AN AUTOMOTIVE INTERIOR LIGHTING APPLICATION USING WHITE LIGHT-EMITTING DIODES

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PLAGIARISM DECLARATION

Declaration

I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own.

Signature _______________________________

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ABSTRACT

Energy drives technological societies. Developing countries such as South Africa are caught between the desperate need for economic growth and the emerging obligations to the environment. Efficient technologies can be used to mitigate the impact of these seemingly conflicting requirements in urban and rural environments.

In this thesis the commercially available white light-emitting diode (LED) with its inherent efficiency, longevity and mechanical strength, is used to show, that success in energy efficiency can be obtained.

Two cases are used to illustrate the need for efficient demand-side technology: the electricity shortages of the Western Cape Province in South Africa and a white LED pilot project in Namulonge, Uganda. The Namulonge Solar-Home System (SHS) is analyzed with the intention of creating a more acceptable general lighting solution. The concept of *appropriateness through self-determination* is discussed within the context of location-specific information integrated into a design procedure.

The major thrust and contribution of this thesis, however, is the design of an interior luminaire for Golden Arrow Bus Services (GABS). This is in part based on the hypothesis that application-specific information will lead to implementation and human-needs success, and is researched, designed, fabricated and then laboratory tested. The biggest challenge to be overcome was the spatial light distribution of the LED array. Thus non-imaging optical lens design became the main focus of this project as it held the key to utilizing available light while conserving the light-systems energy. *Circular Fresnel* and *Linear Fresnel* (an adaptation of the concentric design) lenses were designed. Electrical, mechanical and thermal aspects of design are also detailed.

Far-field, horizontal plane detection over the specified area is used to best gain the uniformity of distribution. The four criteria namely luminance, illuminance, intensity and étendue (collection efficiency), against which each design and focal length

configuration is compared to, are extensively explored and eventually lead to a final design.

In the first designs, the area of the spatial distribution between 50% and 80% of its relative intensity is collimated. The *Hybrid Circular Fresnel* and *Hybrid Linear Fresnel* lenses now redirects the relative intensity in two areas, from 50% to 70% (creating parallel rays) and then from 70% to 100% (away from the central axis), renders a distinct difference is spatial uniformity and a reduction in the peak and off-axis located intensity.

All four criteria are met, with a minor adjustment of configuration within the bus internal luminaire spacing, with the hybrid designs. It is proposed that GABS employ polished designs of the *Hybrid Circular Fresnel,* in any of the configurations, which have collection efficiencies ranging between 64.8% and 78.3%.

TABLE OF UNITS AND QUANTITY SYMBOLS

Unit	**Unit Symbol**	**Applications and Notes**
Clear aperture	CA	
candela	cd	SI unit of luminous intensity
candela per square mete	cd/m^2	SI unit of luminance
étendue	ε	
f-number	$f/\#$	
focal length	f	
lumen	lm	SI unit of luminous flux
lumen per square meter	$lm/\ m^2$	SI unit of luminous exitance
lumen per watt	lm/W	SI unit of luminous efficacy
lux	lx	SI unit of illuminance
numerical aperture	NA	
steradian	sr	SI unit of solid angle

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CHAPTER 1

A CASE FOR WHITE LIGHT-EMITTING DIODES

1. Introduction

Two case studies related to the application of white light emitting diodes (LEDs) are introduced; the energy problems of the Western Cape Province in South Africa and a white LED pilot project in the village of Namulonge on the outskirts of Kampala in Uganda. They form the basis for the theoretical and practical aspects of the final thrust and example of this thesis; white LEDs used in a retrofit for the Golden Arrow Bus Services (GABS) transportation vehicle's interior lighting luminaires.

In the South African case, the efforts towards lighting efficiency have been detailed. These points are introduced in order to understand the need for efficient demand side technology. Namulonge's pilot project is a case in point of the efforts required to deliver on what is needed. Issues related to the eye as the chief discriminator of the lighting requirements have been coupled with the energy concerns of a community under-serviced.

The case studies rely on the comparison between conventional light sources and solid-state technology. They are based on conversion efficiency, energy consumption, costing and integration challenges Concepts within human-perception such as usability, lighting adequacy and a needs-based approach to LED specification are then investigated and form part of a design procedure. The literature review of essential concepts is then tackled. Hence, the aim of the research has been to specify points not often considered within the traditional design of lighting systems.

1.1 Western Cape Energy Crisis

1.1.1 High Capital Investment (increasing generation)

With rolling power blackouts, a rapidly growing economy and environmental politics on the rise, the Provincial Government of the Western Cape and ESKOM embarked

on a retrofit campaign to install 5 million compact fluorescent lamps (CFLs) in an attempt to decrease the power generation deficit. There had also been increased pressure for investments in new generation capacity, with all options including the Pebble Bed Modular Reactor (PBMR), the Open Cycle Gas Turbines (OCGT) as well as renewable energy technologies being proposed. Despite all these efforts it is quite evident given the post-crisis contingency plan that demand-side technologies, along with educational programs, subsidies and research funding, have greater scope for achieving success as they tackle the root cause rather than the symptoms [1, 2, 3].
The light-emitting diode is a new energy efficient option in the lighting sector. Whether from white LEDs or from a mixture of LED-based monochromatic sources, this technology promises superior attributes that include a longer lifespan and higher energy conversion efficiencies when compared to incandescent and fluorescent lamps.

A simple example is the retrofitted LED lumen-equivalent traffic signals installed in Cape Town's Central Business District (CBD). The retrofit consumes 10.6% of the electricity when compared to the incandescent (i.e. 5.8W compared to the incandescent 55W alternative). The small scale of this 10 year long project is expected to yield savings on both electricity and maintenance costs in the region of R300 million over an operating period of 27 years [4].

The white light emitting diode inherently possesses characteristics that make it energy efficient [5, 6]. Other advantages include its usability, functionality and applicability. With respect to the light production mechanism and the component advantages, it is a lighting technology unlike any other. However, for potential residential and commercial users, the case for energy efficient technology uptake must be brought down to financially quantifiable terms. The economics behind replacing common devices (such as incandescent lamps) with new technology (WLEDs) seems to be comprehended via cost versus savings analogies. This is referred to as life cycle costing (LCC).

In light of the energy crisis the Western Cape experienced, the scope for demand-side technology is great. With the aim of increasing electricity security as a short and medium term goal, this chapter contends that the crisis is cause for widespread implementation of WLEDs for general lighting applications.

In this regard the City of Cape Town must be applauded for their foresight in energy efficiency, as they have begun to search for more sustainable development options.

As a case in point the CFL, despite its limitations, defects and environmental hazards; these have not been cause for the lack of penetration. Rather, it has been the user perceptions. The author does not wish to deter users from CFL technology, which has improved greatly, but to make those in the energy sector aware that even though it is by no means perfect, it has still found room for uptake.

1.1.2 A background

At 75% of South Africa's peak load, residential consumers of electricity of every income sector are threatening the security of electricity networks. This sector has been the target of media campaigns to load shift and be more energy conservative, taking into account that they push utilities to invest in greater generation capacity. A number of reports on demand side issues relevant to this country and province directly state that efficiency on lighting will significantly reduce this peak [7, 8, 9, 10].

Constraints in electricity supply to the Western Cape find their roots in the breakdown of two major functionaries, the transmission network to the Western Cape and half of Cape Town's only generation Unit, Koeberg. Peak power cannot be supplied because the available peaking units (Acacia, Palmiet, Atlantis and Steenbras) are inadequate to substitute for the loss of major supply. Consequently, blackouts and load shedding (controlled and uncontrolled) have occurred since November 2005.

The short-term goal during this energy crisis is to save 400MW at peak periods. With the increased use of heating loads, motor loads, and the prolonged lighting loads because of the longer nights and weather conditions (poor visibility on roads, etc.), winter posed a great threat to this target.

Strategies were devised to best tackle this crisis. This demand-side management (DSM) action was reactive as opposed to being preemptive. These costly interventions included purchasing 5 million CFLs from China for residential and commercial application, subsidized electric blankets, 3 x 22MW emergency Mobile

Generation Plants (diesel-powered generators) and the refurbishment of gas generation plants at Athlone and Roggebaai [2]. These ad hoc measures are to cost an estimated five to ten times more than Eskom's standard generation costs.

1.2 Understanding other artificial light sources

Four main types of lamps exist. These lamps are used for different purposes but all essentially to illuminate environments. Not all of the mentioned lamps in this list are suitable for indoor use.

1. Incandescent (including tungsten halogen)
2. Fluorescent
3. Sodium lamps (low and high pressure)
4. Mercury vapour and metal halide lamps

Incandescent lamps radiate heat and light when power is applied through its filament made of tungsten. A fluorescent lamp on the other hand has a mixture of fluorescent powders, which coats the interior of the tube. The powders convert the UV radiation of the mercury discharge into wavelengths suitable for human perception of task.
Two requirements are needed in the conversion process:

1. A fluorescent needs a starter to preheat the current to provide a high voltage peak for ignition.
2. A ballast is also needed to limit the current flow through the fluorescent lamps

Sodium lamps have similar start-up and operational characteristics to a fluorescent lamp. They also require a voltage peak to initiate the lamp. The voltage peak ranges from 500V to 1500V. This is dependant on the sodium lamp type. The internal gas mixture (Neon with 1% by weight of Argon) heats up and renders an illuminated task.

The efficiency of a lighting device is its ability to transform electrical energy to visible light. The efficiencies may be calculated from two perspectives, the devices lamp and luminaire. We shall concentrate on understanding the efficiency of source.

Incandescent lamps have an efficiency of 5% (7 to 14 lm/W) while fluorescents have an efficiency of 20% (35 to 40 lumen/Watt). High Intensity Discharge (HID) lamps vary according to the light source (see

Figure 1). It is these higher efficacy but lower colour temperature, colour render and higher power considerations that exclude them from being used for interior applications.

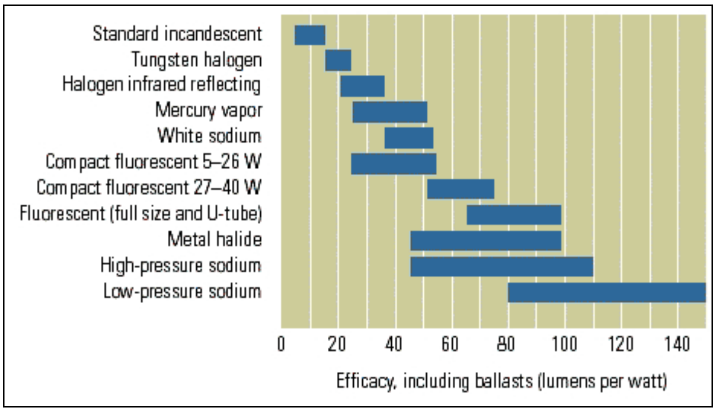

Figure 1: Lamps and their ballasts span a range of efficacies as illustrated above [11].

A comparison between solid-state and vacuum tube lamps can be made on the grounds of the *processes* used to convert electrical energy into visible radiation. The processes used to convert the energy, the package size and robustness, lifetime of operation, energy dissipation and relative cost of purchase are also compared. It can be seen from Table 1 that the energy considerations under the heading ‘Items’ and row title ‘watt per 1 unit’ shows a white LED uses less that a Watt to emit light per package. This is a singular unit comparison as opposed to that of a task-based lumen equivalent.

Table 1: Comparison of vacuum system light sources and solid-state light sources

Items	Vacuum system light source	Solid-state light source
energy conversion process	thermal radiation or discharge plasma luminescence	recombination luminescence
converting steps	2 – 4 steps	1 step
size & dimension	larger (vacuum envelope)	very small (0.3 mm cube)
strength	weak (easily breakable)	strong
durability, life	fundamentally not long	fundamentally longer
watt per 1 unit	larger (several watts – 10 kW)	fundamentally small (<1 W)
cost per lm	relatively lower	more expensive

Table 2: A further comparison between spectral emission of light sources and loss of energy through conduction and convection.

Light sources	UV radiation [%]	visible radiation [%]	IR radiation [%]	conduction & convection loss [%]
solar radiation	2～5	40～50	50～55	—
incandescent lamp	0～0.2	8～14	80～85	5～6
fluorescent lamp	0.5～1	25	30	44
HID lamp (HP mercury)	2～4	13～16	60	16～22
HID lamp (metal halide)	2～7	20～40	50～67	7～20
HID lamp (HP sodium)	0.3	27～30	47～63	10～23
white LED (dichromatic)	0	12～20	0～0.2	80～88

1.3 Lit environments and the South African National Standard (SANS)

The South African Bureau of Standards' (SABS)[1] code of practice for the interior application of light (SABS 0114-1, 1998) states that "the need for good energy management and cost-effective lighting schemes…should not lead to the lowering of the recommended well-established standards needed to promote efficient work, safety and welfare" [12]. Lit areas require ambient, task and general light lux levels. A generalisation of illuminance levels in [12] states that rooms not used continuously for *working purposes* fall in the range of 100-200lux. Tasks with simple visual

[1] The South African National Standards were previously known as the South African Bureau of Standards. The standard on interior lighting is thus referenced as the SABS but for search purposes, the SANS would suffice.

requirements fall between 200-500lux and tasks with demanding visual requirements fall between 500-1000lux.

For residential and commercial applications, despite its high initial cost, there is scope for its uptake in what the SABS standard on interior lighting refers to as “simple visual requirements and continuously lit visual purposes” [12]. These are rated below 200lux. The author contends that once these markets have been achieved the domino effect of lower prices and higher flux LED-based alternatives can be reached sooner in the future.

1.4 Previous efforts at lighting efficiency and demand-side intervention

The author initially went about trying to understand the efforts made by Eskom and the Local Authorities to initiate and institute DSM in the Western Cape. This research proved that the attempts made by the public utility did not have the required strength to genuinely reduce energy consumption. Despite having the knowledge of the impending shortage of electricity supply and the potential disaster that could strike given how critical Koeberg is to the Western Cape during the winter months, noteworthy efforts are not known to the author.

Electricity supply and economics go hand in hand and the vested interests in selling more electricity have become evident today. The political interest in delivering electricity to the unelectrified has proved to be too great a distraction for politicians, and even the National Electricity Regulator (NER) themselves confess their negligence in this regard.

The knee-jerk reaction to the Western Cape’s Electricity Crisis proves that the Utility has the ability, when they desire, to affect change. Now, it comes at great cost with further potential for disaster. Issues will arise in the future that make people reliant on these sorts of subsidies and handouts. Handing out CFLs as if they are applicable to every household is also inappropriate. User safety, implementation standards and conforming to regulation lighting level requirements should be considered [13]. In many instances, residential homes do not have fittings and luminaires that are compatible with them. Their sizes and shapes, colour temperature and colour rendering ability vary and are not as impressive as the incandescent.

CFLs became available to the world during the 1980s. Since then, the product has developed and matured. Local efforts to install CFLs began in the mid 1990s. DSM moved towards implementing a more energy efficient residential lighting technology by researching the economic and system impact of implementing CFLs. Market potential and user acceptance were key factors in implementation and understanding the appropriate action, requiring substantial market surveys. Market surveys, beta-distributed models, scenario-formulation, and demand coincidence and unit consumption factors made up the range of research [14].

The research commissioned by Eskom's Integrated Electricity Planning (IEP) process needed to gain insight into the future of the peak demand, energy consumption and the subsequent electricity pricing schemes.

There were efforts to get all sectors of energy users to buy into an energy saving lighting market and hence 'revolutionise' a sector restricted by the prevailing barriers. The program, known as the Efficient Lighting Initiative (ELI), was housed in Residential Demand Side Management (RDSM). The Efficient Lighting Initiative was designed by the International Finance Corporation (IFC) and funded by the Global Environment Facility (GEF). The question may be raised: Was the initiative suited for our local context? Or was it just another international agency ready to get involved in a Third World program and us accepting because money became available? RDSM's goals were to better manage energy usage because of the increasing evening peak load due to the country's Electrification Programme [15].

The ELI sought to tackle the lack of investment (all role players and future ones), penetration, technical knowledge, awareness and other distributional and institutional issues [16] to set an energy and cost conservative lighting market onto a sustainable trajectory. Bonesa (Pty) Ltd, an energy services company (ESCO) had been tasked with the job of implementing the ELI.

With lighting, unlike for geyser control and various other heating loads, the shifting of its use-time from the demand peaks is not possible. Thus, conservative practices and energy efficient lighting devices is a must. Given the nature, cost and time required for increasing generation capacity and strengthening transmission networks efficient energy use will assist in delaying the eventual upgrade in a very tangible way.

In 1997, 95% of South Africa's domestic electric light sources were incandescent lamps [15]. Up until May 2006, in Cape Town alone, 1.5million incandescent lamps had been replaced with CFLs [17]. This shows the value of an energy efficiency action strategy.

1.5 The City of Cape Town –Bold and foresighted

Developments within the City of Cape Town, the most populous Municipality of the Western Cape, towards an environmentally sustainable and energy-conscious future become evident to its residents [18, 19]. Responsible governance is an important aspect of politics that proves to its electorate that government goes beyond just delivering services. In this instance, the driving force behind the energy and climate change strategy, are those issues pertaining to foreign trade, investor perception and their economic prospects. The author does not necessarily believe that economically driven mechanisms to reduce CO_2 emissions is a viable route for energy efficiency implementation strategies. A more sustainable approach, based on consumer behaviour and environmental awareness, is necessary to achieve this goal. The role of energy efficiency is thus changing. To abate further energy crises may no longer be the primary goal of energy efficiency schemes as we know now that even well managed and well-maintained generation units (like Koeberg) face freak accidents.

Action strategies now look at economic incentives, social entrepreneurship and sustainable development. For example, the City of Cape Town's objectives to increase foreign investment, local productivity and conform to the global initiatives to decrease CO_2 emissions are their objectives linked towards energy efficiency and renewable energy uptake.

Considering that 2MW of electricity is being consumed by the traffic system and its present technology [20], a strategy to retrofit 1200 of the Metropolitan's Major traffic intersections' signals from incandescent bulbs to LEDs is one of the projects initiated by the City of Cape Town. This 10-year pilot project, which started early in the 21st Century, replaces 120 intersections per year with a full retrofit of each signal. A small step in the right direction (given that Cape Town alone has 100,000 incandescents in its traffic lights), it is the local authority's way of reducing its high consumption of electricity that accounts for 41% [21] of its energy mix.

It is estimated that the additive saving achieved on electricity and maintenance over the installation period of ten years could be in the order of R23.8 million [21] with the estimated CO_2 emissions being mitigated standing roughly at 39,000 tons. With a half-lifespan[2] of approximately 15 years (based on how these intersections change between signals), the need for replacement and maintenance will be low.

The maintenance costs of having teams go out and replace incandescent lamps, which have high failure rates, include staffing, vehicle fleet use and maintenance, and stockpiling replacement lamps. These are without considering compromised safety to road traffic users in the case of the often-abrupt bulb failures.

[2] Half-life of LEDs is the time it takes to reach half of its maximum lux level. These may vary based on the degradation rate of the device.

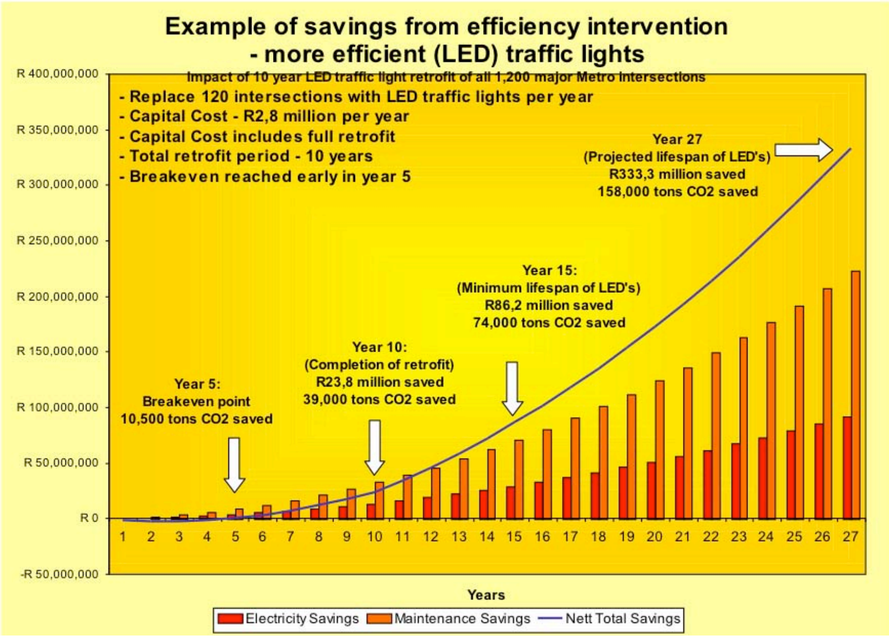

Figure 2: Projected cumulative savings of maintenance and electricity-consumption over 27 years based on the use of the retrofitted LED traffic signals in Cape Town [21]

1.6 The silent emergence of the white LED in the Western Cape

Locally, the general impact of visible-spectrum LEDs has been a silent one. The device is so discrete that is has gone unnoticed over the last 5 years. Tucked under cabinet shelves, set into stairways and used for theatrical stage lighting, people have been enjoying the effect of colourful LED displays. Its ability to render a required luminance and ambience thus cannot be understated. They have captured niche markets in Cape Town. Public display signs and ambience enhancing illumination purposes for retail chains, fast-food outlets, bars, clubs and even emergency lighting are the preferred option for a host of reasons, including its novelty and energy efficiency. The detrimental impact of neon lighting (heat production and frequency of maintenance), the high power consumption of incandescents and the poor colour rendering of high intensity discharge lamps has positively steered commercial entities into an LED market with none of the abovementioned weaknesses.

For this group of users, initial cost has not obstructed them from purchasing LEDs. Rather, it has been the perceived complexity. In addition, LEDs are not widely available in retrofit options for residential and commercial application. These are some of the barriers that exist for a potential market. Other problems include energy efficiency ignorance, poor energy usage habits and something that was never available before LEDs, namely highly satisfactory application-based lighting. See Figure 3.

The discussion above proves that these lighting devices fulfill more than what they have been set out to achieve. With this in mind, lighting and drive technology (circuitry, programmable hardware and software) has progressed tremendously. The present-day lighting sector is vast and multi-facetted. There is need to catch on to this new technology. Estimates of all lighting loads in South Africa show that commercial entities use 35% of their energy on lighting and residential lighting accounts for almost 20% [22].

Since the diagnosis of our efficiency and lighting problem has reached full circle [23], the present climate is now conducive for the application of white LEDs. As an advantage, the device fulfills the needs of the City's objectives.

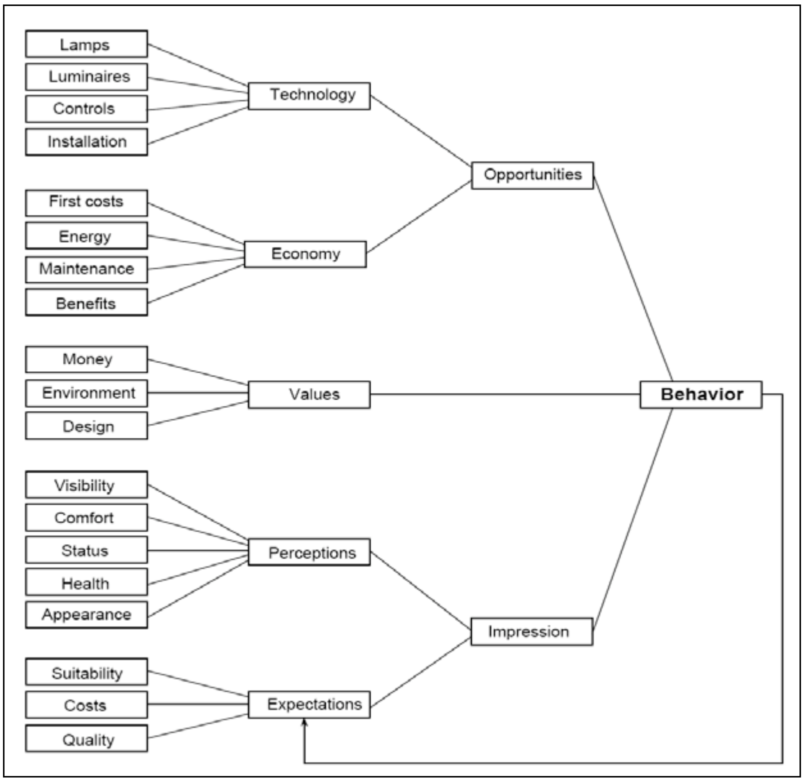

Figure 3: Path towards energy efficient lighting behaviour [24]

1.7 The truth and problem with CFLs

The arguments against CFLs include their detrimental harmonic pollution of electrical networks, the delayed response after switching and its objectionable colour render amongst others. They also contain mercury and yttrium, which have disposal problems for the environment. From a purely technical aspect, the efficiency of mercury vapour source fluorescents is limited to about 90 lm/W. This is due to one critical factor namely the loss of energy incurred when converting a 250nm UV photon to a photon of the visible spectrum [25]. Moreover the technology of CFLs is not likely to improve given this fundamental limitation.

During the 1980's the CFL became a global acronym for energy efficiency. Academics across many sectors had high hopes and expectations for its widespread uptake. Light, they claimed, just light, had the potential to affect communities in such a way that poverty would be alleviated, education improved, industries built and pandemics a thing of the past. But what has stood in the way of this technology is poor user-perception. This issue and not the aforementioned technical or environmental factors have been responsible for the lack of penetration of this technology.

Again from a purely technical aspect while conversion efficiencies of incandescents stand at approximately 10%, a not-so-often publicised fact is that compact fluorescent lamps (CFLs) only have conversion efficiencies in the region of 30% [26].

Table 3 illustrates this fact and puts it into context given the rapid rate of research and development into more efficient white LED light sources. This has seen white LEDs overtake its 2010 projected targets! This statistic is quite relevant in comparison to CFL technology.

Table 3: Comparison of actual level white LEDs with compact fluorescent lamps [adapted from 26]

Items	CFL	white LED (2004)	Current white LED (2007)	estimate white LED (2010)
lm/W	60	30	120	>60
unit lumen	200 - 9000	4	100	>25
usable lumen	30 %	60 %	unknown percentage	>70 %
life [hr]	3000 - 9000	>10,000	50,000	>100,000
cost/lm	$0.01	$0.35	$0.05	< $0.01

Given therefore that this technology has reached its peak there is a great need to research alternate technologies that have the potential of improving the efficiency when compared to CFLs.

1.8 Light from LEDs

Today, LED-based solid-state lights producing white light may be achieved via several methods. Commercially viable options, as cited by the Optoelectronics Industry Development Association (OIDA) in the USA are a blue LED with phosphor(s), a UV LED with several phosphors, and three or more LEDs of different colors [25, 26]. The latest developments include a quantum dot coating on blue LEDs to produce a high colour temperature similar to incandescents. Two diodes of different wavelengths known as the binary complementary method may also be used.

A brief chronology of the production of light from LEDs is given in Figure 4. Table 4 gives the two methods and the materials used to generate white light.

History of light production by LED

1907 The Englishman Henry Joseph Round (1881-1966) discovers the physical effect of electro-luminescence. As at the time he was actually engaged in a new radio locating process for sea traffic the discovery is at first forgotten.

1962 The first red luminescent diode of type GaAsP comes onto the market. The industrially produced LED is born.

1971 From the beginning of the seventies LEDs are available in further colours: green, orange, yellow. Performance and effectiveness is continually being improved in all LEDs.

1980s to early 1990s High performance LEDs (LED modules) in red, later red/orange, yellow and green become available.

1995 The first LED producing white light by luminescence conversion is introduced.

1997 White LEDs come onto the market.

Figure 4: Light-emitting diodes, from discovery to industrial production

[Source: Fordergemeinschaft Gutes Licht]

Table 4: Two methods for obtaining white LEDs

Method	LED source	Luminescent materials	Emission mechanism
3 LED chips	Blue LED		•Three colours (R, G, B)
	Green LED	InGaN	
	Red LED	AlInGaN	•Injection-electroluminescence (EL)
1 LED chip and phosphor	Blue LED	$In_xGa_{1-x}N/YAG:Ce(Y)$ $In_xGa_{1-x}N/G,R$ $In_xGa_{1-x}N/Y,R$	Pseudo-white •Binary complimentary color blue injection EL and yellow emission photoluminescence (PL) •Blue EL and G,R PL
	Near- UV LED 30 to 410 nm UV LED < 380nm	$In_xGa_{1-x}N/RGB$ multicolour phosphors	True- white •R, G, B PL •Multicolor PL

1.9 A future with White LEDs

Energy efficiency and the impact it will have on electrical networks, the directionality of the device in producing light, and light trespass and glare may now be tamed with LEDs. Its rural applicability is also high on the priority list for research. Sebitosi and Pillay in [29] succinctly illustrate how this highly advanced technology should affect rural communities. To date, many projects[3] can claim to this success. But it is the life cycle costing that has given the world a most unbelievable realisation. The longevity of this device will decrease our dependence on fossil fuels, a key prospect that cannot be overemphasized! Market penetration will eventually decrease lamp costs which stand at approximately $2-3 for about 60-80 lumens [30] thus only a major effort to penetrate the general lighting market will lead to more rural successes.

An initiative into solid-state lighting in 2003 was the formation of the Lumina Alliance whose aim was to raise the case for a national initiative in semiconductor lighting. An extension of the Alliance was the South African Lighting Engineering Centre (SALEC) [31]. Although the aims of both organizations where noble and noteworthy, the efforts to make a success of the industry collaboration were 'pathetic' and 'recently forgotten'[4] [32].

1.10 Life Cycle Costing (LCC)

Life cycle costing is an economic and financial tool used to achieve better-projected outcomes from the use of technology [33]. It is a way for consumers to become aware of the costs beyond initial purchasing costs. The environmental impact of the use of the technology may also be quantified via the use of LCC.

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[3] The Light Up The World (LUTW) Foundation are pioneers in social entrepreneurship using WLEDs on solar photovoltaic systems. They document the technical and social benefits of their work very well. They may be searched at the address: www.lutw.org

[4] This information through personal communication between Stelian Matei and the author. It comes out of articles [31] and [32] but it is not known whether the articles were published. It was received via personal communication channels

It is also a way to compare systems with different:

- Initial installation cost
- Operation cost (energy, relamping, maintenance etc.)
- Operational lifetimes

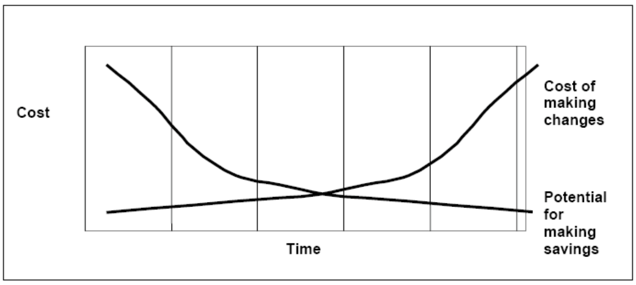

Figure 5: Potential savings and Cost relationship [33]

Good quality, high flux-maintenance WLEDs when operated correctly shows us that through its long life spans it can be used continuously for a number of years. This is dependent on chip structure. The financial rebate, due to longer periods between maintenance and lower electricity consumption is cause for a concerted effort to develop an industry from these devices. See figures in Table 5 and Table 6.

Table 5: Comparison of light output, electrical input, efficacy and lifetime of the most ubiquitous lighting technologies available on the market [34]

Source	Light output (lm)	Electrical input (W)	Luminous efficacy (lm/W)	Lifetime (h)
High-Power White LEDs	60-135	1.2-2.6	50-70	50,000
Halogen lamp (two pin)	950	50	19	2,000
Incandescent (screw type)	890	60	14.8	1,000
Fluorescent T12	2800	32	87.5	20,000
Compact fluorescents (CFL)	900	15	60	10,000

A simple comparison between incandescent, fluorescent and high-power white LED technologies, based on a specific environment (household kitchen) and cost is illustrated in Table 6. It shows, given the lifetime information of Table 5 that the LED outstrips the others but not in initial cost.

Table 6: Comparison of lamp type, illuminance, power required for implementation within a specific lit environment and cost [35]

Source	**Lamp type**	**Average horizontal illuminance** (lx)	**Power per kitchen** (W)	**Initial cost** ($)
Incandescent	75W Halogen	157	300	$212
CFL	18W	156	74	$388
WLED	Type A	161	168	$2,952
	Type B	167	200	$2,384
	Type C	151	120	$1,206

An example shall illustrate cost, energy consumption and required energy for the kitchen environment. Data is used from Table 5 and Table 6. A base period of 50,000hours (in excess of 5 years when operating continuously) is considered. Total cost is that of initial and replacement cost, and not energy cost. This is a cost incurred despite technology type.

If WLED Type C is operated for that period of time at a total cost of $1,206 under the kitchen environment; 6MWh is the amount of energy used. For the 18W CFL listed in Table 6, 3.7MWh of energy is used at a total cost of $1940. For the 75W halogen lamp, 15MWh of energy is used costing the consumer $5,300. The halogen lamps' initial cost is 14 times cheaper than the most expensive LED!

In reference to Figure 3 (Path towards energy efficient lighting behaviour), cost finds relevance in four of the five base criteria for choice in efficient lighting technology and behaviour. 'Technology' does not have that cost component while it can be argued that the 'status' of perception of new or different technologies be considered a cost variable.

1.11 Namulonge: A case study of the rural application of white LEDs

Lighting up villages with white LEDs is being done across the world. The white LED has given much hope to rural communities in the mountain ranges of Nepal and Nicaragua, dispersed villages across China, India, Afghanistan and a subsistence-farming village in Uganda. The pilot project in Uganda was visited and is discussed. It is conveyed through a design procedure that specific information regarding *location* and *purpose of use* would help solve many of the technical issues that exist there. Light is needed, but specifying the area's requirements must form part of the design phase, which presently only uses cost related to energy delivery equipment sizing as the chief decision-maker.

1.11.1 The need for energy efficient lighting

The primary reason for research efforts into energy efficient electrically generated light is to decrease the health issues related to the use of fuel-based energy sources. Other issues include safety, cost, maintenance, and increased levels of illumination.

The dominant system being implemented in the developing world, the PV solar home system (SHS), has in excess of 3million units installed worldwide [36]. With higher efficacies and better user–related performance, the white LED reduces the sizing and subsequently the cost of implementation [37]. The maintenance of PV SHSs, as they are referred to in the field, with white LEDs is reduced as a result.

1.12 Rural Lighting

1.12.1 Uganda: A brief country background

Uganda suffers from a severe shortage of electricity. "Currently, only 225,000 Ugandan households, i.e. 4.3%, are connected to the grid system. In the rural areas only about 2% of households have access to electricity, of which less than half is provided through the national grid, the remainder coming from household generators, car batteries or solar photovoltaic (PV) units" [38]. Rural livelihood with no electrical energy is not a sorrowful experience but it does remain an unnecessary burden on human beings given the plethora of developments in technology. This was experienced from a site visit the author made in July 2006. The country boasts a healthier economy, than in earlier times, with positive growth rates, yet is still unable to conquer this inequality in access.

1.12.2 Namulonge Pilot Project

Namulonge, an example of rural lighting and the challenges faced there is drawn on for reference purposes. The trip made to the village on the outskirts of Kampala city was enlightening. Information on funding, technical partnerships and proposed outcome detailed in the documentation received on the planning of this project we had great expectations of success in technology. Another motivating factor in visiting the site and institutions undertaking project implementation and maintenance was to witness the viability of rural/urban partnership.

1.12.3 Namulonge LED-Solar Home System (SHS) project

Initially, the Namulonge white LED project came out of a suggestion by one of the teachers at the Namulonge Primary School. She remains the liaison between the energy services company (Ultra Tec) and the 10 families that are taking part in the study. The German Aid Agency GTZ, Makerere University and Ultra Tec, together works on the Namulonge Community SHS LED lighting project. Although the area is grid connected, the people of the community were not able to afford the cost of being consumers of the service [39, 40]. Alternatives to fuel-based lighting, the long distance to travel and exorbitant prices for mobile phone charging levied by entrepreneurs in the town were sought through renewable energy equipment, mostly solar PV.

Despite the area having been assessed by engineering students from Makerere University, the adequacy of light for the given spaces was not properly investigated. 1W and 3W phosphor-converting white LEDs were used inside MR16-type lamps with bayonet bases. The picture below illustrates this. Appendix A contains more site pictures.

Figure 6: Bayonet base white LED lamp with battery supply

Figure 7: A low colour temperature, high color render (Ra) LED lamp placed unconventionaly in a corner of the living room.

1.12.4 Luminaire adequacy

From the construction of the luminaire, it was evident that these lamps should only be used as down-lighters. Adequacy (i.e. the light level specified for the task) of light sources was not investigated. It was thus a technical flaw that has led to the installation rendering poor illuminance levels and consequently poor user results. The year round average relative humidity for Kampala for the morning is 84 while in the evening is 64 [41]. It affected the light output of the white LEDs. This together with the lack of drive control, were the cause of the light degrading to less than 50% of its initial lumen level within a month of installation.

1.12.5 Usability issues

The first problem that was envisaged was that relating to user acceptance. This rejection by first time users of electrically generated light could potentially lead users to accept a lifetime of fuel-based light. Residents of rural communities, with little to no exposure to the developed world's conveniences, might easily view any technological advancement as impractical under their rural circumstances. A solar powered system also has its challenges. From charging the battery, to cleaning the panel and attaching other devices for the use by consumer electronics, the fundamental concepts are not readily understood by persons without a technical background. Good levels of education and comprehension meant that many of these initial assumptions where untrue. However, since all recipients of the solar home system were not interviewed the conclusion is not certain.

The system itself was very basic. No user-interfaced panels with signals, push buttons or logic control. The solar panel leads straight to the battery (i.e. no charge controller). From the battery, cables with on/off switches lead to the lamps. Some did not have any light switches but exposed contact points.

- The concerns of the users was related to the adequacy of the system:
- The size of the panel and battery.
- The ability to charge mobile phones,
- Playing a radio from the battery
- The independence that they desired from having to use or purchase dry cells or charging time from a vendor a number of kilometers away.
- The adequacy of the light was important to the user.

1.13 Framework for Implementation

The two cases have highlighted many important issues that need to be considered before a solid-state lighting system may be implemented. This section details two design procedures that may be used to enhance reliability and performance.

1.13.1 Selection Procedure

Brukilacchio and DeMilo describe in [43] a system-level flow down for package (luminaire) design and selection of commercially available chips for demanding applications. See Figure 8. In their view, 'product specification' is the most important aspect in the selection procedure.

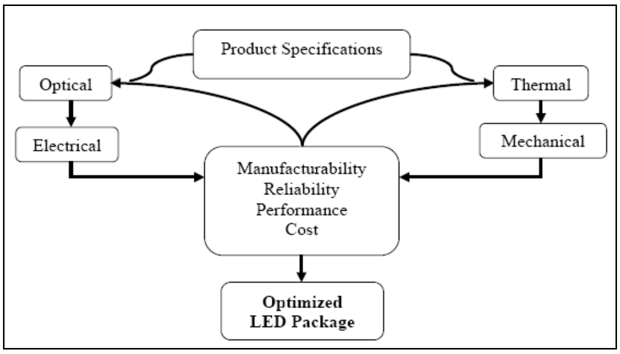

Figure 8: System level approach to optimised package design

The iterative process of maximising optical, electrical, thermal and mechanical considerations to increase manufacturability, reliability, performance and cost are consequential to the aforementioned primary activity (product specification). Luxeon, for their LED signal lamp design process, employ a similar iterative design process given in Figure 9 [44].

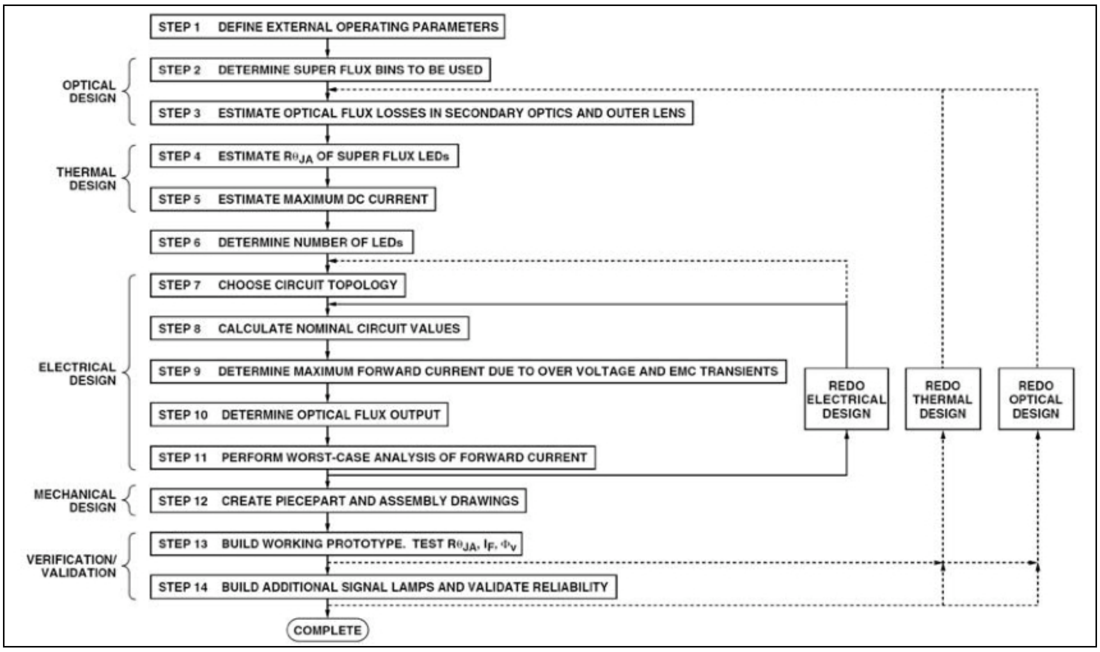

Figure 9: Signal lamp design process using LEDs

The verification phase of this design process creates 'optimal' solutions. Commonly known as error checking. However, on many occasions the concept of optimal solutions is not met with successful implementation. The site visit to Namulonge has led the author to believe that sustainable approaches to implementation and operation should include site-specific details. It is imperative that all projects include details of this nature. We contribute to this flow chart by suggesting that within the product specification phase, there should be information regarding the environment.

1.14 Environmental Challenges

The environmental challenges of rural and remote locations across the world have rendered harsh and hardy approaches to solutions that attempt to conquer the prevailing energy crisis. It is the author's contention that second to evaluating the needs of people are the localisation challenges. Otherwise known as the environmental challenges. For example, relative humidity (RH) is a factor that is unspecified in terms of the characteristics of operation. It does have an impact on the longevity (total usable hours of operation) of the device. The degradation of chip and encapsulant is accelerated further by this environmental condition [45, 46, 47].

Ultraviolet (UV) radiation is another such factor having a similar impact on the chip [48].

Having more environmental site information will reduce the high expectation of the installed white LEDs. If information of this nature is looked at during the product specification phase of Brukilacchio *et al*'s flow process then the consumer is able to fully understand that each installation is unique. This is an important fact in relation to technology acceptance and further market penetration. Namulonge showed signs of this fatal error. The project stands still because of inadequate selection of LEDs.

1.14.1 Environment-priority selection framework

Causality, as a subject, is the representation of phenomena through empirical testing and verifying the claims that specific operating conditions affect lifetime, lumen output etc. In many cases these conditions are known, but scientific proof is able to quantify them and then qualify means to avert the negative impacts derived from those conditions. Testing of LEDs is done in controlled environments (light boxes, spherical photometers etc.) and under accelerated conditions [45, 46]. To date the effects current and temperature have on lumen output, spectral changes and lifetime deprecation have been documented [45, 47, 49]

1.14.2 Impact of weather and ambient conditions

In real world applications, *variables* (as stated earlier) and *conditions* change at random. A full account of the *environmental considerations* (as opposed to operating conditions) is needed. These have been briefly touched on before. A few are listed:

- Relative Humidity
- Ultraviolet radiation
- Dynamic temperature changes
- Air flow

The combinational effects of these ambient conditions can be inserted into product specification.

1.15 Current considerations and future aims

The aim of this chapter has been to demonstrate the impact that LED technology is having around the world. The prospects that SSL-LEDs may have when applied to the stated environments, in particular, domestic and commercial spaces was also examined.

The feasible revolution will be the change in the habit of energy use with a fundamental understanding of the visual needs of users of light. Governmental policy is a major driver that can assist in this matter. This is a responsibility that governments and local authorities must recognize and act upon.

Lower energy-consuming technology is essential if there is to be a major shift in usage patterns and peak demand.

A number of points to consider in the case for WLEDs in the Western Cape:

- Targeting the ambient and task settings, because the lux requirements are lower and the task requirement for lamps are closer than normal respectively, is the first step.
- Because South African research groups are not getting funding for physical and chemical research into LED chip structure, and that we are bound to be gross importers of LED technology, research into the user perception and adaptability of various users is important if we desire to penetrate the lighting market.
- Local government should consider implementing more LED installation projects
- Local government should increase public awareness about the options and energy efficiency of LEDs and other energy efficient technologies.
- There is a need to develop as many high quality lamps and retrofit options based on task requirements.

First-hand experience of the social, technical and strategic importance of rural electrification was observed from the brief visit to Uganda. Most of the rural population of this resource-rich, agriculturally driven country lives with hope despite their condition. Education is not limited to location and those in remote areas like Namulonge are being stimulated academically. This plays a vital role in completing the cycle of technology uptake. Namulonge white LED pilot project has much work still to do before it can claim to be sustainable. The research entities thus play an important role in its progress and prominence.

Namulonge site visit gave us a feel of the conditions under which this specific group of people live and the manner in which the project is attempting to change their lives. Not all rural circumstance are the same and the uniqueness of this area is important to understand in the context of its cultural, geographic, agricultural and economic dispositions.

1.16 Plan of development

Chapter 2 is a summary of the electrical, material and thermal, and spectral characteristics of white LEDs. It also details the behaviour of InGaN-based LEDs when driven by circuits of different topologies. High brightness LEDs are looked at specifically because they offer better thermal and lifetime characteristics. They are also used for the design example.

Chapter 3 is a report on the human perception of light. The subjects of radiometry, photometry, colourimetry, colour render and colour temperature for LEDs are dealt with in depth. The characterization and physical detection/measurement methods for white LEDs are discussed in detail. An illuminance photometer was used to detect light in the laboratory.

LED arrays and luminaires where tested in a laboratory for the Golden Arrow bus design problem. Dark room conditions (stable, consistent environment) were used to evaluate the luminaire design.

Chapter 4 details the background in assessing the optical system requirements and the design hypothesis to address the needs of the bus and the area to be lit. The spacing constraint and spatial distribution, as particular problems of this design, are also detailed. This chapter therefore is a full explanation of the collimating optics sought to give a best fit for the lit environment. Included are subjects of light utilization and light energy capture. The circuit designed to run the LED array for the laboratory testing with the thermal considerations is also dealt with here.

Chapter 5 details the testing results of the retrofit luminaire after physical production of the lenses and the manipulation of the lenses. This chapter holds information about the criteria against which the photometric and optical properties of the luminaire were checked. There are four criteria; illuminance, intensity, spatial distribution and étendue. Since the first design of the linear fresnel and circular fresnel did not meet these requirements, a second design (with new requirements founded on different optical concepts) was sought. An adapted batwing lens design, used for fluorescent tube lights, is researched to keep a lens (as opposed to an encapsulating or reflecting optic) design. The hybrid circular and linear fresnel lens is fabricated.

Chapter 6 draws conclusions on the white LED, its benefits and the application results and explains further the need for its implementation. Recommendations for the design example are given.

An appendix holds information of the white LEDs and equipment used for testing. It also holds extended data captured during experimentation

CHAPTER 2
ELECTRICAL AND MATERIAL CHARACTERISTICS OF WHITE LEDS

2. Introduction

AlInGaN (Aluminum Indium Gallium Nitride) are semiconductor materials used to make light-emitting diodes. Mixtures of these particular elements primarily produce blue, green, and white light. White LEDs from this material composition are also referred to as InGaN, GaN and just nitride [50]. In this way, literature may be confusing for the newcomer. Variations in supply, temperature and product are the three most important aspects to consider when using LEDs. Other competing demands include cost, current matching and functionality. It is the single chips LEDs that use phosphors to convert the wavelengths of spectral emission of the chip into white light that we will concentrate on. This chapter also gives a summary of the types of current control that may be employed to drive semiconductor-based lighting devices. Emitted light is a function of forward current I_f and compliance voltage V_f. LEDs generate light at an intensity that is proportional to the forward current driven through them.

2.1 Anatomy of LEDs

LEDs, embedded into luminaires, must be considered first on their type and then on their conditional characteristic to ensure adequacy for visual performance. There are four package types available on the market. Good spatial distribution have come from the newer technologies like surface mount technology (SMT) and chip-on-board (COB) technology. The other available technologies are the T-1 3/4 (5mm through-hole) and ‘superflux’ LEDs. The main difference in the types of technologies is the method of encapsulation. The radiation patterns give an idea of how they differ from each other. Despite a difference in physical structure, the material composition for the generation of white LEDs is InGaN.

Initially the 5mm through-hole LED *lamps* were designed for exterior signal and interior colour display applications. The superflux LEDs were used for the automotive exterior lighting as a replacement for miniature incandescent lamps and in dashboards. The SMT LEDs were specifically designed to bridge the gap in the illumination market with higher lumen-output per package. Figure 10 to
Figure 12 illustrates radiation pattern of the associated technologies.

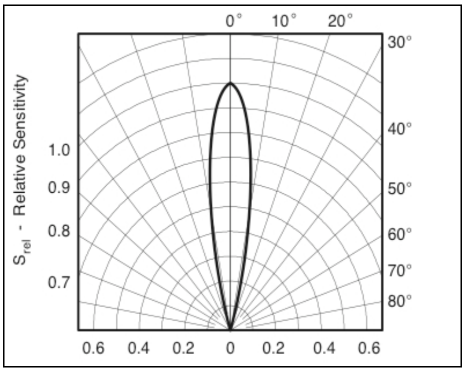

Figure 10: Typical relative radiant intensity versus angular distribution for 5mm through hole LEDs (Source: Vishay Semiconductors)

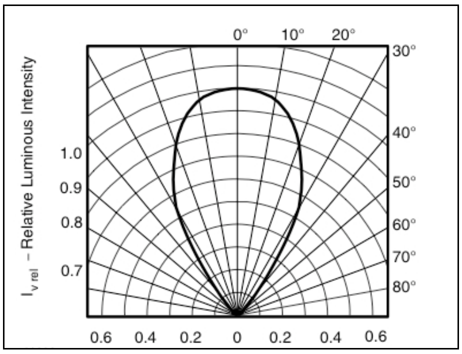

Figure 11: Typical relative radiant intensity versus angular distribution for superflux LEDs (Source: Vishay Semiconductors)

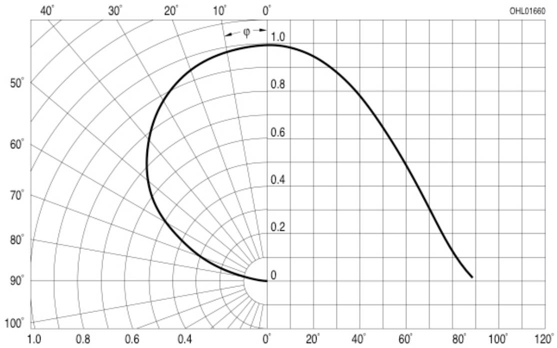

Figure 12: Polar (left half) and angular (right half) distribution of SMT type LED (Source: Osram).

Form left to right, the respective structure of the physical designs for the above listed distribution patterns are displayed in Figure 13.

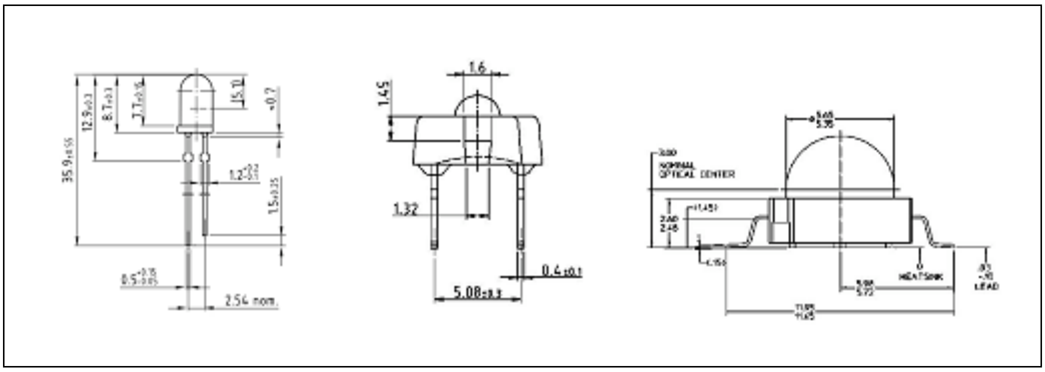

Figure 13: Physical dimensions of the structure of 5mm through-hole, superflux and HB LED technologies respectively (left to right).

2.2 High-brightness white LEDs

The surface mountable high-brightness (HB), commonly referred to as 'high powered' white LEDs, were invented with the particular aim of overcoming the shortcomings of signal lamps and penetrating the general lighting market [51, 52]. These terms are interchangeable. They essentially refer to the higher current densities employed to generate more light from chips/dies. Packages that enclose these chips have a number of special implementation considerations the most important being thermal. A concerted effort to lose the inefficiencies of indicator and signal LED lamps being integrated into illumination rendering fixtures; HB white LEDs have to contend with a market saturated with easily-installed and cheap options. A characteristic of this technology is its ability to emit in excess of 100 lumens per package. The most common commercially available lamps use the phosphor-converting process.

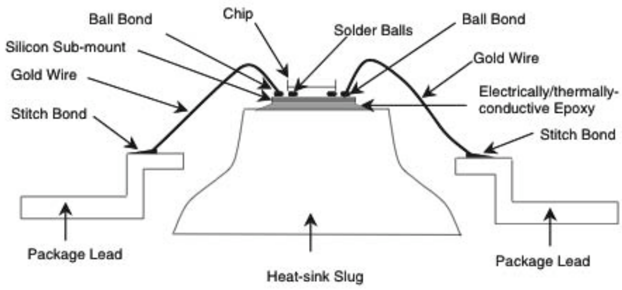

Figure 14: A closer look at the internal structure of an InGaN high-brightness Luxeon® LED

2.3 Implementation Considerations

The following 6 points are considered critical for long-term operation:

- Total light output [P_o]
- Luminous intensity [I_v]
- Emission spectrum
- Colour quality [R_a]
- Bias condition [I_f-V_f]
- Junction temperature [T_j]

The abovementioned characteristics act as variables and are influenced by their thermal dependences. Optimal application-based lighting was discussed in Chapter 1 via a selection procedure. In realizing illuminated environments with white LEDs [28], five areas are to be considered:

- Digital or analog control
- Correct driving

- Light production mechanism
- Light requirement
- Thermal management

So it can be said that colour rendering by synthetic white light sources and the driving mechanisms for them all play important roles in the production of light. These factors are now taken into consideration when industry interacts with developers. This optoelectronics industry is large in developed countries around the world.

Chips/dies are the light-giving semiconductors embedded within an LED typically housed in a structure able to dissipate heat. Light production mechanisms of these chips are important. However, these factors can be said to combine together efficiently only if they are able to satisfy the user. This information points us once again to the suitability of a light production mechanism for a task, hence, giving room for a host of LED-based lighting solutions.

Figure 15: An example of the available retrofits for domestic and commercial use. This is an MR16-style lamp with white LEDs inside. [Source: www.wattmanledlamp.com]

2.4 The Characteristics of LED technology

2.4.1 Light Output

Traditionally LEDs use positive and negative junctions and the laws of radiative and non-radiative recombination [53]. The emissive layer of an LED is made of inorganic materials. It is in this region where carriers (either electrons or holes) recombine to release photons. Most of the released-photons produce light while the semiconductor material absorbs the rest. The entire chip, also known as a 'die', is approximately 0.3 mm² in size, with size varying according to the die structure and lumen requirement. Taking into account the size of other lighting devices, this small size has never yet been achieved.

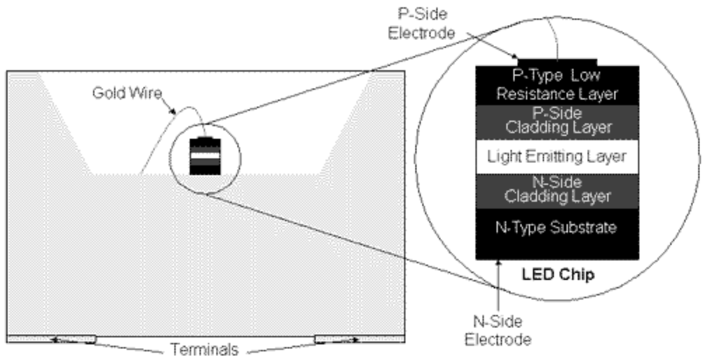

Figure 16: A cross section through a surface-mount LED

With respect white light production, the following methods exist:

- New III-IV periodic elements together with phosphors [54] allow manufacturers to produce white light in various mixtures to change emitted wavelength.
- Near ultraviolet emitting LEDs and a mixture of high efficiency europium-based red and blue emitting phosphors together with green emitting copper and aluminum-doped zinc sulfide renders a similar effect to that of fluorescent lamps.
- Simultaneous emission of blue light from its active region and yellow light from the substrate (no phosphors are used in this method).
- Coating blue LEDs with quantum dots that glow white in response to the blue light from the LED [55] gives the closest possible colour-render to an incandescent.

The high demand of the first-mentioned white light extraction method makes it the most popular on the white LED market. The brilliant colour rendering, simplicity of white light production and tunability of wavelength to produce a desired colour temperature are some of the advantages of this LED.

In the future, researchers estimate that white light will come from a combination of LED-based [56] monochromatic light sources. Additive colour mixing using the primary colours of red, green and blue will be clustered together appropriately to render white light. The increased ability to control white light production at a high colour rendering index, the additive effect of photon production from multiple sources, and application-based shade changing [57] are some of the prospects and challenges that research institutes are weighing up. These options cannot be achieved without closed-loop control.

No white-light producing LED and LED-array are without their inefficiencies. To overcome these inefficiencies, luminous-efficiency and photon-conversion efficiency requires heavily funded research and development. The Optoelectronics Industry Development Association (OIDA) list the following areas for long term research [57]. These include primary (chip structure) and secondary (lens and reflector) components:

- Materials research and the physics of light generation
- Substrate materials
- Reactor Design
- Light extraction
- Photon conversion materials
- Novel concepts of solid state light emission
- Packaging

Light extraction is a fundamental issue that the solid-state lighting (SSL) industry is concerned with. Lighting units/fixtures, consisting of an array of LEDs, also face light-emittance problems. Thus the abovementioned research-areas list falls under a broad spectra of issues and constitutes the first of four significant areas.

Table 7: A list of research fronts to yield higher flux outputs

Material and Device design	Material and device fabrication	Reliability and packaging	Clustered Lighting solutions

2.4.2 White LED Performance and Temperature (Limiting Factors and Thermal Dependence)

The long lifetimes that LEDs have been branded to achieve are the arguing point from which its supporters depart. The applications they are foreseen to be utilized for, LED lifespan must exceed available light sources while maintaining a viable lumen output. These topics also relate to cost; where maintenance of lamps has become burdensome, and in remote areas, practically impossible.

LED thermal junction temperature, ambient temperature plotted against time and drive current are important functions and powerful aides for designers and users.

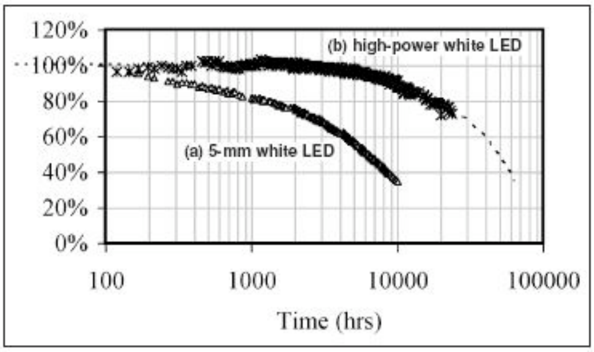

Figure 17: Lumen maintenance data at room temperature for two types of white LEDs: curve "a" describes a 5-mm white LED driven at 20 mA; curve "b" is for a high-power white LED (adapted from [58])

The conversion efficiency is the most important performance indicator for all lighting LEDs [59] with its efficiency decreasing as junction temperature increases. The conversion efficiency relates input power to output lumen. It is also referred to as luminous efficiency.

To produce light, LEDs must be forward biased and current limited to ensure that the chip operates and is protected. It should be noted that while these are electrical conditions to ensure that light is reproducible, there are thermal concerns of package and lead design. The LED is quite dependent on temperature and the general relationship for diodes can be given as:

$$i = i_o \left[\exp\left(\frac{eV}{\beta kT} \right) - 1 \right] \tag{2.1}$$

where, i is the current through the diode, i_o is the reverse saturation current, e is the charge of the electron, V is the voltage across the diode, k is the Boltzmann constant, T is the temperature of the diode, and β is an ideality factor which varies between 1 and 2, depending on the semiconductor and the temperature.

A current of several hundred milli amperes, like in the case of most high power LEDs used for this thesis, passing through the LED with no sinking/cooling can cause rapid temperature changes. Datasheets specify operating temperature range T_{op}, junction temperature T_j and thermal resistance at the junction/solder point $R\Theta_{js}$. A temperature coefficient TV_c of the forward voltage is also given. This 'typical' value describes in mV/K the rate at which the forward voltage changes within the operating temperature range T_{op} at the defined best operating forward current I_f when the junction temperature changes $\Delta V_f / \Delta T_j$. It is clear that temperature plays a significant role in the operation of white LEDs.

Higher junction and ambient temperatures affect lumen output significantly and cause lumen degradation and the above equation may be used to monitor the temperature stability of the LED. Changes in temperature are widely known to cause shifts in the spectral response and colorimetric properties of LEDs.

The most critical indicator is the junction-to-case thermal resistance that is defined as:

$$R\theta_{jc} = \frac{T_j - T_c}{P} \tag{2.2}$$

Where, T_j is the junction temperature, T_c is the LED casing temperature and P is the electrical drive power. The junction-to-case thermal resistance is the ratio of measured light power to the electrical drive power, versus the junction temperature.

Four things to consider when operating white LEDs. These are cause for degradation.

- Change in characteristic of fluorescent substance
- LED chip
- Optical transmission of resin lens
- Change in junction temperature when forward conditions change (e.g. 50° – 90° change when current changes from 36mA to 74mA)

2.4.3 Thermal Management and temperature variations

Temperature plays a significant role and impacts on the behavior of InGaN LEDs. V_f stabilizes as the junction temperature stabilizes. The temperature at the junction rises because of electrical power consumed by the chip and then stabilizes at a particular temperature. This may be influenced by the properties of the type of phosphor used [60]. The relationship is given a numerical value and is known as the *temperature coefficient*. LEDs exhibit a change in forward voltage as junction temperature changes. For InGaN this coefficient is within the range -3.6mV/K to -5.2mV/K [61]. A decrease in voltage occurs as junction temperature increases. InGaAlP (yellow and amber-red semiconductor material) display a temperature coefficient of between -3.0mV/K to -5.2mV/K. There are intensity changes over junction temperatures. This is as a result of the changing efficacies of the semiconductor and not as a result of the changes in forward voltage over the various temperature changes. This temperature change is not linear [60].

High brightness white LEDs have many temperature dependent properties. Consistency during the lifetime of operation is achieved by running away the heat that is generated. Although light conversion is very high the input power cause the junction temperature of the LED to rise. An increase in die temperature causes the dominant wavelength to get longer. The change in dominant wavelength Δλ (nm) over a change in die junction temperature ΔT (ºC) is represented in equation below.

$$\frac{\Delta\lambda}{\Delta T} = \mathrm{K} \tag{2.3}$$

For white LEDs the human eye may perceive these small shifts in wavelength. Thus, consistent colour and power magnitude are immediately affected by thermal management solutions [62]. Light intensity and lifetime are also affected by the rise in heat that is a result of the lack of conversion of available energy into light. Losses (characterized by heat) can be calculated by $P=I^2R$ where resistance is dependant on thermal impedance and thermal conductivity and thickness.

2.4.4 LED stack model and heat transport method

A stack is a representation of the thermal conduction path in a diode. Thermal resistance is described as:

$$R\Theta j - a = \frac{\Delta Tj - a}{Pd} \tag{2.4}$$

while conductive heat transfer q from heat source to air is shown in:

$$\frac{q}{A} = -k\frac{dT}{dx} \tag{2.5}$$

Where, A is the area of device.

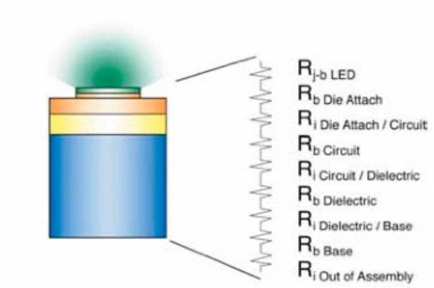

Figure 18: Stack model of a typical light-emitting diode [Source: Bergquest Thermal Manuel]

2.5 LEDs and Efficiency

The question of efficiency in light production is of utmost importance. The global projection of efficiency is now brought down to a microscopic level and is based on chip structure. The energy converting process of present LED sources are examined in more detail. *User efficiency* can be viewed from a number of characteristics of the device. A summary of the measures of efficiency follows.

2.5.1 Efficiency measures of LEDs

Light is emitted when applying forward bias into the p-n heterojunction. There is an efficiency associated in the conversion from electrical energy to emitted light were one photon is emitted for every electron injected. The power efficiency η_{wp}, otherwise known as wallplug efficiency, is expressed in terms of three physical parameters. Schubert's book, *Light-emitting diodes* [63], has illuminated these efficiencies.

Internal quantum efficiency is defined as:

$$\eta_{\text{int}} = \frac{P_{\text{int}}/(hv)}{I/e} \tag{2.6}$$

which is the number of photons emitted from the active region per second divided by the number of electrons injected into the LED per second. P_{int} is the optical power emitted from the active region and I is the injection current.

$$hv = E_e - E_h \approx E_g \tag{2.7}$$

where the photon energy E_g is the difference in electron energy E_e, and hole energy E_h in order to conserve energy. It must be noted that this is a simplified version of the relation between energy and photon extraction.

The extraction efficiency is defined as:

$$\eta_{extraction} = \frac{P/(hv)}{P_{\text{int}}/(hv)} \tag{2.8}$$

where the number of photons emitted into free space per second is divided by the numbers of photons emitted from the active region per second. *P* is the optical power emitted into free space. The high-powered LEDs introduce problems related to thermal management based on the light extraction efficiencies.

The external quantum efficiency is defined as:

$$\eta_{ext} = \frac{P/(hv)}{I/e} = \eta_{\text{int}}\eta_{extraction} \tag{2.9}$$

It is the product of the internal and extraction efficiency. It gives information on the ratio of the number of useful light particles to the number of injected charge particles.

Japanese researchers have further extended the definition to include voltage efficiency η_v into the power (wallplug) efficiency equation. Hence

$$\eta_{power} = \frac{P}{IV} \tag{2.10}$$

where IV is the electrical power provided to the LED, becomes

$$\eta_{wp} = \eta_v \eta_{\text{int}} \eta_{ext} = \eta_v \eta_e \tag{2.11}$$

The voltage efficiency η_v is controlled by chip resistance and voltage barrier [64]. It is the voltage required to cause electrical conduction in a junction of two dissimilar materials.

5.5.2 White LED lighting, design and efficiency

Table 8 shows two production methods for white light from LEDs and their related efficacies. It is clear that efficiency is chemical compound/composite dependant. What is also illustrated is the related rendering ability based on chip type. The voltage forward bias is dependent on the die make-up. For example, LEDs that generate white light have a typical forward voltage drop between 3-4V while green, red and yellow diodes emit light at a forward voltage bias of 2-3V.

These fluorescent-type LEDs have efficacies based on the conversion properties of the chip and the colour-render (Ra) and correlated colour temperature (CCT). With reference to the people of Namulonge, these two issues where of particular concern.

Table 8: Characteristics of fluorescent-type LEDs [adapted from 64]

Method	**White light**	**Peaks** (nm)	**Average colour rendering index** (Ra)	**Luminous efficacy** (lm/W)
Pseudo white	InGaN + yellow fluorescent material	465, 560	60~80	>100
Quasi white	InGaN + yellow + red fluorescent material	465, 580	~88	>100

Table 9: Colour rendering ability based on environment and task [65]

Application	CRI Ra
Indoor retail	> 90
Indoor home	80
indoor work area	60
Outdoor pedetrian area	> 60
Outdoor general	< 40

2.6 Light control

2.6.1 Current dependence

The voltage drop across the LEDs affect the circuit design. The aim of design is to ensure that LEDs remain lit throughout the range of voltages specified.

Although the voltage range must remain the same under forward bias conditions, the vast variation in forward current makes circuit solutions difficult to manage. The steeper the I_f - V_f curve, the more precise the capabilities a power source needs to be. Figure 19 and Figure 20 are a comparison between commercially available, market competing LEDs. The images display the electrical response clearly.

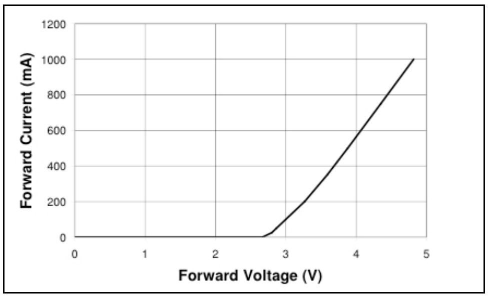

Figure 19: Bias conditions

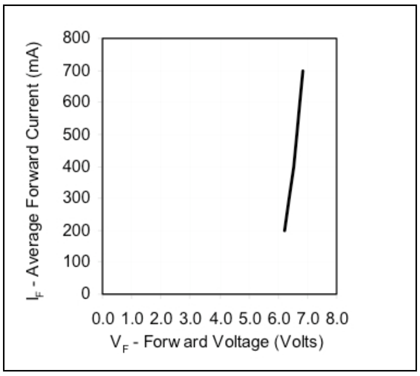

Figure 20: Bias conditions of a high brightness LED

It is well known that LEDs, even though from the same manufacturer and from the same batch may vary in forward condition. In order that the luminous output of any two LEDs are the same, with the same specifications and manufacturer, driving them at the same current and voltage is important. It is relatively easy to do this for a single LED. For an array of LEDs, the main challenge that has to be overcome is to drive each LED with the same forward voltage and forward current.

2.7 Variations in supply

Equations are *single-point* computations [66]. When considering the types of regulation to be used, and the purpose for which the LEDs are going to be driven, the range over which the power supply is able to give power is important to consider.

2.8 Types of regulation

For the purpose of off-grid lighting systems, DC-DC converting systems are available ‘off-the-shelf’. This solution may be based on passive and/or active components. Voltage or current may be controlled. Analog circuitry has traditionally been used for regulating voltage. Switching regulators are common on many energy-critical portable devices.

2.8.1 Linear regulator

To provide a constant current, a linear regulator must be configured as a current source. They may only be used when the input voltage is higher than the output voltage. A linear pass element with a feedback mechanism is used that regulates the current in a path as opposed to the voltage at a node. The top resistor is replaced with a string of LEDs and the lower resistor becomes the current sense resistor. The resistor causes the linear regulator to adjust the output voltage until enough current flows through the resistor equal to the feedback voltage of the integrated circuit [66].

In the design process, sufficient 'headroom' for voltage variation must be accounted for to ensure that the available voltage is sufficient to operate the LEDs. The design phase is shorter for linear regulators as fewer components are used. There is never the question of electromagnetic interference (EMI) as no passive switching components are used.

A current source linear regulator is a cost effective solution to driving LEDs. A disadvantage is the large amount of power dissipated by the supply when the voltage drop across the supply is large. The efficiency of this circuit solution is thus lower than the other available topologies. It is restricted to a 'step down' in voltage only. It employs resistors, which have tolerances and are affected by temperature (self and ambient).

The losses of a linear regulator can be approximated. V_{in} is the input voltage, V_f the forward voltage of the diode, I_r the regulated voltage and *n* is the number of LEDs in a string.

$$Loss = (V_{IN} - nV_F)I_R \tag{2.12}$$

2.8.2 Switching regulators

Buck regulators is similar to the voltage linear regulator in that it steps down the voltage. The Boost regulator switching topology is capable of boosting the voltage.

The Buck-Boost regulator is required when the voltage sources varies from above and below the bias voltage of the LED (or string of LEDs). These three topologies may be used to control LEDs. However, the Golden Arrow Bus design example will use a Linear regulator for laboratory testing.

2.8.3 Circuit efficiency

When choosing a topology that best suits the application, efficiency is important. Figure 21 is a comparison between the linear and switching topologies. The tolerances with which the power supplies are able deliver the required current may be seen here.

Specification	Linear	Switcher
Line Regulation	0.02%–0.05%	0.05%–0.1%
Load Regulation	0.02%–0.1%	0.1%–1.0%
Output Ripple	0.5 mV–2 mV RMS	10 mV–100 mV_{P-P}
Input Voltage Range	±10%	±20%
Efficiency	40%–55%	60%–95%
Power Density	0.5 W/cu. in.	2W–10W/cu. in.
Transient Recovery	50 μs	300 μs
Hold-Up Time	2 ms	34 ms

Figure 21: Comparison between Linear and Switching topologies [Source: National Semiconductor]

2.9 Summary

This chapter has detailed some of the critical relationships between current, temperature, wavelength and the related efficiency in light production. Bias conditions must be maintained by the chosen circuit solution, whether digital or analog.

HB InGaN-based white LEDs, as the superior technology, shall be used with a linear regulator to understand the illuminance and spatial distribution concerns of the design example.

CHAPTER 3
HUMAN PERCEPTION OF LIGHT AND METROLOGY

3. Introduction

Our ability to differentiate between colours, sense light level and various textures of objects has led us to develop systems to quantify light's properties. This lighting measurement system has been developed over hundreds of years and is one of the cornerstones of our development as humans. The perception of light is subject to the observer, even under identical conditions, setting the photometric and colourimetric quantities apart from purely physical quantities. Thus, there is a need for a set of conventions to evaluate environments. These allow the designer (architect, optical engineer, electrical engineer etc.) to make recommendations on a number of criteria.

There has been a dramatic growth in the use of various technologies for lighting coupled with new light sources with efficacies that match or exceed traditional vacuum tube lamps. The challenge has been set to illuminate general environments with them. With the knowledge of the properties of light, its interaction with human beings on a psychophysical level, and the fundamental properties of the latest technologies; it allows us to challenge this market and achieve reduced power consumption targets. This chapter deals with the white light-emitting diode and the receptors/discriminators of its quality and quantity in environments lit by them. The unique measurements of white LEDs are considered within their geometrical properties, spectral distribution and operating conditions.

3.1 Human perception of light

3.1.1 Radiometry

Radiometry is the science and technology of the measurement of electromagnetic radiant energy. This covers the entire spectrum of physical radiation from ultraviolet (UV) to infrared (IR) and is the vehicle through which visible spectrum light may be quantified. Radiometric quantities have the subscript 'e' assigned to them. Photometry and colourimetry describe intensity with respect to the energy or optical power of radiation. The human eye's perception of that optical power and the strength of colour respectively are thus critical in order to understand artificially lit environments.

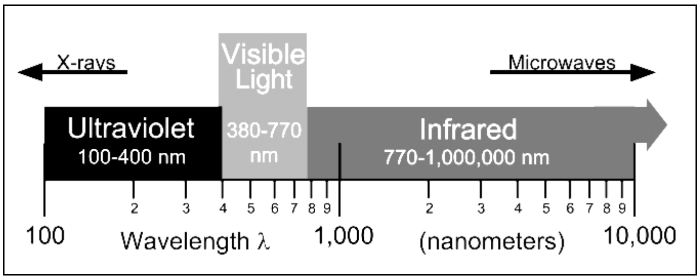

Figure 22: A linear representation of the electromagnetic spectrum. The visible spectrum lies between 380nm and 770nm

3.1.2 Photometry

If an LED emits light in the visible spectrum the photometric analogue of the radiometric quantities use the photopic response of the human eye. The corresponding luminous quantities fall within the narrow visible spectrum of 380-770 nanometers. The eye sensitivity function $V(\lambda)$ describes the spectral luminous efficiency for the photopic (store, office and outdoor light) response within this spectrum [67]. Two other responses exist namely scotopic (dim or overcast light) and mesopic vision (moonlight or early twilight). Under the mentioned lighting/ambient conditions the spectral sensitivity of the eye is mediated by rods and three types of cones. When luminance (luminous intensity in candela (cd) over projected surface area (m^2)) levels are greater than 3cd/m^2, photopic vision and the cones perceive colour. Under scotopic vision the higher sensitivity of rods do not render the same colour perception as the cones. Luminance levels are below 0.003cd/m^2. Illuminance levels between 0.003cd/m^2 and 3cd/m^2 characterize mesopic vision.

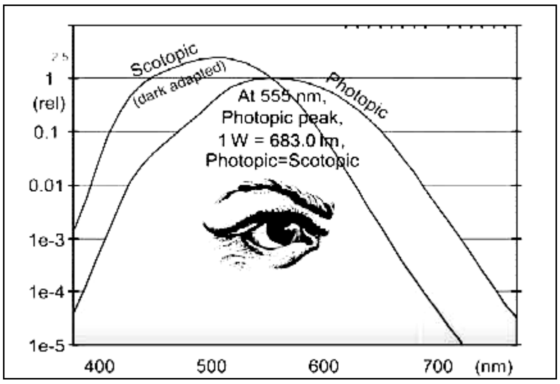

Figure 23: Commission Internationale De L'Eclairage (CIE) photopic and scotopic sensitivity curves

The photometric unit, always with subscript 'v', is defined as:

$$\Phi_v = K_m \int V(\lambda)\Phi_\lambda(\lambda)d\lambda \tag{3.1}$$

Where Φ_V is the spectroradiometric power distribution of a signal (expressed in "watts per unit wavelength interval"), $K_m = 683\,lm/W$, which establishes the relationship between the radiometric (physical) unit watts and the photometric (psychophysical) unit lumen. $V(\lambda)$ is the relative photopic luminous efficacy function normalized at 555 nanometers and λ is the wavelength (usually expressed in nanometers). All radiometric quantities have corresponding photometric quantities and may be attained by integrating and weighting them with $V(\lambda)$.

3.1.3 Colourimetry

Providing a quantitative and qualitative description of colour in relation to the human eye is known as colourimetry [60]. The human eye's sensitivity to radiation is not the same for each of the wavelengths (colours), the intensity of the light or the field of the view [68]. It is also sensitive to colour differences across a lit surface. The most important function of colourimetry is the quantification of colour-rendering properties of sources and the concept of correlated colour temperature [69].

Based on the analogy of the photometric system, a colourimetric system can also be built on additivity and proportionality. Thus to describe colour three independent variables are needed to describe colour or to obtain a match for it [69].

Three integrals of the referred to photometric form are thus required.

$$Ti = k \int_{380nm}^{780nm} \Phi_{e,\lambda}\, \bar{t}(\lambda) d\lambda,\ i=1,2,3 \tag{3.2}$$

Where, $\bar{t}(\lambda)$ is the three monochromatic weighting functions of the stimulus (colour-matching functions), and T_i describes the colour stimulus in the trichromatic system. The above equation may be gained via the following procedure. The units of the matching stimuli have to be set (done by setting so that the mixture of the unit amounts provide a colour match with a particular white stimulus). Using the symbols [R], [G], [B] for these unit amounts of matching stimuli,

$$C_1 \equiv r_1[R] + g_1[G] + b_1[B] \tag{3.3}$$

where, r_1, g_1, b_1 represent the amount of light taken from the [R], [G], [B] matching stimuli (called the tristimulus values). C_1 has a spectral distribution $[C_1(\lambda)]$. If one calculates for every wavelength band of the spectrum and add them up we can obtain C_1. The additivity and multiplicity of colourimetry permits this.

3.2 Commission Internationale l'Eclarage, International Commission on Illumination (CIE)

The CIE is a standards authority on illumination, and the international organization that undertook the task of developing specifications for colour and colour matching. They have developed important conventions over decades. For example, two colour stimuli that look similar under one viewing condition might look different when seen under different conditions (field of view, adaptation, direction of viewing etc) [69].

In 1931 the CIE established the tristimulus system based on the assumption that every colour is a combination of the three primary colours [70]. The integral of spectral power distribution of radiation $S(\lambda)$ and the three response curves $x(\lambda)$, $y(\lambda)$, $z(\lambda)$ over the visible spectrum wavelength range will give the tristimulus terms X, Y, Z. The colour coordinates x, y, z are gained from these tristimulus values. These may be plotted in the chromaticity space. See Figure 24.

It should be noted that other chromaticity spaces exist for example $u`$, $v`$ and L*a*b* that can be calculated by the transformation of the x, y, z values [71]. These are further developments of the coordinate system (that occurred in 1976 and 1986 respectively)[5]. The latter (CIE 1986) includes the concept of brightness (when referring to a source emitting light) and lightness (when referring to a surface being lit).

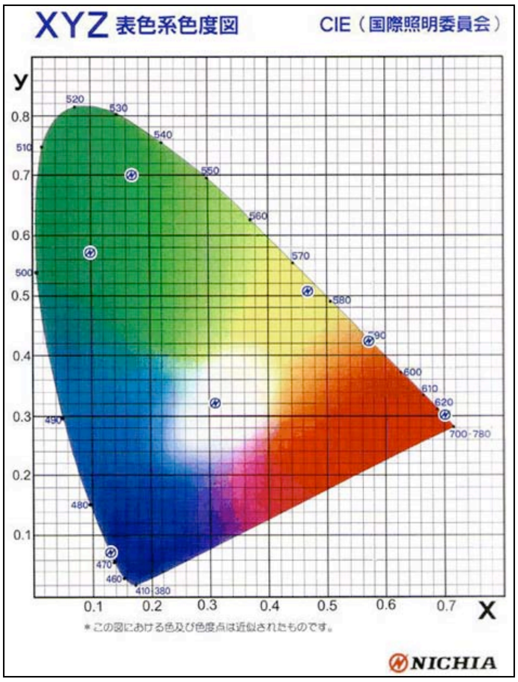

Figure 24 : XYZ colour gamut according to CIE 1931 2° viewing [as reproduced by Nichia®]

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[5] Numerous adaptations, adjustments and further developments have been made to the CIE standards. The list of standards is too numerous. The reader is encouraged to refer to the year given and to make further enquiries into these standards for clarity. The purpose is thus to show that there is some reference criterion to evaluate lit spaces and light giving sources.

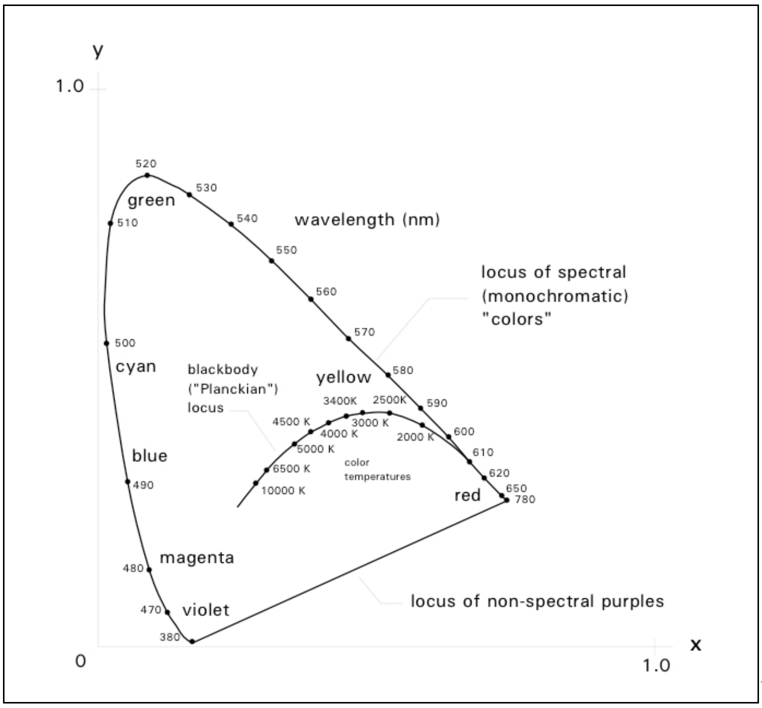

Figure 25: The blackbody radiation line (Planckian locus)

3.3 White light and the coordinate system

The spectrum of white light, known as the blackbody radiation line[6], appears in various shades. Colour is mapped onto the chromaticity diagram with three coordinates. In terms of the tri-stimulus values (X, Y and Z), weight Y represents the perceived luminosity of the light source, and weights X and Z represent the colour or chromaticity of the spectrum [72].

$$x = X / (X + Y + Z),$$
$$y = Y / (X + Y + Z),$$
$$z = Z / (X + Y + Z).$$

$$x + y + z \equiv (X + Y + Z) / (X + Y + Z) \equiv 1 \tag{3.4}$$

[6] This according to the 1964 CIE UV coordinate system which includes the blackbody line over a colour temperature range of 2000 K to 10000 K. The black body radiation line is also referred to as the planckian locus.

z may be obtained from x and y

$$z = 1 - (x + y) \tag{3.5}$$

Hence, the chromaticity coordinate may be expressed by x and y. These simplifications of the coordinate system are there to illustrate how colours may be achieved. Synthetic white light on the other hand, although having coordinates, is the only family of light sources that can be simply represented by its temperature [73].

3.4 Chromaticity, Colour Rendering (Ra) and white light from LEDs

Chromaticity is a description of the quality of colour, independent of brightness/lightness. A white LED is an artificial black body radiator, with a correlated colour temperature (CCT) expressed in Kelvin (K). The CCT gives information about the visual outlook of the LED and its 'whiteness' and can vary according to the beam angle.

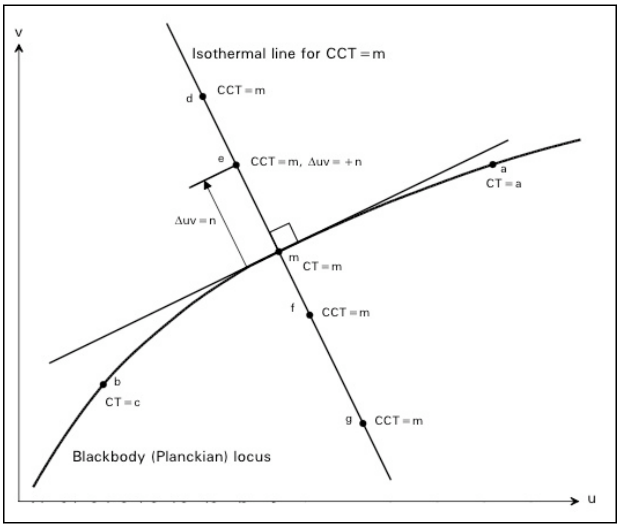

Figure 26: The correlated colour temperature may be 'calculated' from the Planckian locus

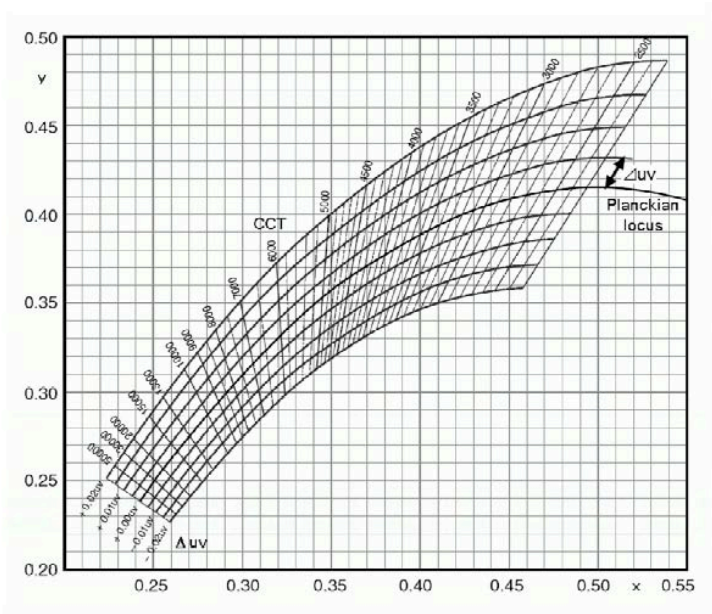

Figure 27: Correlated colour temperature (CCT) through transformation from CIE u-v (1961) to CIE x-y (1931) plane

Figure 28:The specific colour and related 'temperature' in Kelvin of emitted light

Table 10: Black body radiator temperature approximation of various illuminants

Source	Temperature, °K
Candle flame	1900
Sunlight at sunset	2000
Tungsten bulb 60 watt	2800
Tungsten bulb 200 watt	2900
Tungstan/Halogen lamp	3300
Compact fluorescent	4200
WLED	5000
Sunlight plus skylight	5500
Overcast sky	6500

Its rendering ability is described as its ability in rendering the true colour of an object, and is known as the c***olour-rendering index*** (CRI). A system to characterize this property is explained through calculated ***difference***. In other words, a *test* and *reference* illuminant renders colour (which includes hue, saturation and additionally brightness/lightness [67]. These are then recorded and from here the CRI may be calculated. There are different measures to calculate CRI depending on whether the illuminant source lies on or off the planckian locus [67]. It is sufficient to say that the sun renders the best colour and thus has an index of CRI=100.

Table 11: Colour rendering index and application

Application	CRI
all *illumination* purposes	90-100
standard *illumination* needs	70-90
lower quality applications (outdoors)	< 70

3.5 Optical properties

The energy that is distributed spectrally is described by 'spectral' or 'spectroradiometric' terms. The light sources wavelength-dependent response can thus be quantified via instruments like spectroradiometers, spectroscope or multifilter radiometers. There is no *direct* way of classifying LEDs because of the *spectral distribution* of the optical radiation emitted by them. It is neither a true monochromatic source (as emitted by lasers), nor broadband (as with incandescent lamps) but really something between the two [71]. The relative spectral distributions show very narrow bands (20-50 nanometers) for light output. Designers and users require the spectral properties to determine the correct LED for an application.

The spectral tests of LEDs with various colours of Table 12 are illustrated graphically via their spectral response over the visible range. See Figure 29.

Table 12: Test LEDs and their chemical composition

No.	Colour	Chemical composition
1.	white	InGaN (+ YAG phosphor)
2.	blue	InGaN
3.	BG	InGaN
4.	green	InGaN
5.	yellow	InGaAlP
6.	red	GaAlAs

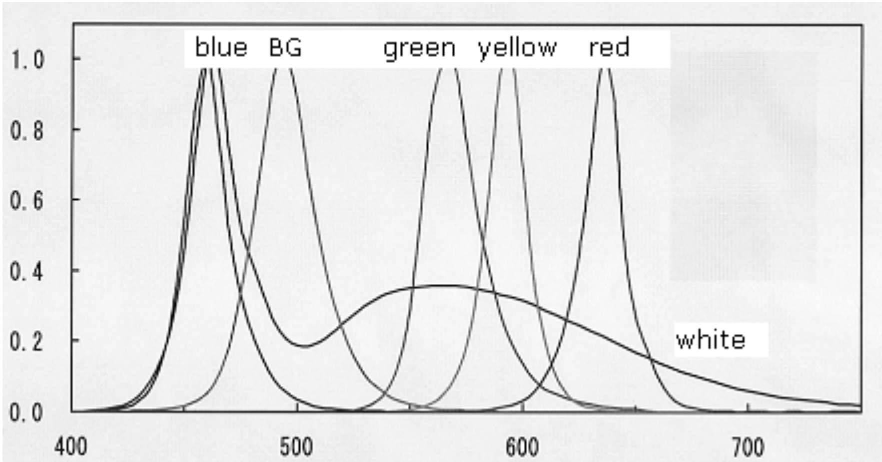

Figure 29: Relative (peak is equal to 1.0) power spectral distribution of monochromatic and white LEDs

A few definitions are necessary.

Peak wavelength λ_p: The wavelength of the maximum spectral power (see relative spectral distribution of Figure 30). The peak wavelength has little significance for practical purposes since two LEDs may have the same peak wavelength but different colour perception.

Full Width Half Maximum (FWHM): The spectral bandwidth at half peak, $\Delta\lambda_{0.5}$ is calculated from the two wavelengths $\lambda'_{0.5}$ and $\lambda''_{0.5}$ on either side of λ_p. $\Delta\lambda = \lambda'_{0.5} - \lambda''_{0.5}$

Center Wavelength $\lambda_{0.5m}$: The center wavelength is the wavelength halfway between the half-wavelengths $\lambda'_{0.5}$ - $\lambda''_{0.5}$.

Centroid Wavelength λ_c: The centroid wavelength is the moment or the mean of the spectral power distribution.

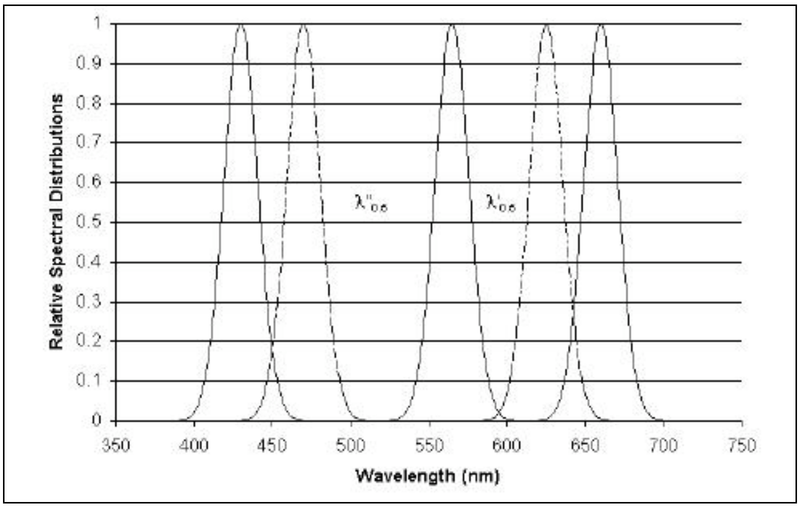

Figure 30: Relative spectral distribution

Dominant wavelength: The dominant wavelength is determined from drawing a straight line through the colour coordinates of the reference illuminant (usually chosen as illuminant E) and the measured chromaticity coordinates of the LED in the CIE 1931 chromaticity diagram. The intersection of this straight line on the boundary on the chromaticity diagram gives the dominant wavelength. It is a measure of the hue sensation produced in the human eye by the LED.

Purity: Purity is defined as the ratio of the distance from reference illuminant (usually arbitrarily chosen as illuminant E) to the measured chromaticity coordinates and the distance from reference illuminant to the intersection with the boundary of the chromaticity diagram. Most LEDs are narrow band radiators, with a purity of nearly 100% i.e. the colour cannot be distinguished from a monochromatic beam. Polychromatic sources have low purity approaching zero.

Viewing Angle or *Beam Angle* (also known as Full Width Half Maximum Angle (2 $\theta_{1/2}$)): The total cone apex in degrees encompassing the central, high intensity portion of a directional beam, from the on-axis peak out to the off-axis angle in both directions at which the source's relative intensity is ½.

Half Angle: The included angle is degrees between the peak and the point on one side of the beam axis at which the luminous intensity is 50% of maximum or half of the viewing angle.

Peak Wavelength, Full Width Half Maximum, Center Wavelength and Centroid Wavelength are all plotted on a scale of (power/λ) vs. (λ).

3.6 LED Measurement and Accuarcy

3.6.1 Measurement Methods

The necessity for reliable measuring methods and equipment for LED development, testing and certification has gained momentum given the rapid rate of uptake. Basic measuring terms will be discussed.

Luminous-intensity (or just Intensity), considered the most important quantity for its characterization is defined as the visible energy flux per unit solid angle in a given direction from a source. It is typically described in units as candela (or millicandela). Three conditions are important to consider for luminous-intensity measurements. The measurements involve a point source, the inverse square law and the assumption of constant illuminance across the detector. The properties of the source are discussed and defined in the section 'Photometric Properties of LEDs' in this chapter. The detectors and various standards for detection are viewed here based on the quantification of luminous-intensity.

The luminous flux per detector area has been given the name illuminance. The unit of irradiance, and illuminance has been given a special unit, the lux (=lm/m)

A point source need not be small [71]. It is dependent on distance from source to point of detection. The angular distribution of various point sources with rotational symmetry (object looks the same with after some angular rotation) can be approximated by:

$$I = I_o \cos^{g-1}\theta \tag{3.6}$$

where, I_o is the intensity normal to the source itself and 'g' can be:

g=1 for an isotropic (property of a source having the same value when measured in different directions i.e. being independent of direction) point source.

g=2 for a Lambertian source

g>30 for an LED point source

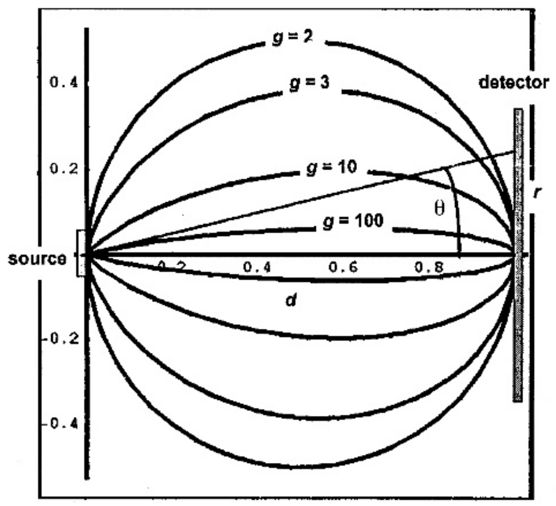

Figure 31: Angular distribution patterns of radiators with rotational symmetry [71]

Given that illuminance E_v at a point on a surface of a calibrated detector normal to the source, varies according to intensity I of the source and then inversely as the square of the distance d between source and detector, illuminance can be calculated as follows when q=0:

$$E = I/d^2 \tag{3.7}$$

The far field distance 'd' can only be determined by finding the $1/r^2$ irradiance (radiometric quantity) fall-off region through measurement. Even in the far-field detection, measurement error can still occur, especially if the illuminance detector is too big. To calculate the 'averaging' effect an equation for the irradiance over the surface area of the detector can be written and solved for as the solid angle subtended by the detector is taken is zero.

$$E(\theta) = d\phi / dA = I(\theta) dw / \pi r^2 \tag{3.8}$$

When approximating the intensity pattern of an LED by $I = I_o \cos^{g-1}\theta$, $E(\theta)$ can be derived by:

$$E(\theta) = \left(I_o / d^2\right) \cdot \left[1 - \left(\left((g+2)/4\right) \cdot (r/d)^2\right)\right] \tag{3.9}$$

The new part to this equation for illuminance accounts for the averaging effect for uncertainty with respect to the true intensity value. One can also derive the relationship between the required radius of the detector and the 'far-field' measurement distance as:

$$d \cdot r \cdot [(g+2)/(4\varsigma)] \tag{3.10}$$

Where, ζ is the uncertainty in question. Therefore, solving for g based on the known fact that the half-angle of the LED for q (detector point, given that orientation is 0°) and realizing that $I(\theta)/I_o$ at the half-angle is 0.5:

$$\cos^{(g-1)}\theta = 0.5 \tag{3.11}$$

where, θ is the half angle.

Solving for g:

$$g = 1 + Ln(0.5) / Ln(\cos(half\_angle)) \tag{3.12}$$

An example is given below:

If distance between source and detector d=1.3m (above reasonable for most LEDs), the radius of detector must be equal to or less than d/24 (=5.5cm) in order to maintain the chosen uncertainty (ζ = 1%). For this geometrical setup, a plane angle of measurement would be the 3.148° ($\arctan(5.5/100)$) and the solid angle subtended would be the 0.003steradians ((area of detection)/100^2).

3.7 Photometric Measurement Properties of LEDs

Solid angle is the surface area on a unit radius sphere. It is described as the projected area from a point through the boundary of an external surface onto a surface of a sphere. If the projected surface area is S, and the radius of the sphere is r, then the solid angle is:

$$\omega = S/r^2 \tag{3.13}$$

The exact definition of intensity of the light source is the *limit of luminous flux in a solid angle divided by solid angle as the solid angle approaches zero* [74]. Our calculation will consider an approximate measure of intensity, which is just *the luminous flux in a solid angle divided by solid angle*. Its unit is candela (cd) and is a value at a point in space in a particular direction. For finite size sources, if the ratio of the distance from the *source* to the *size of the source* is large the approximate and exact results to calculate the illuminance will vary by a small margin. If the ratio is 2 to 1, this value is in the region of 5%. The approximate equation where I is intensity, E is illuminance, L is the luminance and ω the solid angle in steradians subtended by the source at a point far from source is as follows [74]:

$$E = \frac{I}{d^2} = L\omega \tag{3.14}$$

Photometric quantities of white LEDs differ to those of other light-giving technologies. It cannot be overstated how important it is to know them in order to effectively quantify light and efficiency of white light from LEDs. A graphical representation of solid angle is given in Figure 32. Were solid angle is the surface area on a unit radius sphere. The solid angle defined by a whole sphere is 4π and a half sphere is 2π.

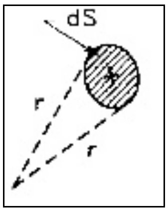

Figure 32: Solid angle with its apex at the center of a sphere of radius r, defines a spherical surface S, such that $\omega = S/r^2$

Flux: Otherwise known as Luminous Flux is π times the Intensity of source in direction of the normal. It corresponds to the power unit 'watt' in radiometry. In relation to the human eye, that wattage is weighted in accordance with its sensitivity to given wavelengths of the source. Lumen is the standard unit.

Luminous Intensity I_v: Flux per solid angle. The exact definition of intensity of the light source is the limit of luminous flux in a solid angle divided by solid angle as the solid angle approaches zero. Our calculation will consider an approximate measure of intensity that is just the luminous flux in a solid angle divided by solid angle. Its unit is candela and is a value at a point in space in a particular direction. It must be noted that luminous flux is described by π times the intensity of the source in the direction of the normal.

The validity of the calculation of intensity is based on two conditions.

- The distance between source and detector should be determined precisely. A goniometric center, the precise position of the emission center, must be determined. This is a difficult exercise.
- Distance between source and detector must be large with respect to the spatial width of the light source (far field condition).

Illuminance E_v: Flux per unit area on a surface when the source is remote from the surface. In standard units the units are lux (lx) or lumens per square meter. E_v is its notation, is calculated by dividing lumens of a source by its area that it illuminates and is measured in lux and represented by lx (lm/m^2). Lux is defined as a unit of illumination of one square meter which is one meter away from a uniform light source thus making 1 cd equal to 1 lx

The inverse-square law: Strictly applicable only for point sources, it states that the illuminance E_v at a point on a surface (a calibrated detector) normal to the source, varies directly with the intensity I of the source (as defined above for various types of sources), and inversely as the square of the distance (d) between the source and the point (detector).

$$E_v = I_v / d^2 \tag{3.15}$$

Luminance L_v: Flux per solid angle per projected area (or flux per projected solid angle per area). It is also described as the intensity of light per unit area of its source. Most formulae for luminance, which has many definitions, are based on the assumption of a Lambertian point source. L_v is its notation represented in standard units by cd/m² [75]. When there are two light sources of the same intensity, one of which has a larger area than the other, the smaller area appears to be brighter. Average luminance is the total intensity, I, radiating from a surface source divided by the area of the source in that direction. Luminance is not constant over the entire area of the source (emitter). Candela (cd) is the unit for intensity.

$$L_v = \frac{I_v}{\omega} \tag{3.16}$$

$$L_a = \frac{I_a}{S \cos a} \tag{3.17}$$

Lambertian Source: A Lambertian source only radiates in one half of the full three-dimensional space, and whose intensity (per unit area of source) varies as the cosine of the angle from maximum output (which is perpendicular to the surface) [76].

$$I(\theta) = I_o \cos(\theta) \tag{3.18}$$

where, I_o is the maximum value of the intensity in the direction normal to the surface.

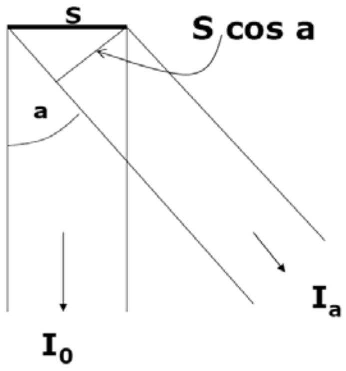

Figure 33: If the intensity varies as the cosine of angle a then the luminance is constant in all directions. This is a Lambertian or diffuse light source

Emittance (of a uniformly diffusing surface): As stated above, the luminous is equal to π times the intensity of the source in the direction of the normal. The *emittance* is the luminous flux per unit area. For Lambertian sources it follows that the emittance is π times the luminance.

Table 13: Summary of photometric lighting units and their abbreviations

Lighting unit	SI unit	Abbreviation
Luminous Flux	Lumen	lm
Luminous Intensity	Candela	cd
Luminance	Candela per m^2	cd/m^2
Illuminance	Lux	lx
Luminous Efficiency	Lumens per watt	lm/w

3.8 Illuminance photometer and the necessary conversions

The illuminance photometer measures lights in lux (lx), the SI unit for illuminance, which is the numerical value for lumen per square meter (lm/m^2). Hence, illuminance considers the incident luminous flux at a point within a defined area (usually the area of the photometer head).

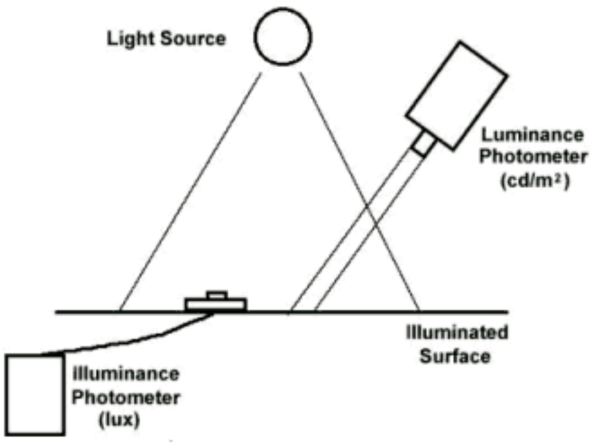

Figure 34: Iluminance photometer versus luminance photometer

Converting lux into the respective values of luminous intensity (cd) and luminous flux (lm) are tedious tasks.

Steps:

- First take reading
- Measure distance from source to surface of detection
- Calculate area of photometer head
- Calculate the hypotenuse of the beam of projected light from source and covering the area of detection.
- Work out the half angle of the cone of detected light
- The solid angle, whose SI unit is the steradian, can be calculated by solving the double integral equation of a hemisphere.

$$\int_0^{2\pi}\int_0^{0}\sin\theta d\theta d\phi = 2\pi\int_0^{0}\sin\theta d\theta = 2\pi[-\cos\theta] = 2\pi(1-\cos\theta) \qquad (3.1)$$

Inserting the half-angle viewing angle into θ of this equation would give a solid angle in steradians. Lumen can be calculated through the product of the measured illuminance and detector area. Luminance can then be calculated by dividing lumens with the calculated steradian per detector area. Intensity can be obtained via two methods. Dividing the measured lumen value by the calculated steradian. It can also be obtained via the Inverse Square Law which give a very close approximate value.

Total luminous flux can be calculated via the Lorentzian or Cosine approximation methods except that the Cosine approximation is less cumbersome. It is a value absolutely necessary for quantifying values related to optical efficiency.

The other method is through putting sources inside an integrating sphere, however, such technology is very expensive.

3.9 Summary

The science of detection, seen in this chapter as radiometry and colourimetry, are essential topics for a designer. They help understand the needs of the user and qualify a set of solutions based on the application. Visible-spectrum LEDs have unique considerations when detecting light from them. These have been detailed under the heading of photometry. This chapter has also detailed the difference in construction of semiconductor technology used for illumination as opposed to signal and indication.

CHAPTER 4
SPECIFICATION AND DESIGN OF THE GABS LUMINAIRE

4. Introduction

Golden Arrow Bus Services (GABS) is a South African transportation company. Initial work by GABS on a white LED-based retrofit was not successful. The problems encountered were related to human perception. Prototypes for a new design have looked at perception extensively. The design of the electrical, optical, thermal and mechanical aspects of the luminaire are described in this chapter. Included are details of the:

- Choice of LEDs
- Amount of LEDs used for the application
- Circuit design for laboratory testing
- Lens dimensions and constraints
- Optics lens design
- Étendue and light capture calculations
- Optimal placement of white LEDs based on thermal and optics considerations

4.1 Luminaire Design Hypothesis

A *luminaire* is a complete electric lighting unit. It includes power supply, light source(s), casing and a lens/cover. A luminaire is able to direct, distribute and focus both direct and diffuse light [77]. This chapter details the theory and method of design of the optics using appropriate LED light sources.

Inside the bus, light's purpose includes ingress, egress and reading without causing unnecessary glare for the passengers or driver. GABS, in its 76 seater buses, use 7 fluorescent tubes recessed into the ceiling. The rapid development of the HB white LED has put it into a general lighting category [78, 79, 80]. Design and test is done to answer the two questions. Are commercially available HB LEDs suitable for general lighting applications? Is the optical system able to distribute the light onto a desired area with a desirable distribution?

Although HB LEDs claim to be for the general lighting market one actually needs to verify through empirical testing whether they are acceptable within three parameters: *quality* (human acceptance), *quantity* (part count and energy efficiency) and *environment* (operating conditions and thermal characteristics).

In previous tests by GABS white LEDs were powered below rated values of current and voltage with no scientifically produced optical system. Without a diffuser cover the lights were distracting to passengers on the bus. A diffuser was then used to reduce glare to passengers but resulted in major energy losses due to blocked light. For uniformity of distribution, it would be ideal to redesign the entire bus lighting system. A retrofit is being considered instead because the redesign would be too expensive. The condition for acceptance is that the white LEDs must first prove that they can give similar or better light levels with better maintenance trade-offs than the fluorescent tube.

4.2 A Review of Past Research and Application Background Information

4.2.1 Maintenance and Application concerns

The utilization of light from LEDs embedded within luminaires is more efficient than the fluorescent and incandescent based luminaires and requires less maintenance [81, 82, 83, 84]. These points must be restated at this juncture as they are very important to a maintenance team that services a large fleet of vehicles which in this case is in excess of 1000 vehicles. Fluorescent *tubes*[7] are not efficient because they degrade quickly due to bus vibration. The rate is not known numerically but is estimated to be 20% based on maintenance information from GABS [86].

[7] At this point, it is important that the reader distinguishes between different types of fluorescent tube technologies. The ***long tube*** type and the modern 'energy saving' ***folded tube*** lamps. There are Low Frequency (LF) and the more efficient High Frequency (HF) ballast circuits that drive them [85].

Extending the lifetime of onboard energy storage devices is another factor being considered while researching alternatives for lighting. If it is possible for a new technology to increase the storage device's lifetime by reducing the load on it, this will improve the performance and energy efficiency of the energy delivery system and reduce fuel consumption.

4.2.2 Background review of optical concepts

There is a lack of literature on 'general lighting' retrofits using white LEDs. It is not known if there is any success in this regard. That said, there are task lighting applications that use Fresnel lenses. Cheng and Uang in [87] have created genetic algorithms to optimize the groove angles for a task lamp to ensure uniformity of distribution and illuminance. Narendran has been the principle author of many journal and conference papers relating to visible spectrum LEDs and in particular application issues related to white LEDs [88, 89, 90].

In terms of optics and étendue calculations specifically for LED systems, Fallicoff [74], Brukilachio and DeMilo [43] and Kaminski [91] have been illuminating in their analysis of the constraints posed by their specific examples. They have detailed clearly the challenges faced in ensuring efficiency for optical systems incorporating white LEDs as light sources for illumination (as opposed to display applications).

4.3 Determining distribution

Considering the entire design and integration of the new luminaire into the bus required a set of design steps. These are listed below:

1. Define an area to be illuminated
2. Measure distance to source
3. Determine angle of distribution
4. Choosing an LED light source
5. A power solution (based on available energy source)

6. Choosing a heat sink

Tabulating results allows one to understand the first three concepts. In relation to the Pythagorean right angle triangle (a two dimensional take on height, lit area and light distribution as listed above), the *opposite* is labeled as *y* and *adjacent* as *x* (see

Figure 35). The *adjacent* value increases while the *opposite* remains constant in the columns of the hypotenuse (r).

The values in the *x* range between zero and 2m and the corresponding change in the *y* range sits next to viewing angle θ in the table. If the intention to make the distribution of light from the white LEDs efficient, the viewing angle must be reduced so that light of specific intensities is not wasted away from the specified lit area. Three tables represent the information for heights 1m, 1.3m and 2m respectively. See Table 14 to Table 16

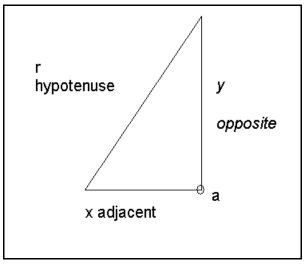

Figure 35: Pythagorean triangle where the detection point for the light source moves vertically and horizontally from point *a*.

In trying to reshape the rays that fall outside the region to be specified a more 'effective' distribution is sought. What is first needed is a clear understanding of the optical solution to be used. This follows shortly.

Table 14: Observing the change in viewing angle when changing height and distance from detector when the height is 1m

x	r	Projected	Theta
m	when y=1	Area	Viewing angle
	m	m^2	y=1
0.10	1.00	3.17	5.71
0.20	1.02	3.27	11.31
0.30	1.04	3.42	16.70
0.40	1.08	3.64	21.80
0.50	1.12	3.93	26.57
0.60	1.17	4.27	30.96
0.70	1.22	4.68	34.99
0.80	1.28	5.15	38.66
0.90	1.35	5.69	41.99
1.00	1.41	6.28	45.00
1.10	1.49	6.94	47.73
1.20	1.56	7.67	50.19
1.30	1.64	8.45	52.43
1.40	1.72	9.30	54.46
1.50	1.80	10.21	56.31
1.60	1.89	11.18	57.99
1.70	1.97	12.22	59.53
1.80	2.06	13.32	60.95
1.90	2.15	14.48	62.24
2.00	2.24	15.71	63.43

Table 15: Observing the change in viewing angle when changing height and distance from detector when height is 1.3m

x	r	projected	Theta
m	when y=1.3	area	Viewing angle
	m	m²	y=1.3
0.10	1.30	5.34	4.40
0.20	1.32	5.43	8.75
0.30	1.33	5.59	12.99
0.40	1.36	5.81	17.10
0.50	1.39	6.09	21.04
0.60	1.43	6.44	24.78
0.70	1.48	6.85	28.30
0.80	1.53	7.32	31.61
0.90	1.58	7.85	34.70
1.00	1.64	8.45	37.57
1.10	1.70	9.11	40.24
1.20	1.77	9.83	42.71
1.30	1.84	10.62	45.00
1.40	1.91	11.47	47.12
1.50	1.98	12.38	49.09
1.60	2.06	13.35	50.91
1.70	2.14	14.39	52.59
1.80	2.22	15.49	54.16
1.90	2.30	16.65	55.62
2.00	2.39	17.88	56.98

Table 16: Observing the change in viewing angle when changing height and distance from detector when the height is 2m

x m	r when y=2 m	projected area m^2	Theta Viewing angle y=2
0.10	2.00	12.60	2.86
0.20	2.01	12.69	5.71
0.30	2.02	12.85	8.53
0.40	2.04	13.07	11.31
0.50	2.06	13.35	14.04
0.60	2.09	13.70	16.70
0.70	2.12	14.11	19.29
0.80	2.15	14.58	21.80
0.90	2.19	15.11	24.23
1.00	2.24	15.71	26.57
1.10	2.28	16.37	28.81
1.20	2.33	17.09	30.96
1.30	2.39	17.88	33.02
1.40	2.44	18.72	34.99
1.50	2.50	19.63	36.87
1.60	2.56	20.61	38.66
1.70	2.62	21.65	40.36
1.80	2.69	22.75	41.99
1.90	2.76	23.91	43.53
2.00	2.83	25.13	45.00

4.4 Illuminance Photometer, Non-uniformity and Specifying test area for Detectors

4.4.1 Photometer and multiple sources

Due to their unique spatial distribution LEDs pose particular problems when quantifying their intensity output at a distance, described as *extended source* detection. This behaviour is due to components of reflection and concentration in some light emitters [76]. When a second source's beam of light intersects the original beam, but at an angle, the measurement of flux in the constant solid angle will be different given the spacing. Figure 36 shows that detection of intensity will be different than the constant value measured for $r \leq r_1$ and $r \geq r_2$.

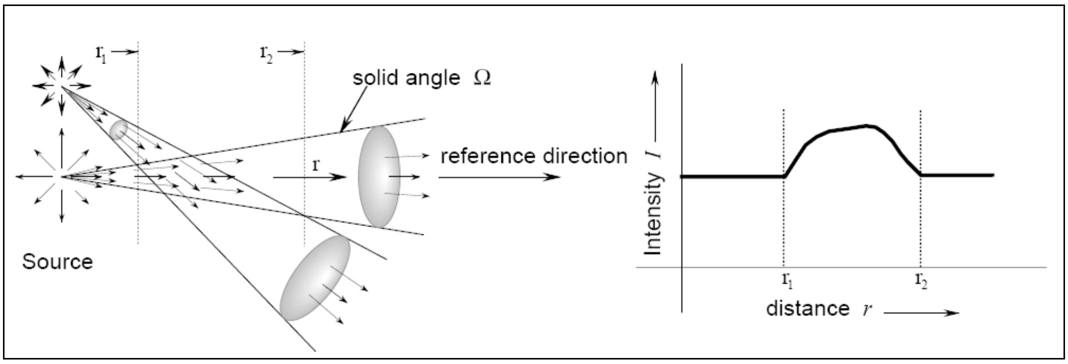

Figure 36: Multiple sources and detection of intensity [76]

Intensity changes with:

- Distance between LED and detector
- Angle with respect to LED at which the measurement is taken
- Size of solid angle used for detection

4.4.2 Specifying lit area

The starting point for any optical system design is to assess what the application is trying to accomplish. Our aim has been to illuminate an area of approximately 1.75m² (a rectangular area 1m X 1.75m) at a distance of 1m from the source. Tests were done with a variable height setup. The vertical arrangement allowed us to test at different heights and at different angles from the mechanical axis with ease. The maximum allowable height was 2.1m. See Figure 37 and Figure 38.

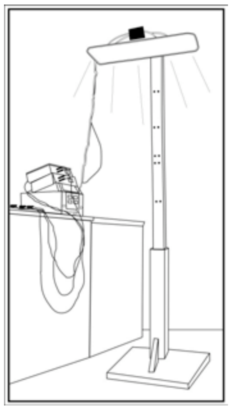

Figure 37: Vertical test rig with variable height adjustment. Power supply, scopes and meters are arranged alongside the rig to easily record data

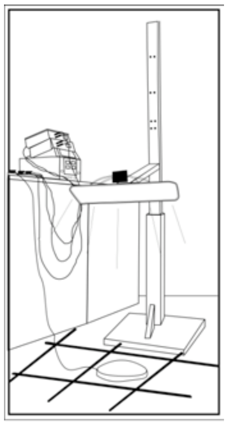

Figure 38: A height adjustment is made when data for angular distribution is needed

4.5 Illumination requirements and luminaire dimensions

4.5.1 Dimensions and illumination requirements

Our aim was to design a single luminaire using commercially bought LED technology. The illuminance (lux) level in the bus was tested under a number of conditions. Deon Scheepers, the Radio/Electronic Systems Manager from GABS, gathered this data. Table 17 is the average lux level of three different buses. The data is taken at a distance of 1.3m from sources i.e. distance from passengers' laps to ceiling. The three conditions used to check and then compare when the fluorescent was on were under daylight, inside the GABS workshop and an outdoor shaded area. These values are checked against the normal (no fluorescent light). Vast variance in detected illuminance was the reason why a single luminaire was tested in a dark room. Data of this kind would give the reader a fair assessment of what is currently installed and to what requirements the new design needed to match or better.

Table 17: Average illuminance levels of three buses taken under three conditions when lights are on and off; daylight, workshop and shaded area

Average lux values											
Seat Position	Lux 1	Lux 2	Lux 3	Lux 4	Lux 5	Lux 6	Lux 7	Lux 8	Lux 9	Lux 10	Lux Cab
Daylight: Passenger lights OFF	1449.7	639.7	696.3	679.0	726.7	805.7	710.7	704.0	652.3	610.7	1313.3
Workshop: Passenger lights OFF	40.3	7.3	7.7	8.0	7.3	7.0	8.0	7.0	8.0	8.3	47.3
Workshop: Passenger lights ON	52.0	42.0	36.7	32.7	39.7	35.0	51.0	27.3	8.7	8.7	119.0
Shaded area: Passenger Lights OFF	73.7	16.0	17.0	14.0	28.0	26.0	56.3	58.0	120.7	65.0	108.7
Shaded area: Passenger Lights ON	94.7	43.7	39.0	38.0	51.7	50.0	94.3	83.7	135.0	61.3	172.0

For the retrofit, lighting up the bus will require more than one LED per fitting. This increases the complexity of design, which must consider multiple point sources and the impact they will have on each other as well as the light distributed. Multiple point sources can cause a variation in the intensity of the output and decrease usability.

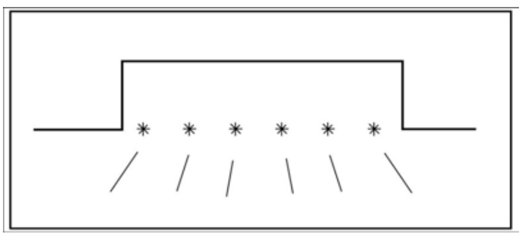

Figure 39: A cross section view of a string of 6 Luxeon LEDs in a fitting

4.5.2 Bus Layout

Most of the new buses have the following layout and are the parameters within which we have designed a new luminaire with a ceiling to floor distance of 1,95m and a ceiling to measuring point (laptop height) of 1.3m.

Figure 40 illustrates an artist's impression of the bus layout. The lighting layout is as follows:

- 7 light fittings down the length of the bus, 4 on the driver side, 3 on the opposite side.
- Approximately 83cm between the two rows.
- Approximately 174cm separating lights within the row.

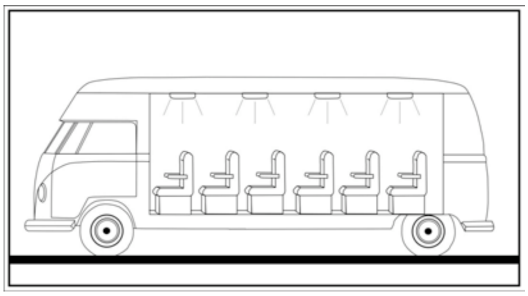

Figure 40: An artist's impression of the general arrangement of Golden Arrow buses through a cross-section. The height from floor to ceiling (1.95m), spacing between luminaires (1.74m) and spacing from each row of light sources (0.83m) is shown

4.5.3 Luminaire and lens limitations

There are physical limits in relation to the width of the luminaire, the depth of placement and effectively capturing the rays of light from the source. There are also limits to the sizing of the luminaire i.e. the depth of grooves and its thickness. The other physical factors to consider are the heat sink size and mounting, veroboard length, and circuitry. Light lost due to these limitations must be weighed up. The length is 614mm, width is 14mm and depth is 35mm.

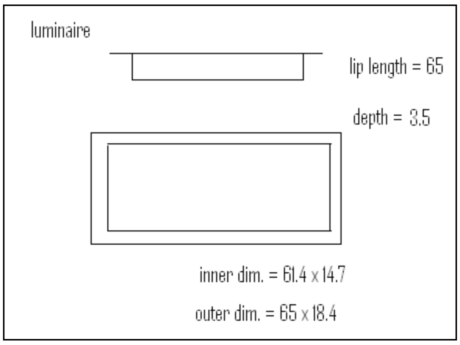

Figure 41: The top diagram shows a side view while the bottom is a top view representation of the metal casing for the luminaire. Dimensions are listed within the figure.

4.5.4 Lens Dimensions and Optic Material

Polycarbonate is ubiquitous in the forward lighting lenses of motor vehicles. Based on a test bed able to mill polycarbonate with dimensions 200mmx150mmx50mm our intention was to fabricate the lens in four pieces and then join them. Local industry (Maizey's and Plastimid) advised not to mill polycarbonate as its transmission efficiency after milling would be poor. It was suggested that making a mold for injection-molding and then fabricating a single lens using polycarbonate would be a better option in terms of efficiency. Hence, upon industry advice, we used acrylic (commonly known as Perspex or Plexiglass). Its transmission efficiency is said to be better even after the material is milled. Perspex is a good solution, despite being a second option, because it is cheaper than polycarbonate and can be milled with ease. The refractive index η for acrylic is between 1.490 -1.494 while that of polycarbonate is 1.584 – 1.586.

4.5.5 Fabrication

The initial manufacturing of lenses was done on milling machines. These machines are the property of the FabLab. The assistants at this open resource center converted the computer-based designs (Rhino CAD) made by the author into models acceptable by the milling machine (Modella). They also scaled down the designs.

It was essential to fabricate these lenses to understand the way light from the sources would react to the Perspex and the shapes designed. The arrangement of the LEDs, its distributional qualities and comparative illuminance levels were important to quantify on a physical level.

4.5.6 Estimated Transmission Efficiency

As in the case of the translucent lens cover for the fluorescent fitting, there will be some transmission loss in its output. Optics considered attempted reducing losses of peak intensity by redirecting the distribution pattern. For a typical prism (Fresnel) design an efficiency of 90% is considered while an efficiency of 94% for a lens using an acrylic material (Perspex) is recorded. The efficiency of the acrylic was measured in the laboratory where all other optical tests were done.

4.6 Comparing light sources

4.6.1 Assumption of the lumens output of the fluorescent

The Phillips fluorescent, TL 20W/33-640 RS, is a 20W tube with a total of 1100 lm at 55lm/W [92]. An estimate of usable lumens (direct, reflected and refracted) gives us a loss of 25% for the fitting (metal casing). Further light is lost through transmission through the translucent lens. From test results this renders a 26.9 % loss and leaves us with a *luminaire* efficacy of 29.2 lm/W. This equates to approximately 584lm that are usable. The tube has a maximum/optimal lifetime range of 5000h (209 days of continuous running), without considering the effect of the road vibration.

4.6.2 Choice of LEDs and the quantity

The information of the fluorescent lighting system's optical and electrical efficiency allows us to specify what types of LEDs can be purchased. Fortunately, researching commercially available white LEDs was not a problem. Information, data and prices, was freely available especially by those companies with a good rate of market success due to LED reliability. In some instances local distribution agencies charged four times more than what it would cost to bring them to South Africa through an internet purchase. The challenge that was faced, and the reasons why we arrived at the following three types of surface mount LEDs, was that of importing LEDs at a reasonable price and within a strict time frame.

The tables below hold critical design information of the bought LEDs. The information held within these tables relate to flux, temperature phenomena, electrical characteristics and optical properties. The datasheets for each of the three LED can be found in Appendix B.

Table 18: ProLight characteristics

ProLight Flux Characteristics	350mA	Ta = 25 °C	PG1N-1LXS
Luminous Flux	Luminous Flux	Maintenance	
Min. (lm)	Typ. (lm)	hours	
30.6	40	-	

Electrical Characteristics			
Forward	Dynamic	Temperature	Thermal
voltage	resistance	coefficient	resistance
Vf	ohms	mV/K	°C/W
3.55	1	-2	15

Optical Characteristics				
Dominant	Total Included	Viewing angle	CRI	Efficiency
Wavelength	angle		Ra	lm/W
	0.9v (degree)	2 theta 1/2		
		(degree)		
5500K	160	140	-	40

Table 19: Philips Luxeon K2 characteristics

Luxeon K2	1A	Ta = 25 °C	LXK2-PW14-U00	
Flux Characteristics				
Luminous Flux	Luminous Flux	Maintenance		
Min. (lm)	Typ. (lm)	hours		
87.4	100	50,000		
Electrical Characteristics				
Forward	Dynamic	Temperature	Thermal	
voltage	resistance	coefficient	resistance	
Vf	ohms	mV/K	°C/W	
3.42	1	-2	9	
Optical Characteristics				
Dominant	Total Included	Viewing angle	CRI	Efficiency
Wavelength	angle		Ra	lm/W
	0.9v (degree)	2 theta 1/2		
		(degree)		
6500 K	160	140	80	40

Table 20: Osram Golden Dragon characteristics

Golden Dragon		350 mA	Ta = 25 °C	
Flux Characteristics				
Luminous Flux	Luminous Flux	Maintenance		
Min. (lm)	Typ. (lm)	hours		
45	52			
Electrical Characteristics				
Forward	Dynamic	Temperature	Thermal	
voltage	resistance	coefficient	resistance	
Vf	ohms	mV/K	°C/W	
3.2	1	-4	15	
Optical Characteristics				
Dominant	Total Included	Viewing angle	CRI	Efficiency
Wavelength	angle		Ra	lm/W
	0.9v (degree)	2 theta 1/2		
		(degree)		
5600 K	-	120	80	40

4.6.3 Matching LEDs to the Application

Although initially three brands of white LEDs were purchased according to the lighting requirements, only a single type was chosen to demonstrate the design concept. A single Luxeon K2, LXK2-PW14-U00, dissipates 3.72 W when driven at 1A and emits a total of 100lm. It has a total efficacy of 26.88 lm/W and a lifetime of 50,000h with 30 % lumen depreciation over that period of time [93]. This timeframe equates to 5.7yrs of continuous operation.

4.7 Integrating Luxeon K2 LEDs into design

4.7.1 Degrading conditions

The perceptibility of task under *degrading conditions*[8] is a design concern. Hence, despite knowing what type of optical system is to be implemented, we first had to ask whether a high intensity beam of light inherent to LED sources is a disadvantage for bus lighting? These degrading conditions with directionality might be disadvantageous on three grounds namely *glare*, *spotting* and *uniformity of distribution*.

Glare is the high contrast between ambient light and source (direct light into the eye). Glare may cause people to be disturbed by the intensity especially since the source at its shortest distance from the average passenger's eye's is roughly 300mm. Studies undertaken by the Shibaura Institute of Technology and Toshiba Lighting and Technology Corporation clarify the influence of LEDs on discomfort due to glare. Multiple LEDs and various arrangements of LEDs have been tested. The research describes that the closer the ratio of luminance of the peripheral area against luminance of the LED lighting (luminance of the peripheral area / luminance of the LED lighting) is to 1, the smaller the discomfort glare [94].

Spotting is an effect produced by the old signal epoxy-coated 5mm through-hole LEDs. The effect can occur when multiplexing any number of surface mount LEDs (like the ones proposed for this system). The punctuate (singular dotted sources) nature of the matrix of an LED fixture further disadvantages integrating many together into a fitting.

[8] This term is not in reference to the chip degradation over time.

Uniformity across the surface of lit area, each individual source in LED lighting and the spacing intervals between sources are considered important [94].

4.7.2 Spatial distribution of a single Luxeon K2 LED (Lambertian source)

The impact that multiple LEDs will have on distribution pattern is important to consider, as it is the aim to smooth the distribution pattern across the desired area of illumination.

An ideal uniformity curve at the point of detection should be flat/even, unlike the distribution given in Figure 42. Can this be achieved given the diagrams for spectral emission? Since there is a variation between peak and minimum intensity, it has become a design consideration. In other words, can the system be designed using the angular roll-off of Lambertian sources?

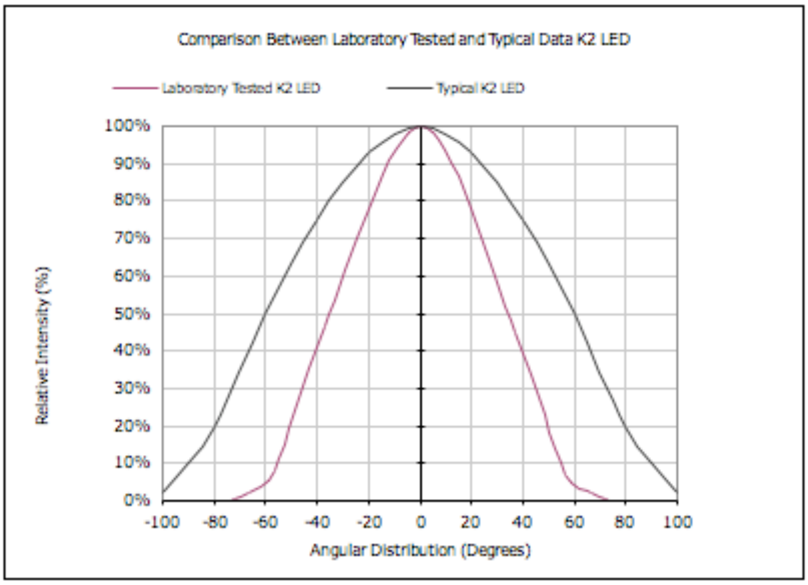

Figure 42: Comparison between spatial radiation of illuminance photometer tested and goniophotometer (spherical) tested single Luxeon® K2 LED. The former is tested at a UCT laboratory while the latter is taken from the LEDs datasheet. This is not a fare comparison as much light is lost to the environment when using an illuminance photometer

4.7.3 Multiple LEDs and distribution

The initial estimates of the area to be illuminated under the center of the LED retrofit helped to put the interaction of each lit area per luminaire into consideration. The interaction between two fittings and how best to optimize this angle to ensure that there was sufficient cross illumination was considered. In doing so we first looked at each light source. Then, how they would interact when lined up on a PCB.

It can be seen in Figure 43 that the spatial distribution of the single LED does not change much when two LEDs are placed at separate intervals despite there being a change in this interval distance. It is the peak intensity and the full width half maximum (FWHM) that is further extended, changing the average illuminance level in a narrow region below the unit. The spatial distribution of six K2 LEDs represents a similar pattern. See Figure 44.

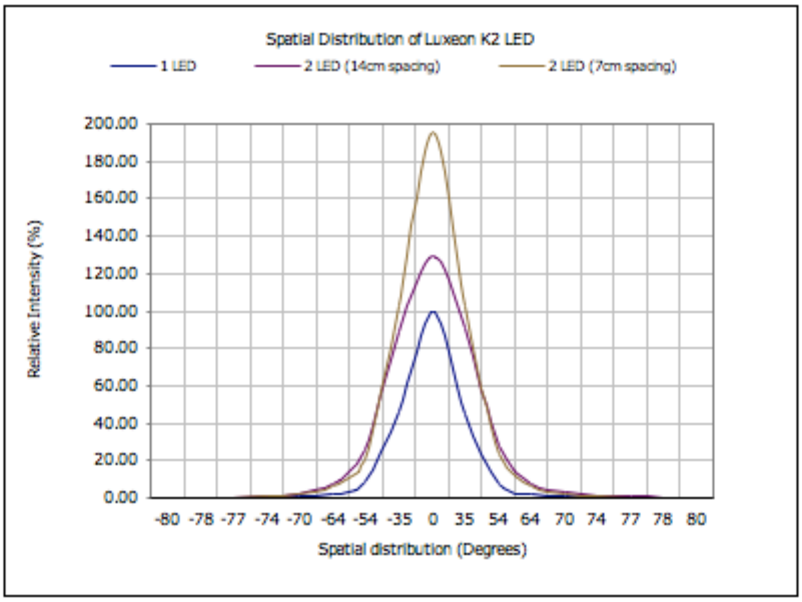

Figure 43: Extended spatial distribution of a single LED, two LEDs spaced 14cm apart and two LEDs spaced 7cm apart

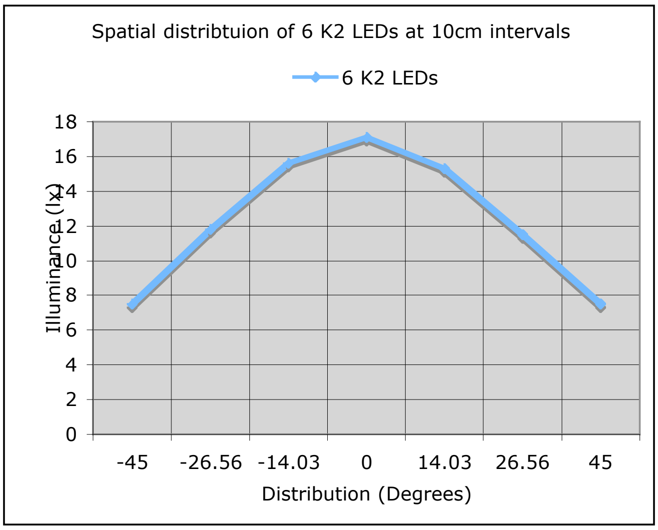

Figure 44: Distribution pattern of 6 K2 LEDs spaced 10cm apart and tested at 1m away

4.8 Proposed Solution

The half-intensity viewing angle of the chosen white LED is so large (120º), the white LEDs had to be placed along the central axis down the length of the fitting. This was done in order to capture the widest rays of light from the sources. See Figure 45. If rays of light are lost due to reflection and absorption on the inside surface of the metal casing the total light output would reduce and intensity of the fitting and empirical predictions would become invalid. When clustered closer together, there are heat convection and conduction problems that must be considered in the mechanical positioning of the LEDs.

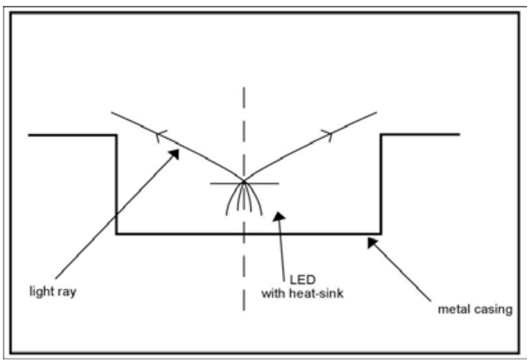

Figure 45: Depth and alignment of LEDs within metal casing of luminaire

4.8.1 First Source Test Results

The fluorescent fitting was tested at the same height as was tested in the bus (1.3m). A single LED was also tested. These results are cognizant of the fact that the photometric testing equipment of the bus company and the one used for lab testing are of the same type (purpose) but are not the same kind (brand). From here on though, all tests were to be done with the same Extech illuminance photometer [95]. See Appendix C for the photometer's datasheet.

4.8.2 Placement of LEDs

For uniform light distribution, two choices exist. Either space the lights closer to each other so that there is further overlapping, or introduce collimating optics to refract radial light rays from the outer edges of the source closer to the defined illuminated area.

A 20° half-angle viewing angle for LED beam intersection was first considered. This gave a distance of 29mm between consecutive optical axes. Extrapolating from an overlap of peak intensity in addition to twice the intensity at 20° (92% of peak intensity) gives the approximate illuminance at the desired distance. The total effect is *a multiplication of 2.4 of the intensity*. The lux level at the center regions of the fitting (if LEDs remain in the linear arrangement) a distance of 1.3m away is predicted to be 3.12 (= 2.4x1.3). This is not the most optimal considering that the column of light below the center of the fitting is bound to be the most concentrated with light. The luminaire will be viewed by a passenger whose expectation is that the area below it be sufficiently illuminated and uniform. Light must be effectively distributed.

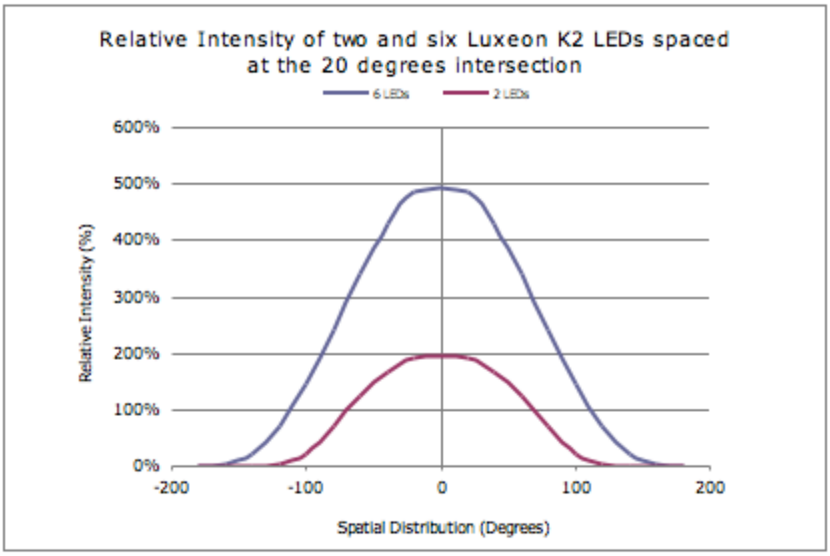

Figure 46: Angular displacement and relative intensity overlap based on the placement of two and six LEDs with a 20 degree intersection [Manipulation of Datasheet information]

4.8.3 Spacing Calculations and Overlapping

The first limitation is the length between source and lens. At a distance of 40mm between source and lens, the placement of 6 LEDs is designed as follows. Using Pythagoras, the LEDs are calculated 14cm away from each other. This is a very large distance considering that a point source is no more than a few square millimeters in size. This interval spacing is further reduced because the metal casing given by GABS will not be sufficient to hold 6 LEDs at that spacing.

The images below are a relativistic interpretation of intensity based on angular intersection of spatial distribution and the peaks of emitted beams and how the overlapping of each beam affects the other. This is what is expected (and gained) if nothing separates light source from lit environment. It will, to a degree, compensate for the use of point sources based on the overlapping.

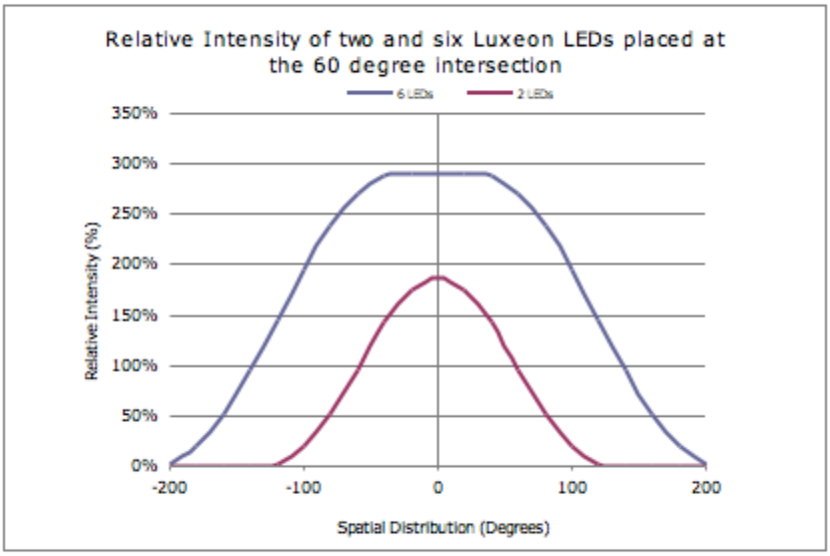

Figure 47: Angular displacement and relative intensity overlap based on the placement of two and six LEDs with a 60 degree intersection [Manipulation of Datasheet information]

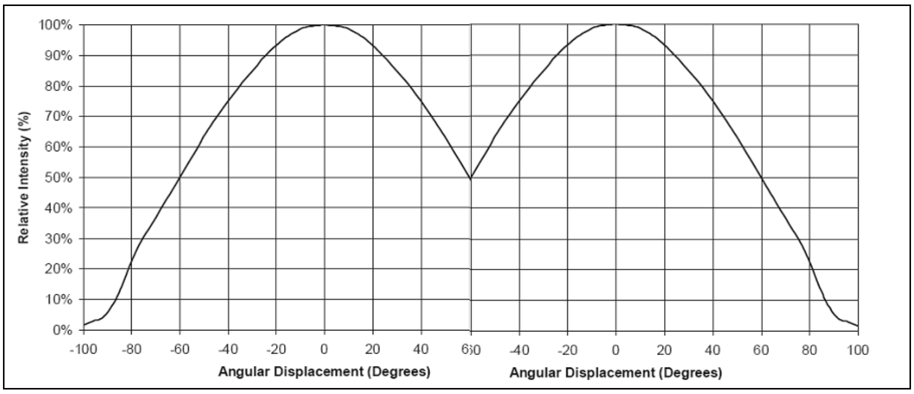

Figure 48: This figures illustrates the relation between angular displacement and relative intensity when placing two K2 LEDs together. Two point sources spaced to overlap where each source emits 50% of its beams intensity. [Manipulation of Luxeon K2 Datasheet information]

Referring to the results in Table 17, the peak intensity results of a single LED will not be sufficient at a distance of 1.3m, considering that the centre of the LED was sought during placement of the detector.

4.9 Inherent qualities of LEDs and optic solutions

The technology has been designed to reduce the thermal stress on the die in order that more light is extracted from the entire package. However, because of the new LED encapsulant design, the viewing angle is so large and has a half-intensity viewing angle of 120°-140°. This results in a loss of light into a space needing no light

For white LEDs it may seem contradictory to use optics as the technology radiates in a 2π hemisphere as opposed to vacuum tube technology that radiate in an entire sphere (4π). The left-most LEDs rays in Figure 49 are redirected. After working out the physical limits of the proposed optic used to increase the efficiency for the final fitting, we fabricated a lens.

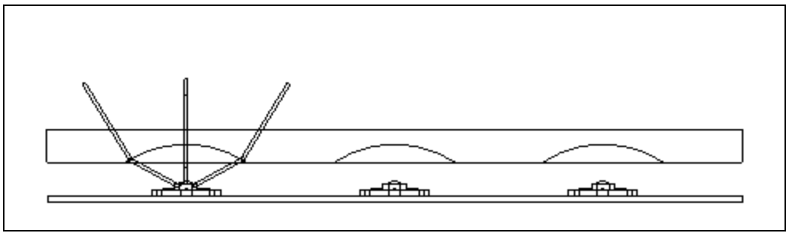

Figure 49: Collimating optics uses the concept of reflection, refraction and reflection-refraction to shape light rays to create a desired distribution (left most LED)

4.9.1 Types of optical systems

For this system, it was necessary to discriminate between two main types of optics, namely imaging and non-imaging systems. Imaging systems transfer a representation of the object to the detector (illuminance photometer, eye etc.). In this application we do not require imaging. Non-imaging systems collect, disperse, resize, focus or collimate light. It is the collimating property of Fresnel lenses that we will use for this design.

Table 21: The measures for non-imaging lens performance are as follows [Source: Edmond Optics® instrument catalog www.edmundoptics.com]

Throughput	Measures energy transmitted through the lens system
Field efficiency	Systems ability to accommodate large detector area or source size
Spot size (for focusing systems)	Used to evaluate a focusing lens's performance.
Angular resolution	Minimum angular separation needed between two objects in order for lens system to distinguish them

The distance from lens to object/source or lens/image plane typifies the characterization of an optical system solution. The relationship is known as the *conjugate* distances. Application solutions can be divided into three types of conjugates; *Finite/Finite*, *Infinite/Infinite* and *Infinite/Finite*. A finite/finite conjugate design focuses light from a source down to a spot. An infinite/infinite conjugate application takes incoming collimated (parallel) light, changes the beam diameter according to the magnification point and emits the collimated light, while an infinite/finite conjugate design combines the process of focusing a source placed at infinity down to a small spot. This application is an *infinite/finite* one [96].

4.10 Flat Fresnel Optic

While realizing that our aim was to redirect peak intensity of the K2's distribution pattern, preservation of the light energy is essential. This must be done without squashing this distribution pattern by a random scatter of light. Collimating optics, come in two varieties:

- Reflecting
- Refracting

Reflecting elements commonly use cavities with metalized coating. They have a straight or parabolic profile. Refracting collimating optics has been used extensively in signal and automotive forward lamps. They are convex shaped with many derivatives (dual, plano and collapsed). Refracting types are more efficient and uniform than their reflecting and non-collimating designs.

Three lens types that are possible namely encapsulation, flat Fresnel or Total Internal Reflection (TIR) lenses. When considering the physical constraints and human factors related to this application the flat Fresnel is the most desirable. Despite the associated losses the flat Fresnel will be tested in the reverse direction as can be seen in Figure 50

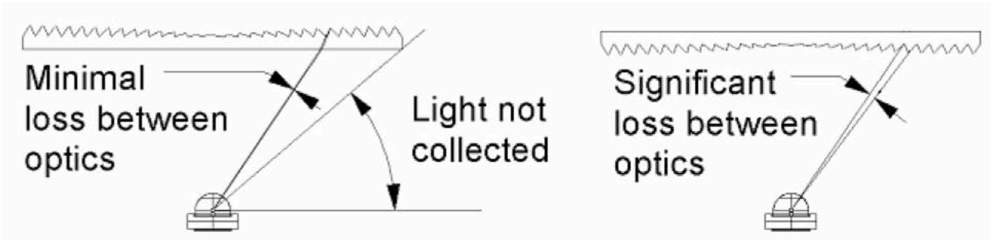

Figure 50: Flat Fresnel lens

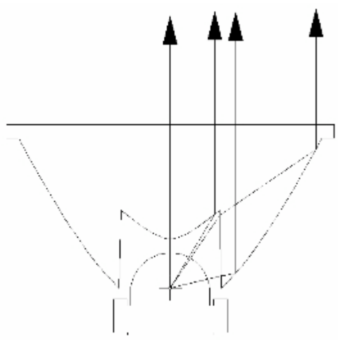

Figure 51: Encapsulated optic

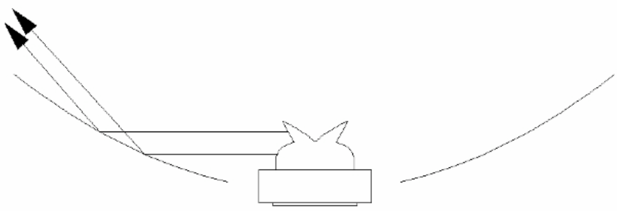

Figure 52:Reflector with side-emitter

The Fresnel optical element is a refracting type collimating lens and Figure 53 is a graphical representation of the concept of the Fresnel that turns a large plano-convex optic with curvature (aspheric surface) into jagged edges.

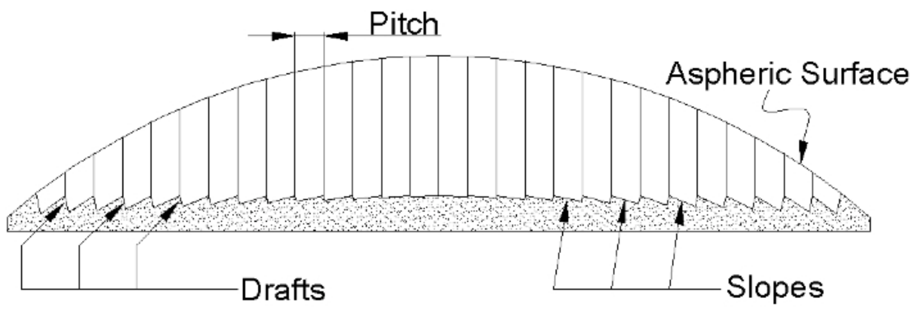

Figure 53: Plano-convex lens based on Fresnel's idea that surface curvature gives focal power

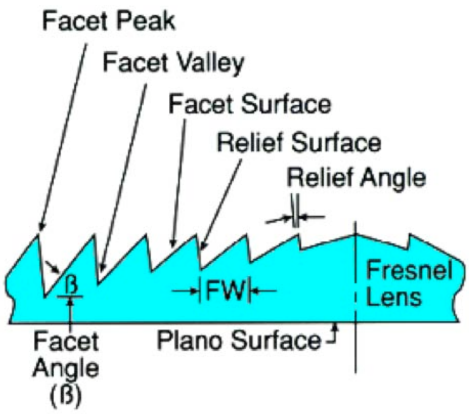

Figure 54: A graphical description for a Fresnel design

The first of the refracting-type lens designed is a traditional Fresnel with concentric jagged-edged prisms that form a lens. See Figure 55. It shall be referred to as the *Circular Fresnel.* The second, an adaptation of the first design, is called the *Linear Fresnel*. It extends the jagged edges of the Fresnel region down the length of the lens. See Figure 56. Laboratory testing and then final manipulation of the luminaire for implementation on the bus is discussed in detail in the next chapter. Investigating the efficiency and distributional trade-offs of the two lenses is also done.

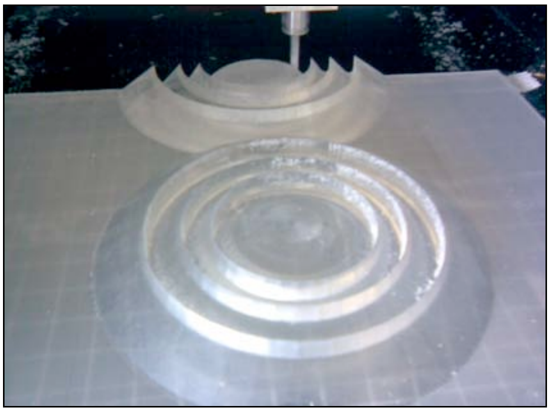

Figure 55: Circular Fresnel design

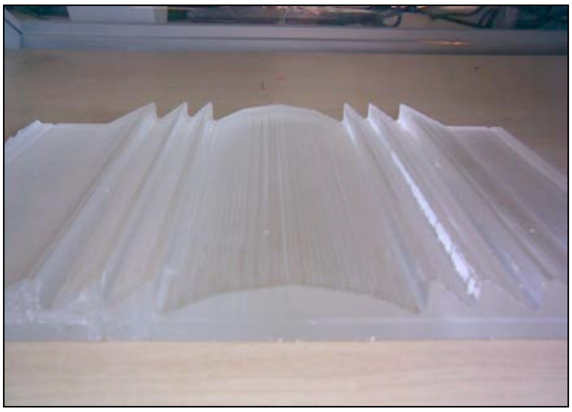

Figure 56: Linear Fresnel design

It is expected that the light travels from the white LED to a uniquely designed lens surface and changes the direction of the beam of light. The ***exitance angle*** to the normal of the LED (centre of LED die) will become smaller at the far field as a result.

4.10.1 Linear Fresnel

The diagrams are a manipulation of the spatial radiation patterns of white Lambertian LEDs. The relationship of these figures is that there is an angular change, from 0° (peak intensity) to 90° (almost zero intensity). The manipulation of this specific output pattern is based on height from source to lens, distance between each source and the intensity that is desired.

The reason why we had chosen a Linear Fresnel arrangement is because the bus lighting arrangement in done in a particular fashion. See Figure 40. The light at the top and bottom of the rectangle with shorter width remains uncollimated while the rays that are likely to hit the eyes of passengers along the aisles and to the window are turned downwards. It is also based on glare reduction for passengers that stand in the bus. Not all passengers are seated when the bus is in use. Estimating the angle of each linear groove was done using Snell's Law of Refraction. Three grooves on each side were used initially from the optical axis to collimate the light. The first order approximation is important for making initial estimates and designing a system and its limits (how loose you want to be on efficiency of collecting the light).

The ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant given that the incident ray, refracted ray and the normal to the surface at the point of incidence all lie in one plane. The refractive indices of incident and refracted ray mediums were considered. Since the angle that we have chosen to limit the Fresnel is a 60° viewing angle, this has set our placement of each LED on the same surface at a particular distance from each other. Now we can set the final area of illumination and the limit of the angle of distribution. This angle will be in the angle of reflection at the edge of the Fresnel lens. At the edge ray (limit), the calculation of angle which we set to 80° from the optical axis. The mechanical axis is then taken as the epicenter of a single LED.

We have chosen that the intensity range of 100% to 80% will be transmitted without any refraction. The half-angle viewing angle from 0° to approximately 35° will shine directly through the convex-shaped lens. The next step is to define the incident angles of the Fresnel and with what accuracy we wish to refract the light with a viewing angle between 35° and 60°. We shall keep the initial design simple and use three grated angles on each side of the optical axis.

The center of each is set to turn the angles to collimate the output of the LEDs. These incident ray angles are 39.1º, 47.4º and 55.8º. The angle of the refracting surface needs to be calculated given that the angle of collimated ray is set to 0°.

Table 22: Physical characteristics of the linear Fresnel lens design

Linear Fresnel			
Radius curvature (mm)			
Facet Number	Facet angle (θ)	Pitch (mm)	Relief (θ)
1	54	4.165	0
2	61	8.33	0
3	66.5	8.33	0

In trying to work out the angle of incidence, angle of refraction and the angle of orientation of the top exiting surface of the Fresnel we needed to manually draw and calculate angles. The top surface is then worked out based on the initial refracted property. By extending rays and normals to surfaces we were able to solve for the angles. We then realised that these results were limited to a certain orientation. A more comprehensive set of result was needed. Thus, manually calculating the values of the incident and refracted ray angle from the normal had to be done when the orientation of a parallel surface - to the first medium of contact - was changed in a clockwise direction. See Figure 57.

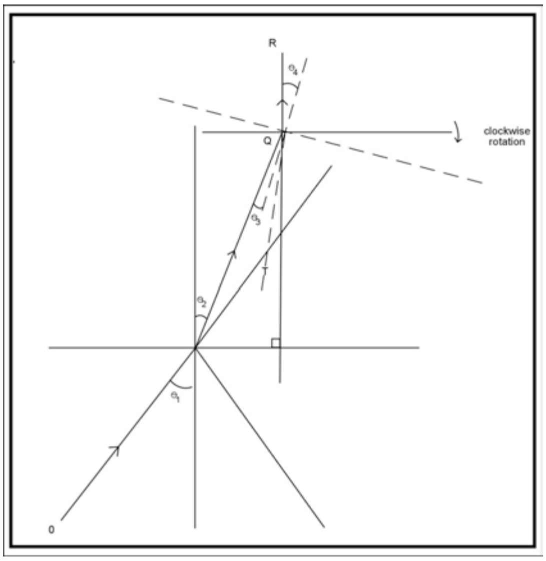

Figure 57: Angular rotation of top surface of lens to direct exiting ray QR parallel to the optical axis

4.10.2 Other configurations for the lens design

The design of this lens is being checked against another. Although the fundamental technique for collimating the light rays will remain the same, a Fresnel with concentric serrated edges will be used to see the effect it renders.

4.10.3 Incident and refracted ray angles for multiple media

For clarity, Figure 57 should be referred to in the following discussion of ray-tracing design. For the region of Fresnel refraction:

- Incident ray OP has a calculated angular range between 35° and 60°.
- The angles are split up in three divisions so that each will have their own 'Fresnel edge'.
- All angles between 35° to 60° are converted to radians.
- The refracted ray angle to normal is calculated from Snell's Law $n_s = \sin(i)/\sin(r)$

The condition of these tests and results are that the distance between the source and bottom surface of the lens cover (focal length) is 35mm. The Excel spreadsheet allows us to plug in any desired distance from source to bottom surface.

The angles of the edges of the Fresnel are floating in space. It was necessary for us to calculate systematically these angles in reference to the optical axis and the initial plane of contact of incident ray.

The refracted ray PQ is treated as the incident ray for orienting the exit rays in a parallel fashion. The incident angle is taken from the desired exit ray QR that is parallel to the optical axis (centre of the LED).

- Second plane of incidence is rotated in the clockwise direction.
- The ray of LED light is moving from a dense medium into one that is less dense.

- Now $\sin(r)/\sin(i) = n$ is the equation for the calculation of refracted angle to incident based on the material's refractive index.

The difference of the angle of refraction, the amount of angular rotation about the point of incidence and the initial plane parallel to the first incident plane is calculated. If the calculated angle is 90°, then the collimated ray is perpendicular to the first plane of incidence.

Once the angle of incidence of the ray PQ is parallel to the normal of the second plane of refraction the values of incidence and refraction become negative. This does not cause any problems in calculation. Our intention was to find out the angles of the Fresnel edges for an intensity range of 50% to 100% of the Luxeon K2 white LED.

These three angles (relative to the the first point of incidence of ray OP) to the right of the optical axis when looking down the length of the luminaire are between 53°-55°, 60°-62° and 65°-66°. For the left side of the optical axis, these angles are 180° minus the range. Thus, they are 125°-127°, 118°-120° and 114°-115°.

Table 23:Physical characteristics of concentric lens design

Circular Fresnel			
Radius curvature (mm)			
Facet Number	Facet angle (θ)	Pitch (mm)	Relief (θ)
1	54	7.2	0
2	61	10	0
3	66.5	14	0

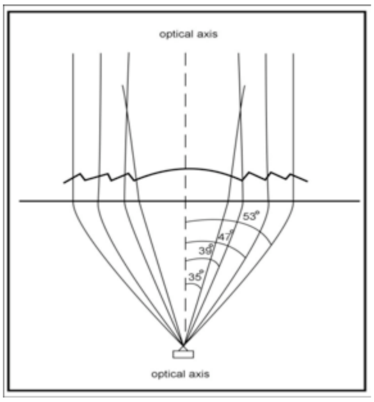

Figure 58: Ray tracing at critical angles. Light is extending from source through the plano-convex lens to the lit environment.

4.11 Lens dimensions and calculations

4.11.1 First order approximations

In designing the convex section of the concentric Fresnel lens, a first order approximation that does not account for aberrations of the system is done. This also known as geometric optics. Properties of the optical platform such as height and conjugate distance are variables considered through the design phase. For the lens itself, the parameters such as the refractive index, medium it occurs in and the radii of the curvature of the surfaces can be calculated by using a 'lens-makers' formula.

Two steps are considered. For the area between the optical axis and edge ray i.e. before the beginning of the Fresnel design, a geometric optics technique to collimate a point source's rays is considered.

A dual-convex collimator lens with the following formula:

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{T(n-1)}{R_1 R_2 n}\right] \tag{4.1}$$

Where,

f = focal length
n = index of refraction of the lens material
R1 = radius of lens surface nearest the LED
R2 = radius of the other lens surface
T = thickness of the lens

The focal length is long (i.e. the thickness of the lens T is less than one sixth of the diameter of the lens). These two conditions and a final consideration, the light sources' flux distribution, change the above equation.

A correction factor C for the spherical aberrations that occur due the edge rays of the LED not being close to the optical axis, is used in the equation. The radius of the bottom surface tends to infinity (R1 = ∞) thus the final equation becomes:

$$\frac{1}{f} = C(n-1)\left[\frac{1}{R_2}\right] \tag{4.2}$$

The correction factor of C≈1.35 will produce good results. The question of under-collimation and over-collimation, and efficiency of light capture and transmission are treated generally. There are more advanced methods of collimating light but it is far too involved for the application under consideration. Maintenance, cost of purchase and vandalism are also deciding factors in the choice of design and material used.

What we want to calculate it the radius, all the other variables are constant.

$$R_2 = fC(n-1) \tag{4.3}$$

When n=1.5, C=1.35, f= 35mm the radius of the curve of the lens will be 28.64mm. The milling machine was able to fabricate that radius with at 29.7mm because of the bit size.

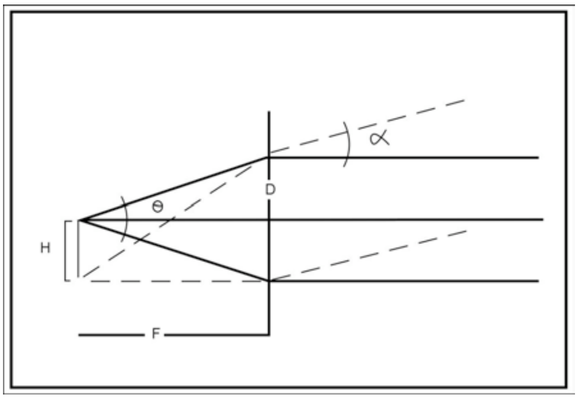

Figure 59: Infinite/finite optical system

4.11.2 Paraxial elements

These paraxial elements (equations) have been taken from an industry application brief titled, *Integration of Optical Systems* [97], produced by Edmond Optics. They are renowned for their optical systems. They serve to predict throughput of the lens.

$$\theta = 2\sin^{-1}(NA) \tag{4.4}$$

where NA is the numerical aperture and θ is the chosen viewing angle of the LED. The numerical aperture is the cone of light accepted by (or emitted in other cases) by the lens.

$$f/\# = (1/2NA) = f/CA \tag{4.5}$$

Where f is the focal length of the whole system and CA is the clear aperture of the lens. It should be noted that the larger the $f/\#$ the smaller the throughput of the optic. An increase in NA occurs with a decrease in $f/\#$.

$$\alpha = \tan^{-1}(H_i/f) \tag{4.6}$$

Where H_i is the image height. Since we are designing for each LED to be fixed along the central axis (mechanical axis) of the optic, α is not required in design.

When θ is 70°, the numerical aperture NA is 0.57 and the diameter of the convex part of the Circular Fresnel will be 45,89mm. The $f/\#$ is 0.8717.

4.12 Étendue concerns

Étendue is a geometric quantity used to characterize an optical system independent of its flux content in order to conserve energy in light collection. Étendue determines the maximum energy transfer of the source and thus the system of components will not be able to transfer any more energy than the smallest étendue element [98]. The aperture and cone angle define it and a system can only conserve it or decrease it. Theoretically 100% étendue conservation is possible (but practical 100% flux transfer is not - the étendue formulations are not concerned with optical loss from reflections and absorbance). For example, if each successive element in an optical layout has slightly larger acceptance étendue than the previous, the étendue at the output should not be reduced [98]. Étendue equations are taken from [99] and [100].

Étendue is as follows:

$$\varepsilon = n^2 \iint dA cos\theta d\Omega \tag{4.7}$$

For a small source area of A_0:

$$\varepsilon = A_0 \int cos\theta \, d\Omega \tag{4.8}$$

Since the radiation pattern can be defined by a cone of half angle $\theta_{1/2}$ and the integral is integrated from 0 to this half angle, the equation becomes:

$$\varepsilon = \pi n^2 A_0 sin^2 \theta_{1/2} \tag{4.9}$$

It is common for the projected solid angle Ω_{proj} to be defined:

$$\Omega_{proj} = \pi sin^2 \theta_{1/2} \tag{4.10}$$

Thus the étendue becomes:

$$\varepsilon = n^2 A_0 \Omega_{proj} = \pi n^2 A_0 sin^2 \theta_{1/2} \tag{4.11}$$

The optic étendue can be expressed in terms of the focal length, f-number and CA as it defines the half angle.

$$f/\# = \frac{1}{2tan\theta} \tag{4.12}$$

$$\theta_{1/2} = arctan\left(\frac{1}{2\,f/\#}\right) \tag{4.13}$$

Which becomes:

$$sin^2 \theta_{1/2} = \frac{1}{4\,f/\# + 1} \tag{4.14}$$

Now the étendue can be expressed in terms of the $f/\#$

$$\varepsilon = \frac{\pi A_0}{4\,f/\# + 1} \tag{4.15}$$

It is likely that the product of the aperture area of the collection optic and projected solid angle is less than the limit for the system. There will be a loss in efficiency. If the optic's aperture is not big enough to overcome the étendue of the source there will be additional losses [91].

$$A\Omega source = A\Omega optic \tag{4.16}$$

These losses may be calculated based on the condition that $A\Omega source \geq A\Omega optics$. The area of the source times the projected solid angle of emission defines the limit of étendue. If the product of the *aperture area* of the collection optic and the *projected solid angle* of the output light distribution is less than this limit, there will be an efficiency loss defined as follows [91].

$$Efficiency : \frac{A\Omega optic}{A\Omega source} \tag{4.17}$$

Another consideration is that efficiency may be changed (increased or decreased) either by changing the focal length or the aperture area. This will be shown through experimentation in the dark room. In Table 24 it can be seen that shortening the focal length *f* from 35mm to 25mm for each of the four lenses, the efficiency is increased. Each element (of which there are six in this design) has an equal efficiency with no element being different in structure. It should be noted that the maximum aperture area is fixed as this is a constraint of the luminaire's metal casing. No comparison can be made between the étendue of these lenses and their respective configurations and that of the fluorescent lamp.

Table 24: Table of optical collection efficiency for the two lens designs and their respective orientations

Lens type	CA mm	*f* mm	f-number	half angle θ	Optic étendue	Source étendue	Collection Efficiency
CF	104.0	35.0	0.3	56.1	17.3	25.1	68.8%
CF	104.0	25.0	0.2	64.3	20.4	25.1	81.2%
ICF	100.0	35.0	0.4	55.0	16.9	25.1	67.1%
ICF	100.0	25.0	0.3	63.4	20.1	25.1	80.0%
LF	145.0	35.0	0.2	64.2	20.4	25.1	81.1%
LF	145.0	25.0	0.2	71.0	22.5	25.1	89.4%
ILF	140.0	35.0	0.3	63.4	20.1	25.1	80.0%
ILF	140.0	25.0	0.2	70.3	22.3	25.1	88.7%

4.13 Utilization of light

Better illumination is not about more lumens but rather the ability to collect the usable light efficiently [101]. This is the true measure of success of the design. The redirection of the light traveling at degrees beyond 71º is done in order to use that light within a specified area. The graphs for the representative spatial distribution for the white LED array and the optic solutions are an indication of the ability to render a more efficient solution. Conserving the available light is what is being attempted by using more of the available light at the detection surface. More of the light energy that is produced is now used.

4.14 Circuit solution

4.14.1Using Luxeon's K2 HB LED

In deciding on using one of the three listed LEDs, flux per package and current drive played a significant role in this choice. The Luxeon K2 offers higher lumen output at 1A with the capability to be driven, if required, to a current of 1.5A. The trade-off though lies in dissipating heat away from each package/source effectively without using any more of the available energy to drive a fan.

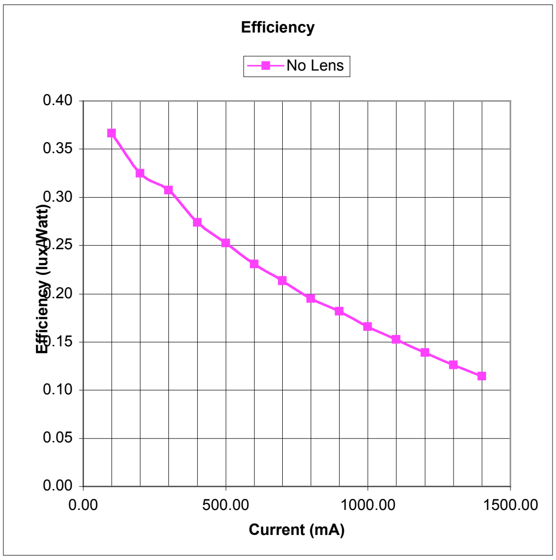

Figure 60: Efficiency of Luxeon K2 over the allowable range of linear regulator circuit

The efficiency to current drive is approximately linear but negative relationship and there is no best/optimal operating current that would allow us to drive the array at a particular bias except that a lower current would render a better efficiency (lm/W). Based on the datasheet, each package emits 100 lm at 1A. This gives an equivalent luminous output to the fluorescent fitting. The optic will increase the intensity in a particular zone below the luminaire but the transmission of lens and proposed optic solution reduces the expected usable lumens by approximately 15.4% from 600 lm to 507.6 lm.

4.14.2 Design of drive circuit laboratory testing

Interior illumination of automobiles requires reliable long-life solutions. A circuit forms part of this long-term solution. The energy source of this automotive application is a dc battery rated at 24V. Typically, a battery does not get charged to its set capacity. Usually it is considered within a range of output voltages based on state of charge, use etc. Variations in battery supply voltage may depend on load and age of the battery too. The choice of 6 LEDs is primarily to do with the optical requirements of the application. However, the forward voltage bias of the 6 LEDs also matches the input voltage supply from the buses battery supply, which makes the design process less complicated. Because optical efficiency is one of the primary considerations of this thesis electrical efficiency will also be discussed. Circuitry with dissipative resistors will have to be considered initially so that the laboratory tests can verify the electrical characteristics of Luxeon K2 over a range.

Given the multitude of available power supplies that may be bought ‘off the shelf’ the efficiency of a circuit designed for laboratory testing was not strictly set. A simple solution that would operate within range of the bias conditions and limit current flow beyond a set maximum drive became the parameters of design.

Range tests (like that of Figure 60) were important because illuminance output versus power over the range of the current needed to be represented and then chosen. A linear regulator was used. A positive voltage regulator, LM317, was chosen. It gives an output voltage adjustable over a 1.2 to 37V to supply more that 1.5A of load, hence suitable for the application. See Appendix D for the regulator datasheet.

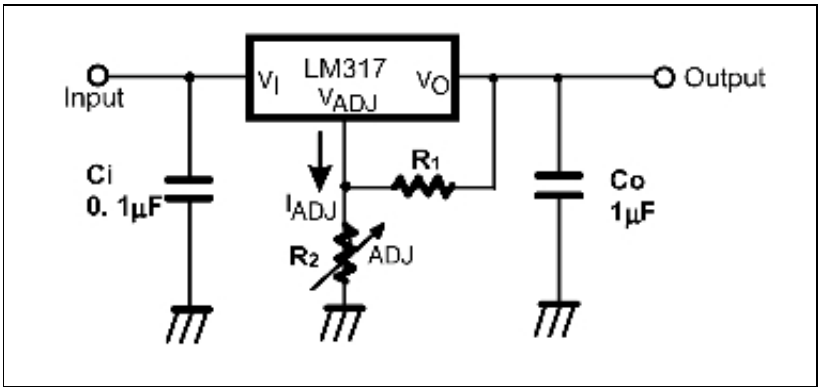

Figure 61: Linear regulator circuit design (Source: LM317 datasheet)

For an input voltage of 24V and a forward current of 1A, the output voltage can be set to 22.32V with the following equation taken from the datasheet [102]:

$$V_o = 1.25V\left(1 + R_2/R_1\right) + I_{adj}R_2 \tag{4.18}$$

Setting $R_2 = 9\Omega$ gives $R_1 = 1\Omega$. Capacitors are neglected. The thermal shutdown occurs when nearing 1.5 A in the case of this application.

4.14.3 Bus Implementation Circuitry considerations

Given that we are using 6 Luxeon K2 LEDs, variations in temperature, production and supply:

- Forward voltage range: 18.18V – 29.4V
- Battery voltage range: 18V – 28V
- Temperature range in bus: 5°C - 50°C

The ability of the design to deliver 1A with little variation in lumens delivered is important for longevity and task perception. It has been pointed out earlier that current and voltage biasing sets the chromaticity of the LEDs.

4.15 Thermal Considerations

Initial questions to answer before thermal design:

- How much heat are we expecting to runaway?
- Consider cost constraints in relation to this thermal issue (lifetime degradation)
- What are the current design constraints?

4.15.1 Important Thermal Properties of LEDs

Our aim is to ensure that the lifetime of the LED is optimised through managing the many temperature phenomena. Datasheets for the light sources describe the effects of multiple LEDs on one PCB and how to best arrange them to reduce the impact they will have on each other. It must be noted that the conditions under which we are testing this fitting are different to the dynamic conditions of the bus. Another concern is that we are unable to strictly stick to the instructions given in these documents [103]. To test the life-temperature dependence of the LEDs would be a time consuming exercise. For the application, the illumination tests are most important. However, it is important to show that we have designed a passive heat sinking system according to well-known procedure. This data will then guide us in making recommendations for creating the complete luminaire.

4.15.2 PCB Thermal Design

For the first design, 4 through-hole vias were drilled under each LED. The PCB was chosen to be double-sided. The through-hole vias were plated to further increase the heat conduction path. In excess of 3.5W from each source must be dissipated. To ensure that there is physical contact between the base plate of the LED, conducting grease between PCB upper surface and the LEDs was used.

We have removed other components like resistors and current control circuitry from the LED board. See Figure 62. The fewer components we have the better thermal management of the light sources will be. The effects of aging had been considered as the datasheets specify that each light source plateau after an initial peak [104]. We 'ran' the LEDs for a night before tests where done. The current remained constant through the course of the tests and attribute it to running the device overnight.

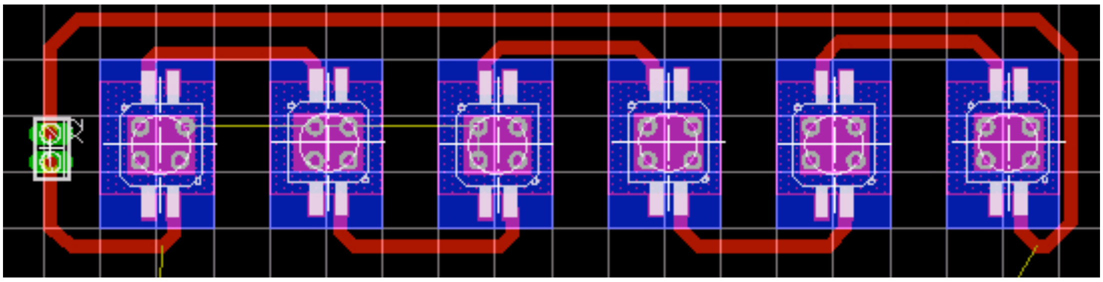

Figure 62: First PCB layout for Luxeon K2 LED

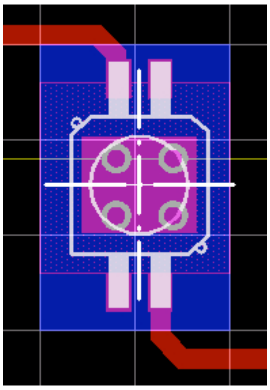

Figure 63: Through-hole vias for the Luxeon K2

4.15.3 Thermal resistance of multiple-emitter Luxeon® products.

Thermal resistance is described as the ratio of temperature difference to the corresponding power dissipation.

Junction temperature:

$$T_j = T_a + P_d\left(R\theta_{J-A}\right) \tag{4.19}$$

Total array junction to board thermal resistance:

$$R\theta_{J-B} = R\theta_{J-S} + R\theta_{S-B} \tag{4.20}$$

Multiple sources clustered together:

$$R\theta_{J-B} = R\theta_{J-B} / N \tag{4.21}$$

Thermal resistance of multiple emitters:

Total array $R\theta_{J-A} = \Delta T / P_{d\_total}$ =(125-15)/(1.5*3.85*6) = 3.17 °C/W

4.15.4 Choosing a Heat Sink

It is important to note that all test results from the Luxeon power light source thermal design application brief [103] are taken from a closed volume test box to control the free convection and to improve repeatability. Initially a nominal temperature of 25°C was taken but as the LEDs reached their steady-state temperatures, this temperature changed. With these facts in mind, the application brief was still sought for design information. The spacing between emitters is 25mm but they also give specifications for surface areas of possible heat sinks when the PCB is densely packed. From Figure 9 in [103] an over-estimate of the surface area to ambient to base thermal resistance $R\Theta_{b-a}$ is given as 645mm². This image is reproduced below.

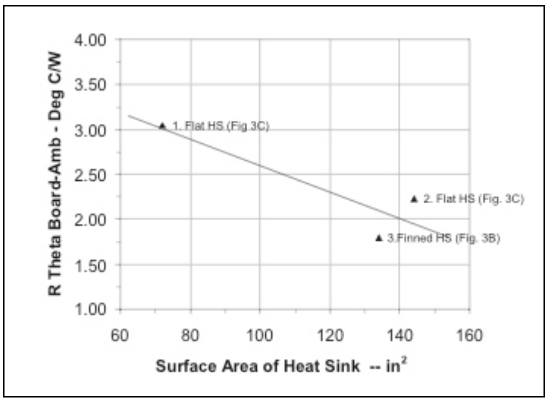

Figure 64: High density heat sink total array thermal resistance between board and ambient versus surface area exposed (taken from Luxeon® thermal application note)

The design needs to be revised for a number of reasons. The unfortunate thing about using glass fiber between copper cladding is that they are poor thermal conductors, with a thermal conductivity of 0.05W/mK. A single heat-sink was needed, because the spacing of the LEDs were so close to each other. This compounded the amount of heat that needed to be dissipated and the thermal impact on each light source. The physical limits of the sink would not allow for it to fit neatly into the metal casing of the luminaire. The orientation of a sink affects design, and this put the current design at a further disadvantage.

Thus it became necessary for each of the LEDs to be mounted directly onto its own alluminium heat sink. On two full lengths of veroboard, 6 squares the size of the white LED base where chiseled away to allow direct contact. The legs were bent upwards to form gull wings. They were soldered to the bottom of a veroboard's tracks.

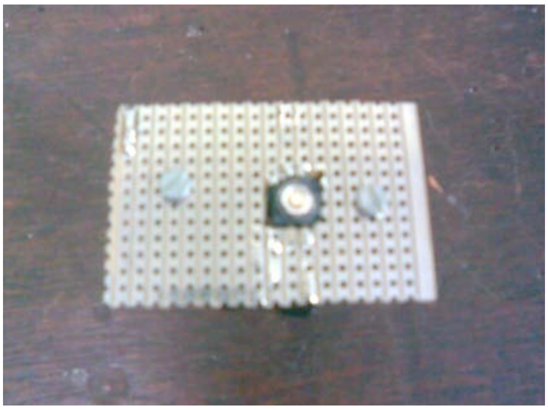

Figure 65: LED leads mounted on to of the veroboard's tracks

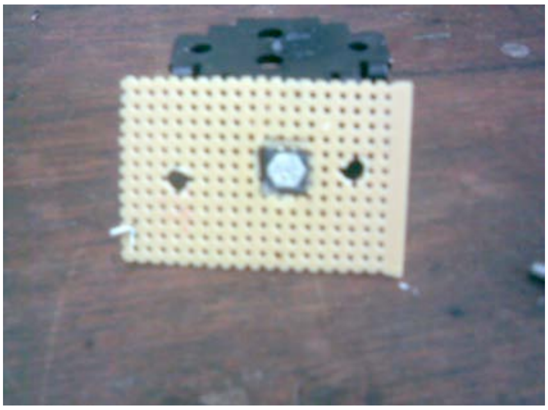

Figure 66: The hexagonal base-plate of the Luxeon® K2 LED

Each Luxeon K2 had its own heat sink for two reasons. The first, because the base of each LED pad is not electrically neutral, and secondly, the heat generated is in excess of 3.5W for each diode.

Considering the variations in supply, voltage and current a single heatsink for each white LED that can reduce junction temperature of approximately 120°C is as follows. These equations are taken from [103].

$$T_J = T_A + (P)(R\theta_{J-A}) \qquad (4.22)$$

where junction temperature is 120°C and the worst-case ambient temperature is 50°C. Junction to ambient resistance will be as follows.

$$R\theta_{J-A} = (T_J - T_A)/P = (120 - 50)/3.72 = 18.8°C/W$$

It is the base to ambient thermal resistance that will be most important in choosing the heatsink for each diode. This value may be attained by subtracting the junction to base (case) value from the junction to ambient value. The junction to base value is taken from the datasheet to be 9°C/W. Hence, base to ambient thermal resistance is as follows:

$$R\theta_{J-A} = R\theta_{J-B} + R\theta_{B-A} \tag{4.23}$$

$$R\theta_{B-A} = R\theta_{J-A} - R\theta_{J-B} = 18.8 - 9 = 9.8°C/W$$

This value of 9.8°C/W gives us a finned heat sink of the following dimensions: length 40,8mm, width 26,9mm and height 12,5mm. See Appendix E for heatsink datasheet. We ran the LED for several periods in excess of 10 hours with positive results. No degradation in illuminance was recorded.

4.16 Summary and conclusion

This chapter has described how the author arrived at the GABS interior light application. The thermal, electrical and optical considerations of three LEDs suitable for the luminaire is given while a single LED is chosen to illustrate the design of an interior lighting application for a bus. Quantifying the efficiency of optics available, thermal pressures by the higher current requirements and managing the PCBs have been discussed.

The spatial distribution pattern of HB LEDs was then taken as the unique problem and thus becomes the design constraint, which needed to be overcome. The use of non-imaging collimating optical elements were sought to turn rays towards the specified area for illumination. The utilization of light is further enhanced, as the intensity of the new distribution is higher.

CHAPTER 5
RESULTS OF LINEAR, CIRCULAR AND HYBRID LENS FRESNEL DESIGNS

5. Introduction

This chapter discusses the criterion for uniformity. Linear and Circular Fresnel lens designs have been tested. The results were verified against this set of criteria. The information from the results and analysis feeds into the recommendations for a new design that redirects the peak area between 70% and 100% of the intensity lobe of the Luxeon K2 white LED. The subsequent designs are called the Hybrid Linear and Circular Fresnel lenses. The methods for redirecting rays of light have been detailed to meet these criteria. Results from testing include efficiency plots and distribution charts.

Initial tests were done on the old fluorescent luminaire that is being replaced.

5.1 Uniformity – Lack of standard for interior automotive application

Unlike plants, which react to light roughly linearly, humans perceive differences in intensity in a logarithmic fashion [105, 106]. The criterion for uniformity and how the human eye perceives differences in intensity, to ensure visual comfort and task performance on a surface a distance away from the source, is important given this issue of perception. The IESNA Lighting Handbook has been consulted extensively in order to fully understand the laboratory results that on first impression show distinct differences in intensity and uniformity. It states that the appearance and character of spaces is greatly dependent on distribution and the pattern of light and shadow [106]. In relation to passenger vehicles, illuminance levels have recommendations for interior application; however, does not specify quantifiable measures for checking uniformity.

5.2 Luminance ratio

A few important subjects require definitions at this stage. These definitions have been taken from [106]. They are ***spatial distribution***, a person's ***visual field*** and the relationship of illuminated surface brightness known as the ***luminance ratio.*** A definition for spatial distribution is that "in general the more uniform the light distribution in the visual field and the larger the area the visual field covers the better one sees the visual task."

The visual field consists of three zones. The first is the task, the second is the immediate surroundings and the third zone is the general surroundings. The luminance ratio is an acceptable range (difference in zonal luminance) that humans generally feel comfortable viewing objects and carrying out tasks. Luminance is expressed in candelas per square meter (cd/m^2) where candela is the SI unit for luminous intensity. For visual comfort, the luminance ratio between zone 1 and zone 2 is between $1/5$ and 5 times the task luminance. The ratio between zone 3 and task is $1/10$ and 10 times the task luminance. These relationships should not be exceeded for the purpose of visual comfort in visually demanding tasks such as studying, sewing or reading [91].

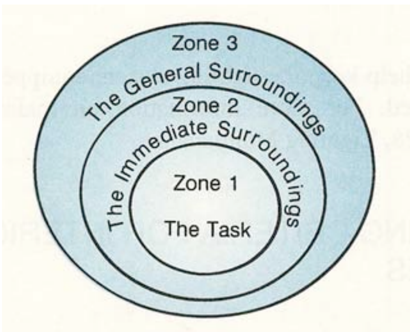

Figure 67: Seeing zones and luminance ratios for visual tasks [106]

5.3 Detectable differences

Two sets of information may be drawn from to better understand human responses to lit areas and uniformity in order to design a more uniformly distributing luminaire.

These act as guidelines. Albright and Both in research toward uniform *lighting systems* for greenhouse crop growth, mention the sensitivities of humans in relation to intensity differences. The authors state that light intensity (candela) must change by 30 to 50% for the human eye to recognize the difference [105]. Although the IESNA Lighting Manuel state that it is difficult to achieve a uniform value everywhere within a space, on a desk or even a workplace; a 15% variation in illuminance for a task is generally ‘tolerable’ [106].

The approach taken by Narendran and Gu in designing for an aesthetics-enhancing and beam-shaping light system refers to the differences in spatial distribution of lambertian (cosine) and batwing emitters. They state that the latter produces more uniform illumination across a surface [107], as opposed to the former, but do not mention the criteria against which uniformity was checked. Figure 68 illustrates the difference in distribution of batwing, lambertian, side-emitting and collimating optics.

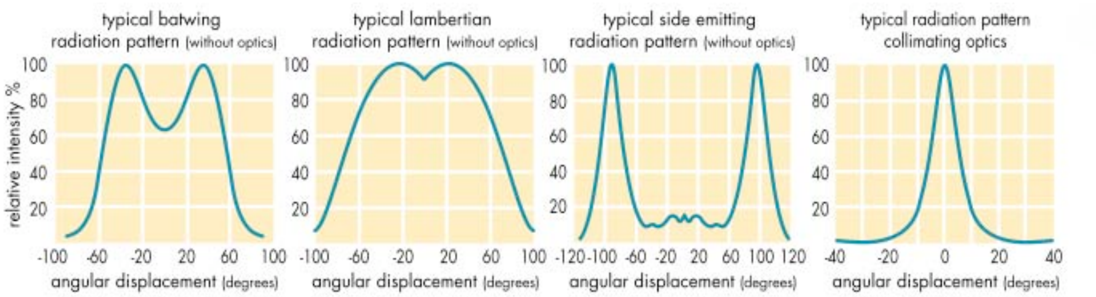

Figure 68: Radiation patterns of LEDs (first two patterns from left side) and LEDs with optic solutions (two patterns on the right side) [Source: Luxeon design guide]

The abovementioned specifications are for variations in ***task illuminance***. The purpose of lighting in the bus is not for a specific task but for passenger safety for easy movement onto and off the bus. The entire luminaire layout is an important aspect of design. However, we have been designing a luminaire retrofit, where a layout change that necessitates more luminaires is undesirable, and where uniformity of distribution is the primary design goal.

5.4 Criteria

The criteria for this design are four:

1. Seeing zone's luminance (cd/m^2) levels
2. Noticeable human difference in intensity (cd) (30-50%)
3. Illuminance level (IESNA recommended 30lx for passenger transportation vehicles)
4. Collection efficiency (étendue)

In terms of the criteria and the subsequent analysis of the results gained, the numerical markers are not the same. The illuminance values detected need to be converted to intensity (cd) and luminance (cd/m^2). This was done and can be found in Table 25 (contains illuminance values from 1 to 27) and Table 26 (contains values from 28 to 55). However, since we are able to see the differences spatially and that the images for spatial distribution have been rendered using the detected illuminance values, all analysis is based on these. And essentially, each of the optical properties can be related to illuminance by using the tables.

The illuminance on a plain at a particular distance is detected. The area of the detection device (since we are only using an illuminance photometer) is measured. The cone and angle of emittance is worked out from these constants (height and detection area) and renders solid angle (steradian). Lumens, luminance and intensity can now be worked out.

Table 25: Calculating lumen, luminance and intensity from illuminance

Ev	Detector Area	radius	radians	theta	Steradian	lumen	Luminance	Intensity	solid angle	candela
lx	m²	m		θ	st		(cd/m²)	(cd)	(st)	(cd)
1	0.0013	1.0002	0.02	1.15	0.0013	0.0013	0.0013	1.00	0.0013	1
2	0.0013	1.0002	0.02	1.15	0.0013	0.0025	0.0025	2.00	0.0013	2
3	0.0013	1.0002	0.02	1.15	0.0013	0.0038	0.0038	3.00	0.0013	3
4	0.0013	1.0002	0.02	1.15	0.0013	0.0050	0.0050	4.00	0.0013	4
5	0.0013	1.0002	0.02	1.15	0.0013	0.0063	0.0063	5.00	0.0013	5
6	0.0013	1.0002	0.02	1.15	0.0013	0.0075	0.0075	6.00	0.0013	6
7	0.0013	1.0002	0.02	1.15	0.0013	0.0088	0.0088	7.00	0.0013	7
8	0.0013	1.0002	0.02	1.15	0.0013	0.0101	0.0101	8.00	0.0013	8
9	0.0013	1.0002	0.02	1.15	0.0013	0.0113	0.0113	9.00	0.0013	9
10	0.0013	1.0002	0.02	1.15	0.0013	0.0126	0.0126	10.00	0.0013	10
11	0.0013	1.0002	0.02	1.15	0.0013	0.0138	0.0138	11.00	0.0013	11
12	0.0013	1.0002	0.02	1.15	0.0013	0.0151	0.0151	12.00	0.0013	12
13	0.0013	1.0002	0.02	1.15	0.0013	0.0163	0.0163	13.00	0.0013	13
14	0.0013	1.0002	0.02	1.15	0.0013	0.0176	0.0176	14.00	0.0013	14
15	0.0013	1.0002	0.02	1.15	0.0013	0.0188	0.0188	15.00	0.0013	15
16	0.0013	1.0002	0.02	1.15	0.0013	0.0201	0.0201	16.00	0.0013	16
17	0.0013	1.0002	0.02	1.15	0.0013	0.0214	0.0214	17.01	0.0013	17
18	0.0013	1.0002	0.02	1.15	0.0013	0.0226	0.0226	18.01	0.0013	18
19	0.0013	1.0002	0.02	1.15	0.0013	0.0239	0.0239	19.01	0.0013	19
20	0.0013	1.0002	0.02	1.15	0.0013	0.0251	0.0251	20.01	0.0013	20
21	0.0013	1.0002	0.02	1.15	0.0013	0.0264	0.0264	21.01	0.0013	21
22	0.0013	1.0002	0.02	1.15	0.0013	0.0276	0.0276	22.01	0.0013	22
23	0.0013	1.0002	0.02	1.15	0.0013	0.0289	0.0289	23.01	0.0013	23
24	0.0013	1.0002	0.02	1.15	0.0013	0.0302	0.0302	24.01	0.0013	24
25	0.0013	1.0002	0.02	1.15	0.0013	0.0314	0.0314	25.01	0.0013	25
26	0.0013	1.0002	0.02	1.15	0.0013	0.0327	0.0327	26.01	0.0013	26
27	0.0013	1.0002	0.02	1.15	0.0013	0.0339	0.0339	27.01	0.0013	27

Table 26: Calculating lumen, luminance and intensity from illuminance

Ev	Detector Area	radius	radians	theta	Steradian	lumen	Luminance	Intensity	solid angle	candela
lx	m²	m		θ	st		(cd/m²)	(cd)	(st)	(cd)
28	0.0013	1.0002	0.02	1.15	0.0013	0.0352	0.0352	28.01	0.0013	28
29	0.0013	1.0002	0.02	1.15	0.0013	0.0364	0.0364	29.01	0.0013	29
30	0.0013	1.0002	0.02	1.15	0.0013	0.0377	0.0377	30.01	0.0013	30
31	0.0013	1.0002	0.02	1.15	0.0013	0.0390	0.0389	31.01	0.0013	31
32	0.0013	1.0002	0.02	1.15	0.0013	0.0402	0.0402	32.01	0.0013	32
33	0.0013	1.0002	0.02	1.15	0.0013	0.0415	0.0415	33.01	0.0013	33
34	0.0013	1.0002	0.02	1.15	0.0013	0.0427	0.0427	34.01	0.0013	34
35	0.0013	1.0002	0.02	1.15	0.0013	0.0440	0.0440	35.01	0.0013	35
36	0.0013	1.0002	0.02	1.15	0.0013	0.0452	0.0452	36.01	0.0013	36
37	0.0013	1.0002	0.02	1.15	0.0013	0.0465	0.0465	37.01	0.0013	37
38	0.0013	1.0002	0.02	1.15	0.0013	0.0478	0.0477	38.01	0.0013	38
39	0.0013	1.0002	0.02	1.15	0.0013	0.0490	0.0490	39.01	0.0013	39
40	0.0013	1.0002	0.02	1.15	0.0013	0.0503	0.0503	40.01	0.0013	40
41	0.0013	1.0002	0.02	1.15	0.0013	0.0515	0.0515	41.01	0.0013	41
42	0.0013	1.0002	0.02	1.15	0.0013	0.0528	0.0528	42.01	0.0013	42
43	0.0013	1.0002	0.02	1.15	0.0013	0.0540	0.0540	43.01	0.0013	43
44	0.0013	1.0002	0.02	1.15	0.0013	0.0553	0.0553	44.01	0.0013	44
45	0.0013	1.0002	0.02	1.15	0.0013	0.0565	0.0565	45.01	0.0013	45
46	0.0013	1.0002	0.02	1.15	0.0013	0.0578	0.0578	46.01	0.0013	46
47	0.0013	1.0002	0.02	1.15	0.0013	0.0591	0.0590	47.01	0.0013	47
48	0.0013	1.0002	0.02	1.15	0.0013	0.0603	0.0603	48.01	0.0013	48
49	0.0013	1.0002	0.02	1.15	0.0013	0.0616	0.0616	49.01	0.0013	49
50	0.0013	1.0002	0.02	1.15	0.0013	0.0628	0.0628	50.01	0.0013	50
51	0.0013	1.0002	0.02	1.15	0.0013	0.0641	0.0641	51.02	0.0013	51
52	0.0013	1.0002	0.02	1.15	0.0013	0.0653	0.0653	52.02	0.0013	52
53	0.0013	1.0002	0.02	1.15	0.0013	0.0666	0.0666	53.02	0.0013	53
54	0.0013	1.0002	0.02	1.15	0.0013	0.0679	0.0678	54.02	0.0013	54
55	0.0013	1.0002	0.02	1.15	0.0013	0.0691	0.0691	55.02	0.0013	55

5.5 Initial laboratory tests of lens objects

We looked at the distribution patterns of the LEDs with no lens, with lenses and inverting the lens. Readings are taken on a grid with 45 points spaced 25cm apart. The fluorescent produces the following distribution patterns when running along the central axis of the luminaire.

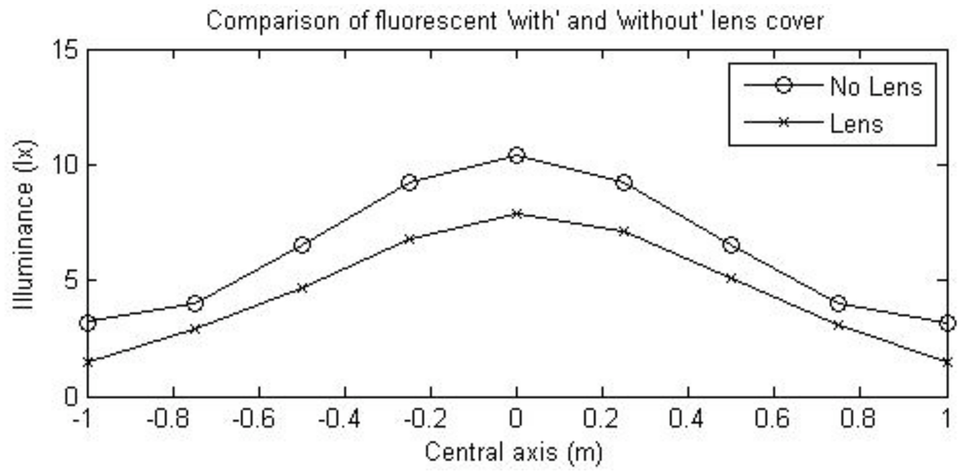

Figure 69: Spatial distribution of fluorescent luminaire currently installed inside Golden Arrow buses. A comparison is made between the existence of an opaque lens and no lens.

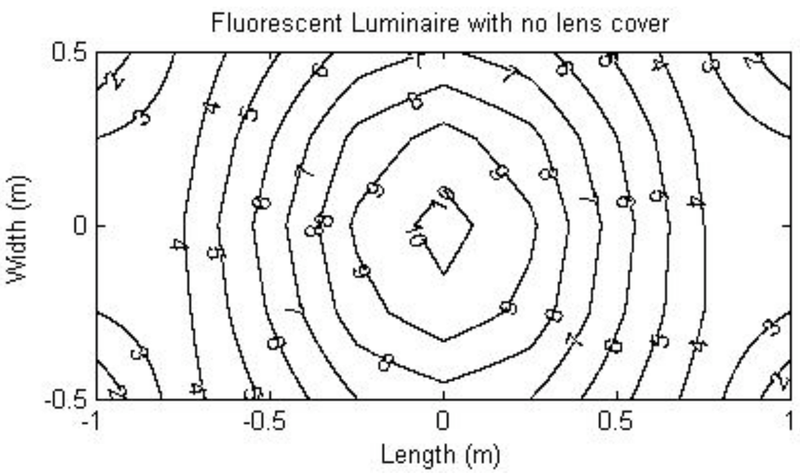

Figure 70: No lens cover for fluorescent-based luminaire

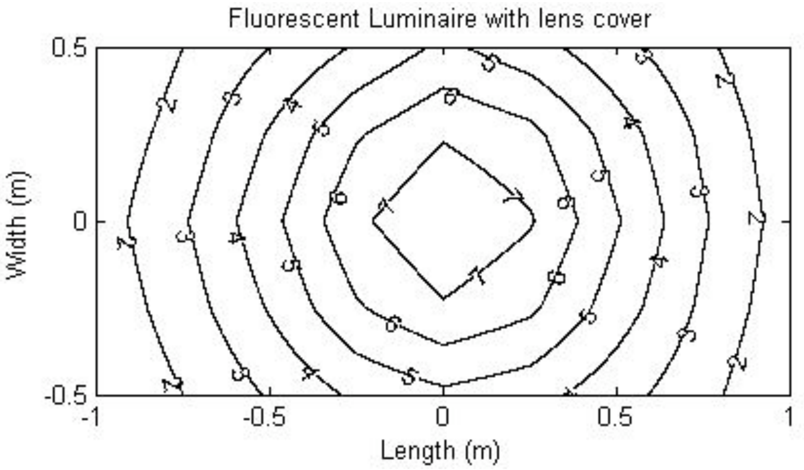

Figure 71: Opaque lens covering fluorescent-based luminaire

5.6 Testing of the integrated optical system

The numerical efficiency does not give any idea of the distribution of light across a horizontal surface a distance away from the luminaire. A few laboratory tests were carried out for both designs. These results are detailed in point form below.

1. A single LED was tested and compared to that of a lens between source and detection surface
2. The entire luminaire is tested for efficiency. This is done to see whether there is a particular power at which the design is more efficient in producing light.
3. A comparison of the performance of the lenses, under normal and inverted orientation, is done and compared to the base condition (GABS LED retrofit having no lens). This percentage of the increase in the intensity of light from an illuminance photometer at a fixed point directly beneath the center of the luminaire is plotted.
4. The pattern of distribution of the LEDs was checked. Iso-illuminance plots are looked at to see the differences in intensity and the places at which they occur. When inverting the lenses the distribution pattern changes. This is proved empirically.
5. A comparison of the linear distribution to show differences in intensity has been done.

5.6.1 Linear Fresnel Lens

The linear lens is able to turn the rays along the length and not the width of the fitting downward.

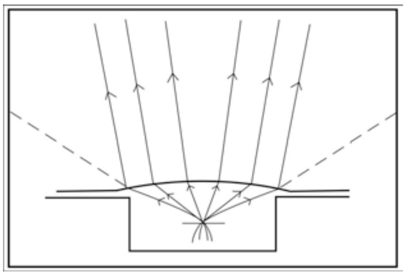

Figure 72: Side image of the luminaire. The dashed lines are the traces of rays that would occur if no lens existed. The linear design turns these rays towards the target illumination area (top of this image)

The spatial distribution when comparing a single LED with no lens and with a Linear Fresnel (LF) lens is given in Figure 73. This has been expected for two reasons. A loss is experienced in the transmission of light through a lens. No light guiding optic is perfect enough to have no losses. It is predicted here that a loss is also experienced because the distance between source and detector is large. A comparison between the datasheet's luminous flux (Figure 74) and detected illuminance (Figure 75) for one configuration is done.

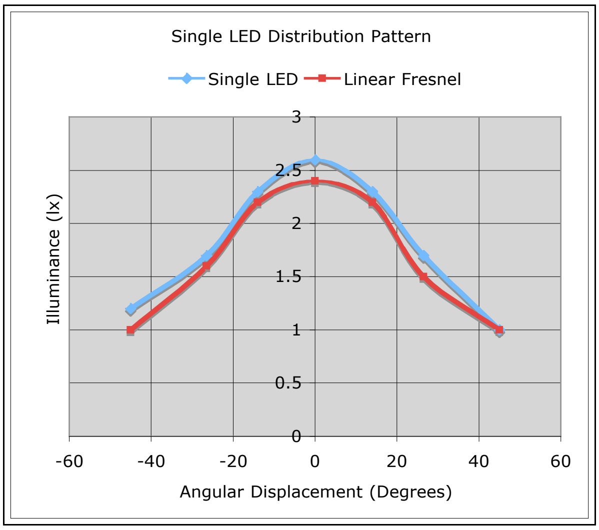

Figure 73: Single LED distribution pattern with and without a Linear Fresnel taken at 1m away

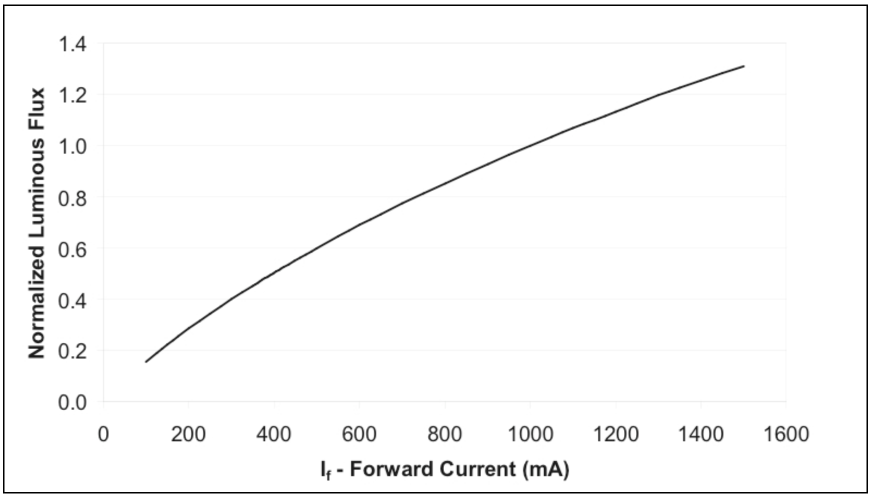

Figure 74: Relative luminous flux or radiometric power versus current white K2 luxeon LEDs at a maintained junction temperature of 25º with test current of 1A.

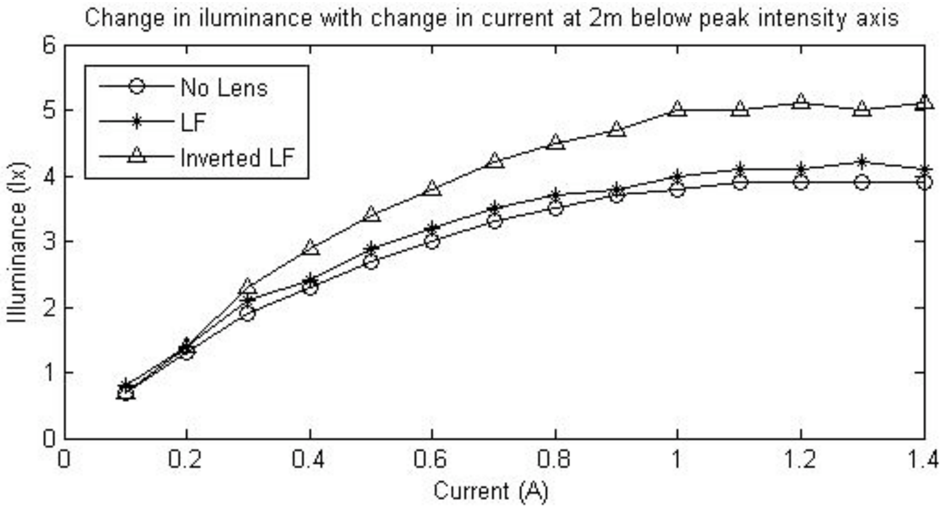

Figure 75: Illuminance levels at a distance of 2m with a change in current in 100mA increments.

The efficiency curves for the LF are given in Figure 76. When doing the test for each efficiency curve, the thermal parameters would not allow the current to remain at 1500mA for more than a few minutes. Light output immediately begins to diminish until there is none emitted. Each test held the current for a few seconds before a reading was taken.

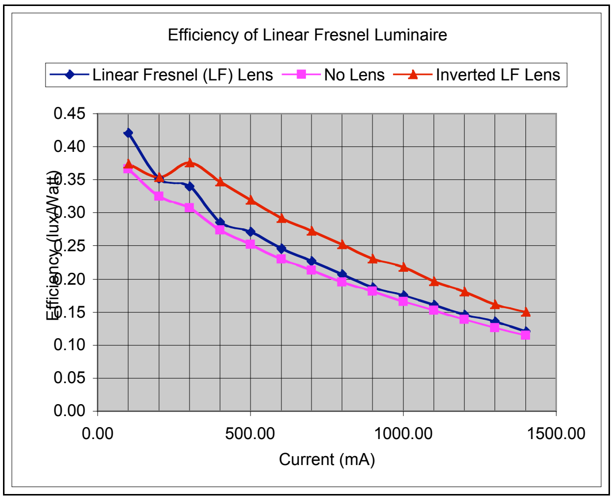

Figure 76: Efficiency (lx/W) for the LF design

The distribution of 6 LEDs spaced 95mm apart with and without a LF lenses. It is proven by Figure 77 that the ability of the optic to turn the rays of intensity between 35° and 60° is done effectively with a LF. An increase in on-axis peak intensity is increased by 34% while that of the inverted LF a 22% increase in peak intensity is achieved.

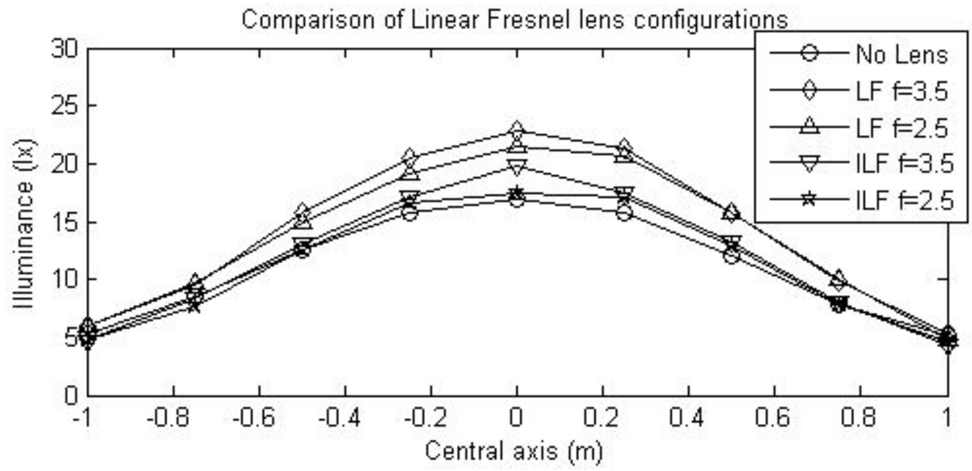

Figure 77: The Ability of the optics to collimate intensities of light within the half-angle viewing angles is proven. Luminaire tested 1m away from source

When comparing the results from a single LED with and without a LF and a complete luminaire is evident that the additive effect of multiple point sources and intervals between them also plays a role in the concentration of intensity at a task point.

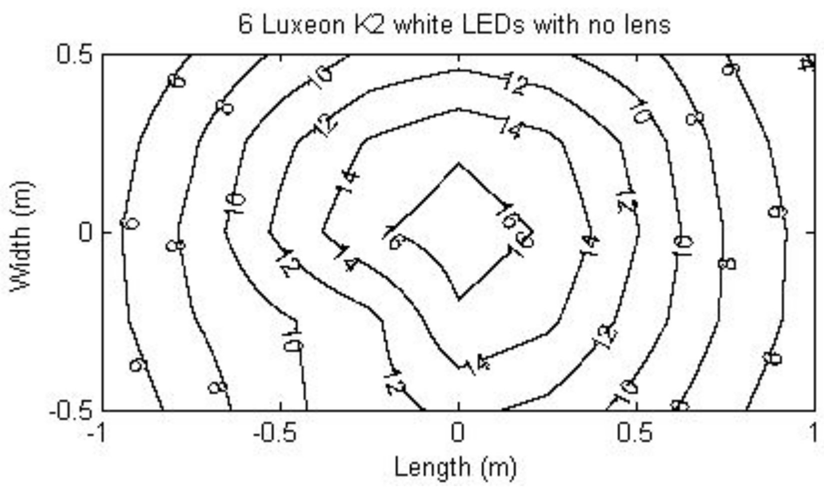

Figure 78: Iso-illuminance pattern of 6 K2 Luxeon LEDs with no lens

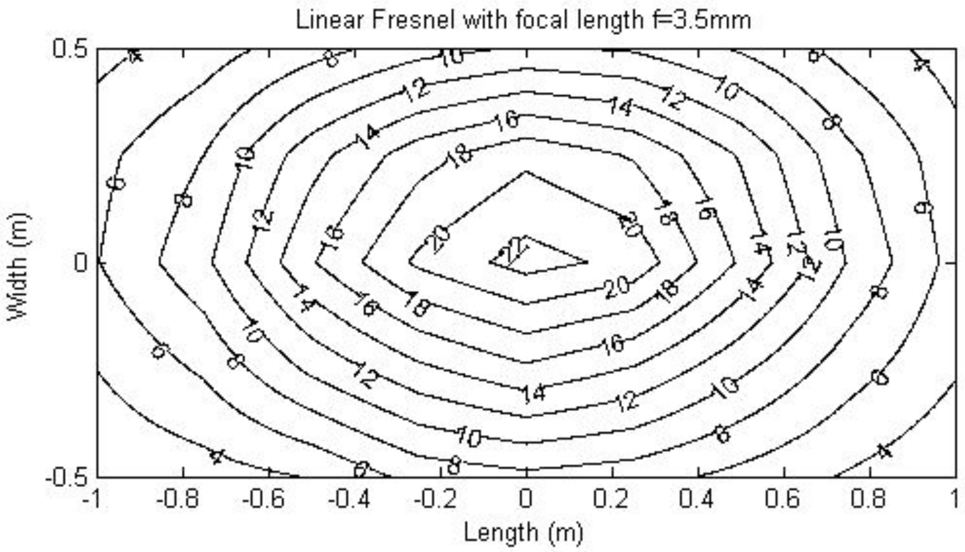

Figure 79: Iso-illuminance pattern with LF lens with focal length f=35mm

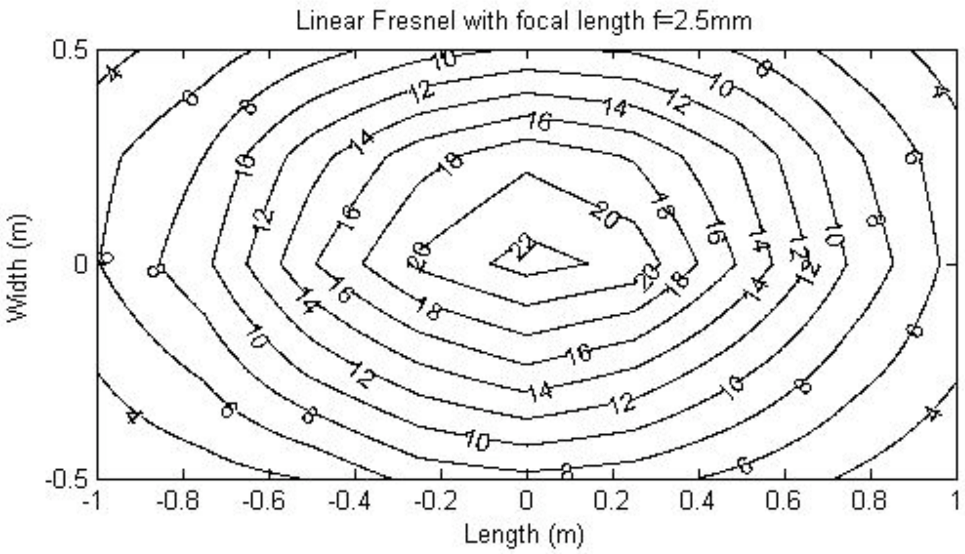

Figure 80: Iso-illuminance pattern with LF lens with focal length f=25mm

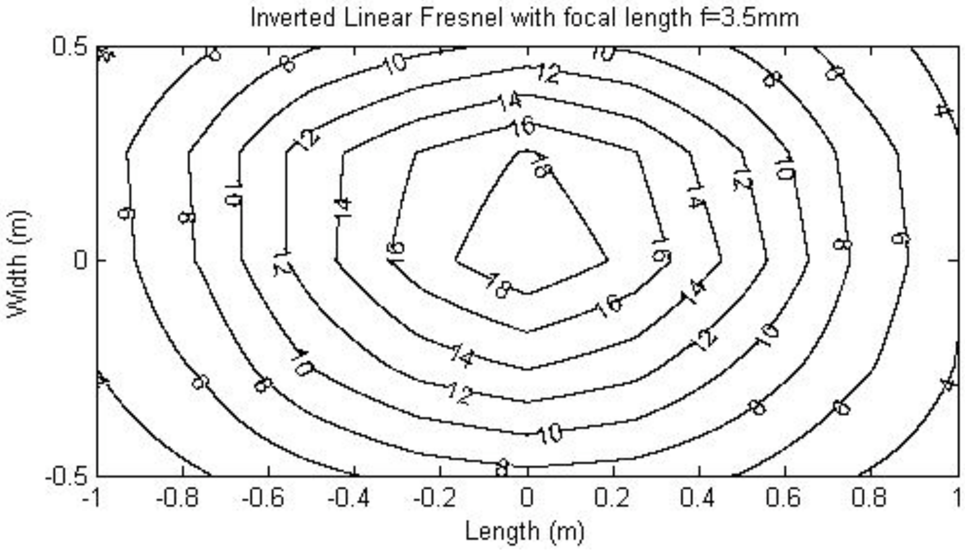

Figure 81: Iso-illuminance pattern with inverted LF lens with focal length f=35mm

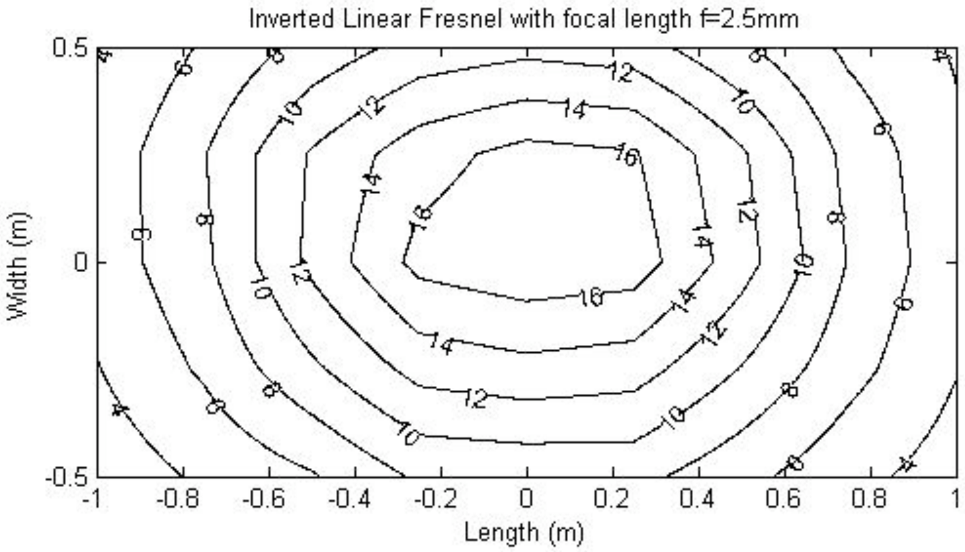

Figure 82: Iso-illuminance pattern with inverted LF lens with focal length f=25mm

5.6.2 Concentric Fresnel Lens

The collimating property of this design gives approximately a threefold increase in intensity along the central axis.

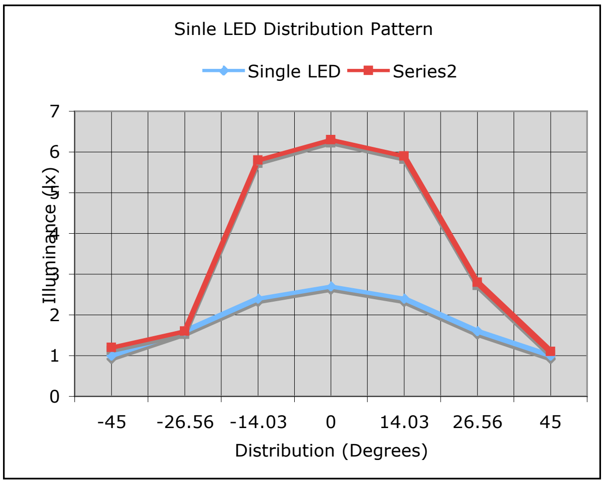

Figure 83: Single LED distribution pattern with and without a Circular Fresnel taken 1m away

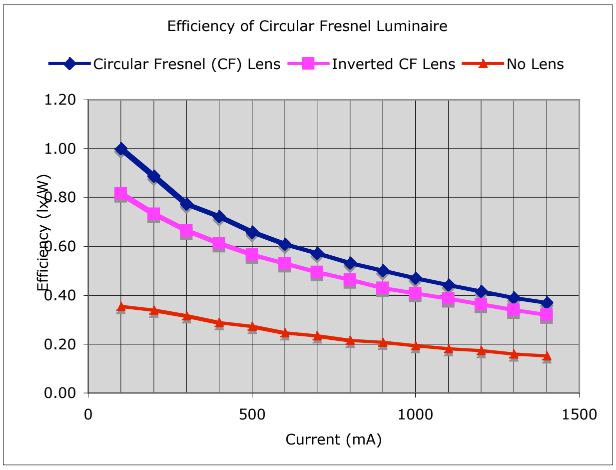

Figure 84: Efficiency (lx/W) for the CF design

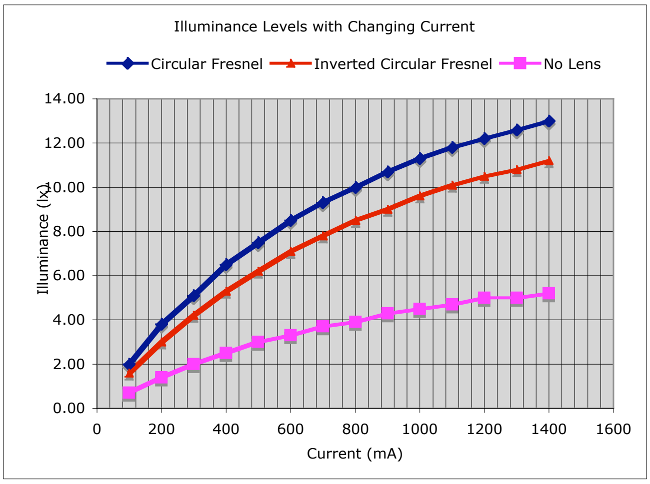

Figure 85: Illuminance levels at a distance of 2m with a change in current in 100mA increments

The concentric design is the most efficient in turning the rays towards the task as it takes the entire cone of light emitted between intensity range of 50% and 80% down towards the target.

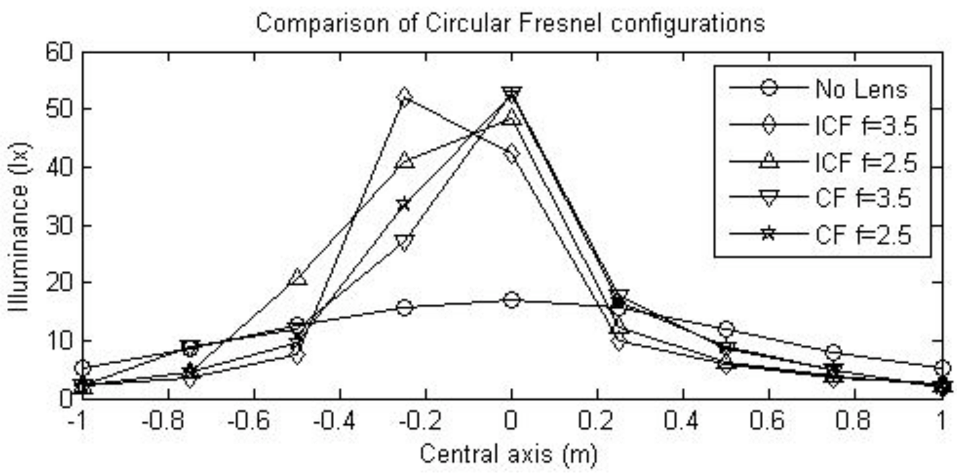

Figure 86: Spatial distribution od circular lens designs and the focal length configurations

The off-axis distribution of the CF and inverted CF occurs because of alignment. Alignment of sources with optic must be completely accurate with this design. This is not ideal. It shall be seen in the charts of iso-illuminance for these lenses that peaks occur at odd places. If the alignment can be made easy through a clip-on structure within the metal casing, this will not be a problem when integrating the two pieces of the luminaire. Apart from the alignment issues, there is a 234% increase in illuminance along the central axis alone and is likely to cause severe contrast for users.

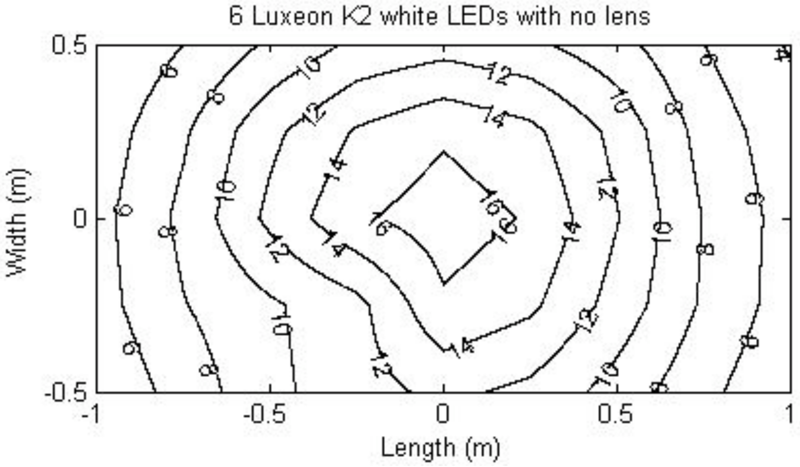

Figure 87: Iso-illuminance pattern with no lens

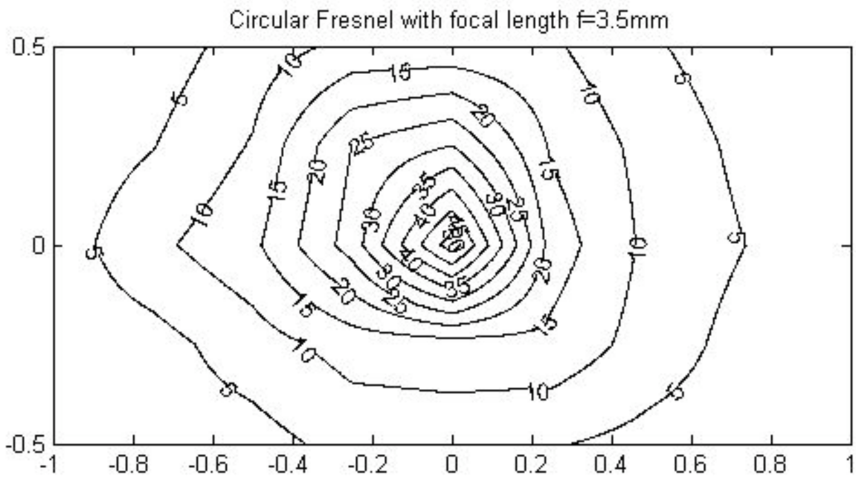

Figure 88: Iso-illuminance pattern with CF lens

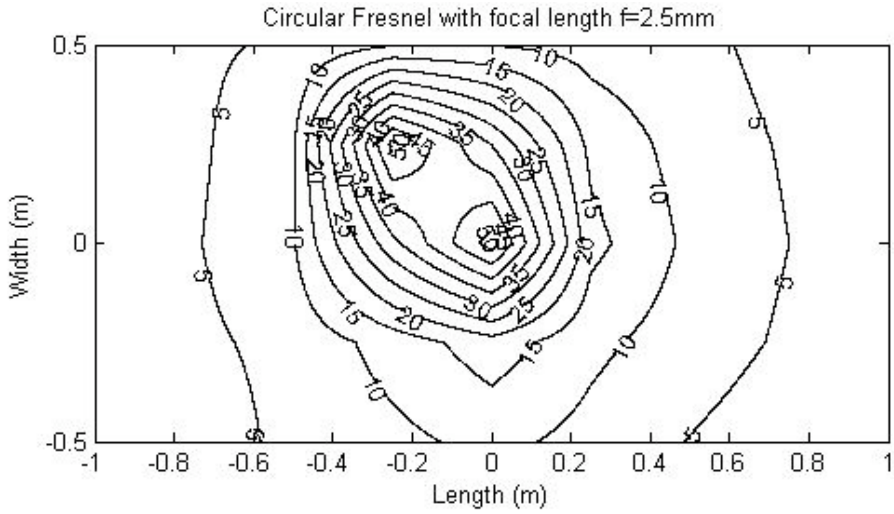

Figure 89: Iso-illuminance pattern with CF lens

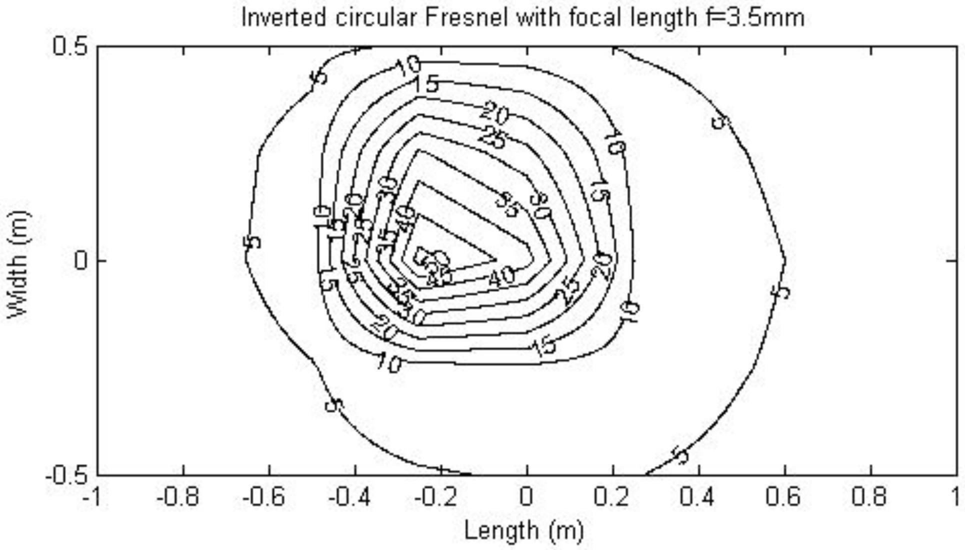

Figure 90: Iso-illuminance pattern with inverted CF lens with focal length f=35mm

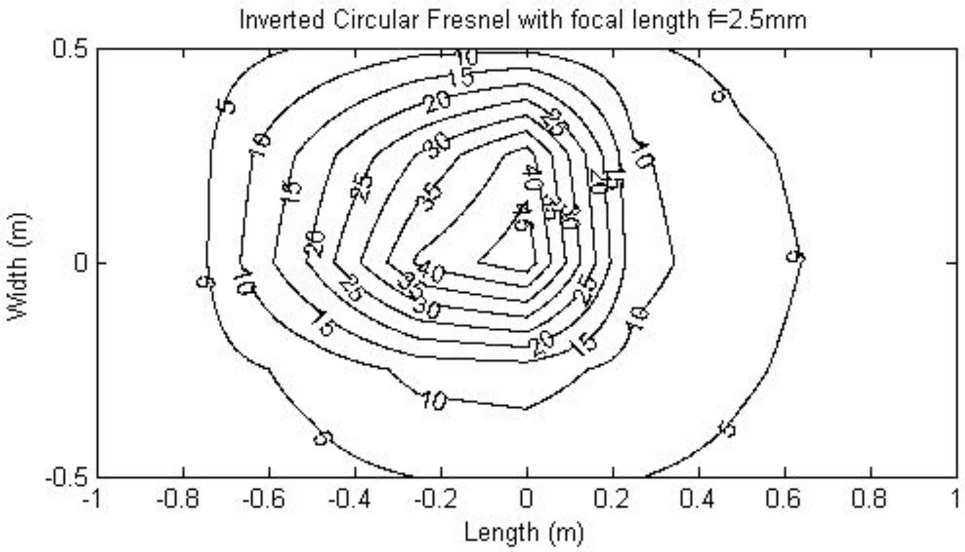

Figure 91: Iso-illuminance pattern with inverted CF lens with focal length f=25mm

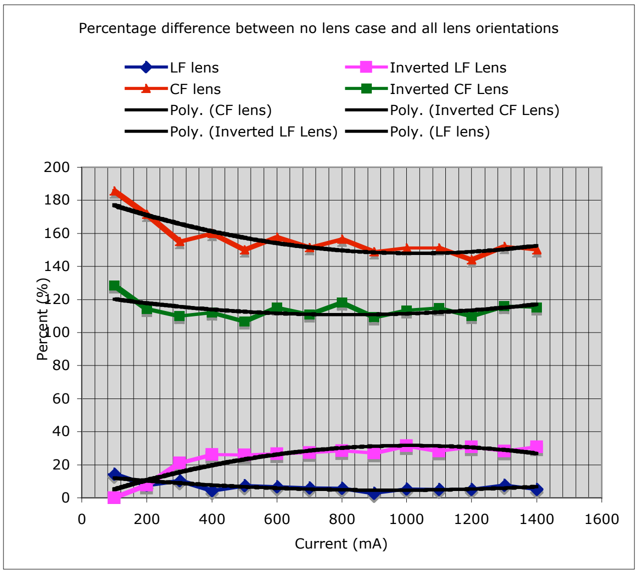

Figure 92: The percentage difference between no lens and the 4 lens orientations based on an increase in illuminance.

5.7 Summary of LF and CF data

The linear lens, although by nature is not able to capture light of the entire cone of distribution of each LED, does posses the ability to turn the rays of light from areas undesirable as set out by the design. This design distributes light in a uniform fashion with a slower gradient over the specified area. The illuminance level is not met. The spacing of the current system would have to be reduced by 1m to meet the requirements. There is no marked difference in distribution when changing the focal length. The pattern and illuminance levels remain the same.

When comparing the cases of white LEDs with no lens cover to that of the concentric design, even though there is an increase in the detected illuminance, the distribution and uniformity of pattern across the plane of detection of these solutions and their respective configurations are too contrasting. The peak intensity is increased by a factor of 3.1 and 3 for the normally-oriented 35mm and 25mm focal length configurations respectively. For this design to be accepted there would need to be an increase in the luminance at each end of the area of the visual field. The spotting-effect is seen to occur twice when changing the focal length of the CF to 25mm. Inverting the design renders a similar spotting effect except that gain in intensity is reduced is some instances. The FWHM of the ICF with f=25mm is doubled in comparison to the other configurations as a result of the shorter focal length.

Table 27: Zones of acceptance for human use

Lens type	Focal length mm	Zone 1 lx	Zone 2 lx	Zone 3 lx
Fluorescent	-	7.90	1.58	0.79
No Lens	-	17.00	3.40	1.70
LF	35	22.80	4.56	2.28
LF	25	21.50	4.30	2.15
ILF	35	19.80	3.96	1.98
ILF	25	17.50	3.50	1.75
CF	35	52.90	10.58	5.29
CF	25	52.30	10.46	5.23
ICF	35	52.00	10.40	5.20
ICF	25	48.30	9.66	4.83

All illuminance data had been converted to luminance. But since the spatial distributions had been represented in illuminance, it made it easy to compare the values of the luminance ratios for the visual field, which has been represented as illuminance zones. Luminance is the flux per unit area per unit solid angle (lumens per steradian per meter squared) while illuminance is the flux per unit area (lumens per meter squared).

Two lenses were produced. The Linear and Circular Fresnel show distinct differences in distribution at a point, detected a distance away from the source. The concept for the two designs was that the intensity area of the lobe between 50% and 80% be redirected from the outer edges down towards the task area. The rays of light exiting from the lens system would now be parallel to the central axis (mechanical axis) of the LEDs. The main design trade-off is that although we have been successful in increasing the utilization of light from the LEDs with the two designs we have not been able to make a more uniform spatial distribution at a defined level. A new design is suggested where the peak of the intensity lobe between 70% and 100% be directed outwards.

We can speak of *on-axis* intensity gain, the change in FWHM of the new lens configuration and the variance from maximum to minimum of the detected illuminance level over the plane of detection. These are tabulated for each of the lens designs and focal length configurations and can be found in Appendix F. The values for intensity and illuminance are the same since the distance between source and surface is 1m away. The main design trade-off is that although we have been successful in increasing the utilization of light from the LEDs with the two designs, we have not been able to make a more uniform spatial distribution at a defined level.

5.8 Re-directing peak intensity of the lobe

Without changing the specification of the LEDs, the directive now is to integrate an optical element into the existing designs to redirect the peak area of the cosine distribution in an energy efficient manner. The author is aware that suppressing the peak of the lambertian distribution of white LEDs is not desirable. The author looked at the distribution of a few designs and LED distribution patterns. The secondary-optic used on side-emitting LEDs and the batwing LED distribution was used as the basis for redirection.

5.9 Batwing

This is the radiation pattern of an LED in which the peak luminous intensity occurs at approximately 40º from the normal. A more general description is that the maximum luminous intensity is angularly displaced but still symmetrical about the central axis. A batwing lens distributes light with this same principle. The peak intensity is at an angle away from the normal to the central axis yet symmetrical about it. The end product is a less collimated and more evenly spread spatial distribution of light [108].

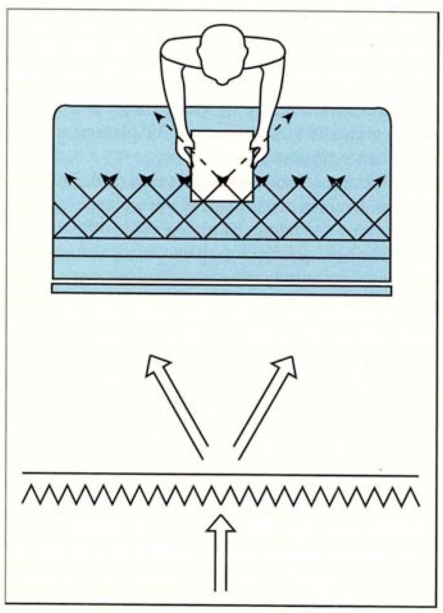

Figure 93: Batwing lens light distribution [106]

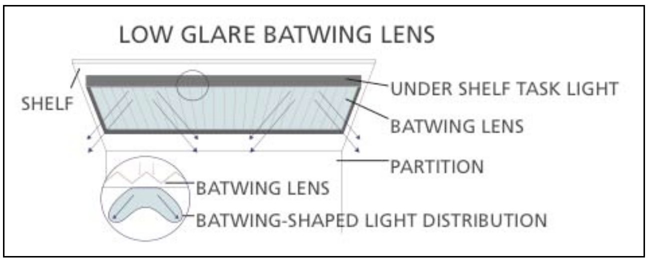

Figure 94: Fluorescent fitting using a batwing lens [108]

5.10 Hybrid Lens Fresnel Design

The area between 70% and 100% (which translates to the half-angles of 35º to 0º) of the spatial distribution pattern of the K2 Luxeon LED is now designed in such a way that it is directed away from the central axis and towards ±45º from the central axis. Collimation for the purpose of utilization of light still exists for both designs. This is done for 60º to 35º.

The batwing area is changed to reduce losses to a graded slope lacking any drafts. See Figure 53.

5.10.1 Incident and refracted ray angles for multiple media

Figure 57 should be referred to in the following discussion of ray-tracing design. For the region of batwing refraction:

- Incident rays between 0° and 45º are refracted to an angle of 45º from the central axis of each LED by manipulating the curvature of the lens.
- The angles are split up in nine divisions so that each 5º segment from 0º will have their own 'Batwing angle'.
- The refracted ray angle to normal is calculated from Snell's Law $n_s = \sin(i)/\sin(r)$ where ns is the refractive index of the material used.

The condition of these tests and results are that the distance between the source and bottom surface of the lens cover (focal length) is 35mm.

The angles of the facets of the Fresnel are floating in space. It was necessary for us to calculate systematically these angles with reference to the optical axis and the initial plane of contact of incident ray.

The refracted ray PQ is treated as the incident ray for orienting the exit rays in a parallel fashion. The incident angle is taken from the desired exit ray QR is 45° from the optical axis.

- Second plane of incidence is rotated in a clockwise fashion.
- Incident angles between 45º and 60º are collimated with three grooves.
- It must be noted now that the ray of LED light is moving from a dense medium into one that is less dense.
- Now $\sin(r)/\sin(i) = n$ is the equation for the calculation of refracted angle to incident based on the material's refractive index.

The difference of the angle of refraction, the amount of angular rotation about the point of incidence and the initial plane parallel to first incident plane is calculated. If the calculated angle is 90°, then the collimated ray is perpendicular to the first plane of incidence.

Once the angle of incidence of the ray PQ is parallel to the normal of the second plane of refraction the values of incidence and refraction become negative. This does not cause any problems in calculation. Our intention was to find out the angles of the Fresnel teeth for an intensity range of 50% to 70% and 70% to 100% of the Luxeon K2 white LED.

5.11 Hybrid Linear Fresnel

The hybrid linear lens produces good distributional results despite the reduction in illuminance over the test area. Larger viewing field with slowly decreasing rate along the central axis follows the nature of the original distribution of 6 LEDs with no intermediate lens. Appendix G holds information of the optical characteristics of the linear lens and distribution.. Table 28 refers to the physical dimensions of the facets and Figure 95 graphically represents the comparison between the various configurations of the hybrid linear lens and the case of no lens when traveling along the central axis.

Table 28: Physical characteristics of hybrid linear fresnel lens design

Hybrid Linear Fresnel			
Facet Number	Facet angle (θ)	Pitch (mm)	Relief (θ)
1	61	8.33	0
2	66.5	8.33	0
Batwing	Facet angle (θ)	Pitch (mm)	Relief (θ)
1	19	3.1	0
2	17	3.2	0
3	15	3.4	0
4	13	3.5	0
5	11	3.8	0
6	9	4.3	0
7	7	4.9	0
8	6	5.6	0
9	4	6.7	0
10	3	8.2	0

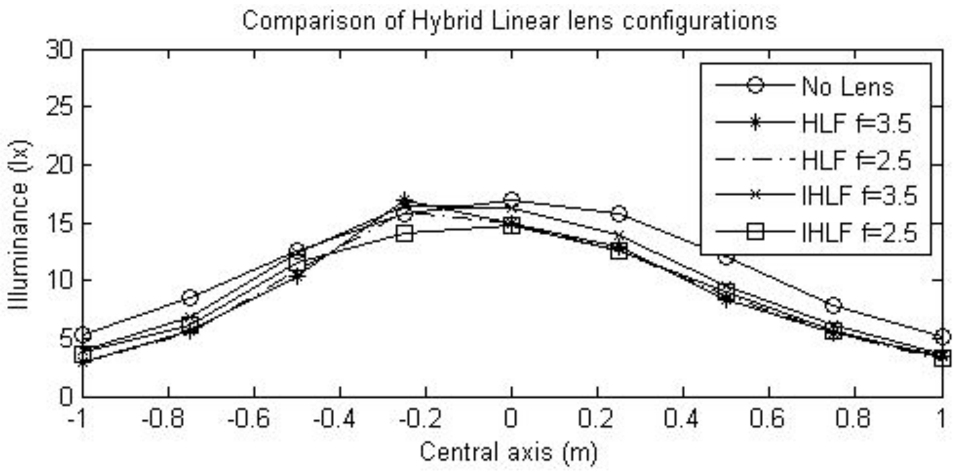

Figure 95: Comparison of hybrid linear Fresnel lens configurations

Figure 96 to Figure 99 are the spatial distribution patterns. They are vastly different in terms of the patterns generated than the information that can be drawn from the central axis distributions of Figure 95.

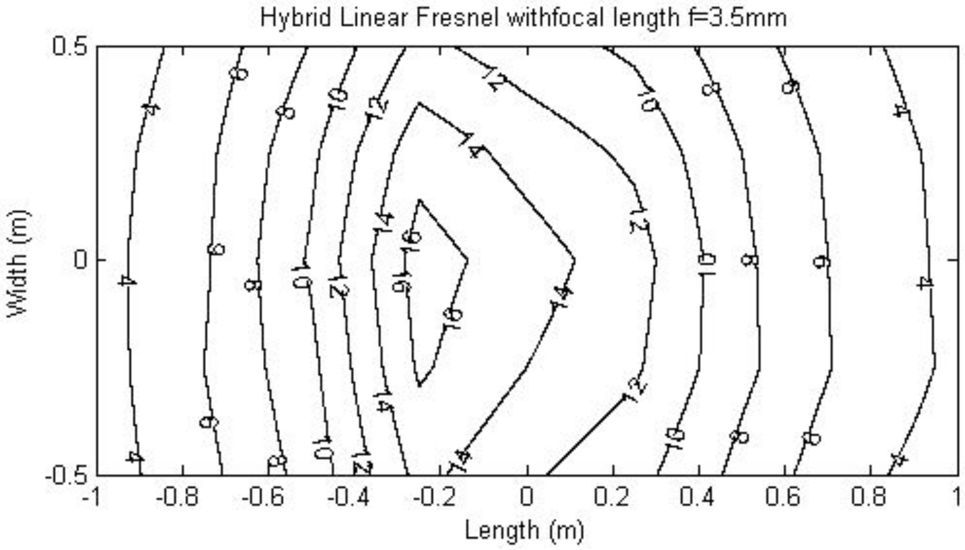

Figure 96: Spatial distribution of linear Fresnel

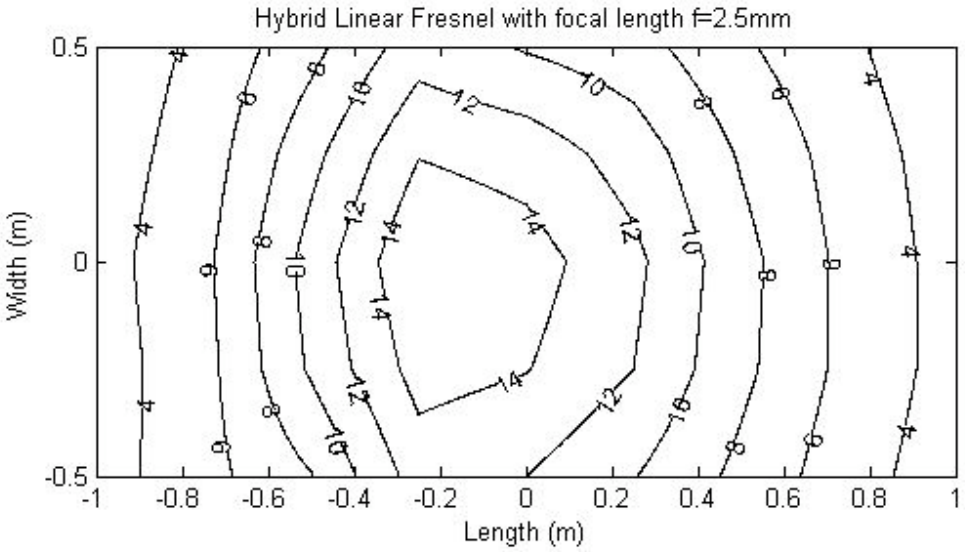

Figure 97:Hybrid linear Fresnel distribution

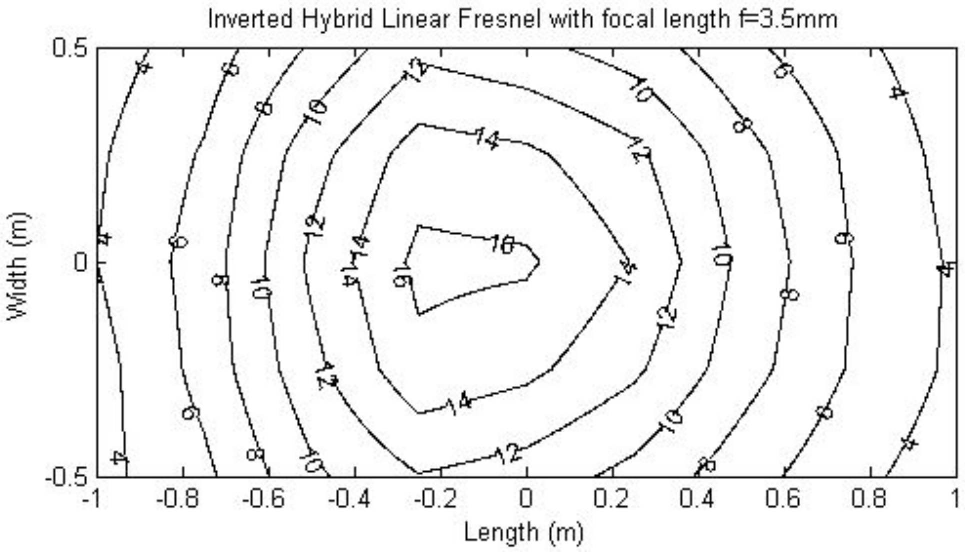

Figure 98: Inverted hybrid linear fresnel

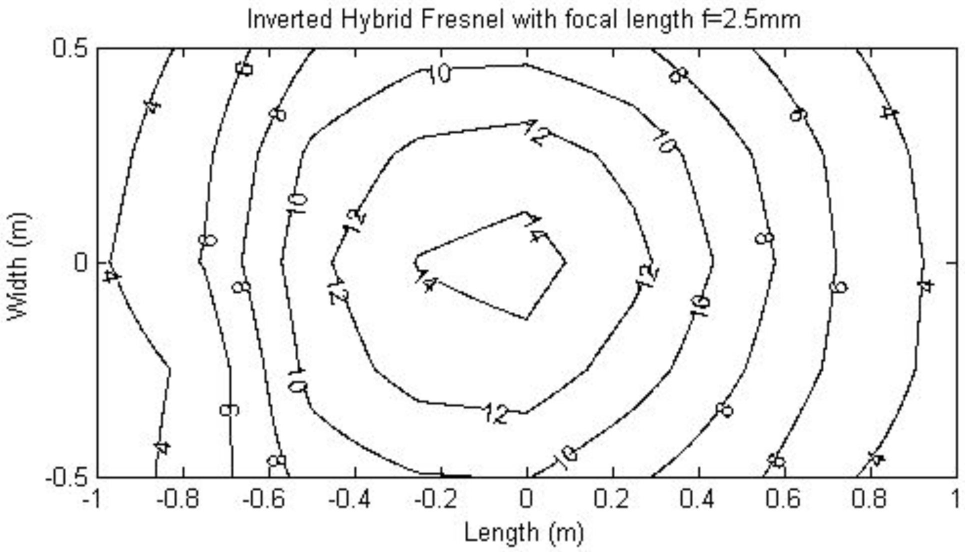

Figure 99:Inverted hybrid fresnel

5.12 Hybrid Circular Fresnel

The hybrid circular lens with *f*=35mm and the inverted hybrid lens at *f*=25mm and its test configurations best fit the criteria set out earlier in this chapter. There is symmetry in spatial distribution about the mechanical axis of the luminaire and along the central axis. A spacing change within the bus would need to be considered but this would be a minor shift (approximately 0.15m – 0.2m).

The occurrence of two spots in the shortened focal length for the normally oriented lens puts it out of consideration despite a collection efficiency of 78.3%. The physical parameters of the design, which is draftless, causes there to be no humanly visible shadows at the plane of detection. This is also shown in the spatial distributions generated. This was something that could possibly have been perceived by the users of these luminaires given that the peak area is being redirected completely. Appendix G holds information of the optical characteristics of the circular lens and distribution. Table 29 gives the physical properties of the design's facets for the collimating area and for the batwing distribution.

Table 29:Physical characteristics of hybrid circular lens design

Hybrid Circular Fresnel			
Facet Number	Facet angle (θ)	Pitch (mm)	Relief (θ)
1		6.7	0
2		8.2	0
3		10.6	0
Batwing	Facet angle (θ)	Pitch (mm)	Relief (θ)
1	19	3.1	0
2	17	3.2	0
3	15	3.4	0
4	13	3.5	0
5	11	3.8	0
6	9	4.3	0
7	7	4.9	0
8	6	5.6	0
9	4	6.7	0
10	3	8.2	0

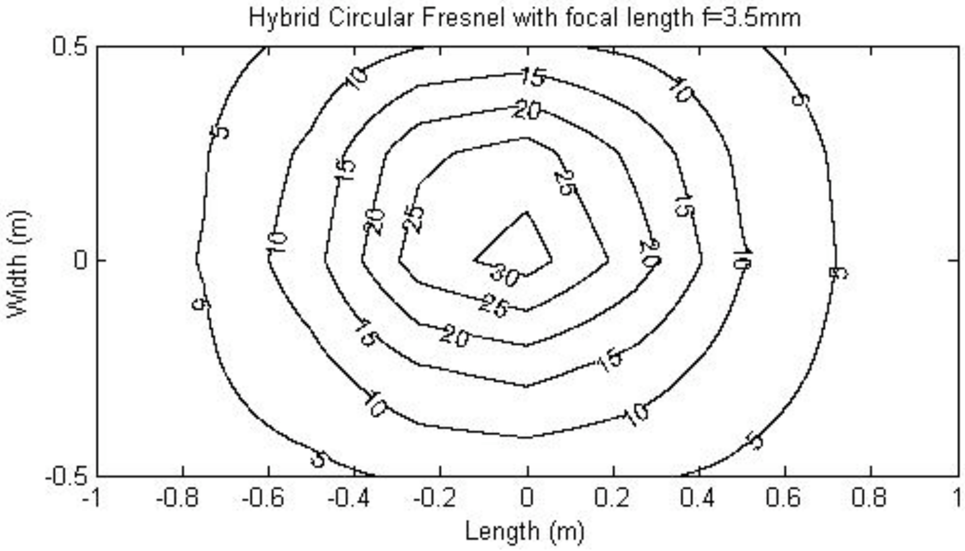

Figure 100: Hybrid circular fresnel with a focal length 35mm

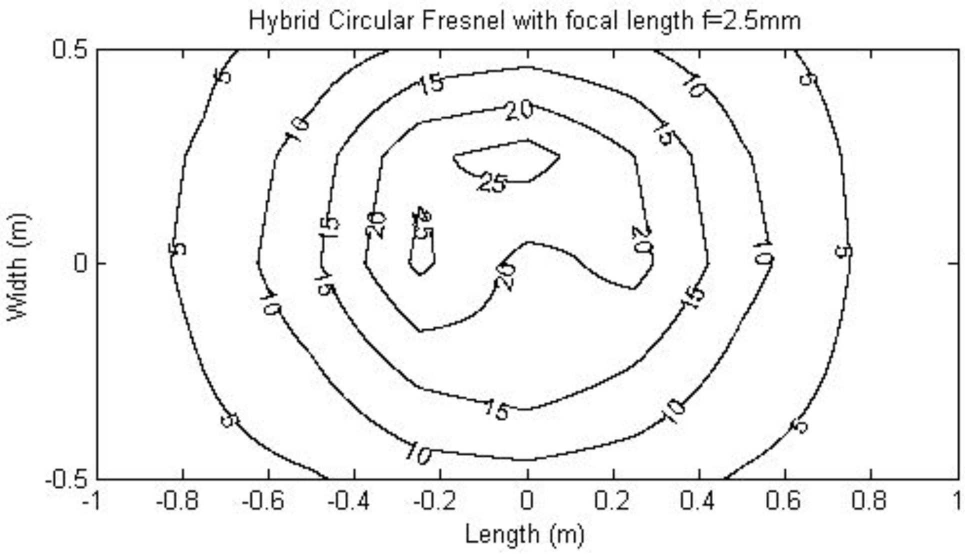

Figure 101: Hybrid circular Fresnel with focal length 25mm

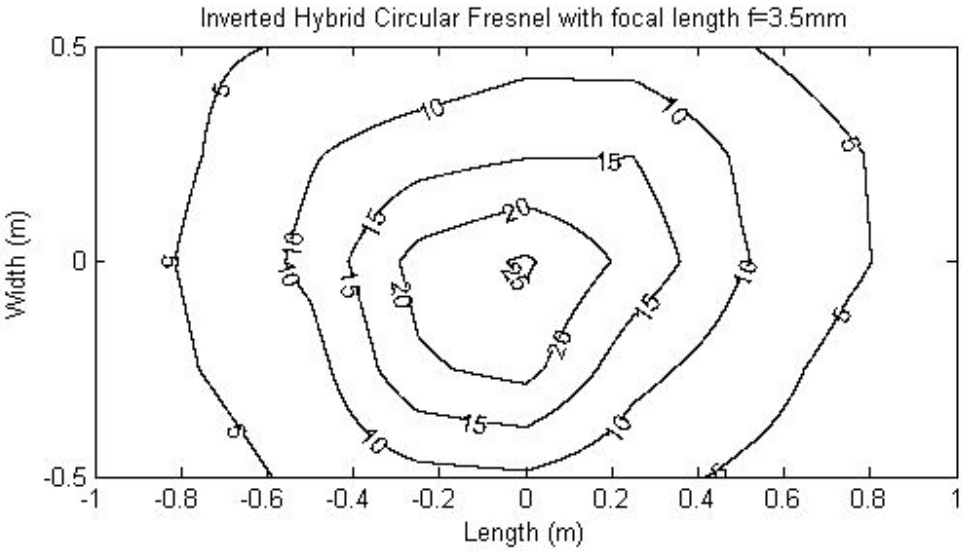

Figure 102: Inverted hybrid circular Fresnel with focal length 35mm

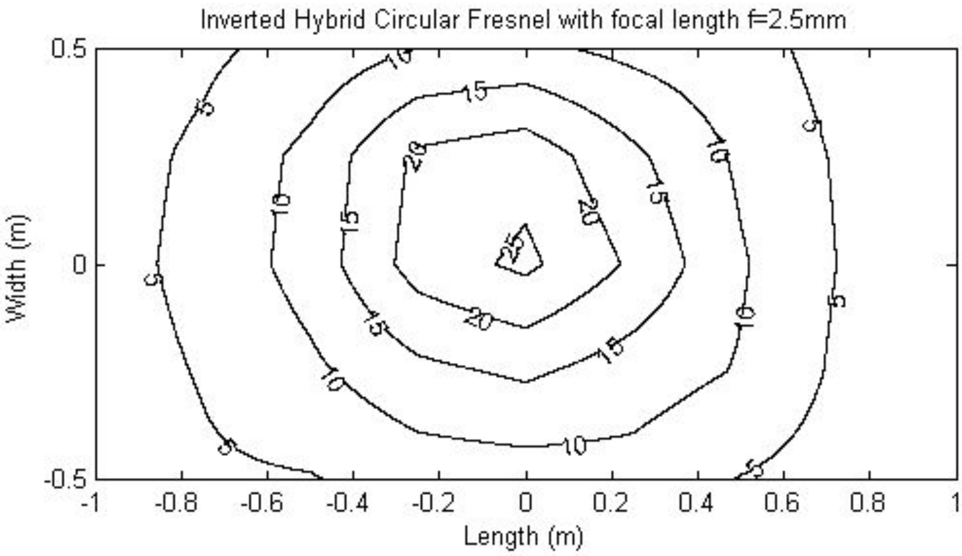

Figure 103: Inverted hybrid circular Fresnel with focal length 25mm

5.12.1 Polished Draftless Batwing area

The milling machine cutting-bit was set to 3mm. The cutting procedure was a fast draft with no fine cutting process. This was done to reduce time. Each of the 4 pieces of the circular lens would have taken in excess of 70 hours to produce. Instead of the extended cutting time, manually polishing the lens with abrasive chemical compounds after using fine sandpaper increased the illuminance level for every case. Figure 105 to Figure 108 are graphical representations of the the spatial distribution of the desired area under test.

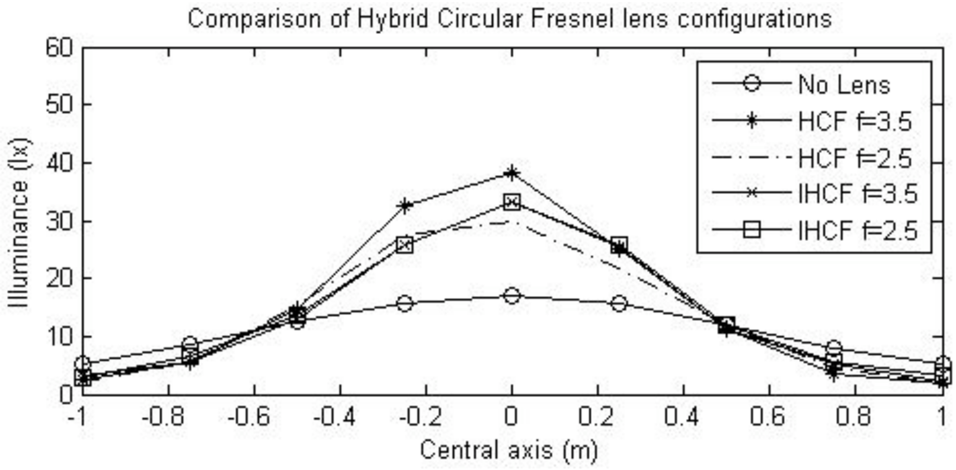

Figure 104: Comparison of the configurations of the polished hybrid circular designs of the spatial distributions along the central axis.

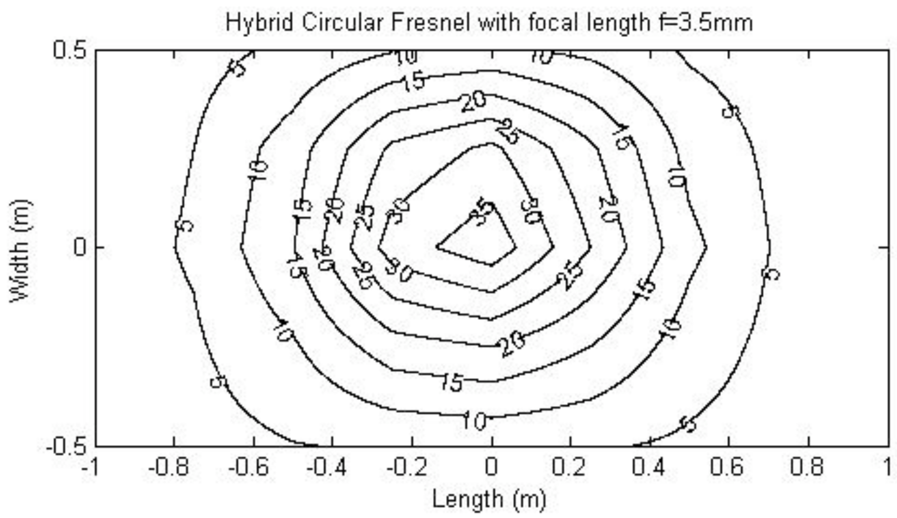

Figure 105: Polished circular fresnel with focal length of 35mm

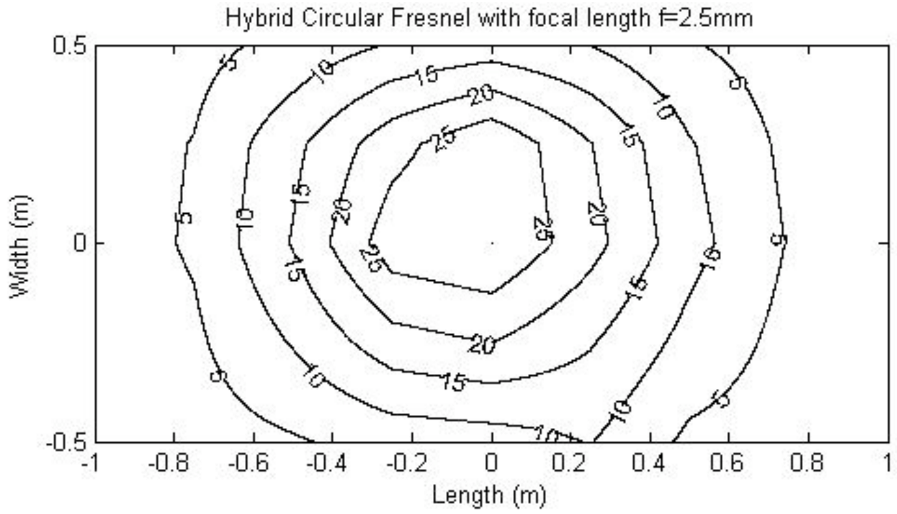

Figure 106: Polished circular Fresnel with focal length of 25mm

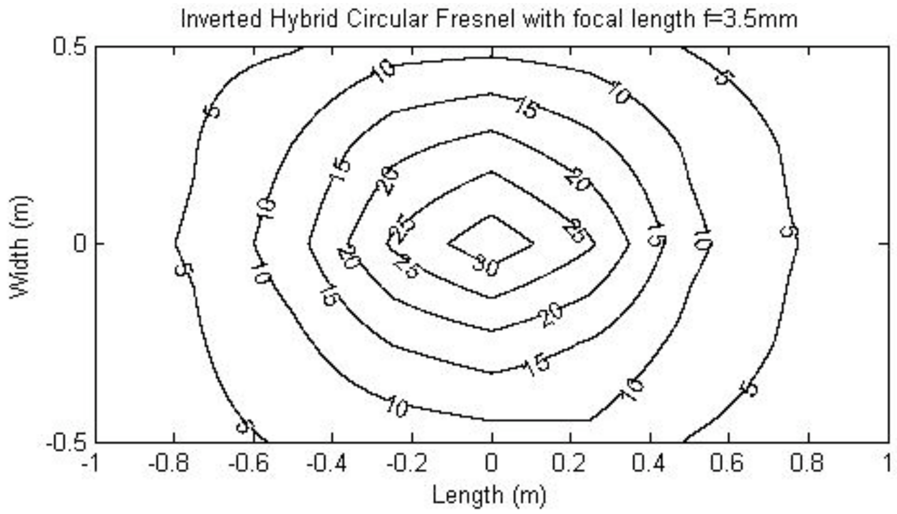

Figure 107: Polished inverted circular fresnel with focal length of 35mm

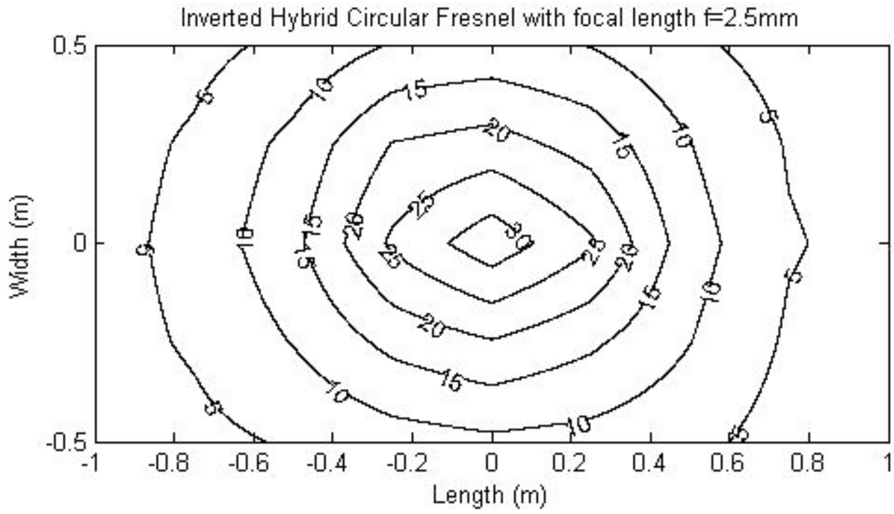

Figure 108: Inverted hybrid circular fresnel with focal length of 25mm

Table 30 is the étendue efficiency of each hybrid lens and its configurations. The percentages of the total flux collected are in the right-most column.

Table 30: Étendue efficiency

Lens type	CA mm	f mm	f-number	half angle	Optic etendue	Source etendue	Efficiency etendue
HCF	95.0	35.0	0.4	53.6	16.3	25.1	64.8
HCF	95.0	25.0	0.3	62.2	19.7	25.1	78.3
IHCF	91.0	35.0	0.4	52.4	15.8	25.1	62.8
IHCF	91.0	25.0	0.3	61.2	19.3	25.1	76.8
HLF	145.0	35.0	0.2	64.2	20.4	25.1	81.1
HLF	145.0	25.0	0.2	71.0	22.5	25.1	89.4
IHLF	140.0	35.0	0.3	63.4	20.1	25.1	80.0
IHLF	140.0	25.0	0.2	70.3	22.3	25.1	88.7
polished HCF	95.0	35.0	0.4	53.6	16.3	25.1	64.8
polished HCF	95.0	25.0	0.3	62.2	19.7	25.1	78.3
polished IHCF	91.0	35.0	0.4	52.4	15.8	25.1	62.8
polished IHCF	91.0	25.0	0.3	61.2	19.3	25.1	76.8

5.13 Analysis

As for the first two designs, the criteria for the hybrid lenses are four:

1. Seeing zone's luminance (cd/m²) levels
2. Noticeable human difference in intensity (cd) (30-50%)
3. Illuminance level (30lx for passenger transportation vehicles)
4. Collection efficiency (étendue)

The hybrid lens, as it is seen in Table 31, fits the zonal criteria. There is a good deal of uniformity with respect to the pattern and location of the peaks. The polished lens with 35mm focal length performs particularly well in this respect. Shortening the distance between luminaires by 0.15m would allow this configuration to fit all the criteria as set out above.

Table 31: Seeing zones and the minimum acceptable range for visual tasks

Lens type	Focal length mm	Zone 1 lx	Zone 2 lx	Zone 3 lx
Fluorescent	-	7.90	1.58	0.79
No Lens	-	17.00	3.40	1.70
HLF	35	16.00	3.20	1.60
HLF	25	15.40	3.08	1.54
IHLF	35	16.30	3.26	1.63
IHLF	25	15.00	3.00	1.50
HCF	35	32.20	6.44	3.22
HCF	25	28.20	5.64	2.82
IHCF	35	25.70	5.14	2.57
IHCF	25	26.10	5.22	2.61
polished HCF	35	38.30	7.66	3.83
polished HCF	25	30.00	6.00	3.00
polished IHCF	35	33.30	6.66	3.33
polished IHCF	25	33.20	6.64	3.32

What has not become clear from the design goal is the shift from the central area being the most intense to that of the outer edge (45º) from mechanical axis of the luminaire. The change in design has affected the distribution significantly. With manual ray tracing it is perhaps unfair to expect such high performance. Appendix H has images of all of the design and tested lenses.

5.14 Summary

The batwing hybrid lens with two regions of refraction is displayed. The results from the spatial distribution of the hybrid circular fresnel lens offers a distinct difference from those generated in Section 5.6. The ability to redirect light is a powerful ability to possess.

The étendue of each of the new designs is lower than that of the circular fresnel and linear fresnel designs of Section 5.6. The visual field performance is stuck to in this design, despite the application not requiring such strict performance. This is a recommendation set out for ‘task’ lighting.

The two lens designs, based on the criteria given, helped to make more uniform distributing luminaires, which may find application beyond the bus. It is important to note the following:

- A uniformly distributing luminaire is an ideal case but not the best-fit solution given that multiple luminaires are required for the bus application.
- The bus application has a general layout but varies based on the bus model.
- When spaced within the bus, the spatial distributions of each luminaire overlap. At the plane of detection, the illuminance is bound to be more uniform given this interaction between multiple luminaires, but this needs to be verified through modeling software or physical implementation.

Light at the horizontal plane is greater because of the new designs. Light that has been redirected from the outer reaches (widest viewing angles) is now normal to the luminaire. For the new design this may decrease unless other optics solutions like encapsulating optics (parabola or secondary optic) is used. This is the author’s hypothesis.

5.15 Recommendations

The use of modeling software and its value in designing non-imaging optics and spatial layout according to specification is discussed and then proposed.

Theoretically, the tools to increase user perceptions with optics are available. If the new technology were human factor tested it would help create better fittings that are more efficient

CHAPTER 6
CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

The range of information in the *case* for LEDs swept across social, economic, location-specific and other intangible (and oft forgotten) factors such as human needs. The case for the application of white LEDs validates the need for research and capital investment into this energy efficient device.

In this thesis an example was used to best display the challenges that were initially identified in the Western Cape and the rural pilot project of Namulonge. The example of Golden Arrow Bus Services allowed us to tackle an interior and remote application with specific illuminance requirements in one. The electrical, thermal, mechanical and optical issues for successful integration were researched. The luminaire, as an entire structure encasing all things related to this lighting system, is designed according to the required criteria and available standards.

Quality of lit environment and quantity of LEDs were important issues. Since cutting-edge technology is over-priced due to market barriers and research and development funding, these aspects of *quality* and *quantity* found prominence through the investigation of a suitable solution. As few as possible light-emitting diodes were used with the aid of optics to tackle the problem.

The following milestones were met:

- The operating current was chosen in accordance with the lighting needs and available specifications
- A spacing criterion was developed
- The utilization of the directional light sources was increased through employing optics

Three sets of optics applications were adapted using an Acrylic material to realize the designs:

- Non-imaging systems (collimating lens)
- Batwing lens from prismatic fluorescent lens covers
- Automotive forward lighting using Fresnel lenses

The priority was to conserve the available energy. Étendue of each optic solution was calculated to numerically quantify what available flux was collected.

Finally, lenses were developed in consideration of passenger safety, human perception and visual comfort. They are the *Circular Fresnel*, *Linear Fresnel*, *Hybrid Circular Fresnel* and *Hybrid Linear Fresnel* linear lenses. These were done on a milling machine with a small test bed area of 200mm by 150mm. Each of the lenses was tested in a dark room with a constant environment in the normal and inverted orientation at a focal length of 25mm and then 35mm.

Uniformity criterion was researched and applied to the spatial distribution on the horizontal plane over the detection area. Photometric criteria such as luminance, illuminance and intensity were also used to check the four lenses.

Through novel placement of heatsink and LED mounting mechanism the author attempted to derate the high power LED, given the luminaire constraints. This method proved successful given that no degradation was experienced during the testing phase.

6.2 Recommendations

The recommendations are primarily for the GABS example. The rest of the subjects covered in this thesis have been concluded upon in their respective chapter.

Uniformity of spatial distribution can be adjusted through computational modeling of optic elements and placement of sources. These user-defined criteria can be modeled effectively by software. Complicated segmented surfaces and facets may be modeled to reduce time in production. It is recommended that any demanding application use computational design tools to do so.

More groove angles/edges should be modeled and used to increase transmission efficiency and the collimating property of the lens.

Transmission efficiencies should be checked computationally and practically with the appropriate devices (like an integrating sphere).

It would be productive to research other spatial distributions (e.g. batwing, etc.) in the far-field and see what spatial distributions they render on the horizontal plane. This would allow for more efforts into uniformity and the possible use of optics that can best utilize light from other LED types.

The circuitry for the GABS application needs to be developed further to enhance the luminaire's robustness and longevity.

The pre-implementation human factors analysis excludes subjects of localization such as bus internal reflectance and the trade-off between CCT and CRI even though a match for the fluorescent was found in the type of LED selected. This study should be carried out before installation.

To gauge whether the technical specifications are relevant to the application it is suggested that feedback from commuters (after empirical testing) is gained. Quality of light is about human perception and the interaction with this lit environment. Feedback from commuters will help future installations, which only use white LEDs for the entire interior lighting of the bus.

Now that the main illuminance demands have been met, an economic appraisal should follow to validate the design.

A clear set of South African lighting standards is needed. These standards would be for:

- All automotive lighting applications (interior)
- Interior applications for human use employing LEDs
- Grid and renewable technology connection circuitry for LEDs

This thesis, a manual of application issues, has put emphasis on energy efficiency, adapting to constraints, a clear systems approach to design and the need for an integrated approach to rural and remote areas needing light. To further elucidate the white LED, the author hopes that reader's research more about LEDs, implement them where possible and create enterprise. All of these ***actions*** would help the greater effort of having energy used efficiently.

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APPENDICES

Appendix A

The pictures below were taken in Namulonge. The pictures were taken from two houses of the ten houses that were part of the pilot project. Village houses are brick and mortar structures with zinc roofs and no ceilings. The irregular mounting of refractor-based single LEDs is shown. The power delivered to the LEDs was from solar PV units. 12V car batteries store the energy and no regulatory circuitry exists between battery and LED. A floor area to be lit was typically 4m by 4m.

Figure 109: A single 1W LED placed in the corner of a room.

Figure 110: The battery used to store charge from a solar PV system

Figure 111: None of the houses had ceilings installed. By installing ceilings, more light could be refracted and used within the desired area.

Figure 112: A contact to switch on and of the white LEDs in a room. Such weaknesses in the system installation reduced the sustainability of the project.

Figure 113: A single 1W LED. It had a blue hue with a very low colour rendering ability.

Figure 114: A typical area to be lit is captured above. This area is approximately 16m². A single white LED was chosen to light this entire area.

Appendix B

Datasheets for the three LEDs initially research to fit the GABS design application

Appendix C

This is the datasheet for the illuminance photometer used during laboratory testing.

Appendix D

This is the datasheet of the linear regulator used to drive the laboratory experiments.

Appendix E

This is the heatsink datasheet used to run away the heat for each of the 6 K2 Luxeon LEDs used for the GABS luminaire

Appendix F

The optical and physical characteristics of the Linear Fresnel and Circular Fresnel

Lens	**No Lens**	**Linear Fresnel**	**Linear Fresnel**
Focal length		Nonimaging (f=35mm)	Nonimaging (f=25mm)
Diameter (mm)		145mm	145mm
Optcal Clear Aperture (CA)		145mm	145mm
Thickness (mm)		4	4
Material		Acrylic	Acrylic
FWHM (±θ)		35	37.5
On axis intensity (cd)	17	22.8	21.5
on-axis gain		1.341176471	1.264705882
peak intensity at angle (θ)	17 (0°)	22.8 (0º)	21.5 (0º)
Min. Illuminance (lx)	3.8	2.3	2.3
Max. Illuminance (lx)	17	22.8	21.5
Illuminance Variance over plain (%)	77.64705882	89.9122807	89.30232558

Lens	**No Lens**	**Inverted Linear Fresnel**	**Inverted Linear Fresnel**
Focal length		Nonimaging (f=35mm)	Nonimaging (f=25mm)
Diameter (mm)		140mm	140mm
Optcal Clear Aperture (CA)		140mm	140mm
Thickness (mm)		4	4
Material		Acrylic	Acrylic
FWHM (±θ)		38.6	35.75
On axis intensity (cd)	17	19.8	17.5
on-axis gain		1.164705882	1.029411765
peak intensity at angle (θ)	17 (0°)	19.8 (0º)	17.5 (0º)
Min. Illuminance (lx)	3.8	2.6	2.8
Max. Illuminance (lx)	17	19.8	17.5
Illuminance Variance over plain (%)	77.64705882	86.86868687	84

Lens	**No Lens**	**Circular Fresnel**	**Circular Fresnel**
Focal length		Nonimaging (f=35mm)	Nonimaging (f=25mm)
Diameter (mm)		104mm	104mm
Optcal Clear Aperture (CA)		104mm	104mm
Thickness (mm)		4	4
Material		Acrylic	Acrylic
FWHM (±θ)		10.2	10.2
On axis intensity (cd)	17	52.9	52.3
on-axis gain		3.111764706	3.076470588
peak intensity at angle (θ)	17 (0°)	52.9 (0º)	52.3 (0º)
Min. Illuminance (lx)	3.8	1.1	1.1
Max. Illuminance (lx)	17	52.9	52.3
Illuminance Variance over plain (%)	77.64705882	97.92060491	97.89674952

Lens	**No Lens**	**Inverted Circular Fresnel**	**Inverted Circular Fresnel**
Focal length		Nonimaging (f=35mm)	Nonimaging (f=25mm)
Diameter (mm)		100mm	100mm
Optcal Clear Aperture (CA)		100mm	100mm
Thickness (mm)		4	4
Material		Acrylic	Acrylic
FWHM (±θ)		11.3	26.6
On axis intensity (cd)	17	42.3	48.3
on-axis gain		2.488235294	2.841176471
peak intensity at angle (θ)	17 (0°)	52 (± 11º)	48.3 (0º)
Min. Illuminance (lx)	3.8	1.5	1.4
Max. Illuminance (lx)	17	52	48.3
Illuminance Variance over plain (%)	77.64705882	97.11538462	97.10144928

Appendix G

The optical and physical characteristics of the Hybrid Linear Fresnel and Hybrid Circular Fresnel

Lens	**No Lens**	**Hybrid Linear Fresnel**	**Hybrid Linear Fresnel**
Focal length		Nonimaging (f=35mm)	Nonimaging (f=35mm)
Diameter (mm)		145mm	145mm
Optcal Clear Aperture (CA)		145mm	145mm
Thickness (mm)		4	4
Material		Acrylic	Acrylic
FWHM (±θ)		35	31
On axis intensity (cd)	17	14.9	14.9
on-axis gain		0.876470588	0.876470588
peak intensity at angle (θ)	17 (0°)	16.9 (± 11º)	15.9 (± 11º)
Min. Illuminance (lx)	3.8	2.6	2.6
Max. Illuminance (lx)	17	16.9	15.9
Illuminance Variance over plain (%)	77.64705882	84.61538462	83.64779874

Lens	**No Lens**	**Inverted Hybrid Linear Fresnel**	**Inverted Hybrid Linear Fresnel**
Focal length		Nonimaging (f=35mm)	Nonimaging (f=35mm)
Diameter (mm)		145mm	145mm
Optcal Clear Aperture (CA)		145mm	145mm
Thickness (mm)		4	4
Material		Acrylic	Acrylic
FWHM (±θ)		34	35.76
On axis intensity (cd)	17	16.3	14.8
on-axis gain		0.958823529	0.870588235
peak intensity at angle (θ)	17 (0°)	16.5 (± 11º)	14.8 (0º)
Min. Illuminance (lx)	3.8	2.8	2.5
Max. Illuminance (lx)	17	22.8	21.5
Illuminance Variance over plain (%)	77.64705882	87.71929825	88.37209302

Lens	No Lens	Hybrid Circular Fresnel	Hybrid Circular Fresnel
Focal length		Nonimaging (f=35mm)	Nonimaging (f=35mm)
Diameter (mm)		95mm	95mm
Optcal Clear Aperture (CA)		95mm	95mm
Thickness (mm)		6	6
Material		Acrylic	Acrylic
FWHM (±θ)		21.8	26.6
On axis intensity (cd)	17	38.3	30
on-axis gain		2.252941176	1.764705882
peak intensity at angle (θ)	17 (0°)	38.3 (0º)	30 (0º)
Min. Illuminance (lx)	3.8	1.5	1.3
Max. Illuminance (lx)	17	38.3	30
Illuminance Variance over plain (%)	77.64705882	96.08355091	95.66666667

Lens	No Lens	Inverted Hybrid Circular Fresnel	Inverted Hybrid Circular Fresnel
Focal length		Nonimaging (f=35mm)	Nonimaging (f=35mm)
Diameter (mm)		91mm	91mm
Optcal Clear Aperture (CA)		91mm	91mm
Thickness (mm)		6	6
Material		Acrylic	Acrylic
FWHM (±θ)		26.6	26.6
On axis intensity (cd)	17	33.3	33.2
on-axis gain		1.958823529	1.952941176
peak intensity at angle (θ)	17 (0°)	33.3 (0º)	33.2 (0º)
Min. Illuminance (lx)	3.8	1.5	1.3
Max. Illuminance (lx)	17	33.3	33.2
Illuminance Variance over plain (%)	77.64705882	95.4954955	96.08433735

Appendix H

Photographs of the luminaire and the designed lenses.

Figure 115:Metal casing

Figure 116: Lens cover for fluorescent luminaire

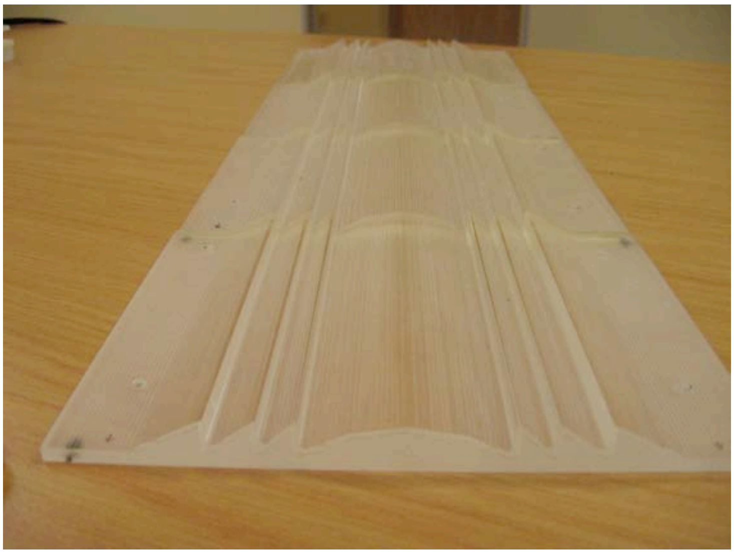

Figure 117: Linear Fresnel

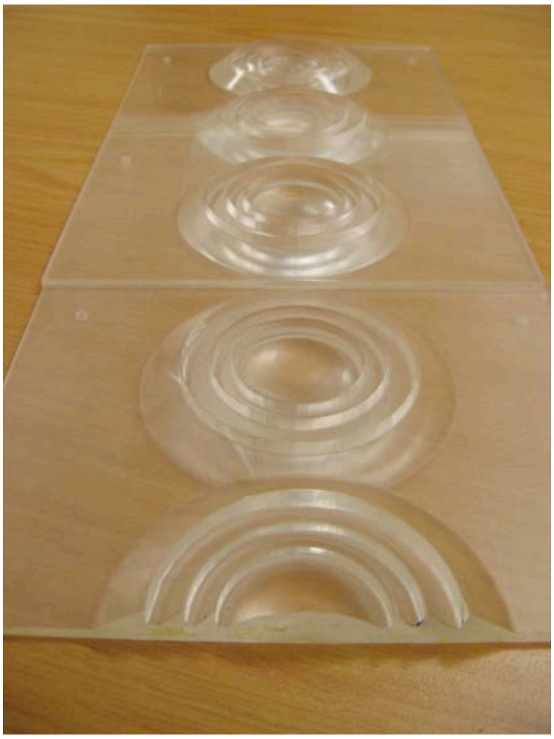

Figure 118:Circular Fresnel

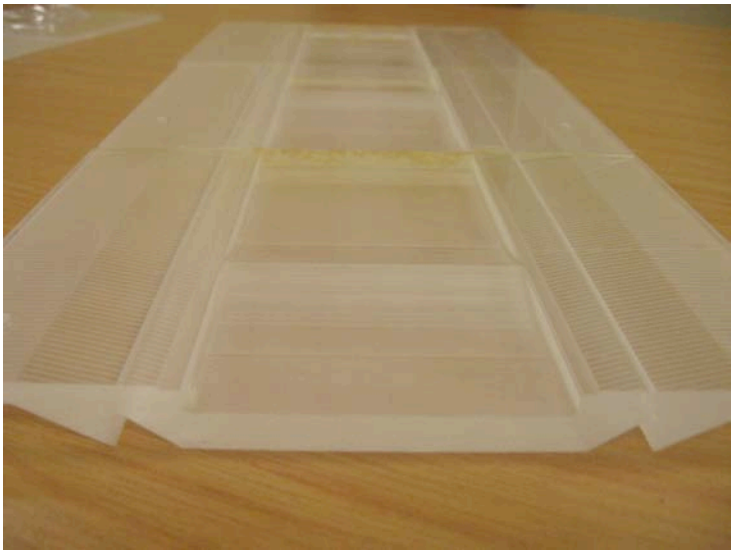

Figure 119:Inverted Hybrid Linear Fresnel

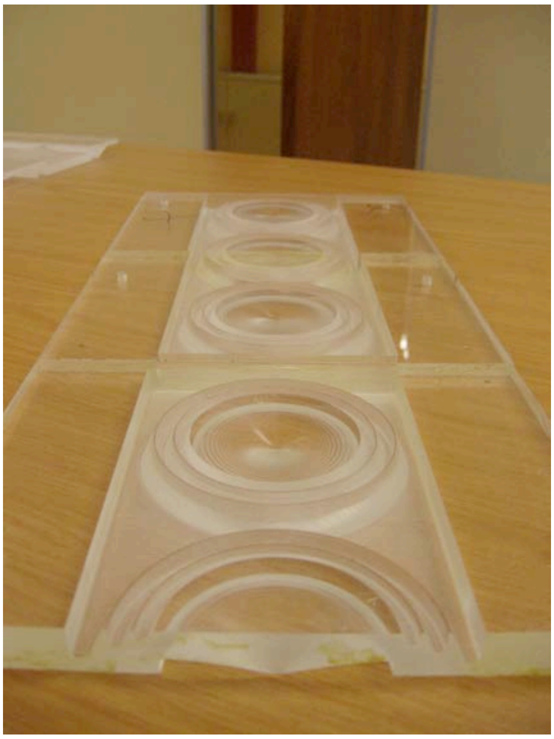

Figure 120: Normally oriented Hybrid Circular Fresnel