

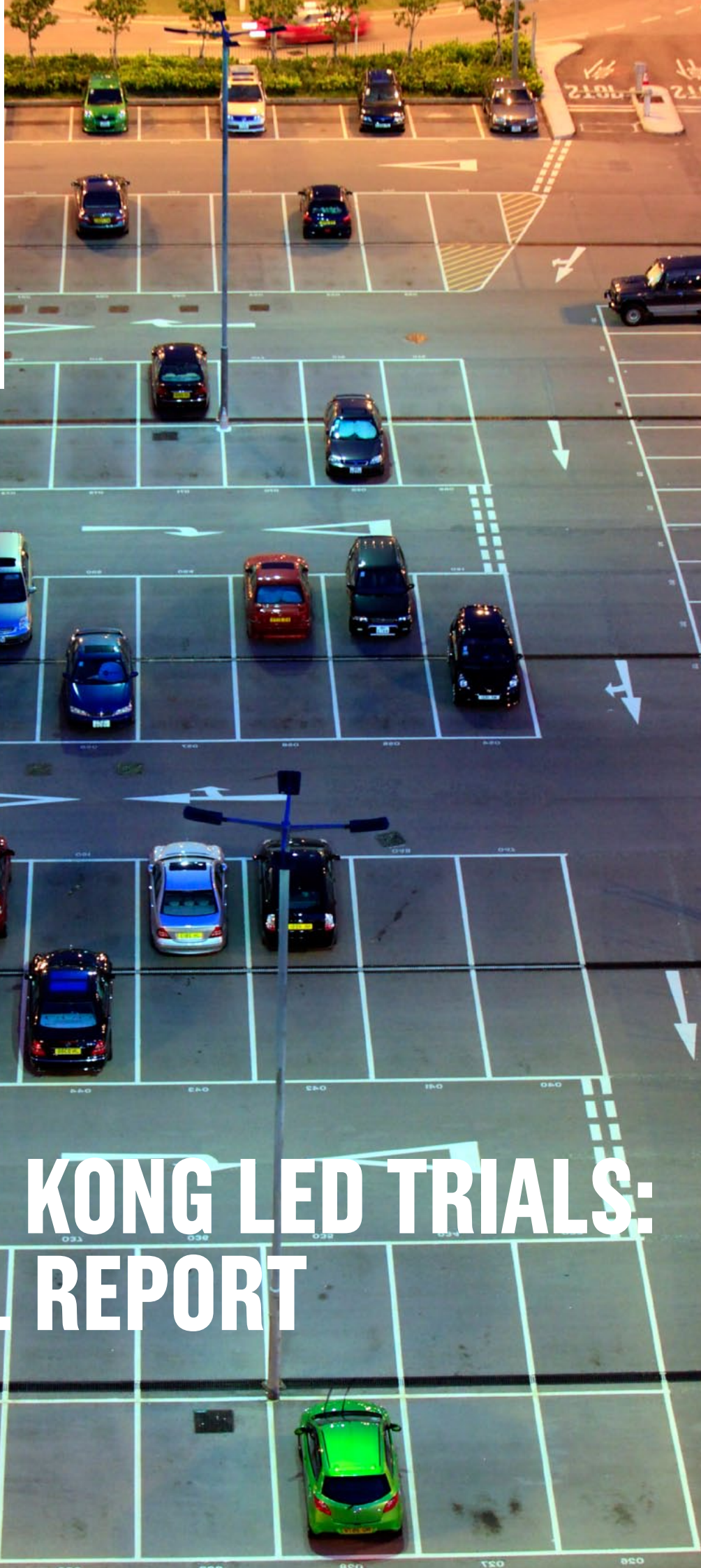
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# HONG KONG LED TRIALS: FINAL REPORT



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## LightSavers: The Hong Kong University of Science and Technology, The University of Hong Kong, and the Airport Authority Hong Kong LED Trials

Final report | September 2013

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## Acknowledgements

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The Hong Kong University of Science and Technology, The University of Hong Kong and the Airport Authority Hong Kong have participated in a unique global trial of LED outdoor lighting organized by The Climate Group. The key aim of the project was to test the performance of a variety of LED luminaire products in real world field conditions, comparing these products with baseline high intensity discharge (HID) lamps using the same measurement protocol and equipment. Other cities participating in the initiative were: London, New York, Toronto, Adelaide, Kolkata, and Thane, a suburb of Mumbai, and Quezon City, the Philippines. Chinese cities Guiyang and Tianjin also participated as observers. In addition to trials, the project brought lighting managers from the cities together in workshops and a summit held in Shanghai in May 2011 to exchange information and experience. Meanwhile, in Hong Kong, an LED Lighting Deployment Advisory Council was organized and supported by The Climate Group over the period of the project.

The LightSavers global LED trials ran from October 2009 to January 2012 and aimed to provide greater certainty about the state of LED technology. During the trials, lighting managers from nine of the cities independently tested the performance of more than 500 luminaires representing 27 different commercially available LED products, using the same measurement protocol. Key findings of the trials were:

- LEDs achieve the expected 50–70 percent energy savings and reach up to 80 percent savings when coupled with smart controls;
- Even with these energy savings, the vast majority of tested products exceeded local lighting standards;
- Many commercial LED products tested show behavior indicative of lifespans of 50,000 hours, though the results from the trials should not be used for predictive purposes;
- LED products generally show very little change in color;
- The ‘catastrophic’ failure rate of LED products over 6,000 hours is around one percent, compared with, for example, up to 10 percent for metal halide fixtures over a similar time period;
- In cities where surveys were conducted the public prefers LED illumination, with about 90 percent of survey respondents supporting a full rollout of LEDs across city street lights.

It should be noted that the LED luminaire products tested in this trial were designed and manufactured several years ago. It would be expected that recent generations of products should exhibit even better performance. The Climate Group’s LightSavers trial concludes that LEDs are now mature enough for scale-up in most outdoor applications, and that LEDs combined with smart controls promise greater savings.

The universities’ and Airport Authority’s participation in the global trial made an important contribution to the global trial results. The author of this report, Philip Jessup, would like to thank Mr. K. L. Lam, Associate Director, Facilities Management Office at The Hong Kong University of Science and Technology, Dr. Clement Wong, Senior Assistant Director, Estates Office at The University of

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Hong Kong, as well as Mr. Ricky Leung, General Manager - Technical Services and Mr. Amen Tong, Senior Manager, Electrical and Mechanical, at the Airport Authority Hong Kong. They provided timely data and related information for this report. Finally, the author would like to thank Natural Resources Canada for additional support allowing the author to extend analysis in all the LightSavers trials. LightSavers is a registered mark of the Toronto Atmospheric Fund, licensed to The Climate Group for use in the United States and elsewhere outside of Canada.

## Executive Summary

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LightSavers undertook three trials in Hong Kong that tested five LED products, three on the campus of The Hong Kong University of Science and Technology (HKUST), one on the campus of The University of Hong Kong (HKU), and one in a parking lot operated by the Airport Authority Hong Kong (AA). The university trials were undertaken with the cooperation of technical staff and students at the universities. The HKUST trial was 19 months in length, January 2010–August 2011. The HKU trial was 12 months in length, July 2010–June 2011. The AA trial was six months in length. Here is a summary of the results from the HKUST and HKU trials (data from the AA trial are confidential):

1. **Illuminance.** All four campus LED luminaires provided average illuminance that exceeded the baseline and significantly exceeded the roadway lighting standards that would pertain to these campus roads, were the standards in Hong Kong's *Public Lighting Design Manual* applicable on Hong Kong's university campuses.
2. **Correlated color temperature (CCT).** Differences in measured CCT annualized changes for all four LED luminaires were below five percent, with three of the LED luminaires below three percent—an excellent result.
3. **Energy.** The four LED luminaires reduced electricity use in the range of 67–89 percent—compared with the mercury blended fluorescent (MBF) luminaires that served as the baseline in the HKUST trial, and the high pressure sodium (HPS) luminaires that served as the baseline in the HKU trial—an impressive result.
4. **Luminaire target area system effectiveness.** The LED luminaires in both campus trials were significantly more effective at directing light to the surface of the campus roadways than the baseline—as much as 11 times more efficient in the case of one product in each the HKUST trial and the HKU trial. These impressive results are due in part to the inefficient and outmoded baseline lamps used on both campuses, amplified by the directional benefits of LEDs.
5. **Lumen maintenance.** For the purpose of this trial and study, we assumed an operational lifetime<sup>1</sup> of 50,000 hours for the four LED products tested on both campuses. In the case of HKUST, this would imply an average annual depreciation rate of approximately 2.2 percent were it occurring on a linear basis. In the case of HKU, this would imply an average annual depreciation rate of approximately 3.0 percent, were it occurring on a linear basis. In actuality, lumen depreciation occurs exponentially, so the linear values noted above are merely intended to serve as useful mileposts in judging a luminaire's early trajectory.

One LED product exhibited extreme volatility. The remaining three products performed very well; one depreciating only 1.9 percent if evaluated on a linear annualized basis, and the other two remained very stable over the trial period.

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<sup>1</sup>Lifetime of LEDs is commonly defined by  $L_{70}$ , a term indicating when the light output falls to 70% of the initial light output, i.e. when 30% depreciation is reached.

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Limitations in the use of the Excel exponential trend line function became evident in the interpretation of these results. Meanwhile, observed correlations between hot summer temperatures and LED light output did not appear to be present. The results from these trials should be taken as indicative, rather than predictive.

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### Background

Hong Kong is located on the southeast coast of China at the mouth of the Pearl River, facing the South China Sea. Covering an area of 1,104 square kilometers, the territory is made up of Hong Kong Island (see photo below), the Kowloon Peninsula, and the New Territories, as well as 262 outlying islands. The City is a Special Administrative Region of the People's Republic of China.

Hong Kong is highly urbanized and dense, with a population of 7,173,900 (2012). Average per capita income in 2012 was HK\$285,403 or US\$36,826. According to the Environmental Protection Department, Hong Kong's CO<sub>2</sub> emissions from the consumption of electricity were 27.4 MtCO<sub>2</sub> in 2010, a rise of about 20 percent since 1990<sup>2</sup>. Hong Kong's per capita CO<sub>2</sub> emissions from electricity consumption was approximately 3.9 tCO<sub>2</sub> in 2010.



There are more than 205,000 lighting points maintained by the Lighting Division of the Highways Department. The lamps annually consume about 137 million kilowatt-hours (kWh) of electricity<sup>3</sup> and account for about 85,899 tons of equivalent CO<sub>2</sub> emissions, based on the carbon coefficients published by the two power companies in Hong Kong, CLP and HK Electric. The Highways Department's *Public Lighting Design Manual*<sup>4</sup> sets out the standards for lighting on Hong Kong's public roads maintained by the Highways Department, which are based on British roadway lighting standards, as well as CIE recommended practices.

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<sup>2</sup>Environmental Protection Department, Hong Kong SAR Government, 2013. Available at: [http://www.epd.gov.hk/epd/english/climate\\_change/files/HKGGHG\\_Sectors\\_201304.pdf](http://www.epd.gov.hk/epd/english/climate_change/files/HKGGHG_Sectors_201304.pdf)

<sup>3</sup>Director of Highways. Hong Kong SAR Government, 2009. Replies to questions raised by Finance Committee Members in examining the Estimates of Expenditure 2008-09, Reply Serial No. THB(T)038. Available at: [http://www.hyd.gov.hk/en/publications\\_and\\_publicity/publicity/replies\\_to\\_legco/0809/doc/1737E.pdf](http://www.hyd.gov.hk/en/publications_and_publicity/publicity/replies_to_legco/0809/doc/1737E.pdf)

<sup>4</sup>Highways Department, Hong Kong SAR Government, 2006. Available at: [http://www.hyd.gov.hk/en/publications\\_and\\_publicity/publications/technical\\_document/public\\_lighting\\_design\\_manual/doc/manual.pdf](http://www.hyd.gov.hk/en/publications_and_publicity/publications/technical_document/public_lighting_design_manual/doc/manual.pdf)

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The Highways Department has taken several measures to conserve electricity consumption by street lighting. The Department is upgrading street lighting from the incumbent technology, high-pressure sodium (HPS) lamps, to lower wattage, higher efficiency lamps. Additionally, dimmable electronic ballasts are being installed in some HPS luminaires to more closely match their illumination levels with roadway standards. These measures are expected to significantly reduce electricity use. Building on these initiatives, the Department is also examining the potential of LED street lighting.

In addition, the government is implementing a three-phase replacement of incandescent traffic signal lamps at 1,900 signalized road junctions—about 80,000 LED modules. The project commenced in September 2008 and was completed in the summer 2012, at a cost of HK\$140 million or US\$18 million.

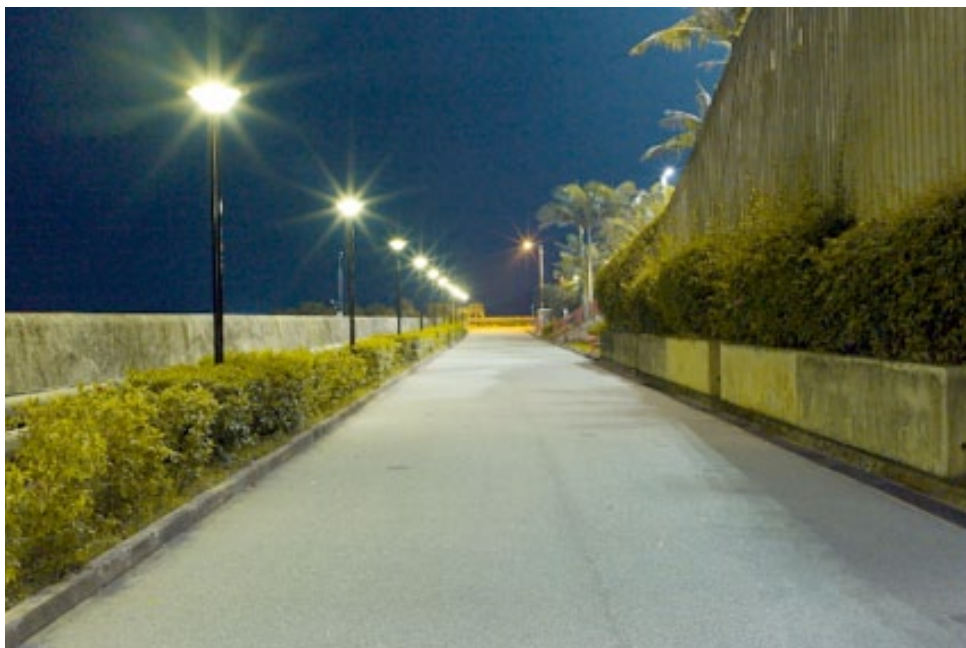
The Highways Department undertook a trial that retrofitted 70 watt HPS with 60 watt LED luminaires on eight poles in Kowloon Tong. The performance was satisfactory but the initial high capital costs could not be justified. The Department is now conducting a more extensive pilot testing on 100 LED luminaires in Kowloon and the New Territories, as well as a trial on 50 LED luminaires developed by the Hong Kong Applied Science and Technology Research Institute.

## The LightSavers University Campus Trials

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### 1. HK1: The Hong Kong University of Science and Technology

The Hong Kong University of Science and Technology (HKUST) is a government subsidized education institute. Its campus is located at the Clear Water Bay peninsula in East Kowloon, Hong Kong and occupies an area over 60-hectares, accommodating over 13,000 students and staff. The Seafront Driveway, a two-lane road accessible by both pedestrians and vehicles, was selected as the pilot site to test LED lighting products. The Driveway is currently lit by 125 watt mercury blended fluorescent (MBF) post top luminaires.



HKUST installed twelve LED luminaires from three suppliers on the road. The new luminaires are rated at 53–78 watts and produce a white light in the range from 4,000K to 7,000K. Installation of the LED luminaires occurred in early January 2010. Monitoring undertaken by a student team under the guidance of a faculty staff person and The Climate Group began in March 2010 and continued through August 2011 for a total of 19 months.

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As HKUST is now expanding its campus, the trial has served as an important reference to the university, which is scaling-up application of LED lighting technologies in the campus development.

Here is a summary of the trial:

- Seafront Driveway is typically illuminated by 125 watt mercury blended fluorescent post top lamps, with an average annual operation of 3,103 hours or 8.5 hours daily;
- There is no specific illumination requirement at the Seafront Driveway. However, the Driveway would be equivalent to category S4 (minimum point: 1 lux; average illuminance: 5 lux) or category S5 (minimum point: 0.5 lux; average illuminance: 3 lux) for lighting requirement specified in the *Lighting Design Manual* by the Hong Kong Highways Department;
- The pole height is 3.5 meters, with the poles mounted along one side of the road;
- The distance between poles averages approximately 10.6 meters;
- Four baseline luminaires used the incumbent BEGA 125 watt mercury blended fluorescent lamps;
- Three LED luminaire products, four from each manufacturer, were installed along the road.

## 2. HK2: The University of Hong Kong



The University of Hong Kong (HKU) is a government subsidized education institute and has a number of campuses throughout the territory. The University owns 50 hectares of land and accommodates over 31,000 students and staff. A section of Sha Wan Drive at Stanley Ho Sports Center, which is a one-lane road accessible by both pedestrians and vehicles, was selected as the pilot site (see photo).

The University installed four LED post top luminaires along the Drive. The new luminaires are rated at 40 watts and produce a cool white light with a color temperature in the range of 6,000-to-6,500 K. Installation was done in early July 2010. Monitoring began in late July 2010 and continued through June 2011—a total period of 11 months.

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As HKU is building the 42,000 square meters Centennial Campus, the trial served as a reference to the university to consider scale-up application of LED lighting technologies in the campus development.

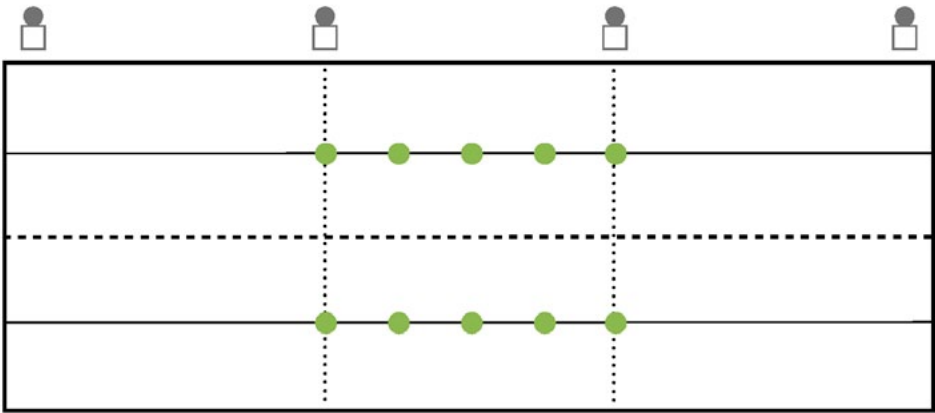
Here is a summary of the trial:

- Sha Wan Drive is typically illuminated by 70 watt high pressure sodium (HPS) post top luminaires, with an average annual operation of 4,380 hours or 12 hours daily;
- As is the case for HKUST, there is no specific illumination requirement on the Drive. However, it would be equivalent to category S4 (minimum point: 1 lux; average illuminance: 5 lux) or category S5 (minimum point: 0.5 lux; average illuminance: 3 lux) for lighting requirement specified in the Lighting Design Manual by the Hong Kong Highways Department;
- The pole height is 3.5 meters;
- The distance between poles averages approximately 20 meters, with the poles mounted along one side of the Drive;
- Four baseline Acrilux high pressure sodium (HPS) luminaires nominally rated at 70 watts were used;
- One LED luminaire product, numbering four in total, was installed in early July 2010.

### The Monitoring Protocol and Methodology

The two study areas on the campuses of HKUST and HKU are located near sports facilities. An issue that arose with respect to the HKUST location was the bright lights sometimes illuminating sports events nearby. In order to address this issue, it was decided to measure illuminance after 10pm to avoid any trespass light. Both study areas were otherwise ideal for trials, straight and usually dark at night, with little or no vehicle or pedestrian traffic.

FIGURE 1: Trial sampling grid on HKUST and HKU campuses



The sampling grid was designed based on Illuminating Engineering Society of North America (IESNA) recommended practice (see Figure 1 above). For each type or model of luminaire, a grid of 10 horizontal sampling points was distributed between the two middle poles—a luminaire cycle—in order to facilitate comparison with other global LightSavers trials. In the case of the HKUST trial, the sampling points were approximately 2.6 meters apart. In the case of the HKU trial, the sampling points were approximately five meters apart.

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HKUST and HKU staff adopted the following protocol in implementing the trial.

1. **Installation.** An existing group of luminaires designated as the baseline was cleaned and relamped with new lamps as per normal maintenance procedures. Meanwhile, the new LED luminaires were installed as previously noted.
2. **Burn-in period and measurements.** For the purpose of analysis in this report, the “burn-in period” for baseline lamps and LED luminaires was approximately 1,000 hours from the date of installation of each trial, a practice recommended by the Illuminating Engineering Society (IES) TM21<sup>5</sup>. Hence, the first set of measurements used for analysis started for the HKUST trial began in June 2010, and on the HKU campus, October 2010. The following initial set of measurements were taken for both baseline and LED luminaires:
  - a. Voltage and amperage,
  - b. Photopic illuminance,
  - c. Scotopic illuminance,
  - d. Scotopic/photopic ratio,
  - e. Correlated color temperature (CCT),
  - f. Ambient temperature.

The monitoring team noted date, time, weather and site conditions when they took measurements.

3. **Power measurements.** Spot voltage and amperage measurements of the baseline group and the LED luminaire group(s) luminaires were taken, from which apparent power was calculated. Power factor was not measured.
4. **Illuminance measurements.** Both photopic and scotopic illuminance readings were taken using the Solar Light SL-3101 radiometer, equipped with photopic and scotopic detectors that conform to CIE spectral luminous efficiency curves. The equipment was calibrated to the U.S. National Institute of Standards and Technology (NIST) and has an accuracy of  $\pm 5$  percent according to the manufacturer. The illuminance and CCT measurements were taken with the equipment placed on the pavement surface, facing the light source. Vertical illuminance measurements were not taken.

Photopic illuminance is used in conventional measures of light reaching the road and is the type of value specified in the Hong Kong roadway lighting standards. Scotopic illuminance measures the efficacy of the eye’s peripheral vision under low light conditions at nighttime. White light LEDs, with a greater blue component in their spectrum than many conventional lighting products, yield significantly higher scotopic values.

Since the error band associated with the light meter is  $\pm 5$  percent, the trial was designed to maximize precision and reduce potential errors through repeated measurements over a long period of time. While there are no certainties when using statistics, we believe the results described in the report can be interpreted with confidence due to the large volume of the sample data.

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<sup>5</sup>Illuminating Engineering Society of North America (IES), Projecting Long Term Lumen Maintenance of LED Light Sources, TM-21-11, published August 2011.

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5. **Correlated color temperature (CCT).** CCT values were measured using the Konica Minolta CL-200 Chroma Meter on each campus on dates as follows:

TABLE 1: Dates of campus CCT measurements used in this analysis

Campus	Start CCT Measurement	End CCT Measurement	Period of CCT Measurement
HKUST	December 2010	September 2011	9 months
HKU	August 2010	June 2011	10 months

The meter has an accuracy of  $\pm 2$  percent according to the manufacturer.

6. **Ambient temperature.** Measurements were taken alongside color temperature and illuminance measurements, using a Fluke 51-2 digital thermometer, to ascertain whether higher summer temperatures would affect light output.
7. **Periodic testing.** Horizontal illuminance measurements were taken and recorded accordingly at random and monthly intervals over the course of the two trials. As noted earlier, the initial 1,000 hours of each trial was deemed a burn-in period, due to the high volatility of lumen output that typically characterizes brand new LED devices. Hence, although measurements were taken during this period, the values used in this report were measured after the initial 1,000 hours.
8. **Lumen maintenance.** LED streetlight luminaire manufacturers claim their products will typically maintain lumen output at 70 percent or above ( $L_{70}$ ) their original output for 50,000 hours or more. It is challenging to evaluate such claims in a real world trial. The Illuminating Engineering Society of North America (IESNA) TM-21 Working Group, during the course of its evaluation of 40 sets of laboratory data on LED light source lumen maintenance over 6,000 hours or more, concluded that lumen depreciation can change in various ways that is difficult to model or predict, especially during the first 1,000 hours of operation when rapid variations have been observed.

According to TM-21, in order to have predictive value, a field trial should be 10,000 hours or more, i.e., three years, with the last 5,000 hours yielding the most consistent and reliable information. While ideal, such a trial is not practicable in a municipal context given limited resources, as well as the need to make procurement decisions in a shorter time frame. However, the lumen maintenance results from the HKUST trial in particular provide a useful snapshot of how the LED products performed relative to baseline during this period. However, the results should not be used to predict how these products will perform in the future.

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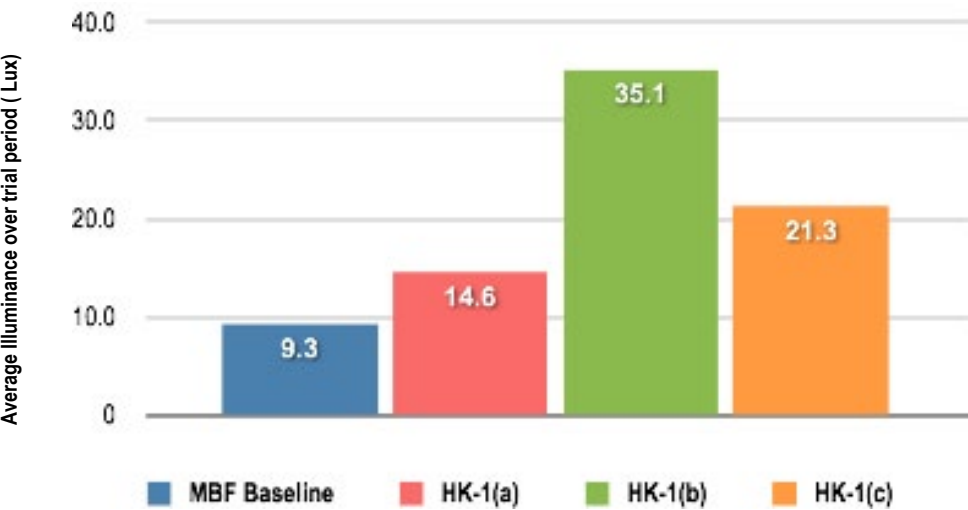
## Results

### Illuminance comparisons

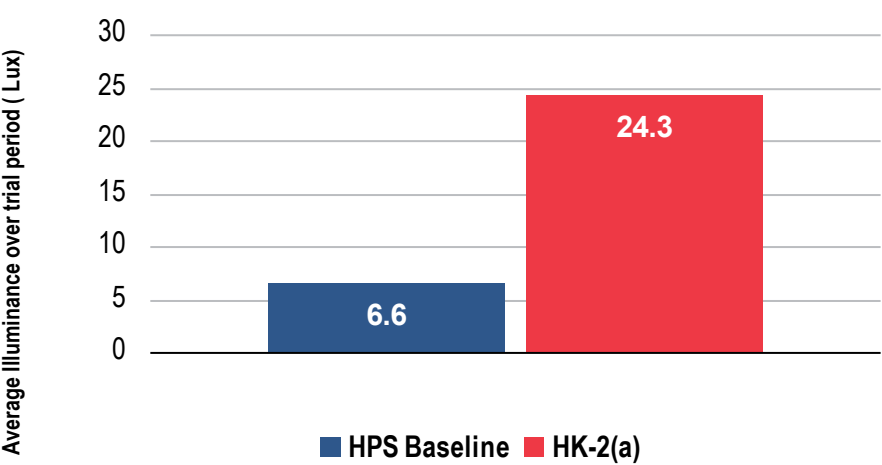
The results reported below in Graph 1 represent photopic measurements taken over the HKUST trial period averaged together. All three LED luminaires produced average illuminance greater than the baseline and exceeded the average 5 lux minimum average illuminance recommended for such locations by three to seven times by the Hong Kong Highways Department's *Lighting Design Manual*.

Meanwhile Graph 2 below shows the photopic measurements taken over the HKU trial period averaged together. The LED luminaire produced average illuminance on the one lane roadway significantly higher than the baseline and exceeded the average 5 lux minimum average illuminance that would be recommended for such a location by five times.

GRAPH 1: HKUST Seafront Driveway illuminance



GRAPH 2: HKU Sha Wan Drive illuminance



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### Correlated color temperature (CCT)

Significant changes in color temperature of the light produced by LED luminaires in the range of five–10 percent (or greater) on an annualized basis may indicate a number of problems stemming from degradation of the components of the LED device, especially the materials that encapsulate and cover the LED source.

Measurements of CCT were taken at the HKUST and HKU campus study areas as noted in Table 1 above. As the Table 2 below indicates, differences in measured CCT annualized changes for three out of four LED luminaires was below five percent. The color temperatures measured for these luminaires were also close to the ranges as specified by the manufacturer. One luminaire showed a more significant annualized CCT change of around 9%, as well as a wider deviation of 8% from the specified value.

TABLE 2: Summary of HKUST and HKU color temperature results

Product Reference	Measured CCT Initially (Kelvin)	Measured CCT End (Kelvin)	% Measured Change	% Annualized Change	Manufacturer Specified CCT (Kelvin)	% Deviation from Specified CCT
HKUST Baseline	3,787	3,722	-1.72%	-2.29%	Not specified	---
HK-1(a)	5,402	5,550	2.74%	3.65%	4,000 – 5,500	0.9%
HK-1(b))	7,095	7,568	6.67%	8.89%	6,000 – 7,000	8.11%
HK-1(c)	5,881	5,664	-3.69%	-4.92%	6,000	-5.6%
HKU Baseline	(below meter threshold)	(below meter threshold)	---	---	Not specified	---
HK-2(a)	6,551	6,432	-1.82%	-2.18%	6,000 – 6,500	0.78%

### Energy savings

Field power measurements were made of the HKUST luminaires on March 2010 and August 2011. Meanwhile, field power measurements were made on the HKU luminaires on a bi-weekly basis throughout the trial period. Table 3 provides the results for both HKUST and HKU trials. All three HKUST LED luminaires achieved significant energy savings, ranging from 67 percent to 78 percent, compared with the baseline luminaire. Meanwhile, the LED luminaire in the HKU trials achieved energy savings of 89 percent compared with the HPS baseline lamp.

TABLE 3: Summary of HKUST and HKU energy use

Product Reference	Measured Energy (Watts)	% Reduction
HKUST baseline	205.5	---
HK-1(a)	45.7	-77.8
HK-1(b)	67.4	-67.2
HK-1(c)	49.8	-75.8
HKU baseline	129.0	---
HK-2(a)	42.7	-66.9

### Luminaire target area system effectiveness

A key advantage that LED streetlight luminaires hold over conventional high intensity discharge (HID) luminaires is this: the light they produce is more directional. Thus, more of the light produced by the LED luminaire is directed to the road surface where it is needed. However, there does not currently exist a standard lighting metric for measuring how effective luminaires are projecting light on a specific surface in a field trial.

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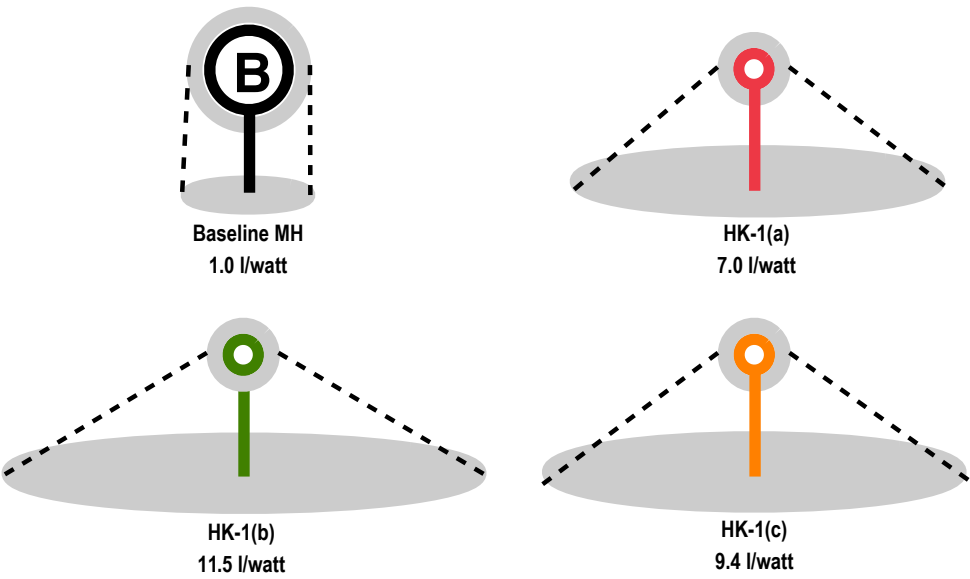


In the LightSavers trials we developed a “target area system effectiveness” metric that is calculated for each LED luminaire simply by dividing its average photopic illuminance measured on a sampling grid by its apparent power value. The calculated value of lumens per watt is then indexed to the comparable baseline value, which is normalized to the value 1.0. This metric does not take into account uniformity.

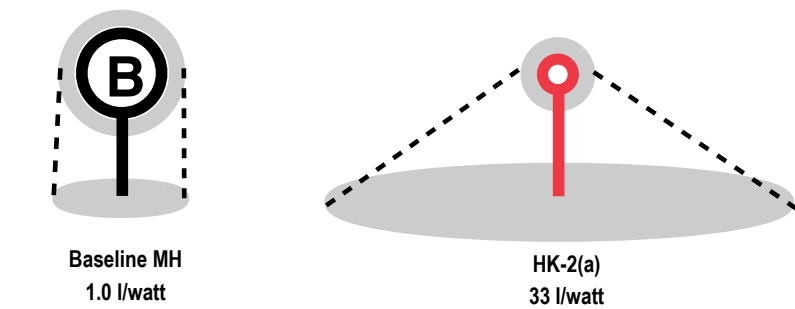
Ascertaining how much apparent power it takes for a luminaire to deliver its light to a surface grid compared with a baseline product can assist lighting asset managers in understanding the directional effectiveness of different LED luminaire products at illuminating a surface, compared with conventional lamps such that rely more on luminaire lens optics to direct and shape their light output. The figures below characterize this metric and compare the LED luminaires with the baseline.

Figure 2 below shows that all of the LED luminaires were able to deliver in the range of seven–11.5 times more average illuminance on HKUST’s Seafront Drive per watt of energy consumed than the mercury blended fluorescent lamp. This explains the significant energy reductions accompanying the use of the LED products compared with an—apparently—extremely inefficient mercury blended fluorescent lamp.

**FIGURE 2: HKUST Target area system effectiveness indexed to the baseline MH lamp (normalized value = 1.0 lumen/watt)**



**FIGURE 3: HKU Target area system effectiveness indexed to the baseline MH lamp (normalized value = 1.0 lumen/watt)**



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Figure 3 above shows that the LED luminaire tested on HKU's Sha Wan Drive was able to deliver 11 times more illuminance per watt in the targeted area than the baseline luminaire. This explains in part the very significant energy reduction noted in Table 3 above, likely due to the translucent globe design of the HPS luminaires currently used to illuminate pedestrian pathways used on campus, which was meant to cast a glow in every direction, but is not effective at illuminating the pathway.

## Lumen maintenance

A key purpose of the LightSavers trial was to determine how the LED luminaires performed over a period of time. For the purposes of this study, lumen maintenance factors affecting LED luminaires can be divided into two groups:

- Factors that can be reversed or recovered through maintenance, such as luminaire cleaning to remove dust and grime from its lens;
- Factors that cannot be reversed or recovered, such as the gradual fading of the LED device's lumen output or dramatic changes in its correlated color temperature (CCT).

In the first category, luminaire dirt depreciation (LDD) is the most significant factor. It results from the accumulation of dust and grime on the luminaire lens over time. This varies significantly from one locale, climate or season to another. Air pollution is obviously an important variable. Also, an electrostatic charge on the plastic lens of an LED luminaire attracts particles floating in the air. The drier the environment, the higher the charge and attraction of particles to the lens. Conversely, higher humidity reduces the static charge and particle attraction. Finally, design of the LED luminaire affects dust buildup. Some manufacturers incorporate self-washing features into their luminaire design, so that precipitation removes dust that has adhered to the luminaire lens. The effectiveness of such designs varies significantly from one product to another.

Note that LDD is not linear. Dust buildup on a newly installed luminaire may be rapid at the start, depending on humidity and temperature, and then decline in rate as the amount of dirt on the luminaire lens reaches a level that dampens its static charge. The luminaires in the HKUST trial were washed part way through the trial, but changes in illuminance measured afterwards were negligible. Seafront Driveway is located next to the sea on a campus far from the traffic intensive urban areas, so significant dust build-up would not be expected.

In the second category of lumen maintenance factors, LED devices, unlike high intensity discharge lamps like MBF and HPS, do not typically burn out. Instead, the light they produce gradually fades over a long period of time in a non-linear fashion. As noted above, the end of lifetime ( $L_{70}$ ) of an LED device occurs when its light output declines to 70 percent of its original output. Since the luminaires on HKUST's Seafront Driveway operate approximately 3,100 hours annually, an LED luminaire rated at 50,000 hours of operation would reach  $L_{70}$  at 16.2 years after its initial start of operation. This would imply an average annual rate of approximately 2.2 percent depreciation occurring on a linear basis. In the case of HKU's Sha Wan Drive, the luminaires operate 4,380 hours annually, so an LED luminaire rated at 50,000 hours would reach  $L_{70}$  at 11.5 years, implying an average annual depreciation rate of approximately 3.0 percent, were depreciation occurring on a linear basis.

Note that lumen depreciation actually occurs exponentially, gradually during the initial years of operation, and then more rapidly during the later years of operation as lumen output approaches  $L_{70}$ . The linear values noted above are merely intended to serve as useful mileposts in judging a luminaire's early trajectory towards  $L_{70}$ .

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For the purpose of this trial and study, we assume a lifetime of 50,000 hours for all four LED products tested on the university campuses, notwithstanding manufacturers' claims. Thus, lumen depreciation significantly exceeding 2.2 percent on a linear annualized basis in the case of HKUST, or 3.0 percent in the case of HKU, would be less desirable than a value less than the above.

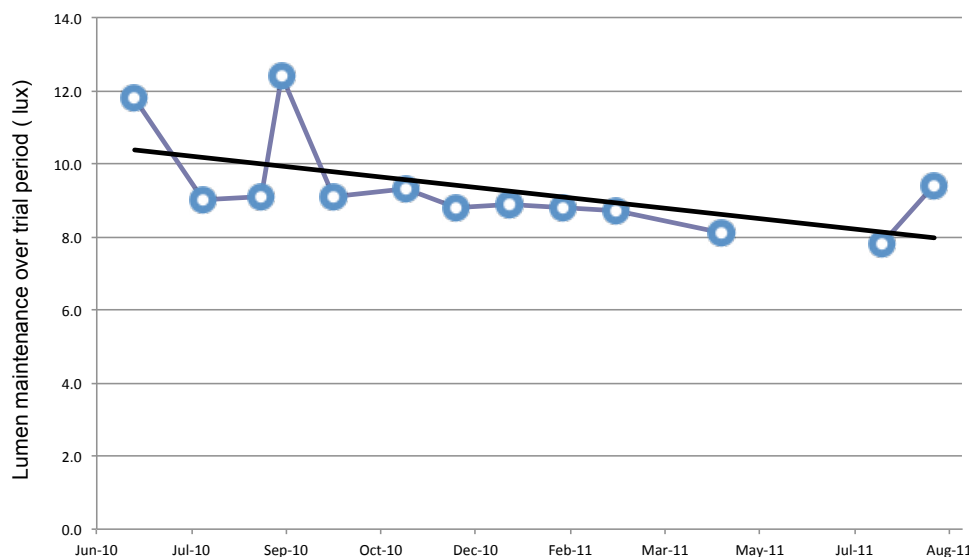
It should be noted again, in respect of the IESNA's TM-21 Working Group's recent findings, that the lumen depreciation metric for the first year or two has no predictive value. However, comparing first-year lumen output performance of multiple products in multiple trials can offer *indicative* insights that enable lighting asset managers in a practical way to better differentiate products from one another.

The five graphs below show the monthly averaged photopic illuminance values (lux) for the mercury blended fluorescent baseline luminaire (blue line) and three LED luminaires (red, green, and orange lines) in the HKUST trial. The black line in each graph displays the set of data generated by Excel's exponential trend line function, which uses the LOGEST function to generate an exponential least squares fit of the individual observed values to a curved line. (This is the equivalent of performing an Excel LINEST linear least squares fit on the logarithms of the observed values, the slope of the generated straight line equaling the logarithm of the depreciation rate of the exponential fit.) The graphs are only approximate visual representations of average horizontal illuminance measurements over the trial period, i.e., some months are omitted during which data were not collected. Also note that the graphs are at different scales, depending on the illuminance values displayed.

Graph 3 below shows that light output from the baseline mercury blended fluorescent luminaire declined in the range of 19.2 percent on an annualized basis over the trial period.

Graph 4 below shows that light output from the LED luminaire designated HK-1(a) declined by about 17 percent, as calculated by the Excel exponential trend line function. However, the values measured over the entire period of the trial were extremely volatile, as shown by the graph. Indeed, the illuminance produced by the two luminaire being measured eventually recovered to 21.5 lux at the end of the trial in August 2011 after starting at 22.5 lux in June 2010, a difference of four percent. So the Excel results are not indicative. There was much too volatility for a trend line to be confidentially observed or calculated.

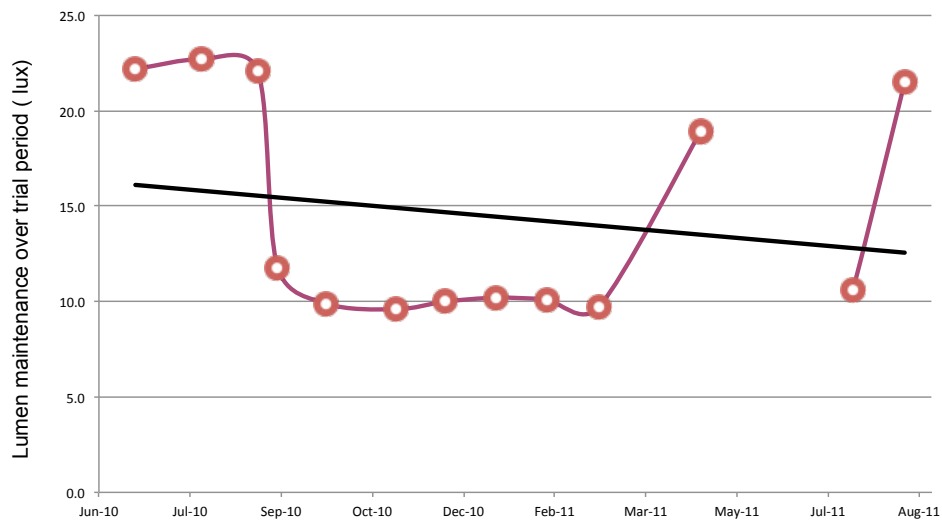
GRAPH 3: Baseline MBF Lumen Maintenance



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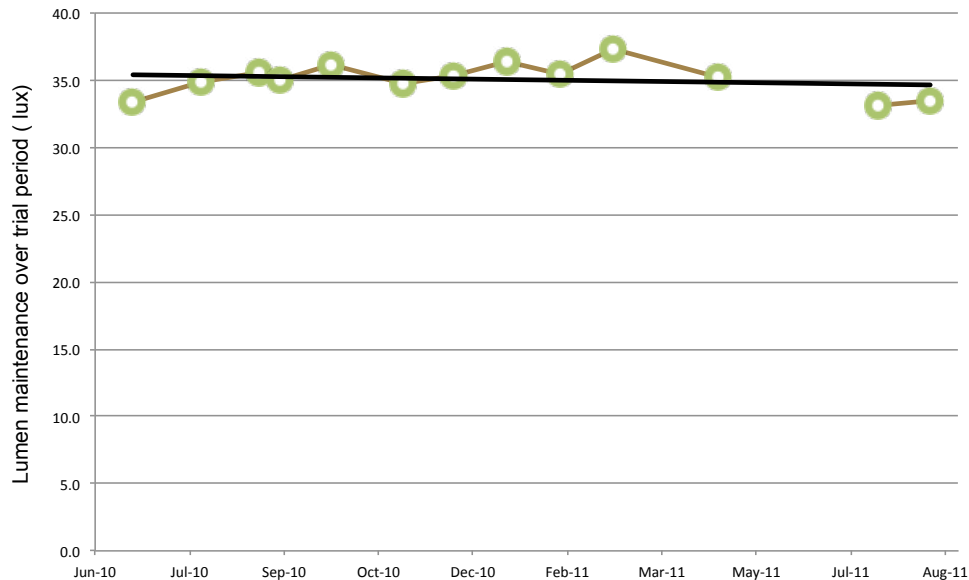


GRAPH 4: HK-1(a) Lumen Maintenance



Graph 5 below shows that light output from the LED luminaire designated HK-1(b) depreciated 1.9 percent over the trial period, an excellent result. Hong Kong summers can be hot and humid. During the trial period, for example, temperatures rose on measurement dates from 16.4°C in March 2010 to 29.5°C in July 2010. Graph 5 below shows that light output from the LED luminaire designated HK-1(b) actually rose slightly during the hotter months of 2010. However, a slight decline in light output was recorded for this luminaire during the period March 2011–July 2011, when temperatures rose from 17.3°C to 27.6°C on the respective measurement dates. However, the values recorded rose again in August 2011, though there was no change in ambient temperature on the respective measurement dates in July and August 2011. These conflicting results observed in the data appear to rule out a definitive correlation between ambient temperature and measured illuminance from one season to another for HK-1(b).

GRAPH 5: HK-1(b) Lumen Maintenance



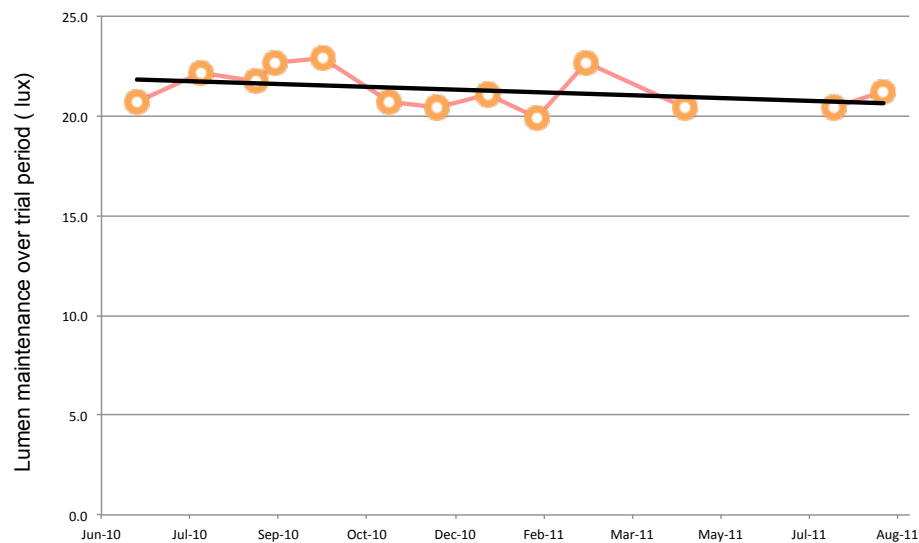
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Graph 6 below shows that light output from the LED luminaire designated HK-1(c) depreciated 4.7 percent on an annualized basis over the trial period. However, it should be noted that the calculated Excel exponential trend line doesn't fully capture what is happening. Illuminance measured rise in during the first six months of the measurement period and then settles back to the measured values at their original level during the remainder of the trial period. Hence, the Excel's exponential trend line function as applied to the HK-1(c) data belies what was observed from month to month data, i.e., very stable maintenance of light output over the trial period. A correlation of ambient temperature and measured illuminance values was not observed in the case of HK-1(c).

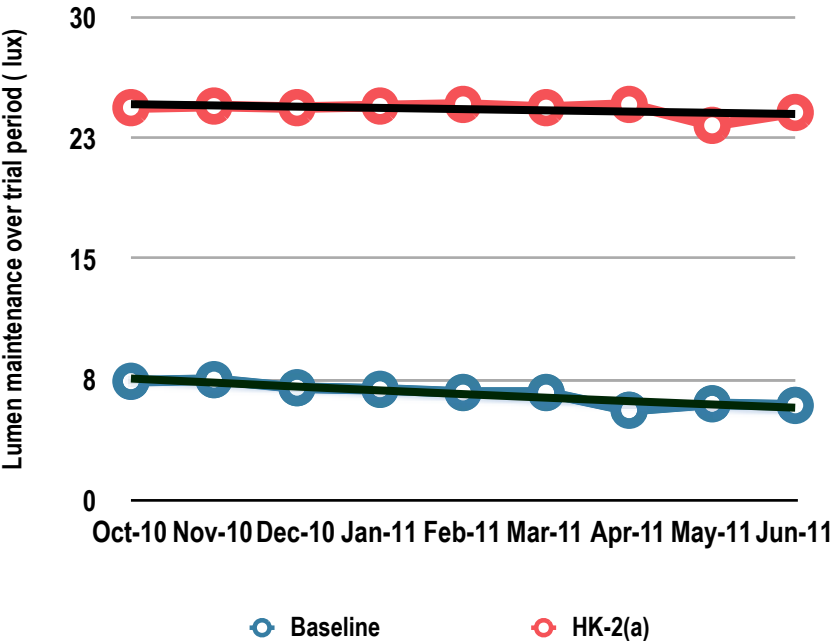
GRAPH 6: HK-1(c) Lumen Maintenance



Although the ambient temperature at the HKU campus study area varied over the period from 11.7°C to 28.9°C, illuminance appeared to fluctuate very little and not in relation to temperature.

Graph 7 below shows the results from the HKU trial. HK-2(a) depreciated at the annualized rate of 3.7 percent and was very stable over the trial period, an excellent result. The baseline HPS lamp depreciated at the annualized rate of 33.5 percent, by comparison.

GRAPH 7: HK-2(a) Lumen Maintenance



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Table 4 below summarizes the lumen maintenance findings from the trial. HK-1(a) performed poorly, exhibiting highly volatile lumen output over the period of the trial. HK-1(b) and HK-1(c) performed very well in terms of lumen maintenance, though as noted above, the Excel exponential calculated figure for HK-1(c) did not capture the stable lumen maintenance that was actually observed in the data. The calculated results for HK-1(a) and HK-1(c) show the occasional limitation of Excel’s exponential trend line function, which doesn’t handle extreme volatility well and sometimes produces anomalous results when the data is “lumpy”.

There did not appear to be consistent correlation in fluctuations of average illuminance in relation to ambient temperature. Hence, evidence that hot summer temperatures might depress light output is not present in either trial.

TABLE 4: Summary of HKUST and HKU Lumen Maintenance

Trial Reference	Annualized Exponential Trend line (Excel) <sup>1</sup>	Lamp Lumen Depreciation (LLD)
HKUST baseline	-19.2%	0.808
HK-1(a)	-16.7%	0.833
HK-1(b)	-1.9%	0.981
HK-1(c)	-4.7%	0.953
HKU baseline	-33.5	0.665
HK-2(a)	-3.7%	0.963

### Summary product evaluation

Table 5 below summarizes the results of the product evaluation. One product, HK-1(a) exhibited extreme volatility—a drop of measured illuminance of 46 percent at one point in the trial. Products HK-1(b), HK-1(c) and HK-2(a) all performed extremely well on all performance parameters.

TABLE 4: Summary Product Evaluation

Product Reference	Measured CCT Initially (Kelvin)	Measured CCT End (Kelvin)	% Measured Change	% Annualized Change	Manufacturer Specified CCT (Kelvin)	% Deviation from Specified CCT
HK-1(a)	***	***	***	Results too volatile	***	Results too volatile
HK-1(b))	***	***	***	***	*	13
HK-1(c)	***	***	***	***	**	14
HK-2(a)	***	***	***	***	***	15

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## Summary

Of the four LED luminaire products in the two trials on the campuses of HKUST and HKU, two excelled on all of the performance parameters for which measurements were taken and calculations made: HK-1(c) and HK-2(a). One product, HK-1(a) exhibited extreme volatility in light output with a dramatic unexplained drop of 46 percent occurring during the trial period, while another product, HK-1(b) exhibited a more significant change in CCT as well as a greater deviation of CCT from the specified value.

All four LED luminaire products excelled in providing energy efficient illuminance in comparison with the two baseline products used on the two campuses. Indeed, the LED products on both the HKUST and HKU campuses provided as much as 11 times the on-site target system effectiveness compared with the baseline mercury blended fluorescent and HPS products in use there, reflecting the superior directional efficiency of the LEDs, as well as the likely outmoded performance of the baseline lamps used in the campuses.

With respect to lumen maintenance, HK-1(b) exhibited annualized depreciation of 1.9 percent, an excellent result. Meanwhile, the observed lumen maintenance exhibited by HK-1(c) was stable over the trial period, although the calculated Excel exponential depreciation of 4.7 percent suggested differently, which was largely due to a four month “lump” in the measured illuminance values after the start of measurements. Meanwhile, HK-2(a) exhibited annualized depreciation of 3.7 percent and was very stable over the trial period, an excellent result. It should be noted that the IES TM-21 Working Group indicated in its report published in August 2011 that a minimum of 10,000 hours of testing after a 1,000 hour burn in period is necessary to make any predictive assessment of LED luminaire products. So the results from these trials should be taken as indicative, rather than predictive.