test site and trying to schedule the field installation at each site. So far, Wisconsin and Michigan have proposed a test site, as shown in Figure 25 and Figure 26, respectively. A field trip occurred during the first week of November 2021 for field installation and test setup. Maryland is still conducting compliance tests of our signal prototypes with their own MMU unit and trying to solve the “dual indication” fault before a field test could be scheduled in the future. New Jersey and Pennsylvania are slow in responding and there is no follow-up schedule for field testing which, hopefully, could be done in the future.



Location: STH 100 & Center Street, Milwaukee County, Wauwatosa, Wisconsin

The selected north-facing near-right signal for SB traffic

An existing PTZ camera to be used for good surveillance of the signal performance
(the right-most/lowest signal head)

Figure 25: The field test site in Wisconsin, located in the intersection of STH 100 & Center Street, Milwaukee County, Wauwatosa, Wisconsin, with a selected north-facing near-right signal for SB traffic. An existing PTZ camera will be used as a good tool for surveillance of the signal performance (the right-most/lowest signal head).

Location: MDOT OFS Operations Field Services,
6333 Lansing Rd, Lansing, MI 48917

The selected signal head in the back of the signal shop

Figure 26: The field test site in Michigan, located in the MDOT OFS Operations Field Services (6333 Lansing Rd, Lansing, MI 48917). The selected signal head is in the back of the shop, for convenience monitoring.

On November 3rd, 2021, we visited the test site in Wisconsin (Figure 25) to install the 5th generation prototypes (R, Y, G) and set up the remote data monitoring system mounted on the top of the pole behind the signal head. As shown in Figure 27, the signal crew with Wisconsin DOT helped with the field installation, wiring, and on-site testing. All tested signals are facing north. Since then, the real-time performance of the R/G/Y signals has been monitored and recorded by the remote system. All temperature data and pictures of the signal lens could be remotely retrieved in the KU lighting laboratory from the local computer of the remote monitoring system. As shown in Figure 28, the signals at the Wisconsin test site have been working normally in both mild and cold weather, ready for the upcoming severe winter storms.

However, it was found that, as indicated in most data figures, in the early morning before sunrise, the green signal light was remained powered on almost all of the time at that intersection due to traffic control, while the red and yellow signals were rarely powered on, resulting in a large temperature increase on the green signal lens above the ambient air, with minimal heat buildup on the red and yellow signal lenses. For future snowstorms, please note that this traffic control in the early morning before sunrise might leave temporary snow and ice buildup on the red and yellow signals (due to no power for approximately 6 hours), which could take a very long time to meltdown when their power was resumed later, much longer than the time otherwise needed under normal operating conditions when possible snow and ice accumulation is being prevented in the first place. This could be a problem for yellow and red signal lights at that intersection in extremely cold weather.









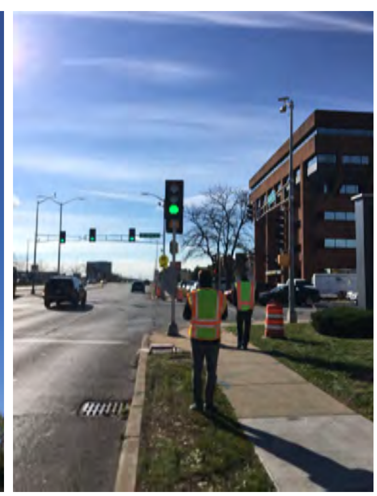
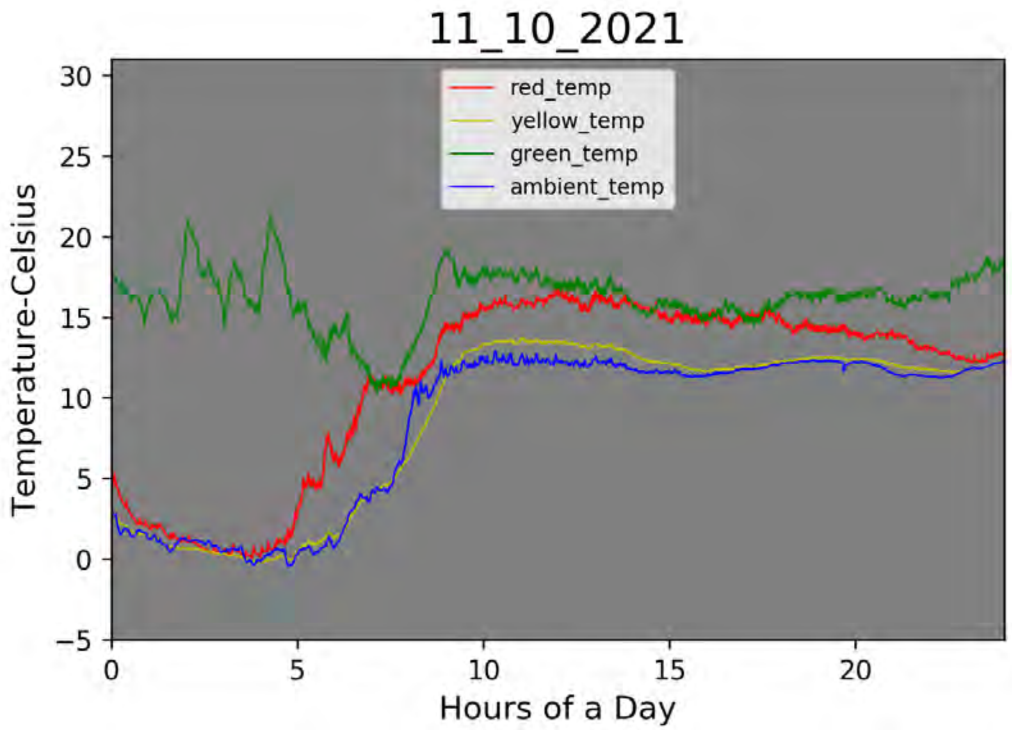


Figure 27: Field installation and setup of the onsite testing at the test site of Wisconsin, with the aid of the signal crew of Wisconsin DOT. A tunnel visor was installed with a hook for mounting the cable camera on each signal module. The signals are all facing north.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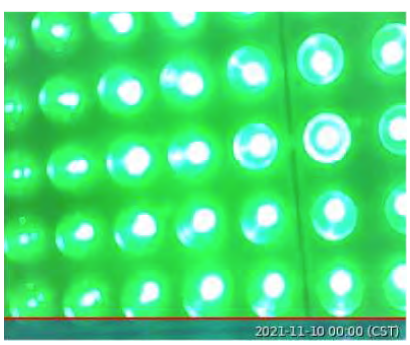
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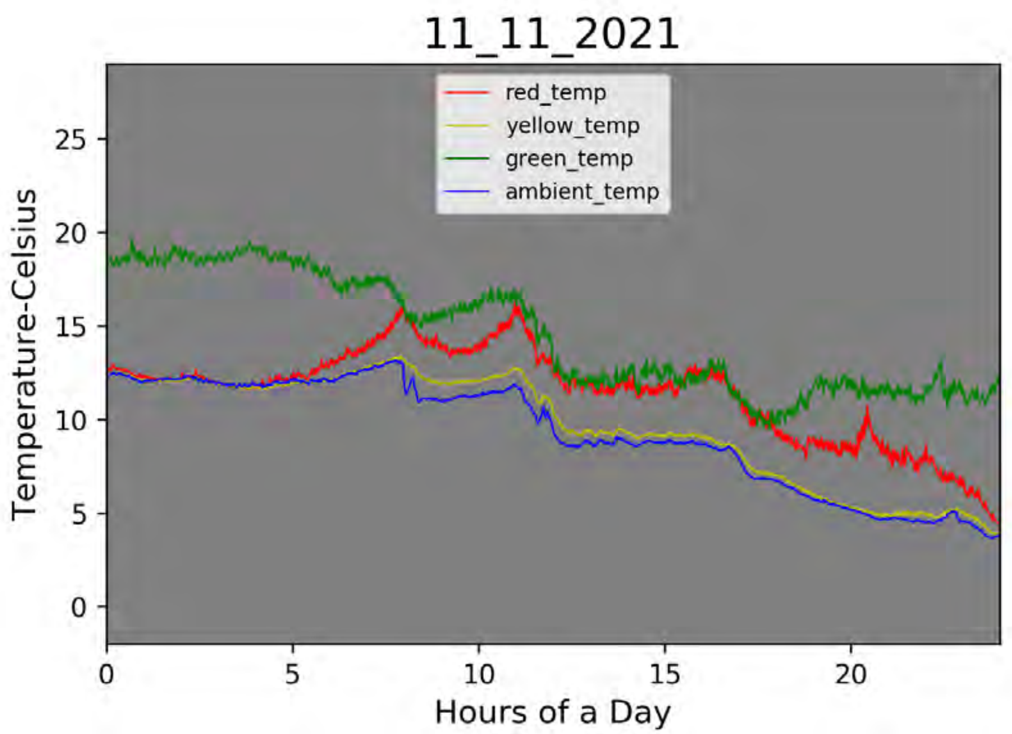
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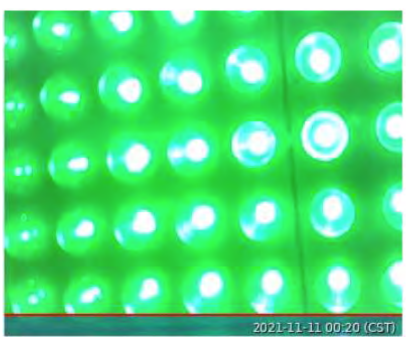
Hours of a Day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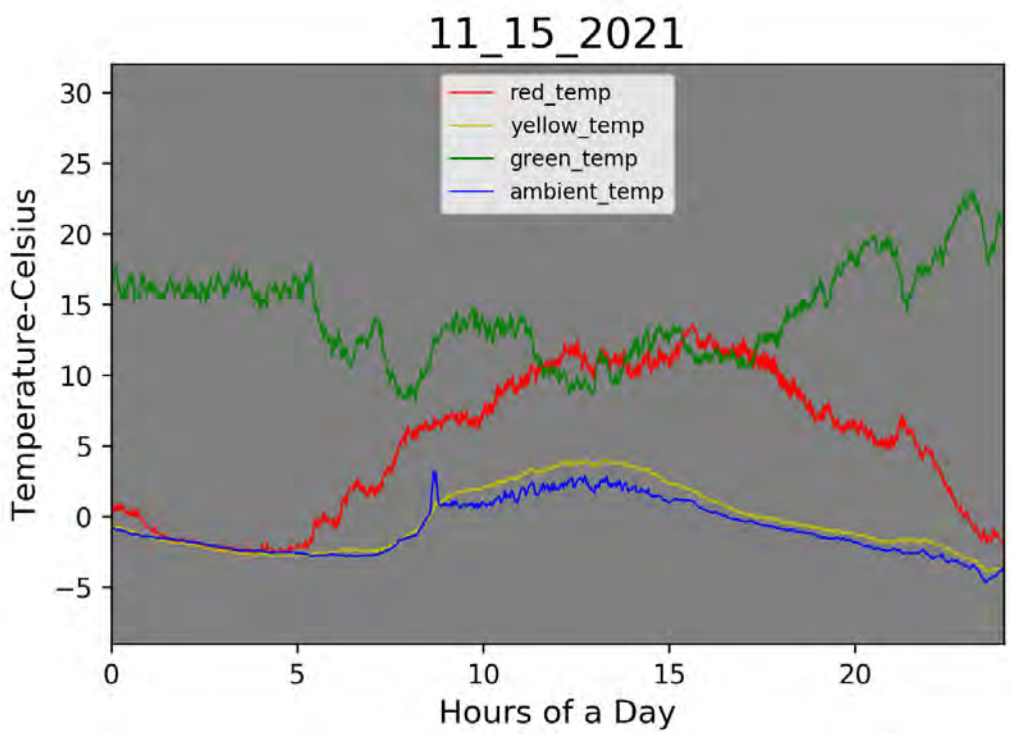
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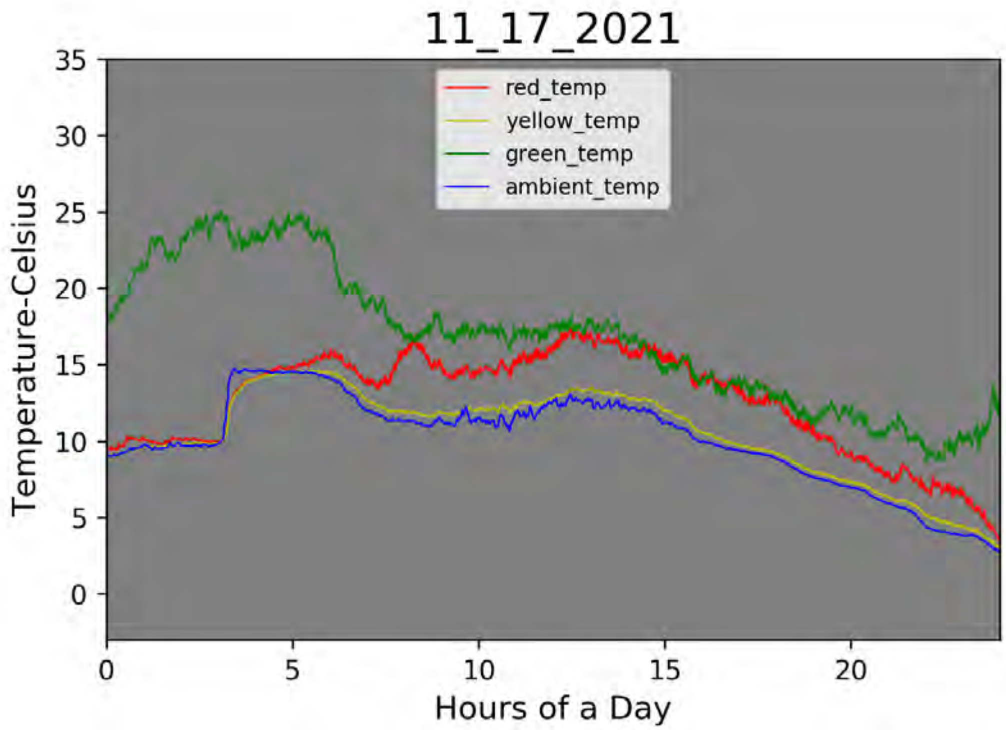
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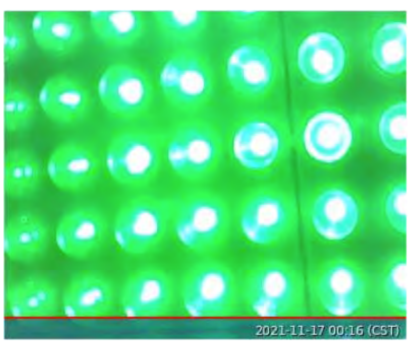
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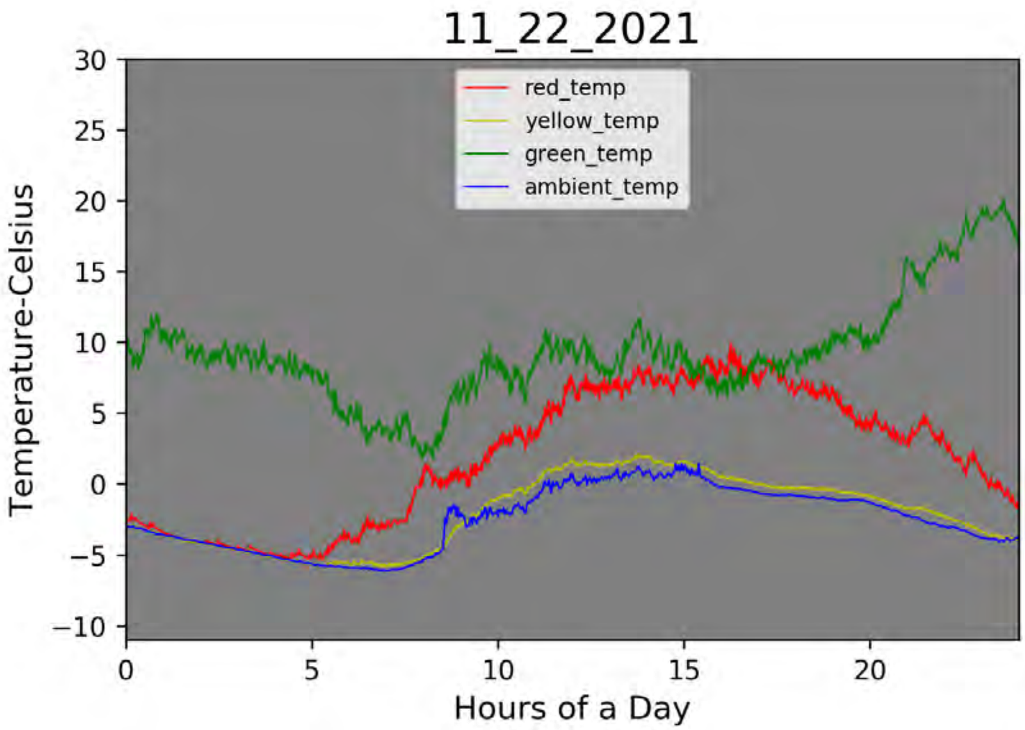
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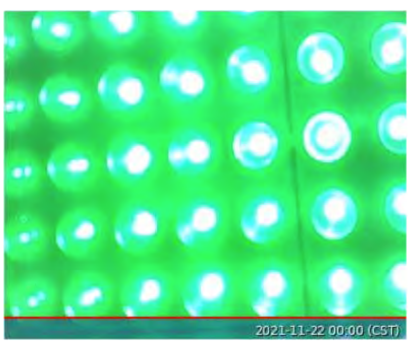
Hours of a Day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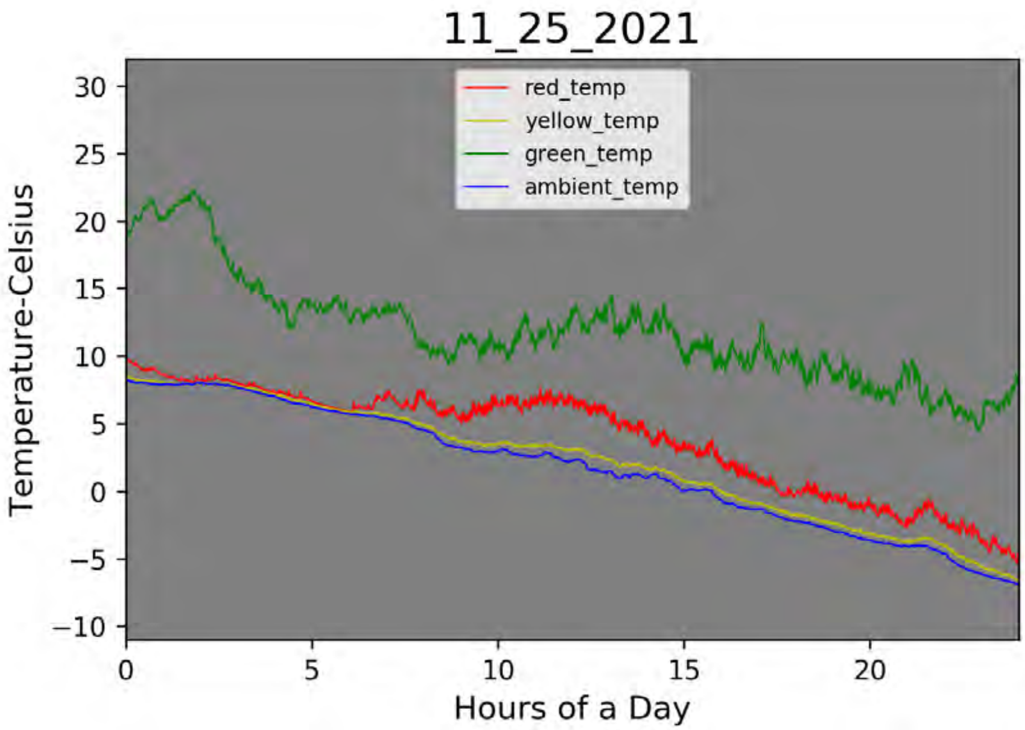
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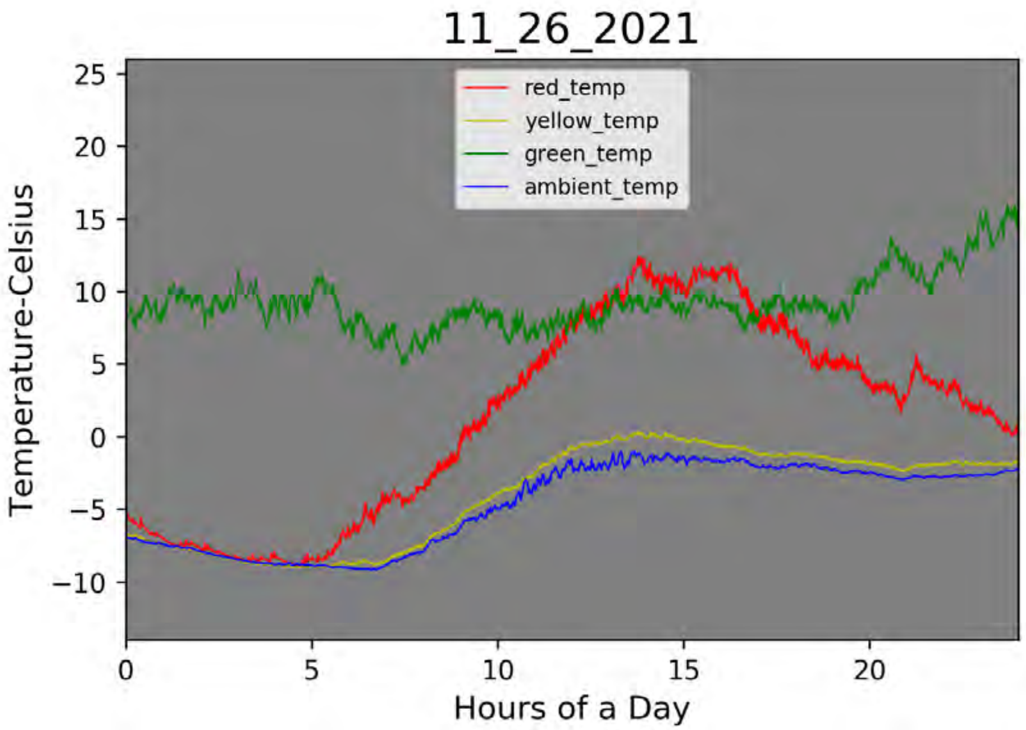
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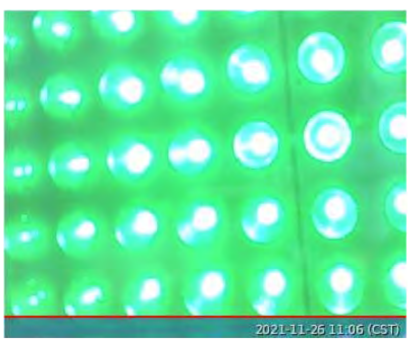
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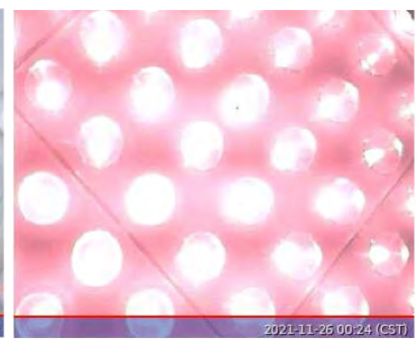
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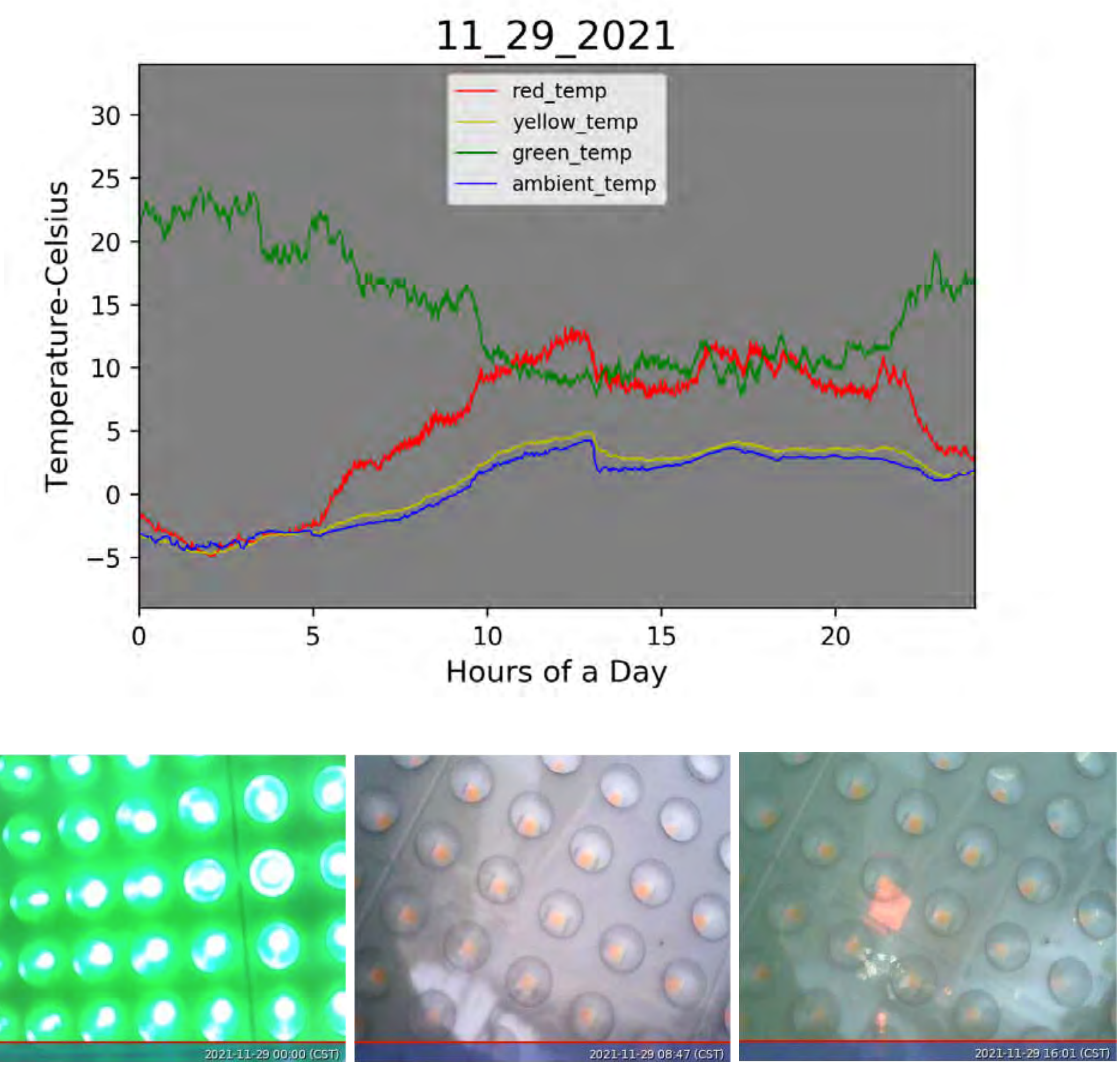
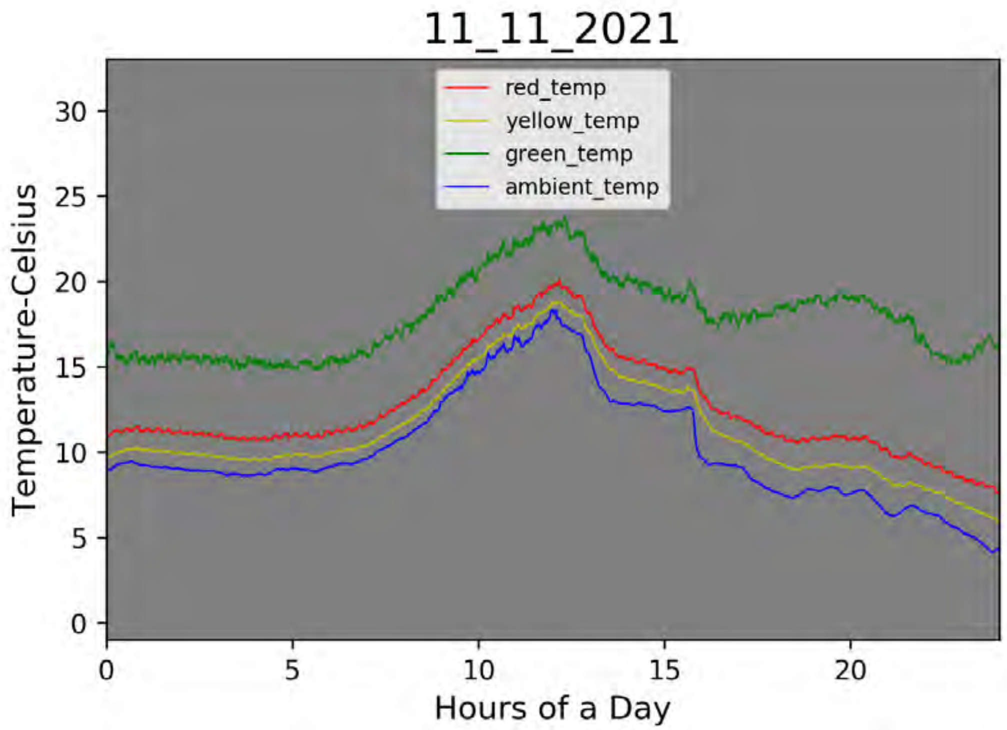


Figure 28: Wisconsin field test data collected in November 2021 after the field installation on November 3rd, showing the normal performance of the red, yellow, and green signal lights under mild and cold weather conditions, especially for the green signal light which had the longest power-on time. Note that due to traffic control in the early morning before sunrise, the green signal light was remained always powered on at that intersection while red and yellow signals were rarely powered on, resulting in a large temperature gap between the green signal lens and the ambient air, with minimal heat buildup on the red and yellow signal lenses during the traffic control period (midnight - sunrise).

Next, on November 4th, 2021, we visited the test site in Michigan (Figure 26) and installed the 5th generation prototypes (R, Y, G) in front of the signal shop with the aid of the signal crew of Michigan DOT, as shown in Figure 29. The remote data monitoring system was also mounted on the top of the signal pole close to the signal head to collect the real-time performance data of the signals, as shown in Figure 30. Since then, the test signals at the Michigan test site have been working normally in both mild and cold weather, ready for the upcoming severe winter storms.

It is worth mentioning that all tested signals could be adjusted in their signal timing by a signal control cabinet located inside the shop. As shown in Figure 30, before Nov. 17, 2021, the green signal light had a higher lens surface temperature due to its longer power-on timing than the red signal light. This timing sequence was changed after Nov. 17 per our request to keep the green and red signal with well-balanced power-on timing, resulting in close temperatures measured on the lens surface for both green and red light.

Figure 29: Field installation and setup of the onsite testing at the test site of Michigan in front of the signal shop, with the aid of the signal crew of Michigan DOT. A tunnel visor was installed with hook for mounting the cable camera on each signal module. The signals are facing north.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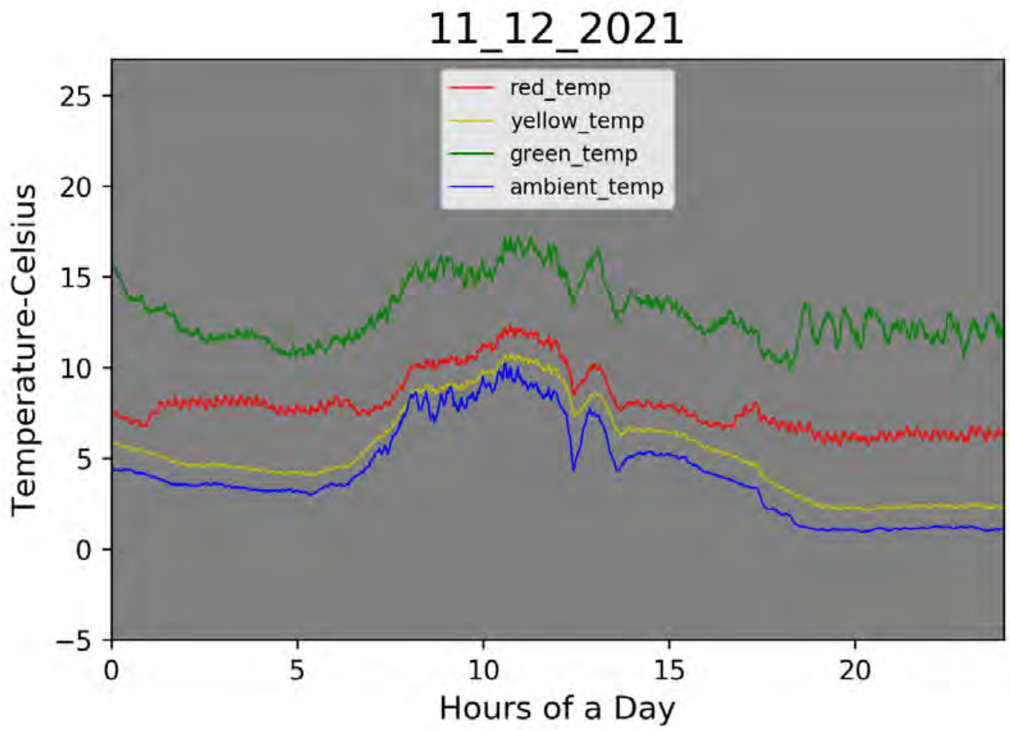
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Hours of a Day


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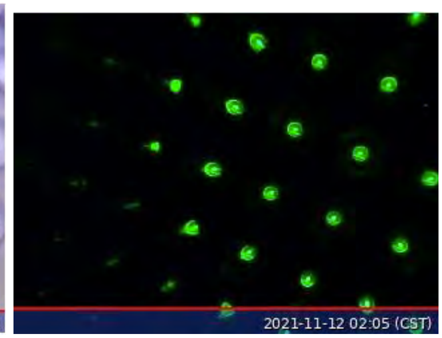
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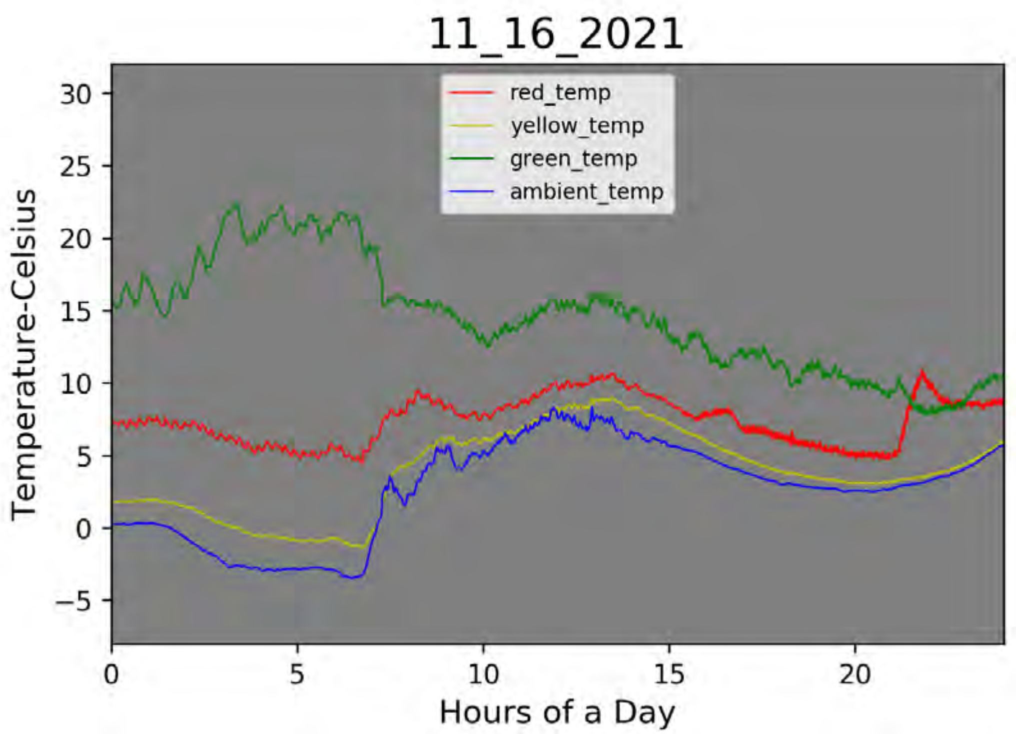
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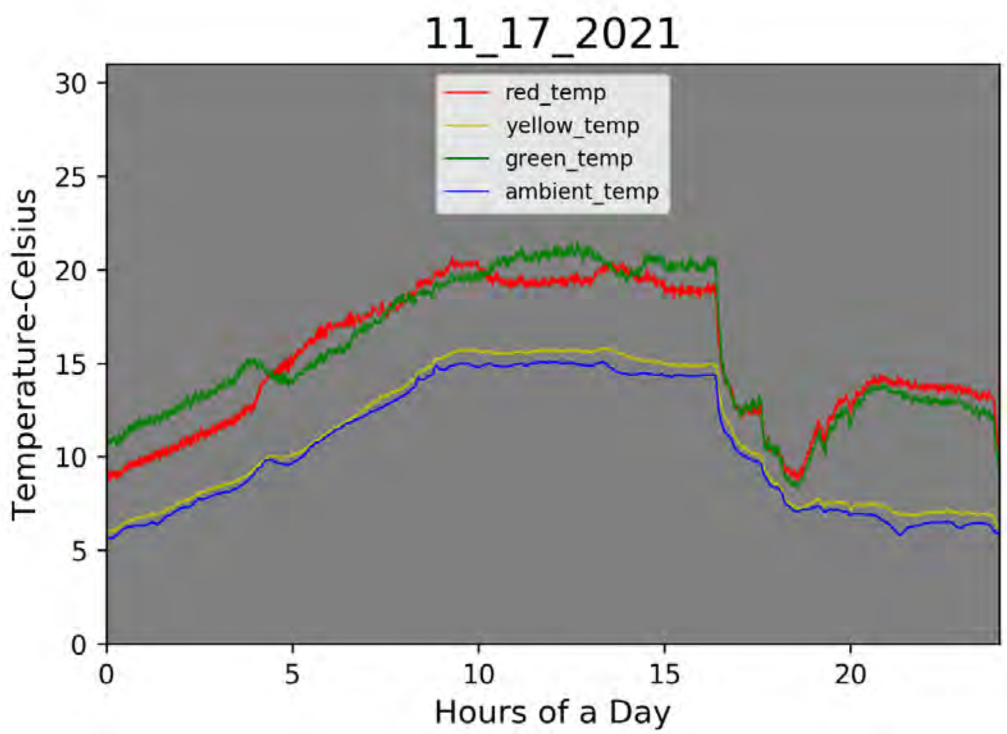
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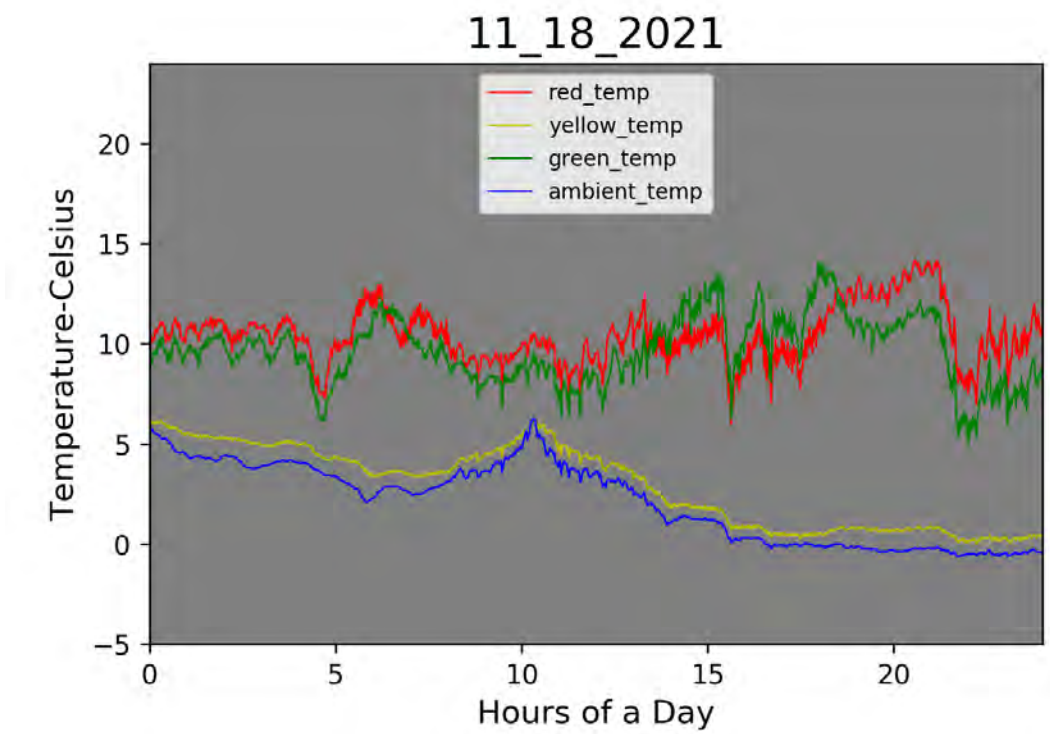

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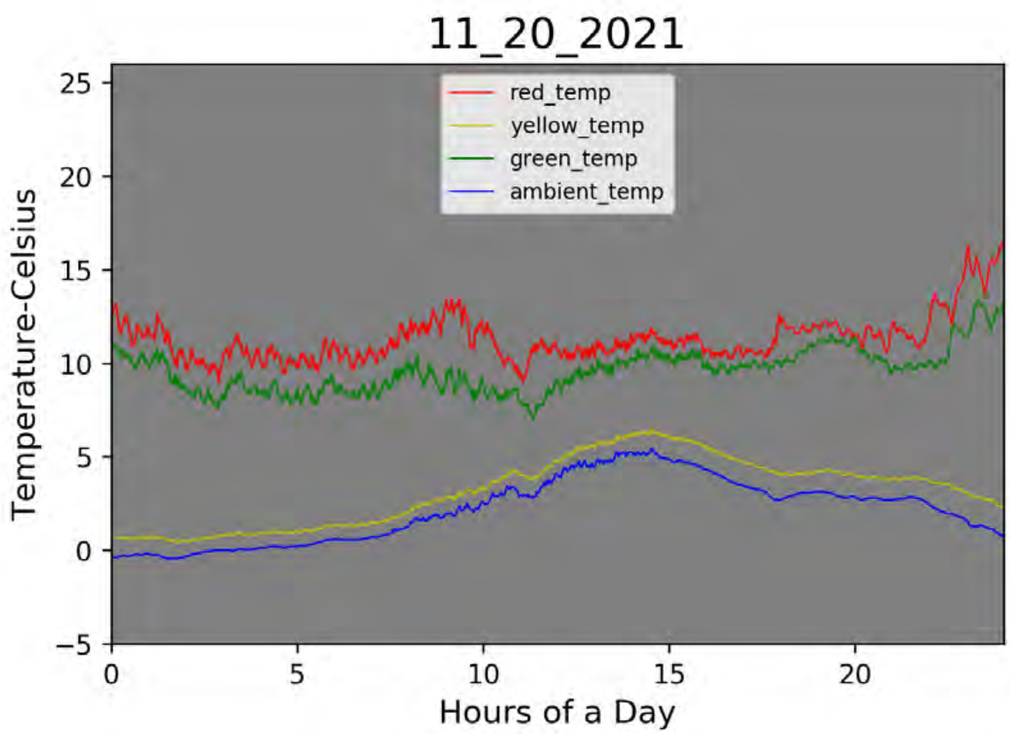
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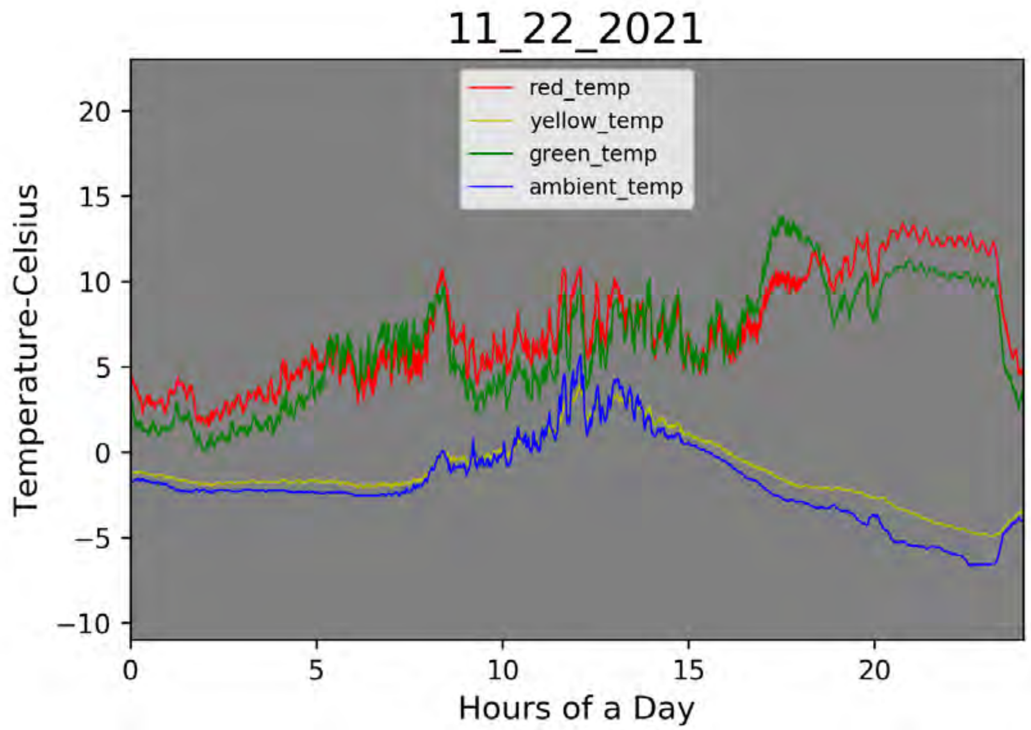
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Hours of a Day


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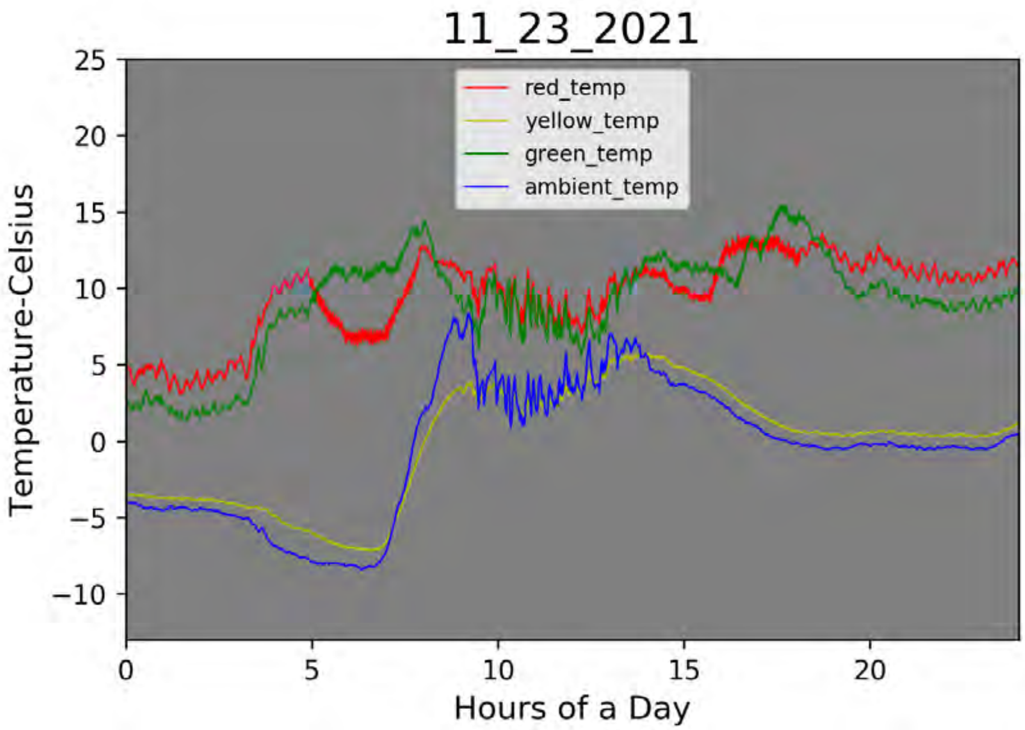
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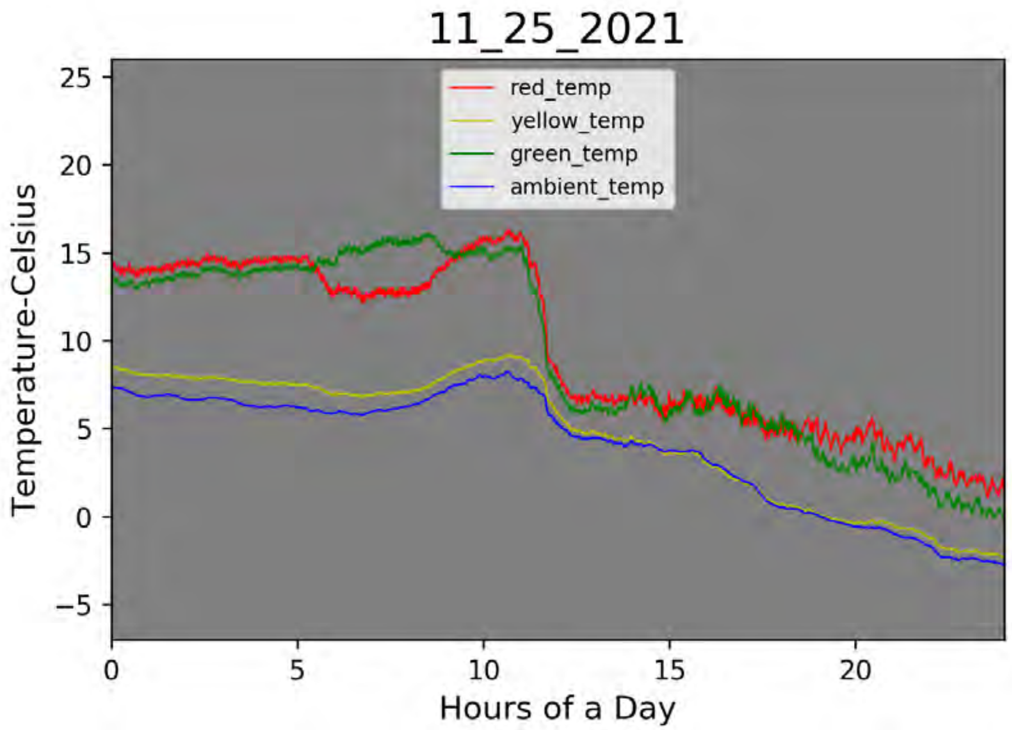
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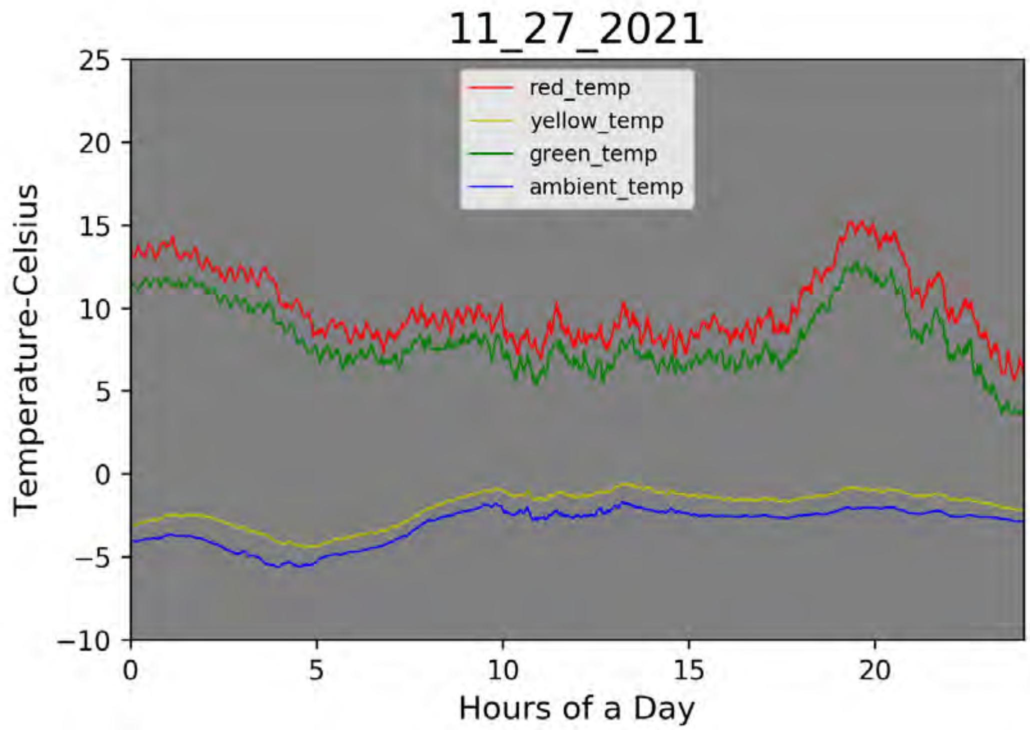
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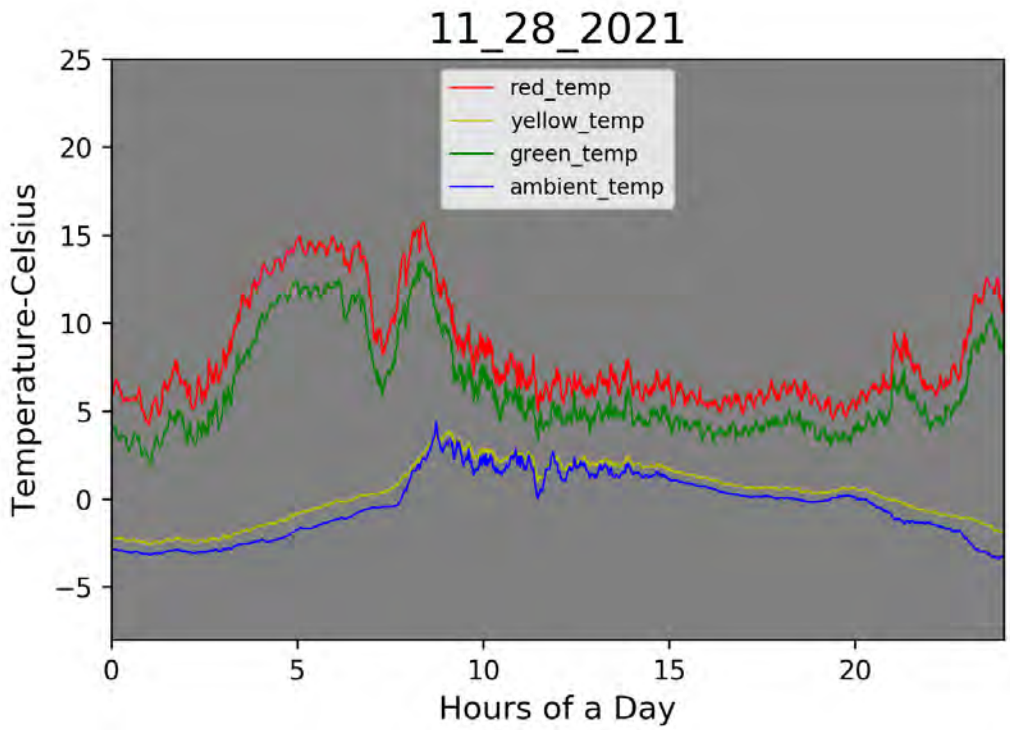
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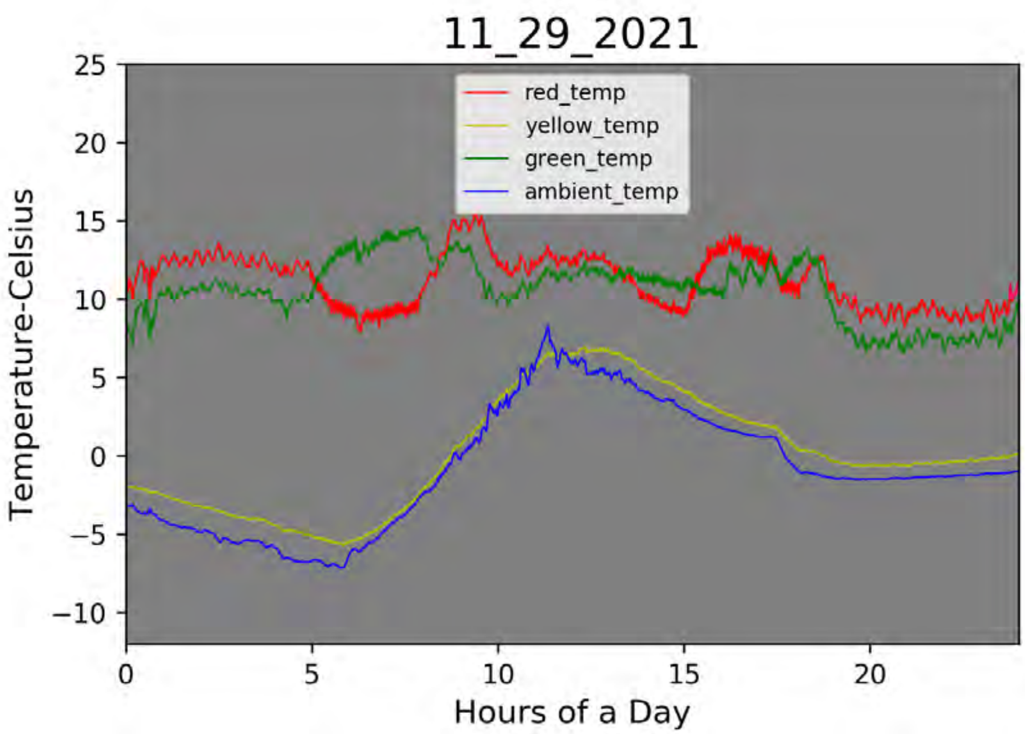

Figure 30: Michigan field test data collected in November 2021 after the field installation on November 4th, showing the normal performance of the red, yellow, and green signal lights under mild and cold weather conditions. Note that before Nov 17, 2021, the green signal light had a higher lens surface temperature due to its longer power-on timing than the red signal light. This timing sequence was changed after Nov 17 per our request to keep the green and red signal with well-balanced power-on timing, resulting in close temperature measured on the lens surface for both green and red light.

Chapter 4: Plans for Implementation

Seven states (Kansas, California, Michigan, New Jersey, Wisconsin, Pennsylvania, and Maryland) have participated in this project for the field testing and evaluation of the prototypes. In the expected implementation, the self-de-icing LED signal lights will replace the existing "cool" LED and any dated incandescent signal lights in the same signal head installed at the highway signalized intersections. As proven in the field tests, the replacement is easy and simple without the need for extra wiring or modification of the signal head. There is no need to alter the function and sizes of the existing signal lights, no need to increase power consumption from the existing controller cabinet or add additional wiring inside and outside of the existing signal controller cabinets, and no need to change anything outside of the signal head 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 to rail applications (e.g., commuter or light rail), or to other surface transportation applications including airport taxiway/apron lighting and seaport applications located in cold-weather zones. We will work with other state DOTs, Union Pacific (UP) Railroad, 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.

The self-de-icing LED signal light has IP and a patent for its innovative system architecture of "Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture" (Patent No. US 10,215,441 B2). We have launched a start-up company SSLaH Tech, Inc., for further R&D, implementation, and commercialization of the product. The University of Kansas Center for Technology Commercialization (KUCTC) could also assist in licensing and marketing the new technology. Table 6 is the timelines for our planned major activities to transfer the technology to practice.

Table 6: Timelines for major activities to transfer the technology to practice.

Date of Completion	Action	Reason
2019 – 2023	Product Testing in field	Ensure product is capable of patent use
2021 – 2022	Initial Market Testing	Launch prototypes into market in the participating agencies
2021 – 2022	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
2022 – 2023	Licensing Pitch	Concept is proven now time to reach out to potential buyers
2022 – 2025	Leverage IP to other Markets	Expand into other markets

Chapter 5: Conclusions

This pooled fund project has developed and demonstrated a new type of self-de-icing LED signals for highway signalized intersections 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 a novel system architecture of "*Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture*" (Patent No. US 10,215,441 B2). 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 wintry conditions. Fully working prototypes of the self-de-icing LED signals have been developed and tested in the laboratory and at closed-course settings on the roof of an engineering building, followed by field tests set up on selected highway intersections in Kansas, Wisconsin, and Michigan, with possible future tests in Maryland, New Jersey, Pennsylvania, and other states and counties interested in the possible implementation of this technology. The realistic performance of the prototype signals in the field tests would help project partners and state DOTs evaluate and initiate the implementation process in the near future.

As of November 30, 2021, we have completed many sub-tasks and achieved the following significant results, listed in chronological order.

This pooled fund project was launched in August 2016 with seven participating states (Kansas, California, Michigan, New Jersey, Wisconsin, Maryland, and Pennsylvania). An expert panel meeting was held in early March 2016. Discussions were held on the 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 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) were developed in-house, each deploying 96 custom-made mediate-power color LEDs mounted in an array via "*Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture*." They were under laboratory testing for lighting and thermal performance. Based on the test results, we improved the design of the 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 "*Integrated Light and Heat Arrangement of Low Profile Light-Emitting Diode Fixture*" with both regular painting coating and tin coating and tested them to improve the heating performance (to make heat transfer faster). Based on the testing results, the signal light engines with tin or painting coating had a similar thermal performance. However, further testing in the laboratory and field was conducted to validate the final choice with regular paint coating.

We finalized the design of the signal housing that adopts a whole piece design with a smooth and flat outside surface and is integrated with 96 additional custom-made Fresnel lenses that sit inside the signal lens niches over each LED on the inside surface to focus the light, serving as a collimator lens. We selected a qualified plastic molding company to custom make the three parts of the plastic housing of the fully working prototypes of the new signals. We also designed and custom made new types of screws to improve the connection strength of the screws integrated with the plastic housing. These types of screws are the finalized products to be used in all finalized plastic housing. We started custom making and modeling 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 accordingly improved and finalized the plastic housing of the fully working prototype signals with changes/improvements, assisted by 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 pieces of the finalized LED engines with the aid of the industrial partner, ready for the upcoming field tests. We updated and custom made 60 pieces of glass disc, removing four small mounting holes on the edge (the original glass disc had eight mounting holes). We also custom made plastic mounting bars for mounting the glass disc to the LED light engine.

We designed and custom made two types of LED drivers, 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 of custom-made LED driver for the green/yellow signal light (input: 100–240 VAC, output: 0.5–0.8 A, max 30 W). Both types of LED drivers are integrated with a remote temperature sensor for controlling the power output in light of the ambient air temperature. When the ambient air temperature is above 4 °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 reason, 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 then started custom making the LED drivers with desired specifications based on our test results. Seven LED drivers were delivered for sample testing.

We started custom making the Fresnel lenses in 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 prices with higher quality control than the current lens vendor. Based on the lab test results, a total of 5000 pieces of new Fresnel lenses (Model #1511) were ordered from the new vendor for field tests.

Next, we started assembling and testing the prototypes of the new self-de-icing LED signal lights in the laboratory. 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° to 70° as measured, even at the derated power output. 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 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 seconds,
2. Unstable output performance of the drivers, due to unsecured soldering of wire connections by hand.

Meanwhile, in the laboratory, a remedying method was developed for flattening the concaved lens surface. Using supplemental heat beneath the lens and added weight on the top inside surface, a thermal lamp was installed inside a box below the glass on which the lens sits, and the lens surface was monitored with four temperature sensors connected to a HOBO data logger. Yet this laboratory method was not used in production, because the problem of defective signal light housing with concave lens surface made during the production process was solved with improved molding technology. A total of 100 new samples were made of Markrolon 2807 and tested with a maximum tolerance of 1.5 mm for mass production.

We then conducted 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 a 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. Based on the test results, 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 improved in-house for enlarging the installation holes to fit the new housing. We custom made 30 more pieces of glass disc which have four larger mounting holes.

Next, we started 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 to the signal housing for quick assembly of the real products. We corrected some problems and resolved issues with 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 a more reliable single switch,
4. Enlarged the inside size of the installation hole to 6 mm 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 in temperature measurement accuracy, redesigned logic circuits, and changes in electronic parts used on the LED PCB boards.

We developed a field monitoring system powered by Raspberry 3B+ 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 put under testing in the lab and on the roof, which would be mounted at each field test site for year-round 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-round real-time monitoring and data recording of the new signals.

The 4th generation fully working prototypes of the self-de-icing signal lights for field tests were assembled and underwent 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 2019. More prototypes of the final products were in preparation for other test sites.

Seven states (Kansas, California, Michigan, New Jersey, Wisconsin, Pennsylvania, and Maryland) participated in field testing and evaluation of the prototypes.

A new Fresnel lens disc with 96 small Fresnel lenses integrated on it was designed with the desired improvements and custom made in a factory through injection mold. As a result, the previously adopted solution using 96 individual lenses mounted in the housing niches with the aid of a glass disc was replaced by a whole piece of plastic disc embedded with 96 Fresnel lenses on it. Corrections have been made in the injection mold for better fitting in the housing niches. Forty (40) samples of the improved second-generation Fresnel lens disc were tested with satisfactory thermal performance, but the lighting performance was not optimized due to an increased focal length of 12.5–13.0 mm (> 11.5 mm). With improvements on the mold injection technology in the factory, 21 new samples of third-generation Fresnel lens disc were tested with a shortened focal length of 11.9 mm, but still > 11.5 mm, and with similar thermal performance. The new Fresnel lens disc was then adopted in the 5th generation prototypes of the self-de-icing signals for field tests. We are working with the factory to revise the mold and change the Fresnel lens focal length to 10 mm, in order to produce the next generation and final products in mass production with a focal length of approximately 11–11.5 mm.

The field monitoring system has added an LTE mobile communication device with a data plan to remotely send the data of the signal performance back to the laboratory on a daily basis for real-time performance monitoring, which is under testing on the roof. We installed the new remote monitoring system with mobile communication in the Lawrence test site, in addition to the original reliable "local" data monitoring system that kept running in the past year. The 4th generation of self-de-icing signals tested in the Lawrence site in Kansas has survived both winter and summer sessions in the past three years, functioning as expected, without any signs of snow and ice accumulation on the signal lens in cold winter, and abnormal performance in hot summer. The 5th generation prototypes and associated field remote monitoring systems have been fully prepared and tested for other field test sites to be conducted in Michigan, Wisconsin, Maryland, New Jersey, and Pennsylvania for continuous field testing and evaluation of the prototypes. On November 3rd and 4th, 2021, two more field test sites in Wisconsin and Michigan were selected, where the 5th generation prototypes were installed and tested on site, for continuous field testing in the following

2–5 years through both winter and summer seasons. The remote data monitoring system was also installed on the pole close to the back of the signal head at each test site and since then, has recorded all data that could be retrieved online on a daily basis. It is expected that a few more field test sites would be selected by Maryland, New Jersey, and other states as well as interested cities and counties for future implementation of the new technology.

A manual was prepared for signal crews of different states for mounting the new self-deicing signals and the corresponding data recording and remote monitoring system for the upcoming field test sites in Michigan and Wisconsin in November 2021. Maryland is testing the prototypes for compatibility, while New Jersey is slow in responding. Hopefully, two more field tests could be done in the future in Maryland and New Jersey.

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