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Development of Homogeneity Requirement for Position Lights

Transformation from Subjective to Objective evaluation

Master's thesis in Product Development

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Volvo Cars

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Abstract

Exterior lighting has become an important factor across all the automotive industry. Conventionally, light was only used to illuminate the road and help the users to have a clear vision of the road in the darkness but now it has become premium design feature for aesthetic appeasement. Lately users have started to identify the brand of the car by just viewing the light from the lamps.

Many car-manufacturers are striving to get a homogeneous intensity of position lights. Light homogeneity has become a major factor under consideration during lamp design and development. Precedence is given to the perception of homogeneity by human eye over equipmental data of the same.

This thesis aims to overcome the subjective evaluation of light homogeneity of lamps by bring in an objective approach and to generate corresponding requirement. The thesis work also aims to generate a verification method that can be integrated to the requirement generated.

Using product development approach and established laws of photometry, an experimental investigation is performed inorder to determine quantifiable limits that assists the requirement. Investigation involves study on various factors that influence homogeneity such as eye perception, distance and angle of judgement, legal requirement and design intent. The thesis incorporates user study, which served as a foundation for obtaining subjective data and setting the requirement.

Threshold values for intensity variation via response threshold was determined. It was investigated and verified that -13% and +9% were the threshold response variation between two regions, violation of which would deem the regions to appear inhomogeneous. The verification of requirement is methodically generated which was specific to the tools that were available.

Keywords: Homogeneity, Position Light, Requirement, Verification, Perceived Quality Illumination.

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1

Introduction

Light is a very important aspect which is involved in perception of aesthetics of any visible structure. It plays an important role when it comes to an individuals visual judgement of anything illuminated. It is equally important for the source of light to have a uniformity in its appearance for the same reason. This would be very critical for an automotive light source which would be directly in sight of a viewer.

The appearance of the lamps, not just in design and optics but also in the uniformity with which it projects light gives a vehicle the desired aesthetic vibrancy. Most of the automotive manufacturers strive for the same. This thesis focuses on the light from the exterior front headlamp and in particular the position light of the vehicle. A well luminated surface looks aesthetically pleasing and alluring. Having such a surface as a lamp of a car would enhance its visual perception. Although the main purpose of an automotive lamp is to illuminate the road in front, lamps in cars have evolved not just in technology but also in its purpose and appearance. Automotive lamps are not only used just as a functional organ of the vehicle but are incorporated into its overall design.

Since the lamps are exposed, blending the functional aspect and aesthetics of lamp becomes both challenge and aim to strive for. Perceived visual quality plays an important role on users emotional reactions and consequences of their experience [1]. Perceived visual quality of a lamp is governed by lamp shape, housing, optics and reflectors. These support the aesthetics even when the lamp is in switched OFF condition. When the lamp is switched ON, aesthetics is governed by the light that is emitted from the lamp. Hence in switch ON position, the luminance from the lamp dominates the aesthetic appearance and this project is focused on generating requirements for the luminance of the lamp to be homogeneous.

Light as a physical entity can be quantified using various measuring instruments available in the market. However, these quantifiable factors of light is not directly transferable to perseverance of light since it is completely subjective to the user. Also the psychological aspect of the user is to be considered since different users have different opinions and priorities on seeing similar illuminated lamps.

1.1 Background to Thesis

Technological evolution of lamps
Looking back at the evolution of a car lamp, right from the technologies of bi-functional

incandescence bulb (Bilux lamp) in 1924 [2] to the more modern technologies of LED's and laser technologies, the effort to make the lamp functionally and aesthetically more advanced is seen prominently. This includes satisfying all the design requirement and legal aspects and simultaneously making the lamp as visually pleasing as possible. Considering the evolution of technology, 1980´s used reflectors and projectors to guide the beam of light straight forward. This classic approach was to collect light from the bulb in a parabolic reflector and then direct the light onto a lens that creates the final beam pattern on the road.[2] Here, the whole interior of the lamp would light-up and only design freedom available is to vary the convexity of the parabolic reflector to make it look visually pleasing.

The year 1999 saw the advent of light guides. The main advantages of light guide is the styling benefits and isolation of light source, socket, printed circuit board and heatsinks away from light-emitting surfaces. However it satisfied both aesthetics and technicalities that was difficult to match with the parabolic reflectors [2].

The year 2007 saw the advent of LED´s in headlamps. It was soon in widespread use and its benefits included longer lifetime, directional light, reduced package size and energy savings [2]. With new technologies such as Organic LED´s (OLED), lasers and LED pixels, development of technically sophisticated and visually pleasing headlamps can be expected in the near future.

In all the above lamp technologies and concepts, design and development is focused to make the light functionally and visually pleasing to a human eye. This thesis is focused towards making the light as visually pleasing as possible.

1.1.1 Anatomy of lamp

The exterior position light of the car not only acts as welcome light of the car but also helps the user to locate the car in a darkness. The headlight of the car basically consists of housing, reflectors, projection models, and the cover lenses. The housing of the headlamp acts as a carrier for all other components such as cables, reflectors, light guides etc. It is also used to prevent the lamp from exterior influences like water, snow, heat etc. The role of the reflectors is to collect the most possible amount of light that is radiated by the bulb and to illuminate the road. Conventionally reflectors were made up of steel but today due to increase in the level of competition such as reduced weight, design, quality etc the reflectors are made up of thermoplastic. Modern headlamp make use of projection models to restrict the path of the beam. The task of the cover lenses is to capture the light from the reflectors and focus or deflect it in such a way that the required intensity of light is directed towards the road. Cover lens consists of dispersion optics on it. Previously lenses were made up of glass but in order to protect the other road users in case of accidents, also due to reduce weight, increase tolerance etc. the modern cover lenses are made up of plastic which is mainly polycarbonate. This enables it to collapse on impact thereby reducing the injury in circumstance of an accident. [3]

Two types of lighting technology currently dominate the automotive sector when it comes to its application in headlamp.

- **Collimator Solution**
  Collimator is a device that aligns the beam of light in one particular direction. The beam of light is made to fall on the curved lens surface of the collimator. Total internal reflection of light occurs and the collimator collects all the scattered rays and aligns it as parallel rays. Depending on the type of collimator the orientation of the light changes. The collimators are used for each individual lamps. [4]

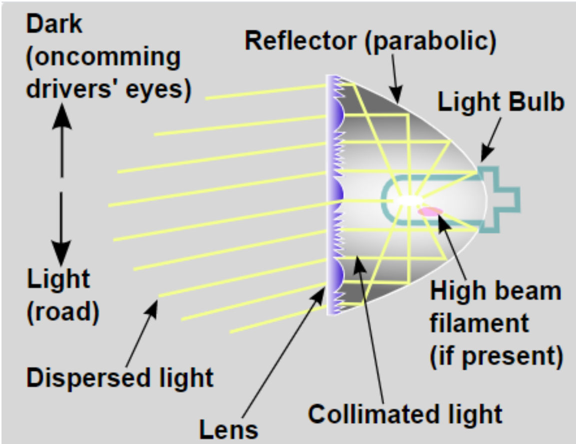


Figure 1.1: Collimator. From [5]. CC-BY-SA

- **Lightguide Solution**
  Lightguide is a tube mostly made up of polycarbonate. the tube is machined with prism at certain distance, size and shapes. One end of the guide is fed with a light source which enables to lit the whole thing along the length of the tube. Light basically gets emitted from the surface of the tube. [6]

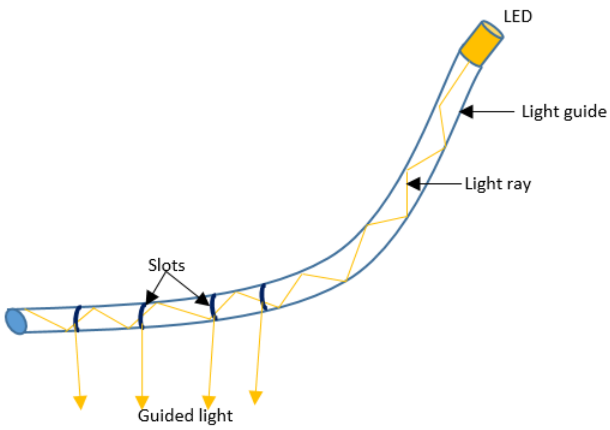


Figure 1.2: Light guide.

1.2 Volvo Car Group

Volvo Car Group is a car manufacturing industry, which produced its first car in the year 1927, on the west coast of Sweden, Gothenburg. Safe, sustainable, and convenient mobility are the most prominent cultures at Volvo cars. In 2010, Geely, a chinese company took over Volvo cars from Ford Motor company. Even though they are influenced by the Scandinavian design which dominates the cars produced, the manufacturing and the research and development operations are performed in Europe, Asia and the America.[7]

Volvo cars strive to produce environmental friendly cars by reducing carbon emissions of all their cars. This means that Volvo cars are creating all-out electrification autonomous cars by 2025. They are also aim towards sustainability by using 25 percent of recycled plastics in their cars by 2025.[8]

1.3 Perceived Quality

Automotive industry around the global are designing the product in such a way that it reaches the customer expectations. Delivering zero defect product is not a challenging task for an industry since anything is made possible by devoting time, effort, energy and cost. Having boundary conditions and limitations in technology, production capabilities and finance will challenge the industry to produce a product that meets the customer expectations and needs. To overcome this, any company needs to step into customers shoes. Hence, Perceived Quality department is introduced in each automotive industry to understand such dimensions and decisions of the customer. [9]

Of several dimensions of defining Perceived Quality, according to Stylidis et al. [9], Perceived Quality has two distinctions in the automotive industry, that is Value Based Perceived Quality (VPQ) and Technical Perceived Quality (TPQ). TPQ acts as a subset of the VPQ. The TPQ is based on the individual technicality on the product. In TPQ engineers having technical knowledge on the particular field and are involved to evaluate the specific component, in order to meet the requirements of the customer. It consists of attributes such as the visual quality, feel quality, sound quality and smell quality. The VPQ consists of all the attributes that are included in TPQ along with some additional components such as customer behavior, brand image, brand heritage and core values etc. Perceived quality as both VPQ and TPQ, have made the automotive sector a competitive environment. [9]

As shown in Figure 1.3, Perceived Quality (PQ) is described as sensory apparatus which consists of several combination of attributes in their primary senses such as olfactory quality, auditory quality, tactile quality, visual quality and gustatory quality [10]. In the second level, based on the previous experiences and knowledge gained by the industry nine sets of PQ sensory modalities are generated: Small quality, sound quality, solidity, paint quality, geometrical quality, material quality, joining quality, illumination quality, and appearance quality. Each second level attributes includes a number of ground level attributes. In this ground level customers are involved to rate the product and get feedback based on their experience on the product. This ground level attribute acts as a framework for other higher levels since it involves both customers and engineers. [9] [10]

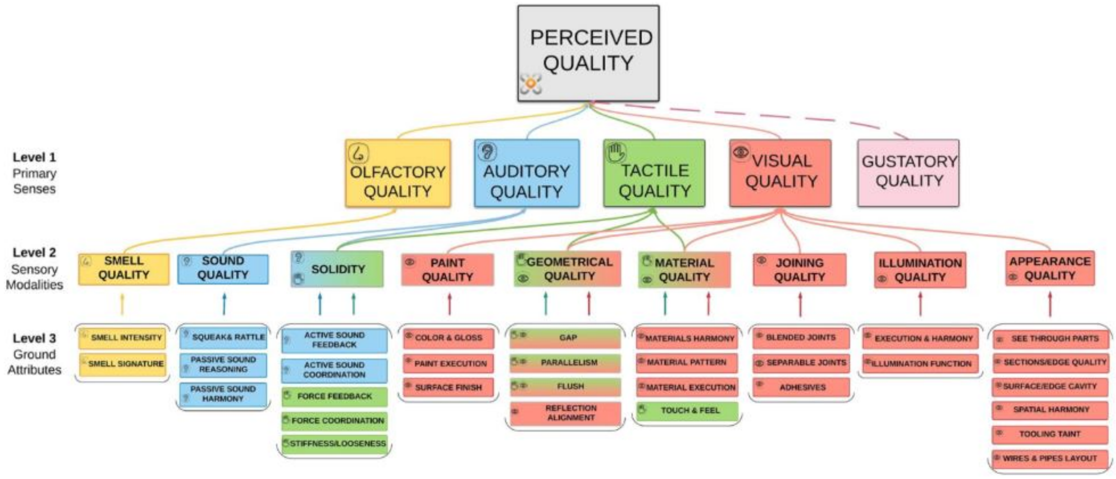


Figure 1.3: Perceived Quality From [10]. CC-BY-NC-ND 4.0

1.3.1 Perceived Quality at Volvo Car Group

"Perceived Quality" refers to the quality that customers acknowledge via look, touch and feel of a car. The Perceived Quality attribute area at Volvo Car Group defines the requirements such that it reflects the needs of the customers in such lines. Perceived Quality is an important attribute for Volvo Car Group to be considered as a competitive premium car manufacturers. Engineers at Perceived Quality, along with similar attribute areas such as mechanical ART's and Design, focus on making the product visually appealing and in accordance with the needs of the target customers. They safeguard the needs and interest of the target customer by setting up requirements, fulfilling and improving upon the same. Perceived Quality at Volvo Car Group consist of five sub-attributes which are Geometry & Appearance, Material Quality, Illumination, Paint and Surface Finish.

This thesis work was carried out at Perceived Quality Illumination where requirements on execution and quality of various light features of the complete car are defined which would reflect and improve upon the customer need. Perceived Quality Illumination defines these requirements and also verify the requirement for a complete light experience right from the virtual phase to physical build. Uniformity, harmony and homogeneity are considered as the major aspects while generating the requirements.

1.4 Purpose of Thesis

As exterior light is now a strong part of the design and vehicle DNA, not only legal requirements on front and rear position light needs to be fulfilled for certification but also visual appearance requirements on light are now becoming more common along with the rapid development of various LED technologies and the limit for premium appearance is close to perfection. Since the the perception of light is highly subjective, there is a need to translate this perception in quantifiable terms. Unlike other aspect of Perceived Quality such as Geometry and Appearance, where tolerance for gaps and flushes are given and Material and surface finishes, where tolerance on color scale, grain size or similar are given, the same cannot be translated to light since there is no limitations on any quantifiable parameter to make the light to be perceived homogeneous. Hence the main purpose of this thesis is to assist the incorporation of homogeneity to the front position lights of the car through generation of verifiable requirement.

1.5 Objective of thesis

The aim of the thesis is to develop a relevant light homogeneity requirements and correspondingly generate a verification method. The study covers a wide range of disciplines involving user perception, CAE light simulation, photometry and image processing.
Furthermore, there is an increased focus on objectiveness in requirements to overcome subjective evaluations that currently dominates the development process. Within the Perceived Quality illumination, the complete vehicle requirements are evaluated and verified using both CAE generated simulations and physical vehicles. In line with this progress, Volvo Cars and Perceived Quality illumination are in need to investigate and set standard for lit surface homogeneity with respect to light intensity and colour.
Proposal on a requirement setup that is comprehensive and non-solution dependant and that can be formalized in measurable specifications. proposal on a verification method to be used on virtual simulations during development and in PQ evaluation on physical prototype and pre-production builds.

1.6 Limitation

The Scope incorporates analysis of current Volvo Car Group and competitors position light performance. The scope is restricted to verification of selected model of Volvo cars and limited technology of the lamp. Scope does not include suggestions or modifications of the lamp anatomy or physics to achieve homogeneity. The homogeneity in intensity is given priority over the deviation in light color if any.

1.7 Research questions

- 1) What are the research approaches and various design parameters to be considered for defining homogeneity of lit surface of the lamp?
- 2) What is an effective and efficient way to record, document and analyse the subjective response from the users for change in light intensity?
- 3) How can one measure human subjective perception and the measurable objective change in light intensity (Stimulus)?
- 4) Establishing relationship that converts objective data into actual user subjective perception. How to objectify the light intensity change affecting homogeneity?

These questions will influence most of the steps taken to conduct the research.

2

Theory

In this chapter, the theoretical background of the concepts and laws incorporated that is necessary when reading this thesis is outlined. This section gives insights to information and content which derives the thesis work and its outcomes.

2.1 Human Visual System

The Human Visual System (HVS) contains three main parts:

- Eyes
- Lateral Geniculate Nucleus (LGN)
- Visual cortex

The parts that constitute the path through which the information of a visual travels from the receptor (eye) to the interpreter which is the brain as shown in figure 2.1. Eye receives the light which is projected as an image in the eye and converted into photo-signal. This signal is transferred via the optic nerve to the visual cortex which processes the visual information. [11] This visual information can be interpreted as the subjective judgement of the brain.

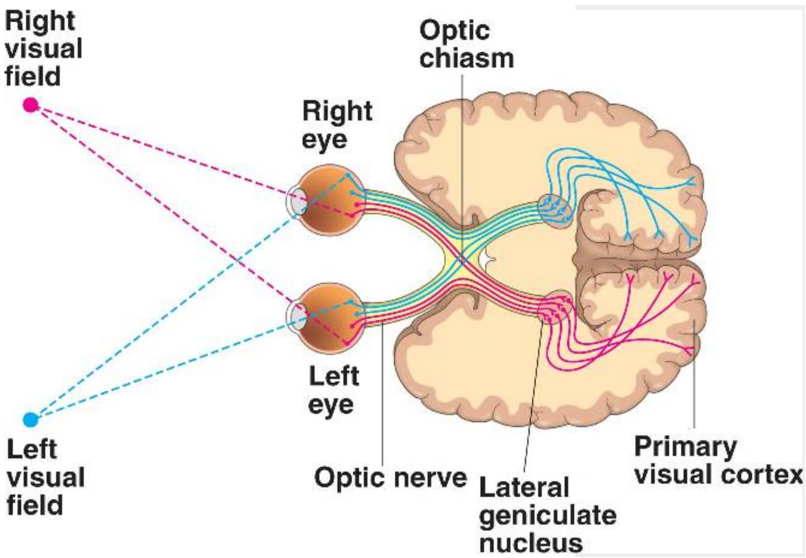


Figure 2.1: Human visual system. From [12]. CC-BY-SA-4.0

Eye is a visual organ as seen in figure 2.2 which is roughly spherical, with a diameter of 2.3 to 2.4cm. In the front there is an external lens, the cornea, which is in contact with a liquid called aqueous humour. Behind the aqueous humour liquid 11 is the iris which controls the diameter of the pupil. Pupil is able to change its diameter from about 2mm to 8mm, in order to allow more or less light to reach the retina. Retina is the membrane that lies in the bottom of the eye where the photo-receptors are present.

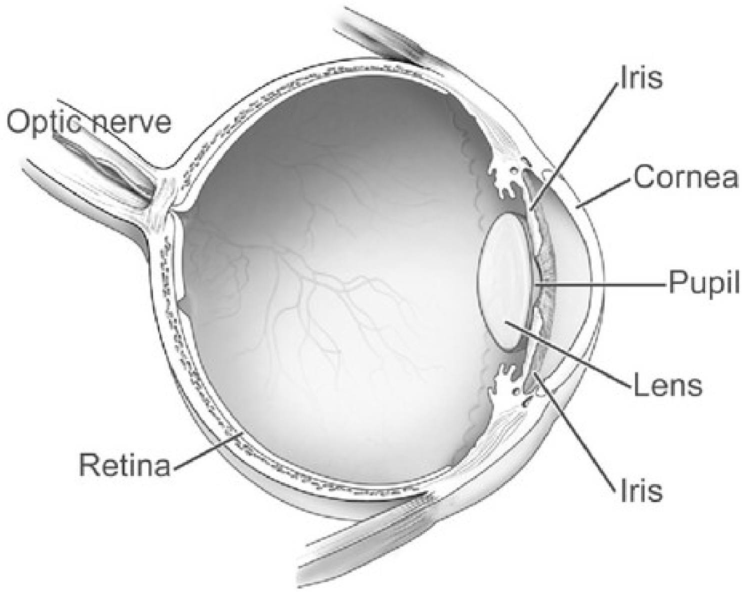


Figure 2.2: Anatomy of eye. From [13]. CC-BY

When we look at an object, an optical image is projected on the retina. The retina contains two types of photosensitive cells, namely rods and cones. Rods are responsible for low luminance level vision also known as scotopic vision. Cones are active at high luminance level vision also known as photopic vision, and they permit the vision of the colours. [11]

At the center of the retina there is an area called the fovea, which contains the highest spatial concentration of cones. This allows the best visual activity in our field of view. Towards the periphery of the fovea, the number of rod increases while the number of cones decreases. There is also a blind spot where the optic nerve connects to the periphery of the eye ball.[11] However, in case when the visual signal is a result of only the light source, studies have shown that the pupil response is very different and the perception of visual signal by the brain is very different than the normal circumstances. [11]

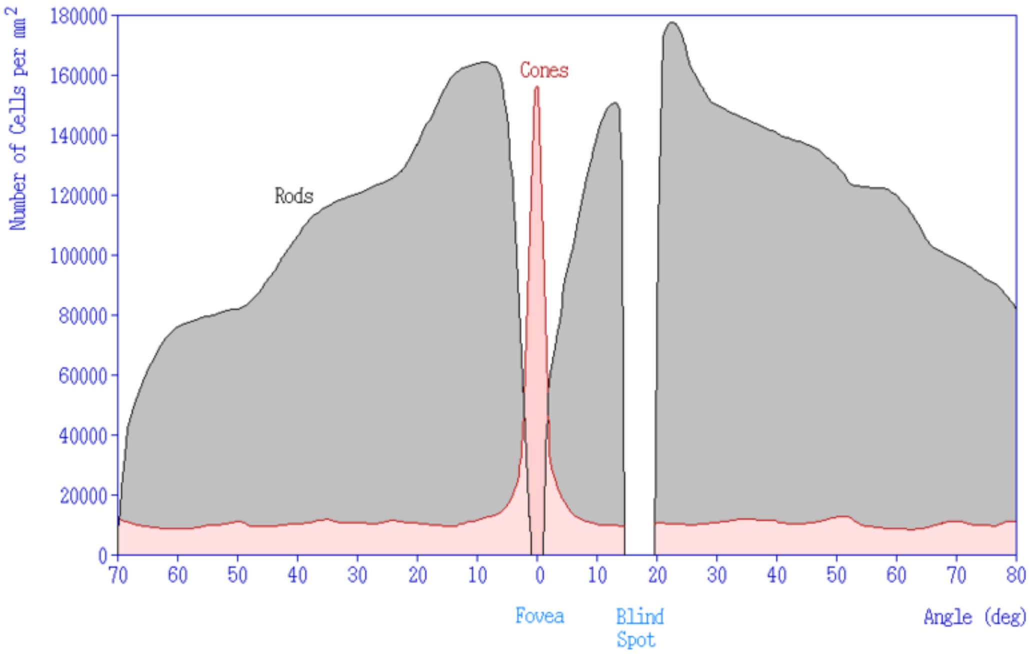


Figure 2.3: Spacial arrangement of rods and cones. From [14] CC-BY-SA.

There are five major factors that affect visibility and its perception: visual size, luminance contrast, retinal image, color difference quality and retinal illuminance[15]. Of the above, major factors which would influence the perception of brightness since it involves intensity of light rays incident are luminance contrast and retinal illuminance. Mathematically, luminance contrast is the difference between the object at focus and background luminance divided by the background luminance. Retinal illuminance is a measure of illuminance falling upon the retina and its interpretation by the brain which dictates the adaptation of the visual system.[15]

Lamp measured by the perception of human eyes
Human eye consists of fovea which is a part of eye's retina, helps to identify wide range of colours. During activities such as watching television, driving, reading and similar, sharp central vision is necessary which is provided by the central region of eye containing fovea. Fovea has three different level of cones in which the highest concentration is Photopic, which is responsible for the sharpened focus of the colour vision. Mesopic and scotopic are the other two different receptor cells in the eye. [16]

2.2 Theory and Laws of light

Light can be defined as a transverse, electromagnetic wave that stimulates vision to the typical human eye. Spectrum of light is made up of many different wavelengths of energy produced by the light source. Visible light falls in the range where wavelength of spectrum is between 380 nano-meter and 780 nano-meter. Technically light is a transverse, electromagnetic wave that is visible to the human eye. In other terms this is the wavelength range that is sensitive to the human eye.[17]

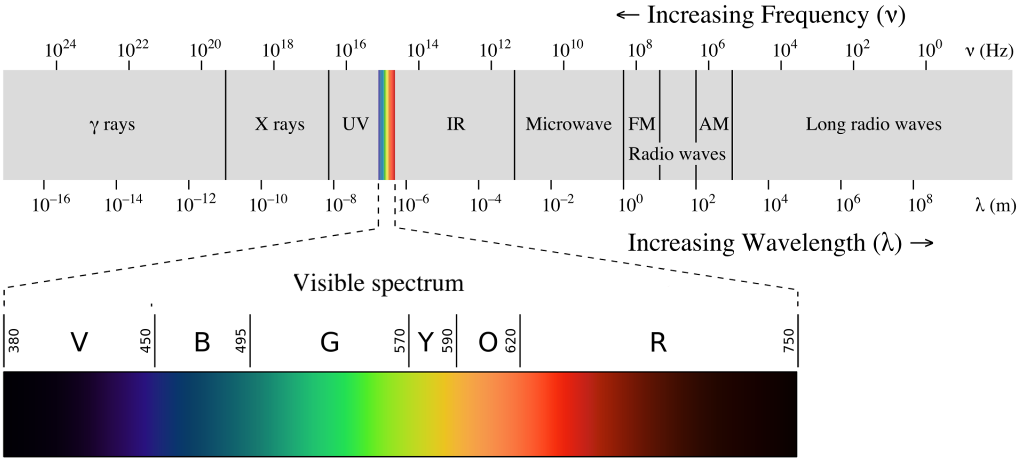


Figure 2.4: Light spectrum. From [18] CC-BY-SA

The light that is perceived is often a mixture of different wavelengths whose varying composition is a function of the light source.[17] White light is obtained by mixing different wavelengths of light. The following sections explains the various laws that are associated with Light and its perception.

2.2.1 Inverse square Law

Inverse square law is one of the basic laws in physics which is obeyed by many laws such as Coulomb´s law and Newtons gravitational law. In general it states that a physical quantity or its magnitude is inversely proportional to the square of the distance from the source of the same physical quantity. [19] In the context of this thesis, the physical quantity is light and the distance under context is the distance of the observer from the lamp.

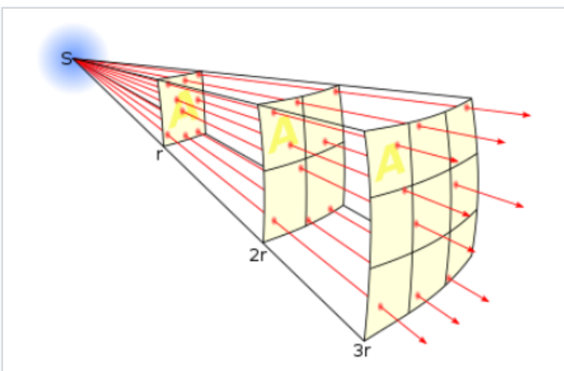


Figure 2.5: Inverse square law. From [20] CC BY-SA.

Hence the intensity of light from the lamp decreases by one fourth of its original intensity if the observer moves twice the distance away from the lamp.

2.2.2 Stevens's power law

Stevens' power law is a psychophysical law that tries to establish a relationship between the objectiveness of a physical quantity and its subjective perception. It proposed a relationship between the magnitude of a physical stimulus and the intensity that people feel with introduction of a psychophysical exponent.[21] The law is in basic form is represented as in equation below.

$$\psi(I) = k(I)^a \tag{2.1}$$

Where:

- I is the physical stimulus magnitude.
- $\Psi$is a psychometric function. This maps I into sensation.
- k is a constant. This dependents on the sensory process and unit of the physical stimulus.
- a is constant which depend on the sensory modality. [21]

The exponent (a) indicates whether magnitude of perception grows more slowly than physical magnitude when ($a < 1$) or directly as physical magnitude when (a equals 1), or faster than physical magnitude ($a > 1$). The exponent is typically determined using judgments based on a single stimuli. [22]
The research by A.Custódio and D.Trigo [23] establishes and co-relates to the research performed by P.Sara. [16] Difference is that here digital camera and image processing softwares are used for the analysis and an attempt is made to calibrate the camera to match with the visual perception. [23]

2.2.3 Lambert's cosine law

Lambert's cosine law says that the amount of light energy falling on a surface is proportional to the cosine of the angle between the directional path of light and the surface normal.[24]

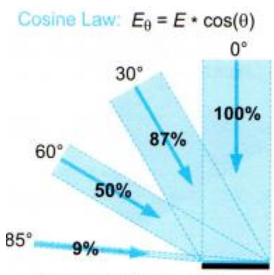


Figure 2.6: Cosine law. From [25]. CC-BY

If the lamp is considered to be point source, then as the observer moves from his horizontal angle of 0°towards 90°, then the intensity of light that is perceived varies as the cosine of the angle as seen in figure 2.6. However in an actual 3D lamp, due to the depth perception and larger area of the light emitting surface, there would be introduction of factors to the formula and the adaptation of the law is essential. [24]

Cosine Correction

Cosine correction is important for instruments that are used in measurement of light parameters directly from the source. As seen from the section 2.2.3, there has to be a correction factor to compensate for the cosine law coefficient.

It is important for the measurement sensors and the light source to include a cosine correcting head to negate measurement errors which would arise when the light source is not directly above or in line with the sensor, but at various angle within the hemisphere of measurement as shown in figure 2.7. [26]

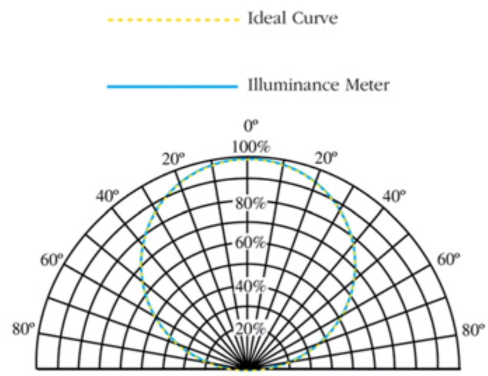


Figure 2.7: Cosine correction. From [27]

2.2.4 Weber Fechner's law

Weber's law attempts to express a general relationship between intensity of a physical quantity and how much more needs to be incremented for a user to be able to tell that difference. It is defined by weber's fraction (K) which gives a ratio between the actual intensity (I) to the change in magnitude of intensity (ΔI) that would be just noticeable by the user. [28]

$$K = \Delta I/I \tag{2.2}$$

This ratio remains constant irrespective of the magnitude of intensity. For example, if a user is subjected to flashes of light with different intervals, it is easier to compare between a long flash of light and a short flash of light. However, if the same short flash is added to the long flash, it becomes difficult to differentiate between the long flash and very long flash. This relationship between the initial intensity of a stimulus and the smallest detectable increment is what is formalized into "Weber's Law". [28]

Fechner's law is an extension or refinement of Weber's law. It has two parts:

- There exists a threshold between two stimuli as seen in figure 2.9 and there could be a visual response (R) if that threshold is exceeded or violated.
- This visual response 'R' to an intensity 'I' is related by the equation 2.3. [28]

$$R = log(I) \tag{2.3}$$

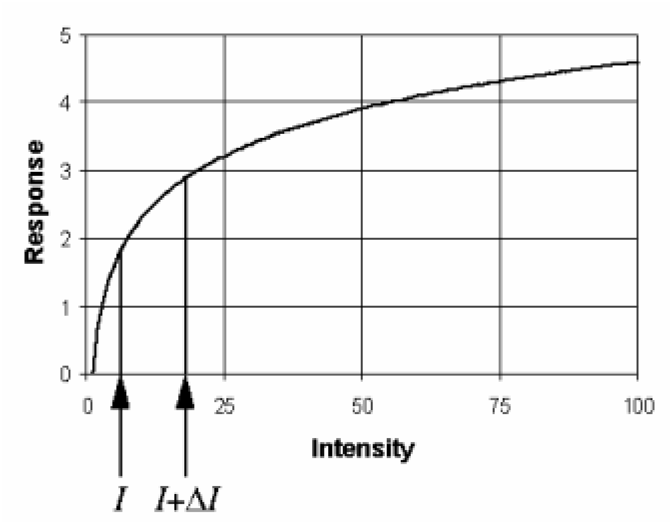


Figure 2.8: Fechner's Law. Adapted from [28]

The graph in figure 2.8 shows the logarithmic nature of response to change in intensity. 'I' represents the magnitude of intensity under consideration and 'ΔI' is the Just noticeable difference.

Just Noticeable Difference (JND) is the amount of change in the input quantity that has to be put in-order to see a difference. In other words, it is the minimum difference between the two stimuli that would be noticeable by the user. This coincides with the Weber's law as discussed above. The threshold between the two stimuli would be a factor to consider while establishing requirement on homogeneity.

Mathematically, for upper threshold it is expressed as follows [28]:

$$\Delta R_h = log(I + \Delta I) - log(I) \tag{2.4}$$

Similarly, for the lower threshold, the mathematical expression is as follows:

$$\Delta R_l = log(I) - log(I - \Delta I) \tag{2.5}$$

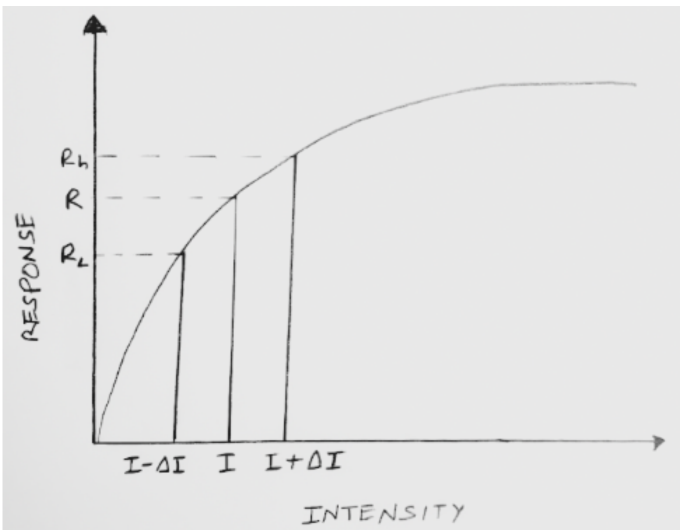


Figure 2.9: Fechner's Law. Adapted from [28]

According to P.Sara [16], Weber-Fechner law is considered to calculate the human eye perception on light. Eye's response with respect to the intensity of the light is approximately logarithmic. But major error when analysing luminance homogeneity, is failure to acknowledge logarithmic eye perception which will not give the accurate value. Since the human eye strongly dependents on eye adaptation and glare. The author also compares the global and local criterion when analysing an image to be considered for homogeneity. Simulations and pictures are subjected to different prepossessing and analysis in-order to determine which criterion is crucial for evaluating homogeneity effectively. [16]

2.3 Units of light measurement

There are four important photometry units that are considered.

- Luminous flux: Measured in Lumen (lm). It is the luminous energy emitted by the source.
- Luminous Intensity: Measured in Candela (cd). It is the luminous flux per Point of View (PoV).
- Luminance: Measured in Candela per square meter (cd/sq.m). It is the luminous flux reflected by an area.
- Illuminance: Measured in Lux (lx). It is the luminous flux incident on a surface.

2.4 Design intent

The birth of an automotive lamp happens with the visualization through design intent. The aesthetic design of the lamp is generated graphically and the appeal of a lit lamp is simulated. The intent is treated as the goal that is to be achieved. However, the intent does not follow physics of light in its illustration. Hence, there is a lot of variation on how the intent shows and how the final lamp turns out. In the design intent, the lit surface is generally shown to be perfectly homogeneous.

2.5 Customer Field of Views (CFoV)

For a company to be successful in this competitive environment and to last longer, they must understand the customer expectations. If they predict the customer expectations, then it is highly related to satisfying the customers. When the customer is satisfied they continue with the same brand for their next purchase and hence it benefits the company. [29]

CFoV is a tool helping Perceived quality and other departments to realise important issues and to predict what is visible to the final customer. It acts as a set to reflect relevant viewing positions for the customer. Using this the company we be able to determine the areas of concern and plan accordingly to make their future product better suitable for customer expectations. [29]

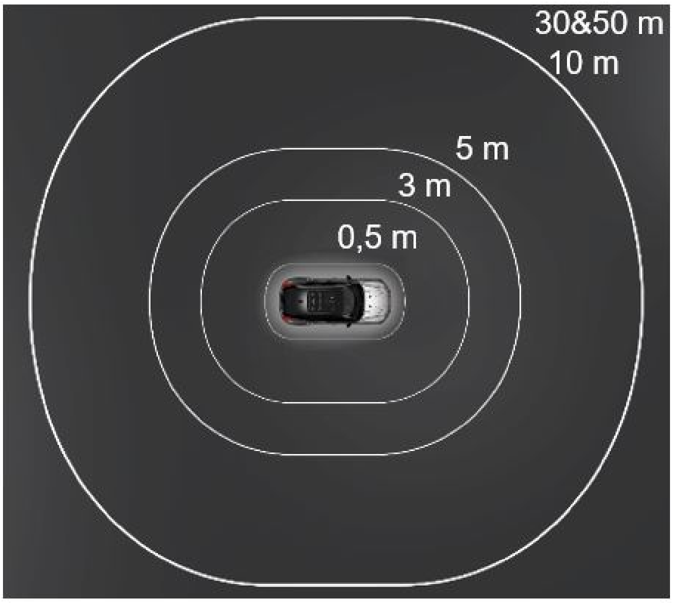


Figure 2.10: Customer field of View. From [30]
Reproduced with permission.

Figure 2.10 shows the CFoV when a person is looking at the car from outside. The author as considered only exterior field of view because the thesis is mainly focused on the front position lamp. Users may notice the position light illuminate the light functions by unlock button on approved key (while approaching the car) or lock button (when leaving the car), in showrooms, or in the garage. The distance from the car and the viewing angles from the users perceptive is predicted by using this tool.

2.5.1 Angles of judgement

All the figures that are shown below is the fundamental positions, used as most preferred viewing angle from the perceived quality illumination perspective on the front position light. This viewing distance and angle is determined to be the optimal mapped cases from where the customer would observe the position light. In most cases, position light of the car is observed in showroom, when you approach the car or when you leave the car. Also the position lights are more prominent in darkness like in garage conditions.

Figure 2.11: Front 0.5M [30]

Figure 2.12: Front 3M [30]

Figure 2.13: Front Angle 3M [30]

Figure 2.14: Front 10M [30]

Figure 2.15: Front Angle 10M [30]

2.6 Legal Requirement on Front Lamp

Legal requirement is a law which is taken by the authority of any governmental body has a preventive measure either to individuals, or to the environment.

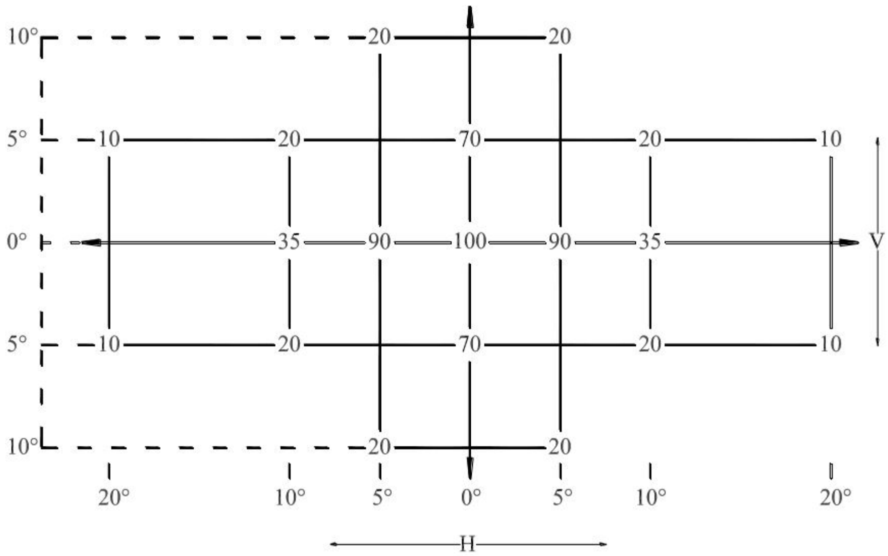


Figure 2.16: Table of standard light distribution. From [31]
Reproduced with permission

As per the legal requirement of front light on the automotive passenger cars, there are some limitation on the level of intensity at different viewing angles. The figure 2.16 shows the percentage of intensity for the corresponding horizontal and vertical degree. In this H=0 and V=0 is considered to be the reference axis which passes through the center of right lamp of the vehicle which has the maximum intensity at 100% and this decreases accordingly. The figure shown give the maximum allowance of luminous intensities as a percentage of the requirement in the axis of each direction. [31]

There is also a requirement that the lamp device must be mounted at a height of 750mm or less above the ground level. The Lamp must not be less than 500mm and not more than 1200mm above the ground level. To verify the lamp will be subjected to photometric and colorimetric measurement of lamps will be performed. [31]

2.7 Product Development Process

For a product or a concept to succeed a structured product development process need to be followed. An overview of the product development process is visualized in figure 2.17. To begin with a proper planning of the product needs to be done which is the foundation of any project. An effective product planning involves benchmarking of competitors, technology roadmap, exposure to the emerging technology, competitors product on the market, etc which helps to identify the scope of the task that is assigned by the company and to define a new value for the product or concept. [32]

To gather further information primary and secondary information search is to be carried out. Primary search involves quantitative interviews, observation, etc and secondary source like literature study, journals, company web portal, etc. User study is one of the important activity in the Product Development process. Direct Conversation with the customers will help to address the problem in a much better way. Then comes the concept generation phase. This phase could be brainstorming knowledge that is gained by the previous steps.
Different approaches like function mean model, SCAMPER, Morphological matrix, etc are made use of in order to generate large number of concepts. Concept screening and concept scoring is used to eliminate and select the possible concept. Here different matrix like Phug matrix, Kesselring matrix, Elimination matrix, etc can be made used to narrow down the possible concept. Once the final concept is achieved, concept testing and detail development is carried out. In concept testing, prototype and feedback from the user test is done as a verification for the chosen concept. For the Detail development, Environmental impact, cost analysis, market analysis, can be considered for further research. [32]

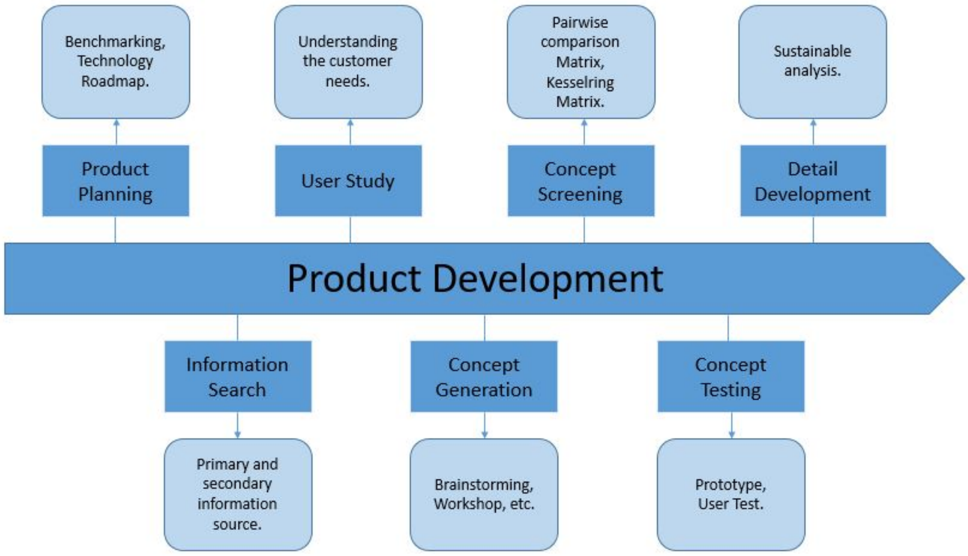


Figure 2.17: Product Development Process

2.8 Interviews

Interview is the best data collection method, the researchers approach respondents to collect their ideas and experience, and also elicit information on the topic on which the respondent may have worked previously, or being working at present. It helps the researches to get information on the research question and may also be used as a verification for the information obtained through other method.[33]

There are different types of interview used in research data collection, they are structured, semi-structured and unstructured interviews. In structured interview set of questions will be formulated by the researchers, the order of questions will be defined in advance and the exact order will be followed for all the interviews. In semi-structured interview set of questions will defined be the researchers in order to cover the required topics but the exact order will not be followed for all the interviews. In Unstructured interview set of questions will not be formulated and there is no formal way in conducting the interview. [34]

In order to deeply comprehend the step by step process of development of lamp, to notice what things are being done in each phase, who is involved into that particular phase and to study the overall process within the company, many unstructured interviews were conducted. The main objective of all the interview were to collect first hand information regarding the homogeneity of the front position lamp.

2.8.1 Exterior light design team

Exterior light design team express that the brightness will be the most important part of the lamp. Homogeneity depends on the material that are used, if it is a diffusive material then homogeneity is more preferred and homogeneity is less considered if the material used is in the form of crystal. From the design perspective, all lamps are designed for Horizontal-0 and Vertical-0 angles. For visual verification of the lamp, day light is most preferable. The verification of lamp is mostly done on the day light environment in order to check the brightness.

2.8.2 Supplier's point of view

Usually requirements are defined by the company, but the technical feasible aspects are suggested by the suppliers. Homogeneity requirement are specific. Before satisfying homogeneity requirement they must fulfill the legal and customer requirement. Legal requirement is given more priority and then the packaging space that dictates the rest. According to the suppliers, setting objective for the homogeneity requirement is inconvenient. When producing a lamp the main focus is on H=0 and V=0.

2.9 Psychophysics

When considering contrast on a surface emitting monochromatic light, Some researchers have observed experimentally that a sharper contrast gradient especially along the edges can cause a perception of color shift due to chromatic fringe adaptation of the eye.[35] Hence the necessity that the gradient in contrast to be smooth is to be prioritized.

Also the role of illusion due to complexities of the eye mechanisms play a major role in perception of luminance distribution. Some researchers argue that the luminance distribution perceived by the eye is different to the actual luminance distribution measured by the devices.[11]

According to Yun-Chin Li et.al [36], there exists a relationship between the visibility threshold and the background luminance. For a low background luminance, eye has a higher visibility threshold and for a higher background luminance, the threshold gradually increases in a linerar scale. [36] Hence when testing the lamp for homogeneity, it is required to determine the testing conditions. This includes whether testing should be done in broad daylight or in a darkroom since the background luminance could affect the perception of homogeneity.

When dealing with the subjective perception of homogeneity, D.Kersten et.al [37] determined experimentally that the HVS considers the cause of smooth luminance gradient before it determines the surface lightness. If there is a luminance gradient across the surface and the edges are curved, it is perceived as more homogeneous than if the edges were straight. Hence, the perceived shape of the surface plays an important factor in luminance gradient perception and in the overall homogeneity. [37]

2.10 Factors influencing Homogeneity

Perception of homogeneity is a result of various factor, that influences how the light uniformity is visualized by the HVS. These can be either external factors or specific factors which are used in measuring homogeneity. Major factors are discussed below.

- **Distance from the lamp**
  Distance from the lamp of the car is one of the major factors to be considered while setting a requirement for the homogeneity. Viewing an object when its distance is fixed is different compared to when the object is viewed when it is in motion. The human eye captures the image of an object through retina, the optic nerve, and the nerve cells. All these visual cortex gets activated in the brain by creating an image of the object that is viewed.[38] When the position light is viewed from a distance of 30 meter the lamp looks to be perfectly homogeneous. The same level of homogeneity continued even when the lamp is viewed from 10 meter distance. Further moving towards the lamp slight area of dark spots and hot spots can be seen by the eye. The position light of the car is normally viewed when you approach the car or leave the car. More dominant when one is in a showroom or in a garage. Hence all the said distances are nearer, less than 10 meter from the lamp. Thus, the distance of the lamp is considered to be the major factor.

- **Angle of viewing**
  All the lamps are designed based on the legal requirements. The legal requirements are set in order to increase the driver and passenger safety and to prevent the environment from been violated [39]. Every lamp is allowed to have higher intensity at H0V0 position where most of the light hits the road. So, the main focus when designing or manufacturing the lamp will be given to H0V0 position. But most of the time the position light is not viewed from H0V0 position. This leads to

be a challenging factor for the manufacturers to maintain homogeneity even when the lamp is viewed from different angles. The great difficult is to maintain the homogeneity of the lamp with reduced intensity.

- **Surrounding brightness**
  Surrounding brightness may affect the results of homogeneity. During conduction of the thesis, the testing of light homogeneity was done in a dark room so that the surrounding light will not be a factor that influencing glare, reflection etc. Viewing the light inside the dark room will help to identify the original defect of the light since it as clear appearance without any disturbance. All hot spots and dark spots can be noticed in the dark environment. However, in the real case scenario, lamp is viewed in the outdoor environment where sun, sky, clouds, buildings, trees and other surrounding objects influence reflection and shadow. These reflection and shadow may sometimes causes the lamp to appear inhomogeneous.

- **The curvature of the blades (Depth perception)**
  The front position lamp or the signature which is designed at Volvo cars have curved surfaces that bends back in the three dimensional plane. Hence the factor of depth comes into picture. The distance from the observer to the curved back region of lamp is more compared to the distance from the unbent front lit surface. Hence the depth perception plays an important role especially while viewing the lamp from the front of the car.

- **Apparent surfaces**
  Apparent surface is the 2 dimensional representation of a 3 dimensional plane. Here the depth axis is compromised and the length and width axes are considered. Therefore any representation of a 3 dimensional object such as a lamp onto a two dimensional plane of the same such as a picture of a drawing constitutes to the apparent surface. To compensate for the depth, cross-sectional representation of the object can be considered. For example, in this case if the lit surface of the blades have to be considered without the outer glass covering, then the apparent surface is considered only for the lit surface negating the outer lens. According to legal requirement [31], the apparent surface of the position light has to be more than 400mm from the extreme outer edge and the inner edge of the apparent surface of the of both left and the right lamp should be less than 600mm apart from each other.

- **Luminance camera**
  No camera can replicate the visual experience of human eye. Luminance camera is one of the device which tries to replicate the human photopic response. The luminance camera used in this thesis is a charged couple device based camera system having a matrix detector. The advantage of using this device is that it enables us to test wide range of colour and luminance, to measure the characteristic property of light. [40] The luminance camera is considered to be the most appropriate way to measure the luminance of the light. The camera and the lens needs to be calibrated time to time to ensure that the image is captured without any inconsistency. Luminance camera plays a prominent role in verifying the homogeneity of the lamp by capturing the luminance value of the lit surface.

- **Prometric Software**

Prometric is a equipment specific software. The luminance camera runs on this software. It is also used in applications of sophisticated image processing and to detect the defect of the light.The response of light is shown in luminance and the software enables various filters and features that could be used to analyse the behaviour of light. The image obtained in prometric is an attempt to replicate the human photopic response. [40]

2.11 Sustainability

Sustainability is about meeting the needs of the present without compromising on the resources of the future. It has its focus on three aspects mainly economic, environmental and social. These are referred to as the pillars of sustainability where all the three aspects has to be addressed in order for the product to be deemed completely sustainable. [41]

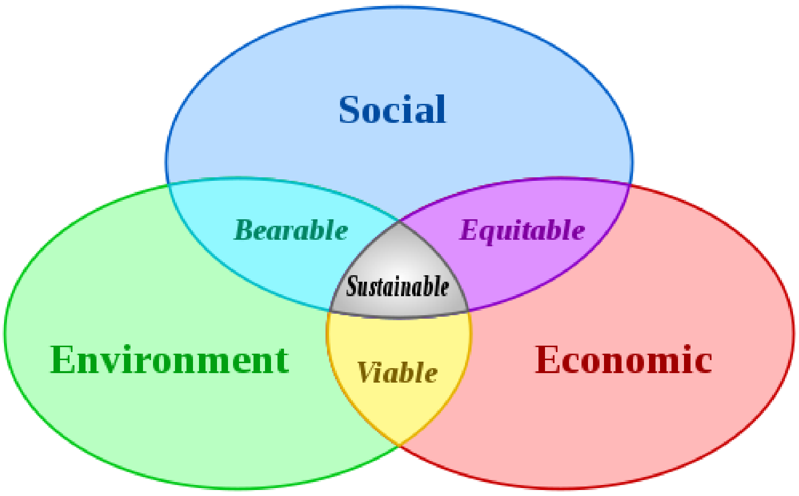


Figure 2.18: Sustainable development. From [42] CC BY-SA 3.0.

In the product developmental cycle, sustainability is encouraged to be incorporated early in the development cycle as Design for Environment (DFE). It operates on the concept that the product life cycle has to be looked upon in two cycles. The first is the industrial life cycle and the second is the environmental life cycle where the impact of complete life of the product right from its raw material generation to its decomposition is considered. Modern development cycles are also encouraged to incorporate the ethical and social implications of the product.[43]

At Volvo Car Group, Sustainability is considered has the company's highest priority in their requirements. By 2040, the main focus of the company is to work towards climate-neutrality, embracing the circular economy and conducting business responsibly, in order to achieve the highest standard of sustainability and to protect the environment. The Climate-neutrality means to reduce the CO_2 emission by producing all electric cars and to reduce the usage of plastic. Circular economy means to design a product which would benefit the business, society and the environment. [44]

3

Methodology

In this section, the methodology adopted to establish requirement is explained. Justification for the usage of the particular method and the various adjustments that were adapted in accordance to the need is presented.

Since the perception of homogeneity is highly subjective, there was a need to transform this perception in measurable terms in other words to document the subjectivity. Hence the method had to be adopted which had to act as a medium which translates subjectivity to objectivity. It was important while generating requirements that even the verification of the generated requirement had to be performed in co-relation.

The purpose of co-relating verification with requirement generation was mainly to avoid the following risks:

- Establishing or comprehending parameters which could not be quantified for analysis.
- Not including any foreign parameter influencing values which would be a direct or indirect effect on the required parameter.
- Not comprehending how the requirement should be altered when verification is performed with different conditions or different measuring equipment.

The whole approach to this research was to determine what affected homogeneity and can it be quantified to write a requirement. Hence, the focus was to collect data of such quantifiable factors.

Of all the law's and parameters discussed in section 2.2, very few has the capability to co-relate between the perception and quantification of visual responses. Most of the laws deal exclusively with defining the subjectiveness of light with exponential factors or variables which are very rigid and non adaptable.

Contrarily, as discussed in section 2.2.4, measurement of Just Noticeable Difference (JND) which abides the law of Weber's and Fechner´s is one of the parameter that was found to bridge the gap between the subjective perception and objective measurable value. This was mainly because this parameter considers and compensates for the visual and biological threshold of the eye and it provides a quantifiable value that can be measured and validated.

3.1 Quantifying subjectivity

According to dictionary,

> “ Subjectivity is the influence of personal beliefs and feelings rather than facts.” [45]

Since the subjectivity is inevitable and unpredictable, it should be seeked out systematically while the research is progress and not during the later analysis phase.[46] It was a challenge to channelize opinion into measurable or quantifiable data. There exits a branch of psychology know as Psychometrics that focuses on the quantification of subjective outcome.

Reliability and validity are the main parameters that the judgement of subjectivity can be based upon. Reliability is the measure of obtaining consistent result with repeated measurements and validity is the verification if the measured parameter is what was intended to measure, without influence of any external parameters.[47]

Hence, there existed a need to have an actual measurable or visual parameter to judge or to co-relate to, in order to validate the subjective response. Color coding was one of the effective method that was found to be an effective medium to translate visual parameter onto paper.[48] This involved using different colors on papers to convey the visual response of light. This eliminated the need for detailed dialogue to express what was perceived and also provided the response on paper. Hence judging the color coding method on its reliability and validity was found to be an effective way of gauging the subjective responses.

3.2 Product development approach

Since the main aim of the thesis was to generate the requirement, the conventional product development cycle had to be adapted [49]. This was because in the conventional product development cycle as in section 2.7, the generation of requirement fall at the early stages of the cycle. Hence the conventional cycle is adapted such that selective tools of the conventional cycle are incorporated in the generation and verification stages of the thesis as seen in figure 3.1. [49]

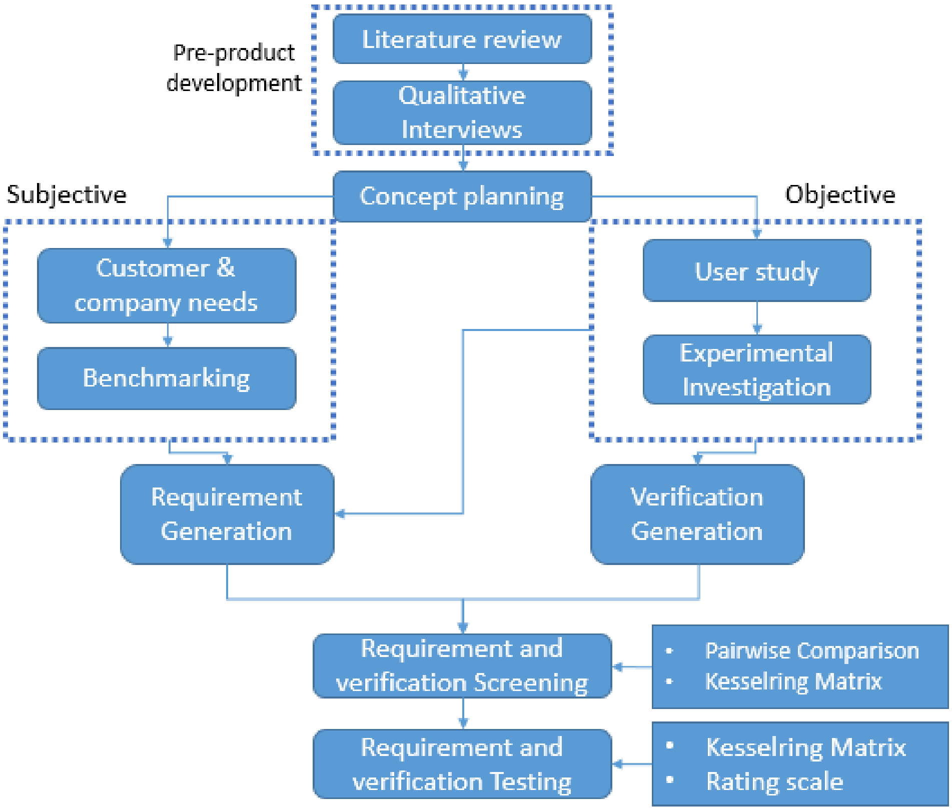


Figure 3.1: Product development approach

The main purpose of the approach was to document the subjective response as well as to incorporate an experiment to calculate the luminance threshold of the eye. Hence the method to be adopted had to to involve the above two aspects for analysis. Experimental investigation was deemed to be ideal for this cause since it would help in both subjective data collection and the JND threshold experimentation.

3.2.1 Literature review

Literature review is an effective way of analysing the information, performed to get a deeper knowledge on a particular field, which is mostly conducted at the beginning of the project. It provides an essential support for the researchers to carry out new findings based on the research that has been made previously [50]. Literature review gives a brief description, prevailing theories, methods and approaches that were followed, concepts, principles and finally the outcome of the project. It serves as a foundation for the main study [51].
Literature review can be conducted by following these different stages. The first stage in the literature review is the Problem formulation. In this stage, researcher will frame the research questions and start finding the answers for those questions. The questions that are framed will significantly focus on the field of study. The second stage is the data collection stage where primary source (i.e. interviews, observation, focus group etc) and secondary source (i.e. the internet) of information will be collected and documented. The third stage is the data evaluation stage where the gathered information will be evaluated. Next stage is the data analysis and interpretation stage. In this stage researcher will try to analyse the evaluated information. The goal is to integrate the information that are

relevant for the researchers to future develop the information. Final stage in the literature review is the public presentation stage where the relevant information will be presented leaving out the irrelevant information. [50]

3.2.2 Qualitative interviews

Qualitative data collection aids in exploration of perception of individuals through broad ranging discussions and individual interviews rather than using structured questionnaires. Subjects are given space and freedom to express their opinion and elaborate on points which helps in knowing their point of view.[52] The whole approach was partially questionnaire based and partially perception based.

3.2.3 Customer needs

Inorder to translate the subjective perception in measurable terms, Customer needs and company needs had to be collected and analysed. Customer needs form the basis of any development cycle [43]. However, the freedom for manipulation of the headlamp inorder to satisfy the customer needs were very limited. Hence the customer needs were collected more as a stepping stone towards generating requirement rather than destination.

3.2.4 Benchmarking

Competitive benchmarking forms a very strong part of the development process. It also forms an important part of identifying customer needs. The competitors products and solutions are compared to the existing product and rated in a chart [43]. Similarly benchmarking was incorporated into the user study inorder to facilitate the users to be involved in the process of benchmarking. Their ratings were generalized using mean and standard deviation for analysis and comparison.

The results were compared using two parameters:

- **Mean**: The arithmetic mean gives a simple mathematical average of a set of two or more numbers. This is used to gauge and assess the performance of the ratings over different users. The result would be a single numerical value that is comparable.

$$M = \frac{1}{N}\sum_{i=1}^{N} a_i = \frac{a_1 + a_2 + \cdots + a_N}{N} \tag{3.1}$$

  Where a is the rating of individual participants and N is the total number of participants. [53]

- **Standard Deviation**: This is the measure of difference of each observation from the mean. This showed by what magnitude the ratings varied from the mean.

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{3.2}$$

  Where x_i is the number of participants from 1 to maximum attended, $\bar{x}$ is the arithmetic mean and N is the total number of participants. [53]

3.2.5 Experimental investigation

Performance of user study was found to be ideal to gather the required data. The reason being subjective response would vary for each individual since it is based on ones judgement and taste. This meant not everyone sees or perceives similar responses for the same stimuli, in this case would be the light from the lamps. Hence for a reasonable accuracy of the data, there was a requirement to have multiple participants of mixed personalities to enable high levels of reliability and validity [47]. Experimental investigation provides a means through which an independent variable can be manipulated to obtain the desired data. Hence, experimental investigation for homogeneity was chosen as a method to collect the required subjective data.[54]

3.2.6 Analysis method

The response that were obtained from the user study was then uploaded in the excel and later graph were generated in excel using the same user response. The results were gathered lead us to generate various concept. In this section, the tools that were used to eliminate and obtain the feasible concept for the thesis study are presented. Also, this section contains a method that was used to analyse the actual users perception.

Pairwise Comparison matrix
Pairwise comparison matrix is also known as Analytic hierarchy process, it is a decision making matrix using several criteria. In this pairwise matrix alternate criteria are compared to each other in which One criteria is graded subjectively with respect to another criteria in a matrix form. Then these grade will be combined giving an overall sum of each criteria.[55] In figure 3.2 an example of pairwise matrix is shown, where criteria of both sides were graded accordingly and total score for each criteria were being calculated. These values were further used as weights in the kesselring matrix.

Criteria	A	B	C	D	E	F	G	Total Score
A	-	1	0	0	1	1	0	3
B	1	-	1	0	1	1	0	4
C	0	1	-	1	1	0	1	4
D	0	0	1	-	0	0	1	2
E	1	1	1	0	-	1	0	4
F	1	1	0	0	1	-	1	4
G	0	0	1	1	0	1	-	3

Figure 3.2: Example of Pairwise Matrix

Kesselring matrix
The Kesselring matrix is an elimination matrix. This matrix was made used in this thesis to obtain the final concept. In this matrix, the concepts were graded based on their performance and how well the concepts fulfill the criteria. The weights for the criteria was taken from the results obtained in the pairwise matrix. Weights were then multiplied to a ideal concept that gives the highest score for all criteria. These weights were then multiplied with the actual concept grade to give a score. Later the scores of each criteria were combined giving an overall total for that concept. The grading scale that were used was between 1 to 5 where simply, 1 being bad and 5 being good, The ideal score were used as a reference to see how good each concepts fulfills each criterion. [56] Figure 3.2

shows the example of kesselring matrix, where the criteria and weights were taken from the pairwise matrix.

Kesselring Matrix				Concepts											
Criteria	Weight	Ideal		Concept 1		Concept 2		Concept 3		Concept 4		Concept 5		Concept 6	
		Value	Total	Value	Total	Value	Total	Value	Total	Value	Total	Value	Total	Value	Total
A	3	5	15.00	3	9	4	12	3	9	1	3	4	12	3	9
B	4	5	20.00	2	8	2	8	4	16	4	16	2	8	3	12
C	4	5	20.00	3	12	4	16	3	12	1	4	4	16	3	12
D	2	5	10.00	3	6	3	6	3	6	3	6	3	6	3	6
E	4	5	20.00	3	12	3	12	3	12	3	12	4	16	4	16
F	4	5	20.00	1	4	2	8	4	16	4	16	2	8	3	12
G	3	5	15.00	2	6	4	12	3	9	2	6	3	9	4	12
	Total Score	120.00		57.00		74.00		80.00		63.00		75.00		79.00	
	Rank	-		0.48		0.62		0.67		0.53		0.63		0.66	

Figure 3.3: Example of Kesselring Matrix

ANOVA Method

Analysis of variance (ANOVA) is the most used statistical tool, to analyse the difference between the any identical values [57]. ANOVA enable us to mark the difference between the means of two or more independent groups. This gives us the comparison of means of atleast two of the groups which you are interested in and tells us the difference between those two groups statistically . It helps to find which all groups are different from each other.[58] ANOVA is differentiated in two ways that is One-way ANOVA and Two-way ANOVA. The One-way ANOVA is used to find the statistical difference using one independent variable. Continuation of one-way ANOVA is the two-way ANOVA. In this it has two independent variables. [57]

4

User Study

The user study was an effective tool used to gather data related to user experience, their perception on homogeneity and the crucial subjective data to base the subjective analysis upon. The various technical aspects and decisions considered for the user study are discussed in this chapter.

4.1 Number of Participants

According to *Griffin.et.al* [59], 90% of the requirement is generated after 30 interviews with the users. and according to *Ulrich.et.al* [32], 10 users in too less and 50 users are too many to write a requirement. Hence, 30 users would have been an ideal number for consideration. Also, according to *Lewis.et.al* [60], 12 to 20 people would be sufficient to produce a reliable requirement. We were able to perform user test with 20 users due to limitations. The only prerequisite was to have participants with reasonably good eyesight.

4.2 Sampling of Participants

Sampling is the selection of target group from the total population under consideration. The sampling approach that was used for the study was the "opportunity sampling" where the participants were asked to undergo the user-test based on their availability at the time [61]. Majority of the participants that were involved in the study were employees of Volvo cars and their age varied from 30 to 65 years. Since the only pre-requirement for the study was to have a reasonably good eyesight, all the participants did fall under that criteria. The gender of the participants were not given priority but there were reasonable representation from both.

4.3 Experimental Investigation

To get both the subjective response from the users on homogeneity and the threshold of the eye, the experiment was divided into two parts:

- The first part was to judge the headlamps of car in-order to document the **Subjective Response**.
- The second part was to judge the intensity difference between two strips of light

in-order to calculate the **Eye Threshold**.

Both parts of the experiment were performed at different testing conditions and involved different tasks that were to be performed by the users. The same sample of participants were subjected to both the experiments to maintain uniformity in the results. The experimental setup that was used for both the above stated parts are as described below.

4.4 Experimental Setup 1

This setup was organised in daylight conditions outside. This was to test the position lights perception from the photopic vision of the user to catch any prominent irregularities. All the 5 cars were parked next to each other. The cars were also positioned such that all throughout the day they had a shadow cover over them. This was to reduce the influence of sunlight falling directly on the lamps causing glare while the users are judging.

- **Objective of Experiment**
  The objective of this first part of the experiment was to collect the subjective data of the lamps from the users. There are some measurable and non measurable parameters that are considered while performing the experiment.

- **Measurable parameters**
  Luminance from lamp in Lux or Candela per square meter, surrounding brightness in Lux.

- **Non-measurable parameters**
  Personal judgement, health of eyes.

4.4.1 Tools used

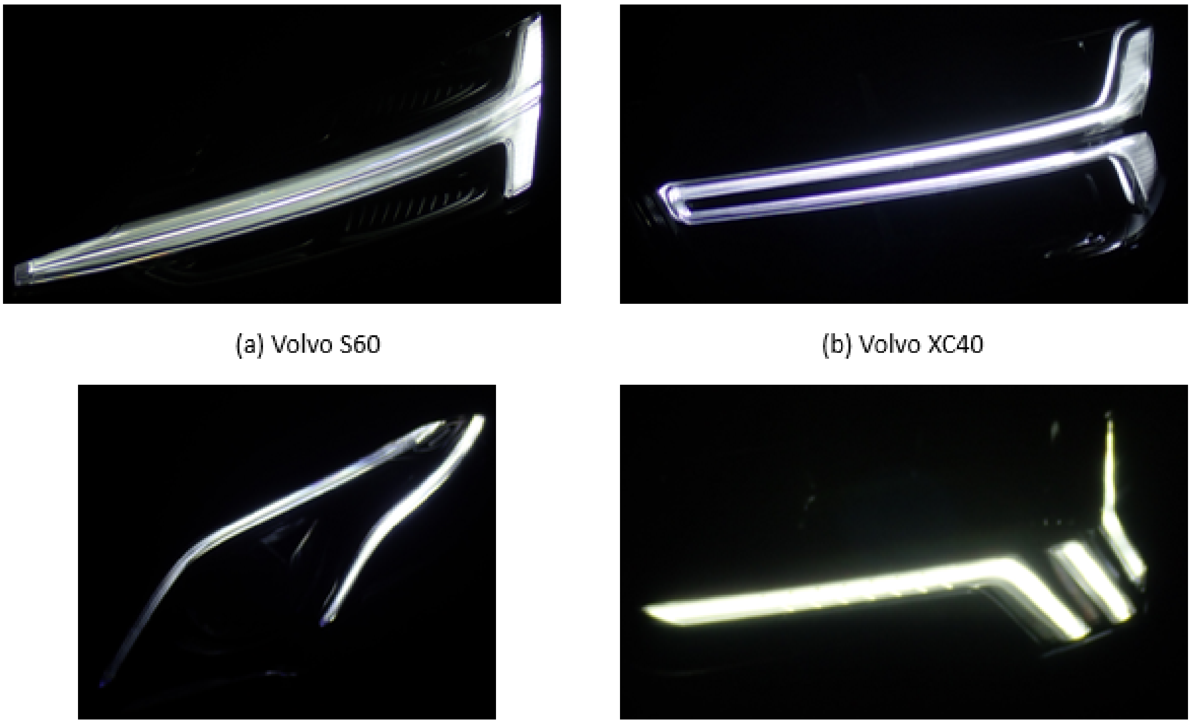
Four cars in total were used for the study. Two Volvo cars and two competitor cars were the subjected vehicles.The cars were:

- Two Volvo cars were Volvo S60 and Volvo XC40

- Two competitor cars were Audi Q3 and Mercedes E350

The main reason for choosing these cars were because they all have similarities in-terms of technology involved in lighting having LED´s and light guides for producing position lights. The models used in the study were the latest cars in the market.

Figure 4.1: Cars used for user study



(a) Volvo S60

(b) Volvo XC40

(c) Mercedes E350

(d) Audi Q3

Figure 4.2: Position lights of the cars

4.4.2 Distance for judgement

For the front lamps, Volvo has a defined customer fields of view as discussed in section 2.5. Since there was limited time with the users, the subjective analysis had to be carried out in a short time space. Hence, the Field´s of view used for the study was further narrowed down to one distance.

During the initial pilot runs, it was seen that if the user is too close or at 0.5 meters CFoV, the whole lamps would not be at a gaugeable view of the eye. This would result in the judgement being skewed since here would be not be an opportunity to compare with the hidden or not-visible part of the lamp.

On the other hand, when the CFoV 5 meters was tested, it was observed that the overall homogeneity perception of the lamp improved and any known imperfections could not be spotted. This compromise of imperfections could be due to the effect of inverse square law as discussed in section 2.2.1. Hence, CFoV of 3 meter was chosen for the user study as seen in figure 4.3. Using laser meter, distance of 3 meters from the center of the left headlamps were marked for each cars.

Any subjective judgement and analysis performed by the users would be sensitive to distance. Hence three meters is the distance at which the results of this experiment would be valid.

4.4.3 Positions for judgement

Once the distance from the lamp was finalized, the next step was to narrow down the positions or angles from which the users are expected to judge. As discussed in section 2.5.1, H0V0 was the most important position to do the subjective analysis since it represents the position used by Volvo and the suppliers to measure and judge the lamp.

- **Position 1** : To mimic this position, a chair was placed at 3 meters distance and the users were asked to judge the lamp being seated. This position 1 as seen in Figure 4.3 was also used in rating of aesthetics and homogeneity.

- **Position 2** : As discussed in section 2.10, the nature of homogeneity changes with the viewing angle, hence the next position chosen was to the eye-level of the user as seen in Figure 4.3.

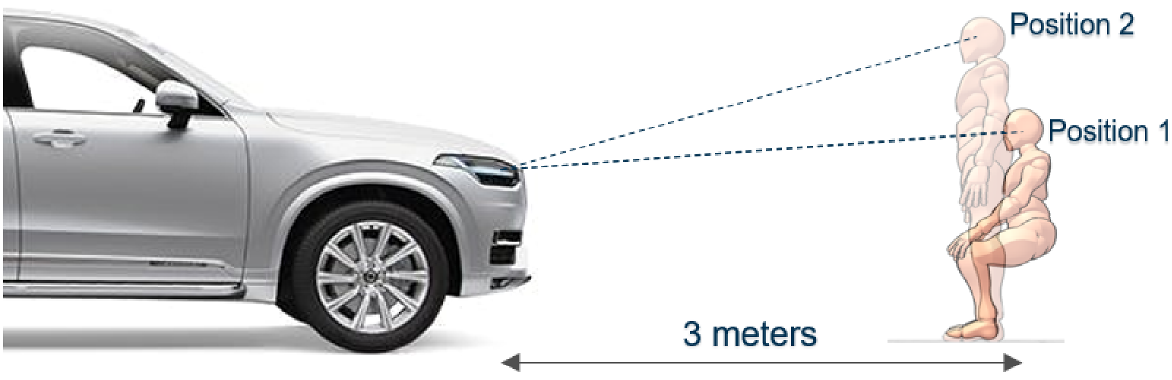


Figure 4.3: Representations of Positions 1&2

- **Position 3** : This position makes an angle of 22.5°with the horizontal and the user is standing during evaluation as seen in Figure 4.4. This position is to get a dynamic behavioural perspective of the position light specifically from position 2 to position 3.

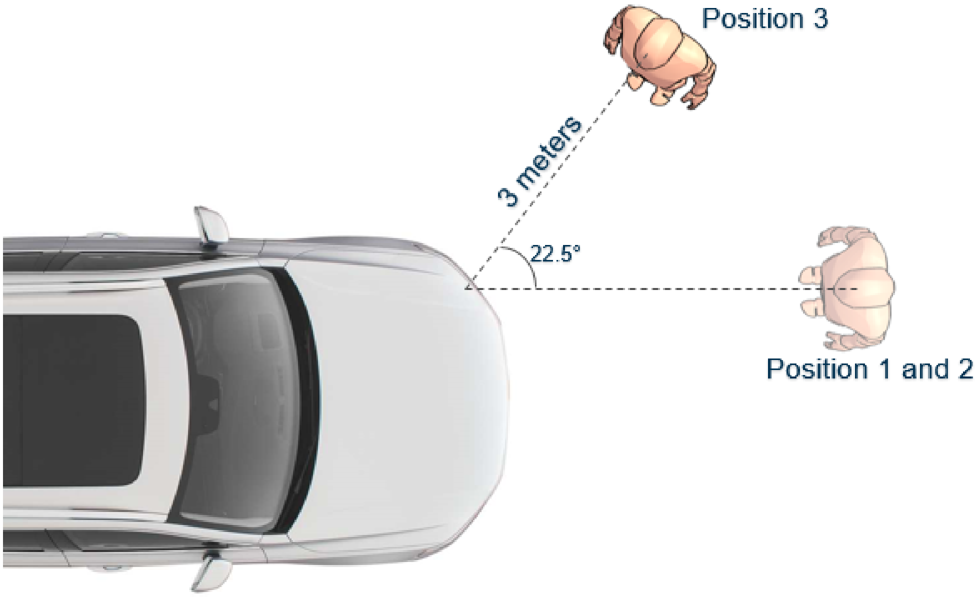


Figure 4.4: Representation of Positions 3

All the above positions were marked and chairs were placed for position 1 in front of every cars as seen in Figure 4.5.

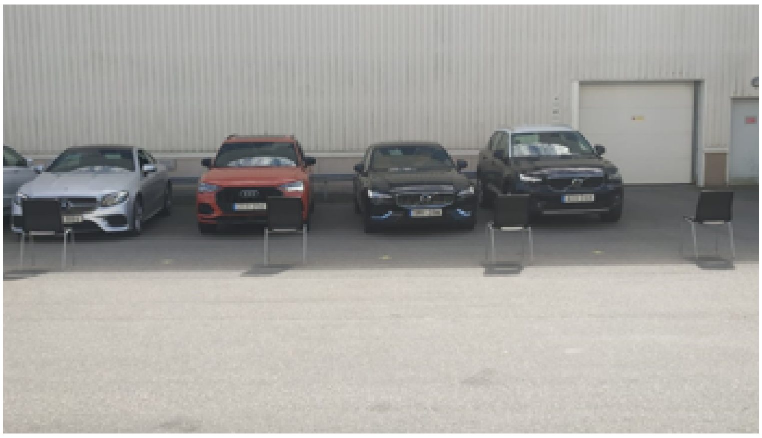


Figure 4.5: Experimental setup

4.4.4 Data collection methods

Before the start of the experiment, the intention of the experiment and the concept of homogeneity was explained in detail to the user. This was done to help users to streamline their judgement towards the behaviour of lights and not towards any other distractions.To enable users to communicate their subjective perception, the outline of the blades of the lamp of each cars were printed for each of the three position from which the judgement had to be made. The experiment started with position 1 and was continued to position 2 and 3.

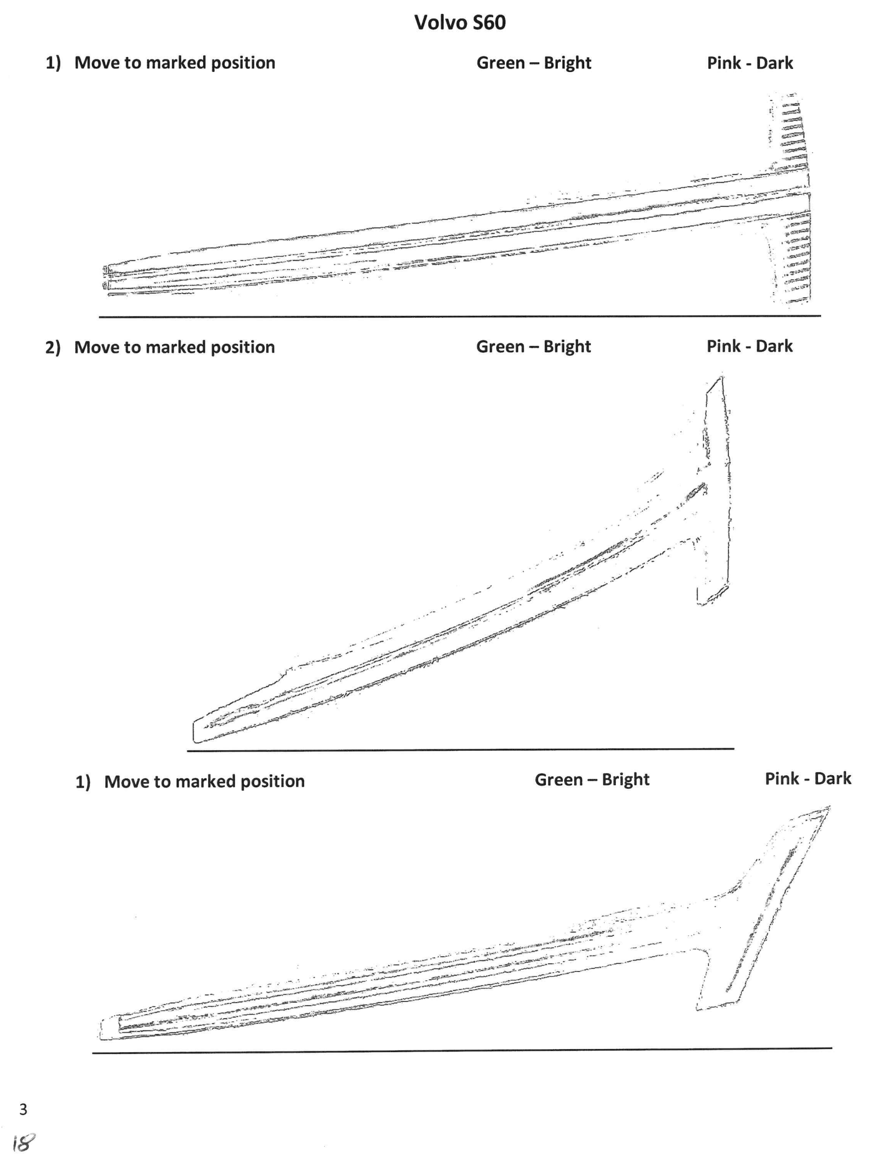


Figure 4.6: Blade outline of S60

For each position, the users were asked to observe the lamp and gauge its homogeneity. Then the users were asked to screen out any irregularities such as bright spots or dark spots or lights which they perceived to be out of place affecting homogeneity. Then the users were asked to mark such irregularities on the outline of the blades using colored markers. Pink markers were provided to mark areas which are darker on comparison to homogeneous parts and green marker to mark the brighter areas when compared to the homogeneous parts of the blade.

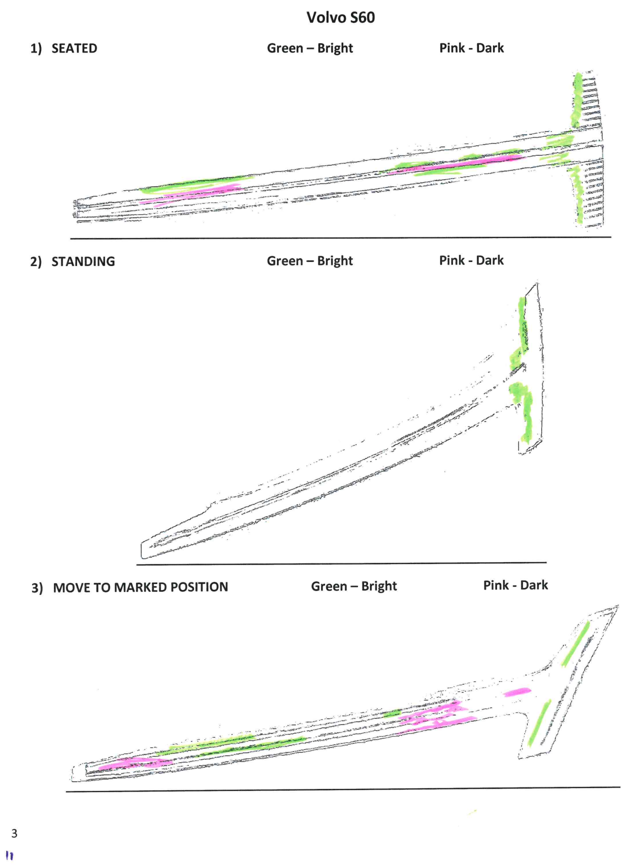


Figure 4.7: Blade outline of S60

4.5 Experimental Setup 2

This experimental setup was performed in the dark room which was at a walk-able distance from the first experimental setup. After the completion of the first part of the experiment, the users were escorted to the dark room and were made to be seated and were requested to close their eyes to start with the experiment.

- **Objective of experiment**
  The main objective of this part of the experiment was to measure the luminance threshold of the eyes.There are some measurable and non measurable parameters that are considered while performing the experiment.

- **Measurable parameters**
  Luminance from the apparatus in Candela per square meter.

- **Non-measurable parameters**
  Health of eyes.

4.5.1 Tools used

A light box was used for the experiment. This light box was fabricated in-house at the company. A luminance camera was used for the purpose of measuring the luminance output from the apparatus. Radiant prometric was the camera compatible software that was used to run and record data from the luminance camera.

4.5.2 Anatomy of the light box

The purpose behind the light box was to project a homogeneous lit surface so as to mimic an apparent surface that is lit uniformly. Since the objective was to find the threshold of luminance or the Just Noticeable Difference (JND), there had to be a constant luminance which the user should be able to compare to. Hence, the box had two horizontal strips of LED that are separated by a distance. These brightness of these LED´s are individually controlled by manual dimmer dials. The LED´s are enclosed inside a wooden box with detachable top and front lids.

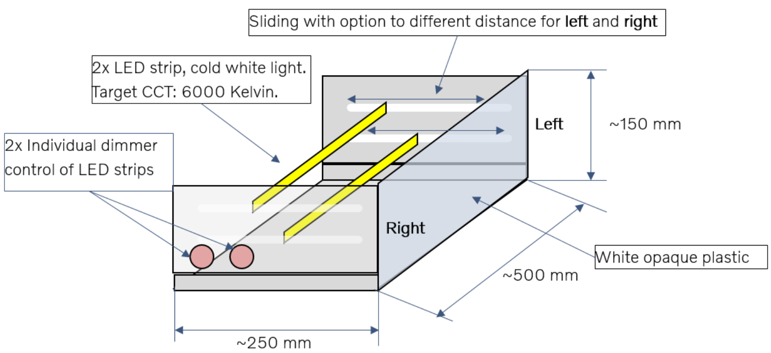


Figure 4.8: Outline of light box

Also the LED´s and its supporting structure could be adjusted and moved across the length of the box. Also, the two LED´s were separated by an opaque partition in between them so that there would not be any light leakage between the strips which would affect the readings.

Figure 4.9: LED strips separated by partition

The front panel of the light box was made up of a diffusive material that would enable the light from the LED´s to be spread uniformly. The distance of the LED strips from the front panel were adjusted such that the light emerging from the from panel had a nearly equal intensities when the dials were set to maximum. Using black opaque tape, the width of the slots that the users would see were adjusted to the actual width of the hammer.

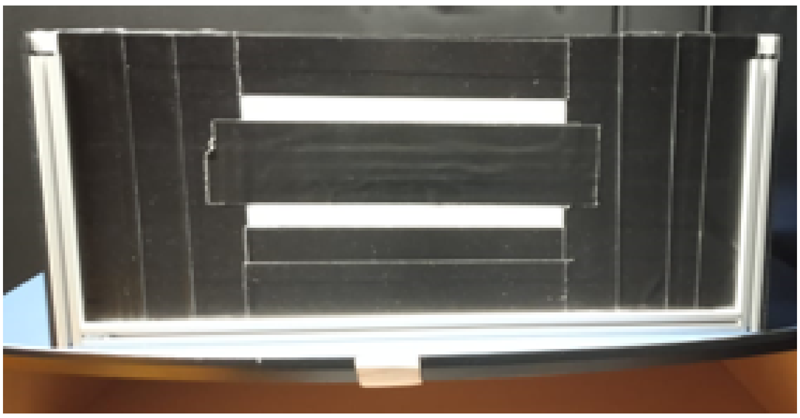


Figure 4.10: Light box used as apparent surface

4.5.3 Distance for judgement of intensities

The distance of 3 meters was maintained to match with the distance of the experiment 1. Since the results were highly sensitive to the distance from observation [16], the results obtained through this experiment was only adaptable to the measurements from 3 meters distance from the lamp.

Regarding the positions for measurement, unlike the actual lamp that is a 3 dimensional surface, the surface here was a 2D apparent surface. Hence the variation of intensity due to depth effect would not be a factor in this case. Therefore, only a single position of 3 meters from the front surface of the box and at the eye-level of the light box was considered during the experiment. A chair was placed at a distance of 3 meters and the box was placed on a stand such that it would align with the eye-level of a seated user. The luminance camera was placed at a distance of 1 meter from the surface of the box and at an angle away from the sight of the user. Hence three meters is the distance upon which any judgement of homogeneity would be considered for analysis.

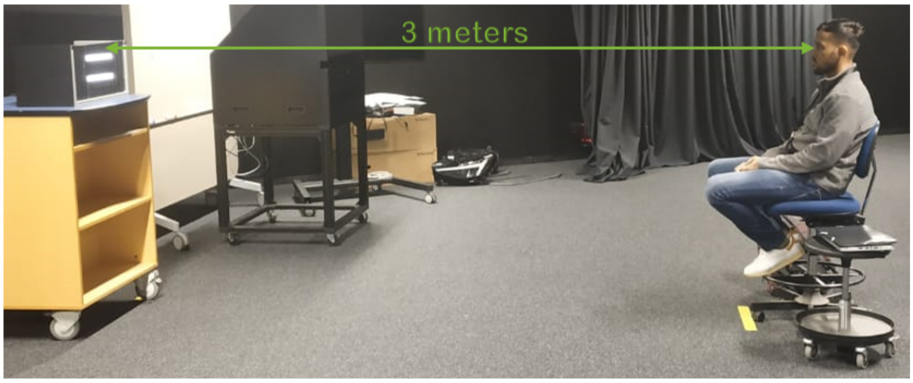


Figure 4.11: Light box experimental setup

4.5.4 Data collection Method

As discussed in section 2.2.4, the main aim behind this experiment is to calculate the eye threshold such that the user is perceives a certain range of intensity as similar. Before the start of the experiment, the users are seated at the marked position and are asked to close their eyes. The whole room is darked out by switching off the lights. This is to make sure that the scotopic vision of the users are activated as discussed in section **??**. In this way the users eyes are more sensitive to changes in intensities.

Figure 4.12: Light box experimental setup in darkness

The upper part of the strip is used as a reference strip and the lower strip as variable strip. As discussed in section 2.2.4, the expected nature of Fechner's law graph was logarithmic in nature. To get the response threshold interval, the reference intensity was segregated into 5 intervals of 20% increment. The values were marked onto the dimmer dial while the camera was measuring the intensity to mark the closest values. The lower strip would be varied from low (0%) to high (100%) and high to low for each intensity interval of the upper strip. Hence, there were 10 trials in total and the duration of the experiment was 5 minutes.

The users were asked to open their eyes and to look at the upper lit strip and to keep the intensity of that strip as reference. Then the intensity of the lower strip would be gradually varied using the manual dimmer switch. The users were instructed to stop the variation in the lower strip once they perceived that the intensities were matching. Once the variation in intensity were stopped by the user, the luminance data which were recording live in the camera were manually registered for both upper and lower strips. To ensure that the users would not get accustomed to the linear change in intensities, the intensity trials were randomized.

5

Analysis and Result

5.1 User rating - Benchmarking

From the experimental setup 1 at the parking as detailed in section 4.4 during the user tests, the users were asked to rate the lamps as seen in figure 4.2 from a scale of 1 to 5 with the former being the lowest. To avoid limiting the users to specific rating intervals, they were instead given a sheet of paper with an arrow with 1 and 5 printed at the extremes. The users had to mark a cross on the arrow. Two types of ratings were marked by the users. The first was based on the homogeneity of the lamps and the second was based on the visual aesthetics of the lamp. Both used the same magnitude in the rating scale. The marked ratings were then measured and transposed into numerical data for comparison. As discussed in section 3.2.4, mean and standard deviation were calculated and the results were analysed using the said two factors.
The results were calculated using tools in excel and the detailed table of calculation is as seen in appendix C. Since the participants consisted of 12 experts and 8 non experts, the analysis were divided accordingly for both homogeneity and aesthetic ratings.All the 4 cars under consideration were asked to be rated accordingly and there were constant communications with the users to get to know what were they basing their judgement upon.

5.1.1 User rating on homogeneity

The results from the user rating on homogeneity were calculated and as seen in Figure 5.1. On comparison of both experts and non-experts responses, it can be clearly seen that the Mercedes and S60 were the cars that were distinctly different. While the experts rated the homogeneity of Mercedes to be the least, the non experts rated it better than the other cars. The main reason for this could be the intensity of light from both the lamps. S60 had a dimmer light intensity compared to the Mercedes and the orientation of the light blades were opposite to each other. Regardless of these variations in mean, the standard deviation were consistent on comparison except for S60. This meant that there were variation in the opinion of the experts regarding homogeneity of S60.

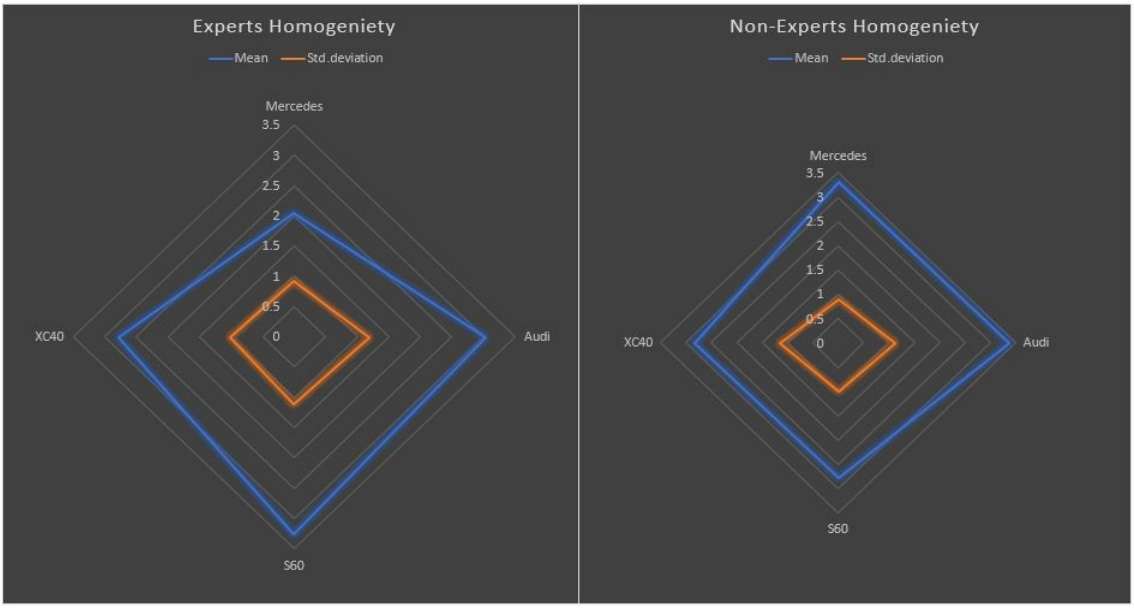


Figure 5.1: User rating on homogeneity

5.1.2 User rating on Aesthetics

The ratings based on aesthetics were based on how well the lamp appealed to the user. The result is summarized in the figure 5.2 and the detailed summary can be seen in Appendix C. Although aesthetics is more dependent on personal inclinations and preferences, an attempt here is made to generalize it for an measurable output. It was seen that the Mercedes scored the lowest from both experts and non-experts and it also had a low standard deviation which meant that the opinions were consistent. AUDI also had a lower rating compared to the Volvo's. However its standard deviation is higher compared to other cars which meant a few participants rated it higher than the rest. Non-experts were clearly rated the Volvo's higher than than the experts which is evident from the low standard deviation and higher rating of the mean.

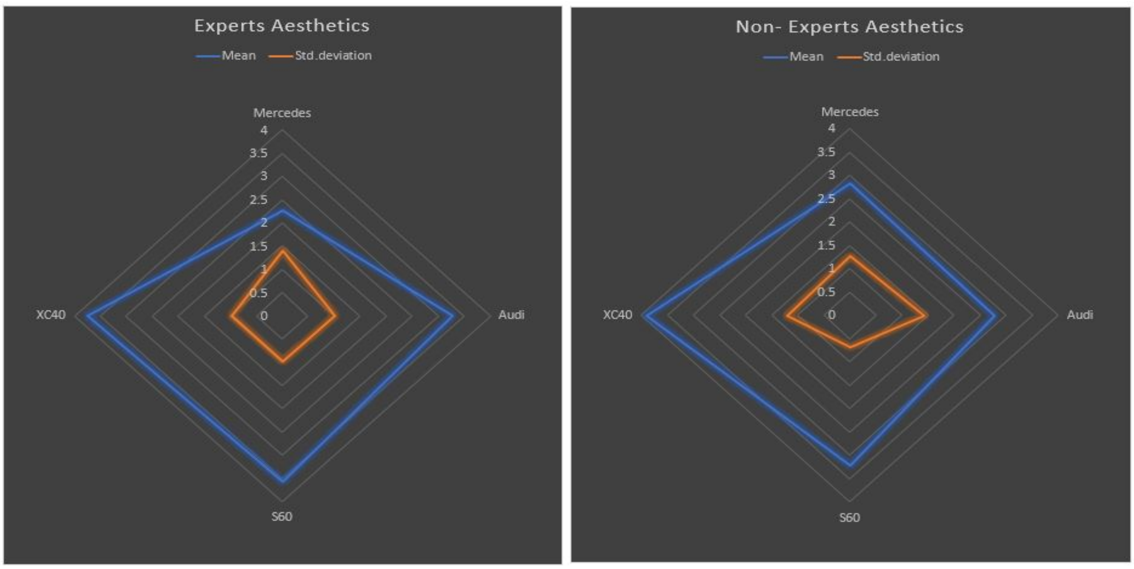


Figure 5.2: User rating on Aesthetics

To conclude, the effort to compile the user rating was to benchmark the Volvo's with the competitors of Mercedes and AUDI based on their homogeneity and aesthetics. S60 gave a better performance than XC40 on both ends. Regarding homogeneity, non-experts had more liking for the competitors. On interaction, it was mainly based on the higher intensity of the position lights compared to the Volvo's. Experts clearly weighed Volvo's higher than the competitors with less standard deviation. Hence based on the ratings, the performance of position lights of the Volvo's were better if not equal to that of the competitors.

5.2 Processing subjective response of the Users

As explained in section 4.4.4, the users were asked to mark their responses with different color codes on the outline of the light blade. For further analysis, these individual inputs from 20 participants had to be combined to make a quick referable entity. Hence to enable this, the users were divided into experts and non-experts, and their data were divided into sets was processed accordingly.

The collective data can be obtained through overlapping of the response sheets and projecting the colors through the layers to obtain a darker shade where the concentration of color is higher. In other words more users would have marked at the regions of dark shade, thereby establishing such regions as a significant response. Image editing software was used for this purpose and the final result had the subjective response of the participants on paper as intended. An illustration of a response can be seen in Appendix C.

5.3 Weber's fraction

As discussed in section 4.5, the main objective of this experiment was to determine the visual threshold of response as perceived by the eye and thereby to establish limits for contrast or intensity variation between two intensities. Hence the slope of the line Initially, the users are again distinguished between experts and non experts for comparison. To summarize the experiment, the users were asked to stop the variation in intensity of the lower strip once they perceived the upper strip of having the same intensity. The intensity readings were recorded using live feed from the luminance camera and they were analysed with the help of a statistical analysis software. The intensity of upper strip versus the intensity of lower strip were potted in the graph. The mean values of the responses and linear fit of the line were generated. The slope of this linear fit would influence the JND value of the users. If the users would have matched the intensity to precision, then the slope of the line would be 1. However if the lamp is perfectly homogeneous without variation in intensity, then the slope of the line would be 0 or parallel to the x coordinate. Steeper the slope of the line, more sensitive is the eye to the variation in intensity.

5.3.1 Experts Weber's fraction

The experts responses were considered here. To ensure that the responses of the experts were specific to the reference intensity and not influenced by any other factors, their data were subjected to a Multi-compare ANOVA test. Multi-compare is used to make sure that the mean of the responses of the users for each intervals are distinct and there are no overlap in the responses. If their intervals overlap, then the two group means are not significantly different.[62] A function in Matlab was used to generate the Multi-compare results.

As seen in the Figure 5.3, all the four groups under consideration have distinct regions and there are no influences between two pairs of responses. Hence any two pairs are significantly different from each other.

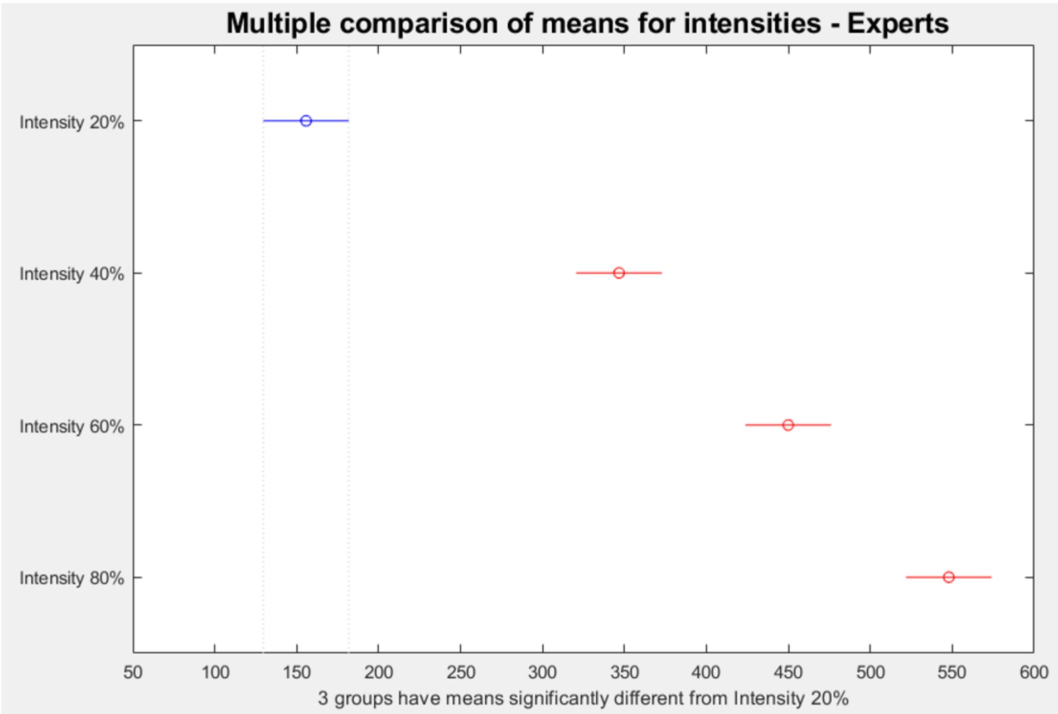


Figure 5.3: Multi comparison - Experts

With the upper strip intensity on the x-coordinate and the lower strip intensity which varies on the y-coordinate, a liner plot of the means were generated using a statistical software as seen in Figure 5.4. The shaded region around the line represents the confidence interval at which the probability of existence of mean is high. the confidence interval was set at 95%. The plot was extrapolated to higher magnitude of intensity to compensate for the practical intensity values of the lamp.

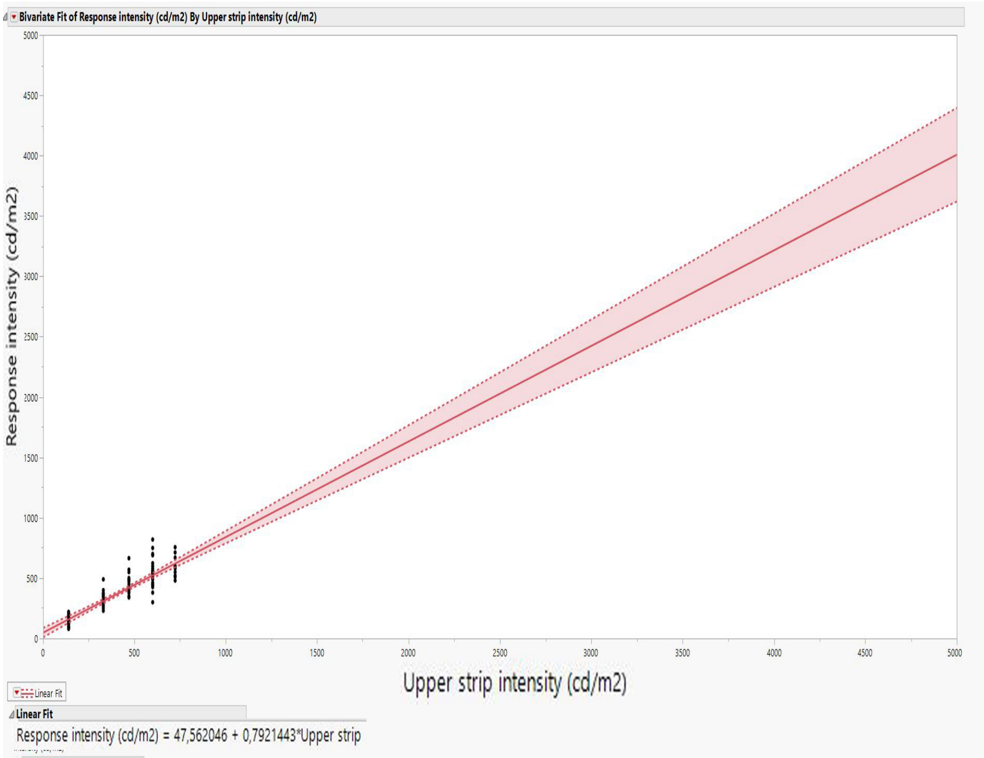


Figure 5.4: Experts JND graph

As seen from the Figure 5.4, the slope of the generated linear line was 0.79. This is the Weber fraction value of the experts. Since the slope is not 1, there is a measurable threshold that is in existence.

5.3.2 Non-Experts Weber's fraction

Similar analysis was performed for the responses of the non-experts. The multi-compare result obtained was as seen in Figure 5.5. It was seen that there was an overlap in the intensity range of 40% and 60%. This meant that there is no significant difference between the responses of the two intensities or there was some influencing factor that might have caused this overlap. One of the factors causing this could be less number of non-experts who participated in the experiment. With more users, the overlapping boundaries might have been pushed to separation. Other intensity pairs have no overlap and hence are significantly different and reliable for analysis.

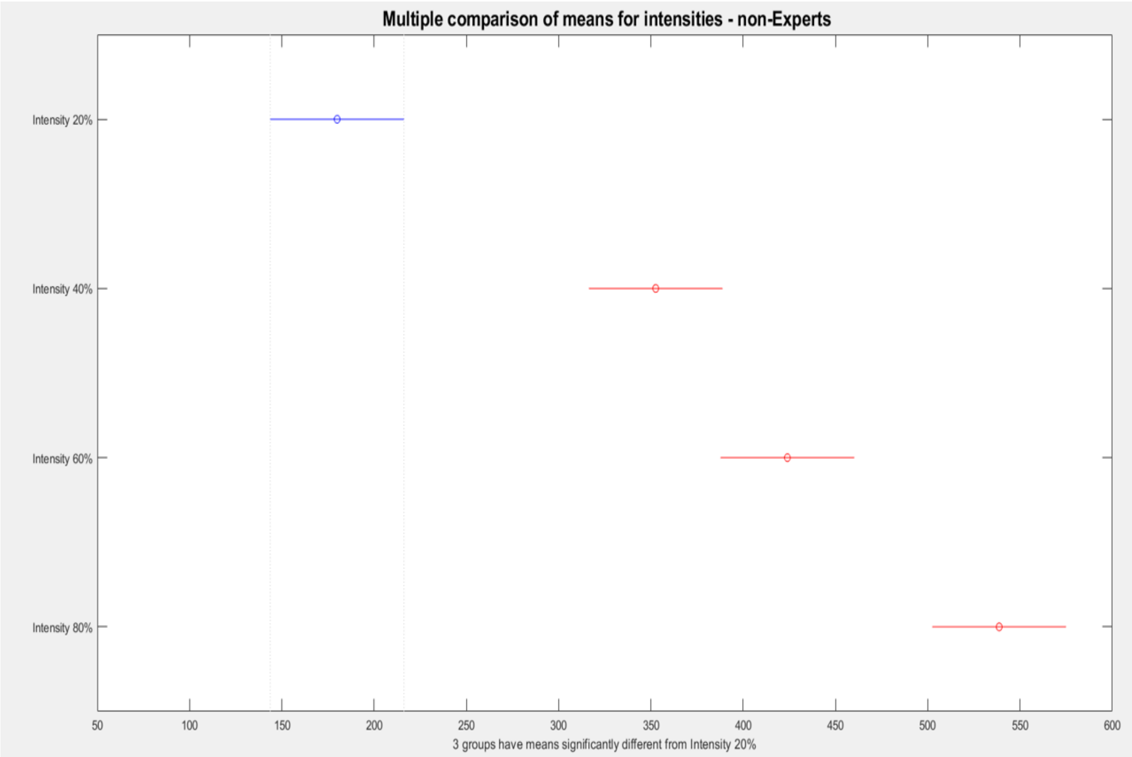


Figure 5.5: Multi comparison - Non Experts

The linear plot of responses from the non-experts is as seen in figure 5.6. Again a confidence interval of 95% was considered and the slope obtained was 0.75 which was lower than that of the experts. In other words, weber's fraction of non-experts were 0.75. Since slope of 1 would be an ideal value, the response closer to 1 would be more sensitive to change in intensity. Hence since the experts were closer to ideal scenario, it can be concluded that the experts have a more sensitive threshold than that of the non-experts.

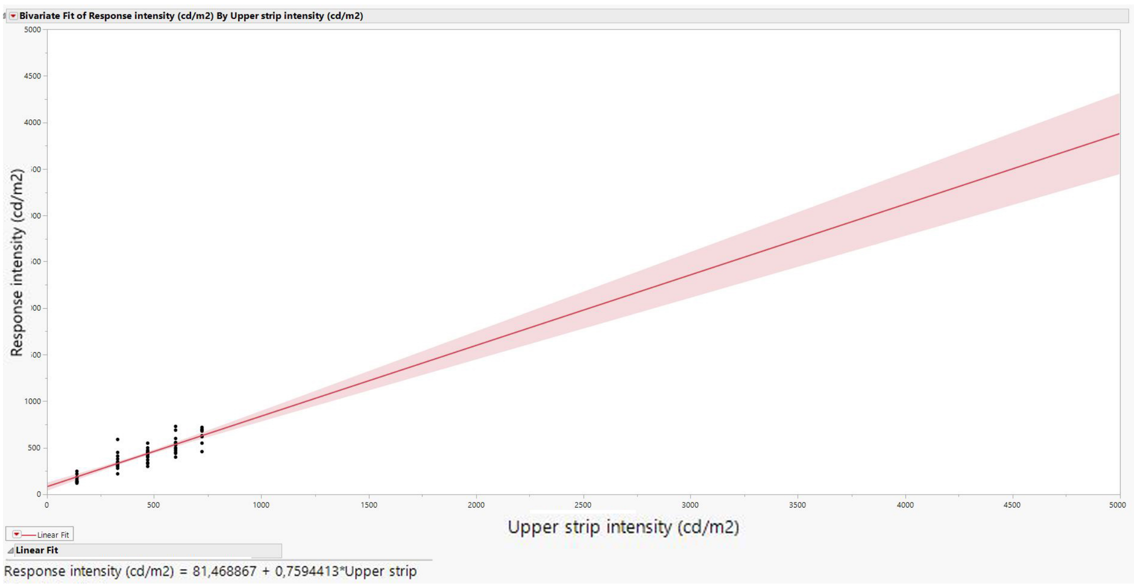


Figure 5.6: Non-Experts JND graph

However, this response analysis through only Weber's law is carried out for the purpose of establishing variation in intensity perception between experts and non-experts. Further application of the results obtained to apply limits for contrast variation was not pursued. The obstacle encountered was that the obtained slope was highly specific to the experimented magnitude of intensity. In practical analysis of lamps, these intensity variations are highly randomized and there would be a higher magnitude of y intercept which is very different than the y intercept obtained in the graph. Hence further analysis through only Weber's law approach was halted at this stage.

5.4 Threshold of Human Eye

According to the relationship between the Weber's and Fechner's law as discussed in section 2.2.4, the response is plotted as a logarithmic function inorder to evaluate the magnitude of JND.

$$R = log(I) \tag{2.3}$$

The response of the users were converted to logarithmic scale and plotted with the reference intensity as x coordinate in accordance to equation 2.3. [28] The resulting graph is as seen in Figure 5.7.

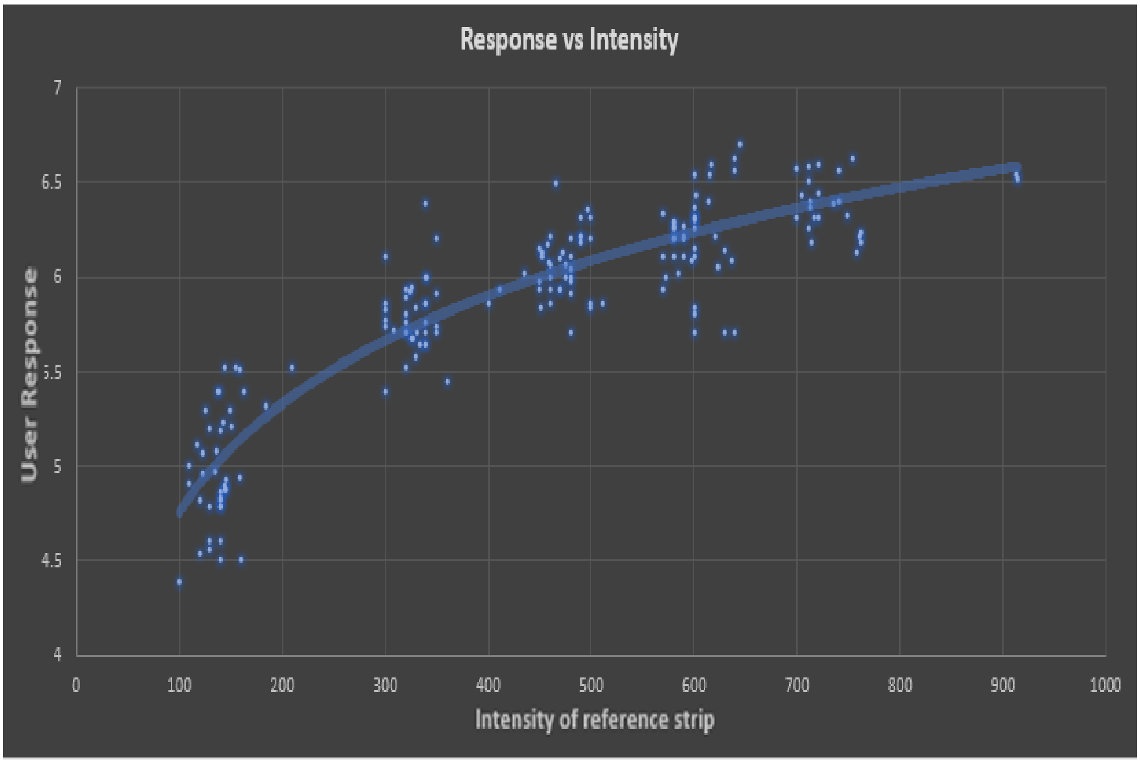


Figure 5.7: Logarithmic graph of responses

The x coordinate represents the intensity of the reference strip in candela per meter square, y coordinate represents the logarithmic value of the lower strip intensity that was matched by the users keeping upper strip as reference. The blue points are the actual user responses that are a function of the reference upper strip intensity in x axis and logarithmic converted lower strip intensity in y axis. A curve generated is logarithmic in nature as shown in the graph. The equation of the above logarithmic graph is:

$$Y = 0.8249 \log_e X + 0.9576 \tag{5.1}$$

Fechner's law states that the two lights will be just discriminated if the responses they generate differ by a constant amount. Hence referring back to equation 2.4, the difference in ΔR will remain a constant on comparison of two intensities. Hence the first step is to reverse engineer in-order to find the value of ΔR which would remain the same for further analysis.

Establishing threshold followed the below sequence:

- The response values from the lightbox experiment were in intensity magnitude measured in candela per square meter as seen in appendix C.1. Using the intensity responses that the users had given, keeping the reference intensity of the upper strip as constant, the responses given with variation of the lower strip intensity were grouped into two sets.

- The first set containing response intensities whose magnitude lay below the reference value and the second set containing responses intensities whose magnitude lay above the reference value.

- The above sets were segregated and grouped and the intensity value of the lower strip in candela per meter square was converted into logarithmic values which would now be the user response.

- The converted logarithmic response was again organized based upon the magnitude of reference intensities into segments of 20%, 40%, 60% and 80%. The values in each segments with higher and lower intensity were averaged as seen in appendix C.3.

- Hence using the curve equation 5.1, the averaged segmented response (Y) was used to find the corresponding intensities (X) in candela per square meter.

- The aim was to obtain a response interval Δ R that would remain constant in-accordace with Fechner's law. Hence the obtained logarithmic curve was replaced by an ideal logarithmic curve and the equations 2.4 and 2.5 were used in further calculations.

- From the set of lower threshold values, the resultant value of ΔI was calculated and along with the reference intensity I they were used in Equation 2.4 to get the resultant lower threshold response as seen in appendix C.4.1.

$$\Delta R_l = log(I) - log(I - \Delta I) \tag{2.4}$$

- As it was evident from the difference between the upper and lower values of the responses that it was not constant, there was a need to introduce an error factor into the result.

- The obtained values of ΔR_l were averaged and the resultant value was decreased by 20%. This 20% error was due to two factors. The first 10% is due to the fluctuation in the recording of readings from the luminance camera and the remaining 10% was due to the manual control of the dial. Also when testing for higher threshold, there were instances where there were crossing over of responses below the reference intensity. These crossed over responses were attributed to the lower intensity in-order to prevent dilution of upper threshold.

- Similar procedure was followed for the upper threshold using the Equation 2.5. The value of ΔR_h was determined and was reduced by 20% owing to the same reasons as stated above.

$$\Delta R_h = log(I + \Delta I) - log(I) \tag{2.5}$$

Values can be seen in Appendix C. An example of calculation for a value(20%) lower threshold is shown in Appendix E.

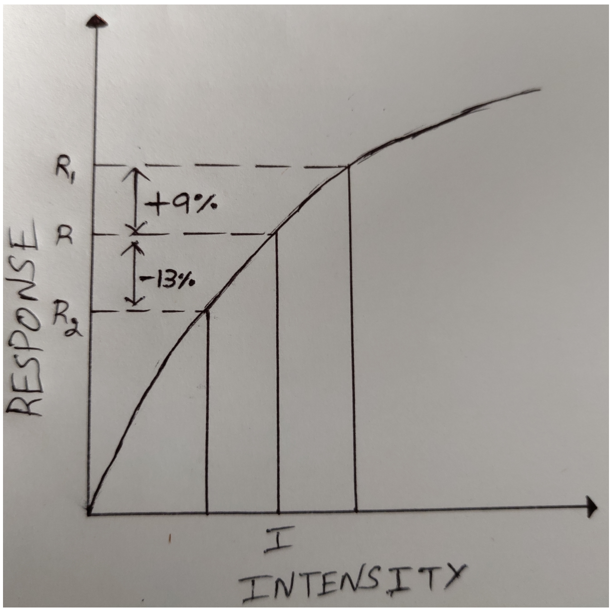


Figure 5.8: Graphical illustration of the threshold

To conclude, the threshold value or Just Noticeable Difference (JND) varies from +9% and -13% from the actual intensity response of the user.

- For further calculations, the obtained response threshold values were considered constant in-accordance with Fechner's law. ΔR_h = 9% and ΔR_l= 13%.

- Further, given any reference intensity 'I', the value of threshold intensities 'ΔI' would be calculated by rearranging equations 2.4 and 2.5. Example of calculation is shown in appendix E.

- A macro was developed in Microsoft Excel incorporating the above formulas to find the thresholds of any input intensity and to indicate if the thresholds are violated.

5.5 Relative comparison

After establishing the threshold range of intensities from the previous section 5.4, the following proposes a tool by which the above said threshold could be used on the actual automotive lamp. Regional comparison works on the concept of comparing the intensities within the defined boundary with another similar defined boundary and incorporating threshold between them. Hence two regions can be comparatively quantified with respect to its intensities based on the boundaries of threshold derived.

With the available prometric tool, the above said regional boundaries can be defined in terms of *Points of Interest* (POI) which can be manually assigned in the prometric software. As discussed in section (REF), the prometric tool captures the luminance values of the physical lamp. The data is pixel specific where each pixel is assigned a luminance value. This would lead to a highly detailed and fluctuated output whenever an attempt to comparison is made. Hence there was a need to simplify the output to be able to comprehend the results. The apparent surface mimicked in the prometric had to be simplified to comprehend the resulting output.

Hence, while defining the *Region of Interest* (ROI) in the Prometric, the luminosity values are averaged to the center for the pixels contained within the region. By doing this, the microscopic anomalies are nullified and a more holistic luminosity value of the ROI is obtained. Two regions with averaged luminosity values in the ROI's can be relatively compared with threshold ranges as limits. One ROI is kept as reference and the second ROI is relatively compared to the reference. the resultant analysis is whether the region in comparison is darker or brighter than the reference, or are they perceived as same intensities by the naked eye.

Shape of the ROI
With the available shape that could be drawn in the Prometric, such as circle, rectangle, point and manual free-form, Rectangle was chosen as the better suitable shape. The reason being it could occupy the desired space of the light blade and it had a definitive boundary line which can be used as a reference to plot the next region. Also a uniformity in size can be maintained while plotting the ROI's. Hence, square is selected as an optimum shape of the ROI.

Two important aspects has to be established before the analysis with relative comparison could be made. They are:

- Size of the box
- Regions of comparison

5.6 Size of Box

An optimum size of the box has to be established in-order to have a uniformity in the analysis approach with the company and the suppliers. The following criterion were found to be influenced by the size of the box:

- **Fit to size**: The size of the box had to fit within the boundary of the lit surface of the lamp. If the ROI exceeds the boundary of the lamp by a large extent, chances of error in the averaged luminosity value would be higher.

- **Human error**: Since the plotting of the ROI's is manual, there will be an error factor. Human error is the closeness with which the ROI's can be drawn next to each other, neither with a gap nor overlapping each other. The closer the ROI's are drawn next to each other, the better results are obtained.

- **Degree of closeness**: This refers to the closeness to which the result obtained would be to the actual user inputs from section 5.2.

- **Threshold magnitude**: Threshold magnitude is a feature in Prometric that considers only the pixels which are above the specified magnitude. Since the luminosity value of the pixels would be averaged, lower the magnitude of threshold, closer the averaged value would mimic the original.

- **Holistic comparison**: This relates to how harmoniously could the whole lamp be compared. Comparison between different regions of the lit surface which are at different orientation to get the overall homogeneity of the lamp and not limiting to selective surfaces.

- **Time to generate**: Time taken to complete the whole analysis starting from generating the boxes to weighing the results with threshold.

The above factors were weighed based on the pairwise comparison method as discussed in section (REF).

5.6.1 Pairwise Comparison

pairwise comparison is used to evaluate and give weightage to multiple factors under consideration. The above factors were relatively compared to each other and the dominant factor were given more weightage. The initial results were extracted for the initial position (P1) of S60. Boxes were drawn manually and the analysis was timed. The relative comparison was made from left to right. The box drawn to the left was considered as a reference and the box to the right was compared to the previous with threshold restrictions on intensity. This would continue for the sets of pairs of ROI's. The result from the pairwise comparison was as seen in the figure 5.9.

	Fit to size	Human error	Degree of closeness	Threshold magnitude	Holistic comparision	Time to generate	Total
Fit to size		1	0	1	1	1	4
Human error	0		0	1	1	0	2
Degree of closeness	1	1		1	1	1	5
Threshold magnitude	0	0	0		1	0	1
Holistic comparision	0	0	0	0		1	1
Time to generate	0	1	0	1	0		2

Figure 5.9: Pairwise comparison - Size of box

From the results, it is evident that degree of closeness precedes the other criterion's followed by fit to size. Hence, these two criterion were assigned higher weightage.

5.6.2 Kesselring Matrix

Range of different sizes could be drawn from Prometric. Since we have established that the square would be the best shape, different sizes of squares were considered with sizes of 2X2mm, 3X3mm, 5X5mm and 10X10mm. As discussed in section (REF), the luminance camera had a focal length of one meter to obtain the actual scale of distance. Disadvantage here would be the whole lamp would not be focus from one meter distance. Hence the pictures of the lamps were captured from two distances, whole lamp from a distance of three meters and zoomed and segregated lamp from a distance of one meter. Analysis had to be performed for both the distances incorporating all the four sizes of the box. Hence, kesselring matrix was used to filter and weigh the results to obtain the size of the box that can be used in further analysis. The Kesselring matrix is as seen in figure 5.10 and the defined grading scale is represented in appendix D

Kesselring Matrix				To scale at 1m distance								Whole Picture at 3m distance							
Criteria	Weight	Ideal		2X2		3X3		5X5		10X10		2X2		3X3		5X5		10X10	
		Value	Total	Value	Total	Value	Total	Value	Total	Value	Total	Value	Total	Value	Total	Value	Total	Value	Total
Fit to size	4	5	20	3	12	4	16	3	12	1	4	4	16	3	12	2	8	1	4
Human error	2	5	10	2	4	2	4	4	8	4	8	2	4	3	6	4	8	4	8
Degree of closeness	5	5	25	3	15	4	20	3	15	1	5	4	20	3	15	2	10	1	5
Threshold magnitude	1	5	5	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Holistic comparision	1	5	5	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4
Time to generate	2	5	10	1	2	2	4	4	8	4	8	2	4	3	6	4	8	4	8
	Total score	75		39		50		49		31		51		46		41		32	
	Rank	-		0.52		0.67		0.65		0.41		0.68		0.61		0.55		0.43	

Figure 5.10: Pairwise comparison - Size of box

From the Kesselring matrix, the box size of 2X2mm with the picture taken at three meter distance was found to be optimum for further analysis.

5.7 Regions for comparison

Three different ways in which relative comparisons could be made were established :

- **Comparing adjacent boxes**: In this method, the adjacent boxes are compared with each other. For the next comparison, it will be cumulative such that the first comparison box will act as a reference box for the next set. As seen in Appendix C
- **Comparing boxes with common reference**: In this method, the reference box is considered common throughout the analysis. This reference is selected based on the subjective judgement of the lit surface. The whole lamp intensity is expected to follow the intensity of the reference box. As seen in Appendix C
- **Divide the surface into regions and compare between each regions**: The whole lit surface area of the lamp is segregated into different regions and the relative comparison of the boxes are done within their respective region. The regions as a whole are then compared with each other to determine if they are brighter or darker to each other. As seen in Appendix C

Inorder to pick the best method for further analysis, the above methods were again subjected to kesselring matrix.

5.7.1 Pairwise comparison

The criterion's for judgement are similar from section 5.6. Only *fit to size* is removed and the pairwise comparison is done for the remaining criterion's.

	Human error	Degree of closeness	Threshold magnitude	Holistic comparision	Time to generate	Total
Human error		0	1	1	0	2
Degree of closeness	1		1	1	1	4
Threshold magnitude	0	0		1	0	1
Holistic comparision	0	0	0		1	1
Time to generate	1	0	1	0		2

Figure 5.11: Pairwise comparison - analysis method

5.7.2 Kesselring Matrix

Using the rankings of the criterion from the pairwise matrix, kesselring for the three analysis methods were performed. The analysis was done to the S60 P1 position with the resultant box size of 2X2mm. The matrix obtained was as shown in figure 5.12 and the defined grading scale is represented in appendix D.

Criteria	Weight	Ideal		Adjacent Comparison		Averaged Comparison		Divide, Average and compare	
		Value	Total	Value	Total	Value	Total	Value	Total
Human error	2	5	10	2	4	2	4	2	4
Degree of closeness	4	5	20	4	16	1	4	2	8
Threshold magnitude	1	5	5	3	3	3	3	3	3
Holistic comparision	1	5	5	4	4	4	4	4	4
Time to generate	2	5	10	2	4	2	4	2	4
Total score		50		31		19		23	
Rank		-		0.56		0.35		0.42	

Figure 5.12: Kesselring matrix - analysis method

From the kesselring matrix, it is established that the method of adjacent comparison is the best suited for further analysis on homogeneity.

Henceforth the analysis and results would be based upon the adjacent comparison method with the box size of 2X2mm with the picture of the lamp captured through the luminance camera at a distance of three meters.

6

Requirement and Verification

From the product development aspect, requirement means describing what the product must achieve in the end, tells how the product must be and also gives guidelines when generating solution.[63] This Chapter contains the requirement that was set in this thesis to ensure that the front position lamp appears to be homogeneous. It also consists of physical verification and verification methods to verify the homogeneity of the present cars at Volvo Car Group.

6.1 General requirement

The following are the basic requirement that is to be fulfilled in-order to continue with the objective evaluation.

- The design intent needs to be considered as reference for the final output. Latest revision are to be prioritized.

- The subjective evaluation precedes technical evaluation.

- At different positions, the nature of variation of intensity to be consistent with the reference along the same horizontal axes. If the reference intensity plot of a section of lit surface say at H0V0 is a smooth curve, on changing the angle of view or position, the intensity plot of the same lit surface should follow the nature of of reference curve (in this case an identical smooth curve).

- No area outside the designated lit surface of position light is allowed to have glare when the position light is ON.

Requirement on homogeneity need to have a holistic approach where the whole lamp is incorporated in the analysis. Also the different regions of the lit surface needs to be compared with each other. The verification of the requirement has to go hand in hand with the stated requirement. Hence the following 3 step approach is suggested to be included in the requirement which also enables verification.

- Intensity homogeneity requirement

- Horizontal holistic requirement

- Vertical holistic requirement

6.2 Intensity Homogeneity requirement

The homogeneous distribution of intensity of the lit surface is the focus in this step. The method of adjacent relative comparison is applied here and the calculated threshold is used as the limits in this comparison. Established box method forms the basis where the homogeneity between a pair of boxes, which represent a segmented region on the lit surface is focused. This method aim to detect the minute anomalies on a micro analysis scale.

Requirement

- A requirement is that the response between two regions of interest under comparison has to be within the threshold range of -13% to +9% in-order to be deemed homogeneous.
- The comparison is made between two adjacent regions in the order in which the boxes are drawn.
- Cluster of 3 or more bright or dark boxes to be considered as a noticeable irregularity or glare.
- Repeated pattern of bright or dark boxes are to be treated as spotted in appearance

Verification

The boxes of 2X2mm are to be drawn adjacent to each other on the visible lit surface of the lamp such that the maximum area of the lit surface is within the box. The edges of the box has to be as close as possible with no overlapping. In-case the whole lit surface is not covered, another layer of boxes should be drawn parallel to the original layer. The magnitude of response intensity threshold should not exceed 50 cd/sq.m. This reduces the error of overcompensation while averaging the intensity of the pixels.

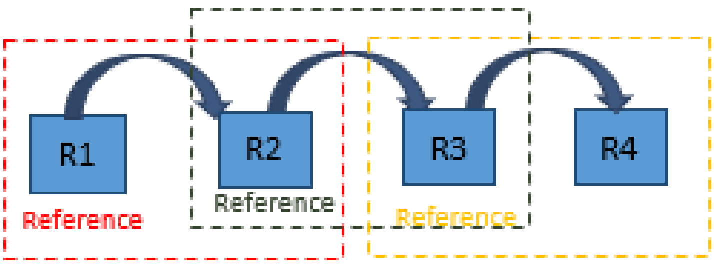


Figure 6.1: Illustration of Box comparison for lit surface homogeneity

In the above illustrated figure 6.1 where the boxes are drawn from left to right, in the adjacent comparison, a pair of boxes are compared with its limits. Here the region R2 is compared with reference intensity R1. If the intensity of R2 is less than 13% of R1, then the box R2 can be perceived as dark in comparison to R1. If the intensity of R2 is greater than 9% of intensity of R1, then the box R2 is perceived as bright in comparison to R1. Likewise, for the next pair of boxes, R2 is taken as reference and is compared with R3. This cycle repeats until all the adjacent boxes are analysed. Detailed illustration with example can be seen in Appendix A.

The drawback of this method is that it does not give the whole holistic homogeneity of the lamp. Also for the vertical regions of the lit surface, this method is reliable if the boxes are drawn next to each other. However drawing the boxes adjacently in the vertical section is found to have many drawbacks such as break in intensity continuity while analysing and more time requirement in rearranging the values and hence not recommended. In the vertical section, the boxes have to be drawn from top to bottom or vice-versa for easy illustration. Hence this method is not recommended for analysis of the vertical part of the lit surface.

6.3 Horizontal Holistic requirement

This requirement is to satisfy the homogeneity between the horizontal regions of the lit surface thereby giving a holistic comparison on homogeneity between the two horizontals. Here the comparison is made between two regions which are vertically aligned. The threshold limits of -13% to +9% of the reference is to be satisfied here too.

Figure 6.2: Illustration of Box comparison for lit surface homogeneity

As illustrated in figure 6.2, the box R1 at the top is compared to the Box R34 which is below it. During the whole analysis, the boxes in series with R1 would be compared with the similar adjacent boxes in series with R34. The boxes in series with R1 represents the upper horizontal lit surface and the boxes in series with R34 represents the lower horizontal lit surface. Hence during this analysis, the lower horizontal is compared with the upper which is kept as a reference. The requirement is for the lower boxes in series to be within the specified threshold range of the upper intensities.

However, although the comparative differences in intensities are determined through the above analysis, the magnitude of difference in intensity, if present is not illustrated. Hence a graphical representation of the intensities of the upper region as well as the lower region would assist in knowing the magnitude of difference in intensity as shown in figure 6.4.

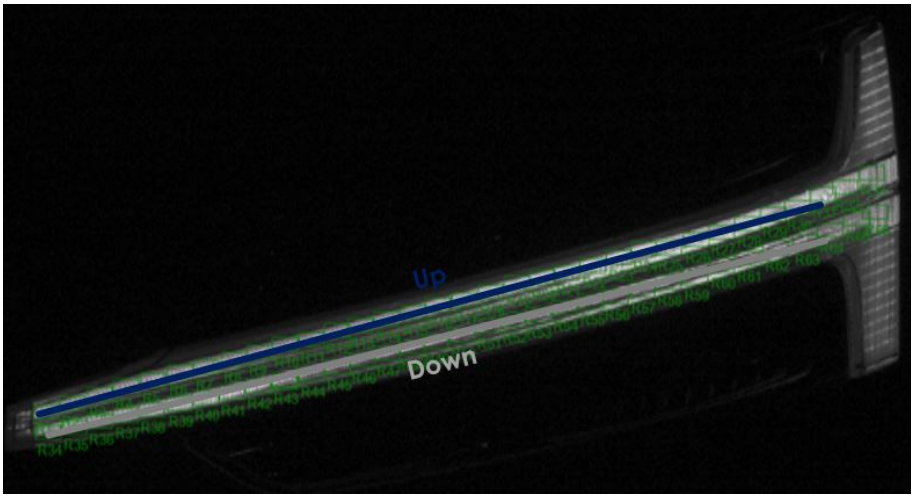


Figure 6.3: Comparing Upper Intensity versus Lower Intensity

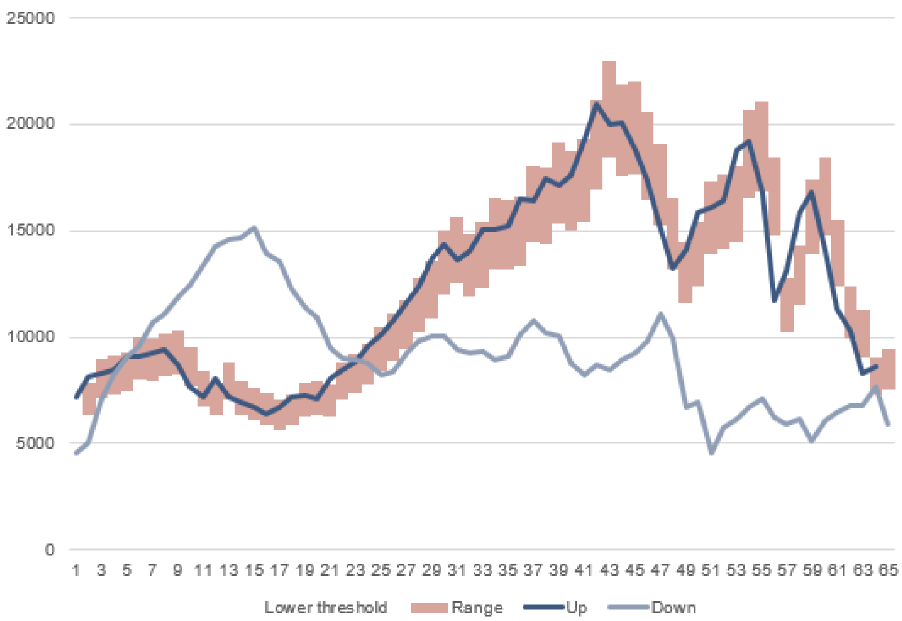


Figure 6.4: Horizontal intensity comparison

With the graphical illustration, the magnitude of variation and the regions where the intensities are within the range of the reference are shown. Ideally if the intensities of both the upper and lower horizontal lit surface are similar, the curves should overlap or exist within the range. However to avoid any undesired spikes in brightness or dark-spots, the nature of both the curves should be similar. more illustration can be found in Appendix A.

6.4 Vertical Holistic requirement

This requirement attempts to encompass the homogeneity between the vertical regions of the lit surface along with comparison with the intensity of horizontal lit surface in-order to achieve a holistic homogeneity visualization. Since the length of the horizontal lit surface exceeds that of the vertical lit surface, the eye judges the vertical lit surface in the same pattern as that of the horizontal lit surface. Hence, the regions of the vertical lit surface are relatively compared in vertical columns as shown in figure 6.5. The boxes in column of R1 would be compared with the adjacent boxes in column of R2 on the vertical section of the lit surface.

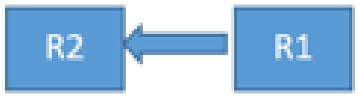


Figure 6.5: Illustration of box comparison with vertical homogeneity requirement

Similar to section 6.3, for the purpose of illustration of magnitude of intensities, a graphical representation of the intensities are drawn along with the a reference intensity of the horizontal lit surface.

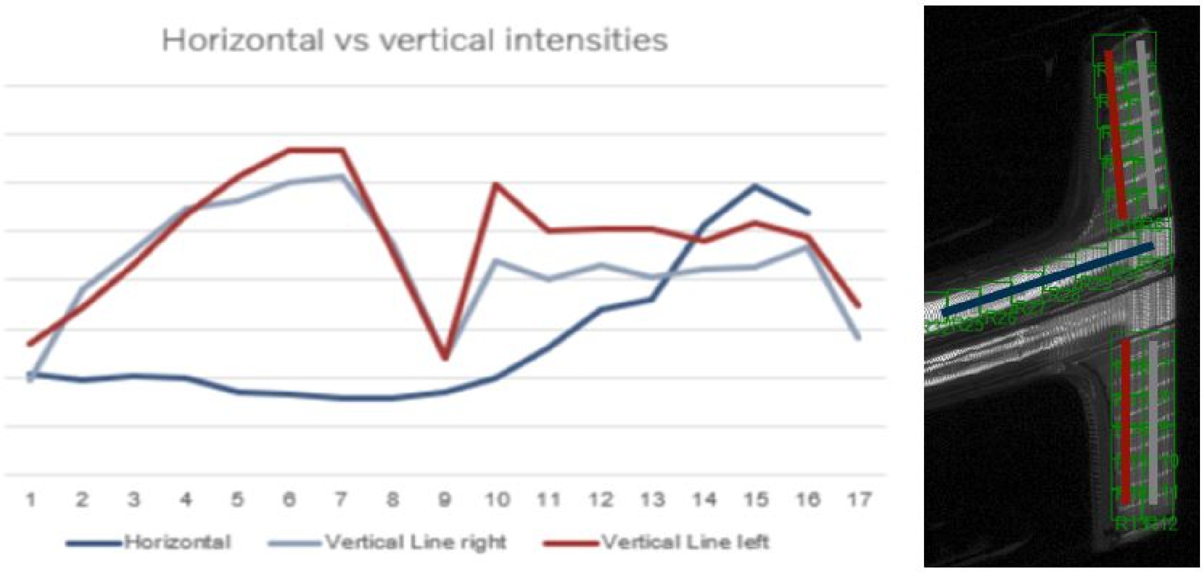


Figure 6.6: Horizontal Vs Vertical Holistic Homogeneity graph

As seen in the figure 6.6, The vertical lit surface has 2 columns named left and right and is compared with the horizontal upper lit surface region whose region is chosen for the sake of comparison. The curves of the vertical intensities is expected to overlap over each other ideally. Practically the curves are expected to follow the same nature as that of the reference intensities. Detailed illustrations can be found in Appendix A.

6.5 Rating scale of Homogeneity

This requirement is an attempts to meet the subjective rating that was set by Perceived quality illumination, Volvo car group. The figure 6.7 shows the rating scale that is currently used at Volvo Car Group to see where the lamp stands in terms of homogeneity.

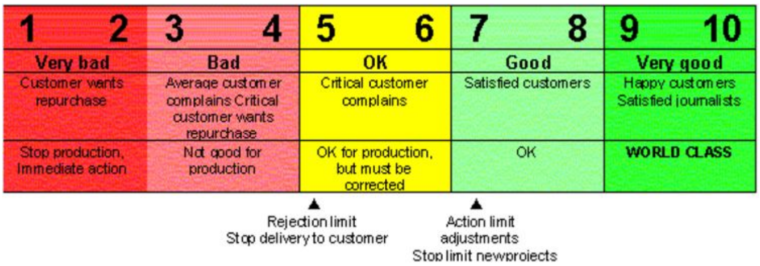


Figure 6.7: Rating Scale

Criteria	S60		
	P1	P2	P3
Individual Points	2	1.33	1.33
Cluster areas	1.33	1.33	1.33
Irregularities	1.33	1.33	1.33
Horizontal Up v/s Horizontal Down	0.66	2	1.33
Vertical holistic Comparison	1.33	1.33	0.66
Total	6.65	7.32	5.98
Average Total	7		

Figure 6.8: Rating for S60

The figure 6.8 shows the example of rating table which is been done on Volvo S60. The rating is purely subjective. The criteria that are used is based on the requirement that is mentioned in the previous section.

Following is the brief explanation on each criteria.

- **Individual Points** - One or two points occuring at some random distance (Rating is done based on the number of points)
- **Cluster areas** - Group of points having same pattern of colours (Rating is made based on the total number of the cluster present)
- **Irregularities** - Sudden change in level of intensity from Dark to bright (or Bright to dark).
- **Horizontal Up v/s Horizontal Down** - Rating is done by seeing the graphical representation 6.4 of the intensities of the upper region as well as the lower region. Ideally, the intensity of the lower region should be within the range of the upper region.
- **Vertical Holistic Comparison** - Rating is done based on the closeness of the vertical lines along with the horizontal line as shown in a graphical representation in figure 6.5

The rating include all the positions of Volvo S60 (P1=H0V0, P2=H0Veyelevel, and P3=H22.5Veyelevel). In order to match the values of predetermined rating scale, the scores for each criteria is divided as good, Ok and bad that is 2, 1.33 and 0.66 respectively. The scores of each criteria is been added up and the total average of all the position is been determined. This average Value is than compared with the rating scale (figure 6.7).

7 Discussion

Discussions below attempts to answer the research questions, summarize and reflect the results, methodology used, final requirement suggestion and its verification approach. The whole thesis was conducted at the premises of the company Volvo Car Group, Gothenburg, Sweden. The authors worked in close collaboration with the supervisor present in the same department of Perceived Quality which enabled smooth knowledge transfer by means of dialogue and information accessed through company database. In person interaction with persons from different departments involved in the development of the lamp helped in gaining overall knowledge about the different stages of development.

1) What are the research approaches and various design parameters to be considered for defining homogeneity of lit surface of the lamp?

Although the topic to homogeneity seems simple at the surface, there were various influencing parameters which needed to be considered and initially it took time to get a sure footing to take a reliable approach. The parameters were prioritized, filtered and the very critical parameters were carried forward through the process. With many approaches such as technical, which deals with the technology (LED's, light guide), optics, packaging and similar. On the other hand, based on the perception of the observer, dealing with biology of the eye, distinguishing different intensities, interpretation of light and similar. Thirdly, using artificial intelligence or self learning neural network to compare two lamps and make judgement on homogeneity thereby removing any human interaction. All three approaches were looked into and the second approach of perception of the observer was pursued since it was backed by strong researches and was within our competence. The research approach was backed up by the conventional product development methodology. Some fragments from the product development cycle was implemented in the approach for generation of the requirement.
Though only one approach was used, it would be interesting and efficient to incorporate the third approach of using a neural network with established history of lamp data to make decisions on homogeneity. Hence this research question opens up more avenues to explore for generating ideal requirement.

2) What is an effective way to record, document and analyse the subjective response from the users for change in light intensity?

In wider sense, method of approach used was primarily focused on objectifying the subjectivity. However there was a need to quantify this subjectivity in measurable terms.

Hence an experimental investigation was carried out where 20 users were involved in 2 sets of experimentation. Circumstantially all the participants were from the company and hence there could be a probability of favoritism in their responses. Also on increasing the number of participants to more than 30, the result of the response could have been more crisp and reliable. Also by masking the brand of the cars under test, the effect of favoritism could have been minimized. This could have also influenced the scale of rating and its application in requirement would have been more impactful. The participants were given ample of time and there was a constant communication with them in-order to make sure that they are judging based on the required parameters. The demographics of the participants were also not prioritized since the light perception would be generalized irrespective of the gender.
The first part of the experiment was conducted in daylight inorder to get the photopic response from the eye since the defects are more prominent. However, there was a problem with glare effect due to light reflecting from the surrounding buildings which would have minutely affected the users subjective response. Also the responses recorded were segregated based on the profession of the subject. The main reason behind this is to know the variation in judgement since the professionals who dealt with light on a regular basis would be more sensitive to changes and hence would influence the overall response.
After performing the analysis, though a practical and simple approach was used for documenting the subjective response, many uncontrollable factors such as their eyesight, perspective, preference and similar would have influence their response. Hence if the screening of participants for the study would have been more focused on wellness of eyesight and if the lamps were judged anonymously, the subjective response would have been more detailed and specific.

3) How to measure human subjective perception and the measurable objective change in light intensity (Stimulus)?

The experimentation with the light box to find the threshold of the eye yielded results in-accordance with the law. The overall response was statistically unique for different intensity ranges and hence the obtained threshold is reliable. However, due to manual intervention in operating the dials and fluctuation of the camera readings, a compensation error of 20% is used for maintaining the reliability. Negating this error by making the whole experiment automatic would provide an accurate resulting threshold.

The concept of relative comparison is mainly influenced by the objective to have a holistic approach to homogeneity. Performing analysis on 2D representation of a 3D lamp as in apparent surface gives an advantage where variety of operations can be performed via supporting software tools. Limitation here is the extent to which the analysis can be done depends on the competence of the software tool. The version of camera specific Prometric software available had essential but limited features and the objective analysis method had to be constructed around the available features. The distance range along which the threshold exists is very rigid and at the distance of 3 meters from the lamp. Although the subjective rating is unique for an individual, they are generalized for the sake of simplification in the analysis. The behaviour of light on the lit surface changes at different heights and height of the individual under consideration was also generalized. Ideally each individual has to be analysed separately which was not practical with the time limitation on the thesis. The threshold generated is also sensitive to the distance between the two LED's strips used in the experimentation. The behavior of the threshold can also be calculated and predicted for different lengths of LED strips and different distances from the observer.

The obtained threshold ranges of -13% and +9% from the reference response are highly specific to the efficiency of experimentation. Ideally, without any error inclusions in the experiment, the threshold ranges are expected to vary symmetrically across the reference response. However, with usage of manually controlled dimmer dials and value fluctuations in the luminance camera, 20% error was incorporated into the analysis. Although this error incorporation shrinks the threshold ranges towards the actual experimental response, it does not compensate for the symmetry of the threshold ranges. There was a noticeable pattern during experimentation with light box where few users failed to catch the reference intensity while testing for the upper threshold value. Hence there was a cross over in their response which had to be filtered out from the analysis of upper threshold. The reason for this pattern of response is inconclusive and can be attributed to factors such as variation in eye adaptation between different users to lag in recording the answers to overestimation by users while comparing intensities or an unknown effect or factors that was not considered. However it is important to note that this pass-over of response exists only while experimenting for the upper threshold. Hence with more controlled experimentation it is possible to obtain more crisper and symmetric threshold ranges.

One of the main purpose of using the apparent surface representation of the lamp was to help reverse track any fluctuations in intensities back to the apparent surface. this would help to get a pictorial representation of the lamp with any anomalies marked at the specific location. Although the initial efforts were on performing micro image analysis of the lamps, failure to recover the segregated image to get a whole view of the lamp was a major setback. Hence performing analysis of the apparent surface through conventional tools and software available was prioritized. Hence the experimentation for balancing the subjectivity and objectivity will be more efficient with controlled variations which would reduce the error and the research question is hence answered.

4) Establishing relationship that converts objective data from the lamp into actual user subjective perception. How to objectify the light intensity change which affects homogeneity?

Once the subjective response from the users were documented and an objective approach was streamlined, attempt was made to establish a relationship between them with the help of the available tools and equipments.
The features of the available Prometric software was the driving factor to narrow down the verification. The shape of the Region of Interest (ROI) was chosen to be a square mainly based on trial and error method. This generalization of the ROI could have been made more flexible if the software had such features that could be manipulated to usage of area as to usage of shape. Using such flexible feature to mark the ROI will save time while generating the ROI. The verification of the requirement being a three step process contributes to the time and effort it would take to generate the result. Hence an excel supported macro was generated to decrease this effort. To visualize the regions of anomalies, the regions have to be marked using a photo edit software such as photo-shop or similar. This process can be further simplified if the regions in the Prometric software can be linked to the regions in the photo-edit software such that they are automatically

color coded.

The final rating of the holistic homogeneity is based on the ratings given over the three step verification process. However, the ratings are again based on the subjective decision of the analyser. Hence further quantification of the ratings by establishing limits in the number of defects would help eliminate this subjective approach while rating. The final requirement is purely based on how the human eye perceives the lamp and can the user spot any difference in intensity along the lit surface of the lamp and with the usage of established laws and analysis methodology, the subjective perception can be transformed into objective performance with established limits hence answering the research question.

Incorporating sustainability in the early product development cycle is highly crucial in the automotive sector. Design for Sustainability (DFS) is seen as a goal which prioritizes human well being and environmental impact. However there are many challenges and uncertainties on its implication in the pre-product development cycle. The main reason being it is not possible to quantify the environmental and social impact of the product due to lack of information of new raw materials or new production processes [64]. Hence it would be highly improbable to gather all the information withstanding the quality and certainty during the early phase of development. Although the thesis does not directly address the sustainable concepts, it influences the economic part of the sustainability by establishing better communication with the suppliers based on the objective data and defined thresholds.

8

Conclusion

The aim of this thesis is to generate a requirement for the homogeneity of the front position light and thereby establish a way to measure the homogeneity of light. It also aims to reduce the subjective evaluation and adopt an objective way to evaluate the homogeneity of the front position light. The user study helped us to know the threshold value which the human eye can detect with the change in the intensity of light. The solution for the stated aim was fulfilled with the help of this user study.

- An attempt was made to objectify the subjectiveness of homogeneity by giving preference to the actual user perception.
- Based on the Weber's and Fechner's law, response threshold value was defined and the range was found to be -13% to +9% which is in order to be the deemed homogeneous.
- The boxes of size 2x2 is suggested to be created by using the equipment specific Prometric software.
- Relative comparison of the regions is the method best suited for verification. A three step verification method is proposed to have a holistic homogeneity comparison of the lamp.

To conclude, this thesis attempts to provided a platform and a fresh perspective of measuring the homogeneity of lamp objectively as perceived by the human eye. Although not all aspects affecting Homogeneity is addressed, this thesis is a stepping stone for the industrial sector in lighting to make progress in order to set requirements using objective methods for the future lamps developed.

9

Future Work Recommendations

This section details and suggests the further developments that can be adapted to the suggested method. Suggestion is also made on using AI for doing the analysis of homogeneity.
The proposed method is limited by the competence of the software tools used which might vary from the suppliers and across the departments of the company. Hence to have a uniform requirement irrespective of the nature of software, the proposed method has to be checked and adapted to produce similar results across various software platforms. Performing analysis on different lamps of same vehicles is suggested to establish the variance.

Since the obtained threshold values are highly specific to distance of observation, repetition of the experiment using electronically controlled intensity variation and at different distances and angles would help in establishing precision thresholds at various CFoV's.
Image processing software's such as ImageJ or similar can be used to mimic the results similar to that of the Prometric software. Here the simulations generated prior to the prototype phase can be analysed similar to the proposed method. In this way, defects if present can be caught very early in the development cycle. The analysis follows similar trend to the proposed method. The brightness of the pixels are quantified and the regions are compared which is similar to the way analysis is performed through Prometric. However, the threshold ranges in candela per square meter has to be adapted or modified to match with the brightness of the pixels.

Using AI via Matlab or Python scripts for image processing is the prospective solution across the horizon. Processing the image of the lamps either from the simulation stage or from the prototype stage and using AI for processing these images forms the core concept of this method. It functions by generating artificial neural networks which can learn by itself and applying it on images of lamps to judge the scale of homogeneity. In-order to do this, images of ideal lamp has to be simulated and fed for the neural network to learn. When the picture of the practically simulated lamp or picture of the prototype lamp is fed, pixel to pixel analysis can be performed by the neural network and corresponding comparative results can be obtained. The main advantage here would be minimum human interaction throughout the process. Hence the error can be minimized and the results can be highly dependable.

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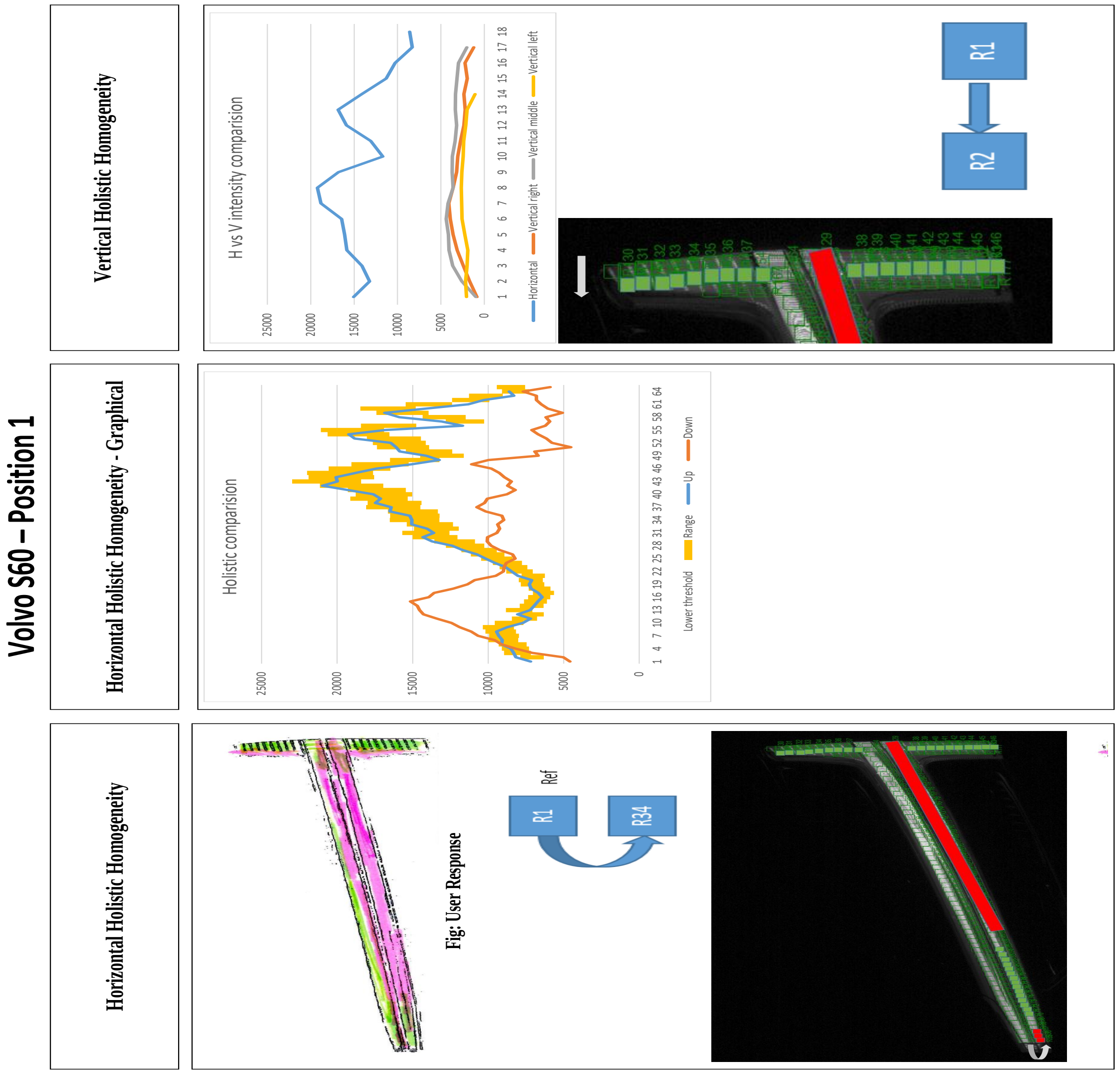
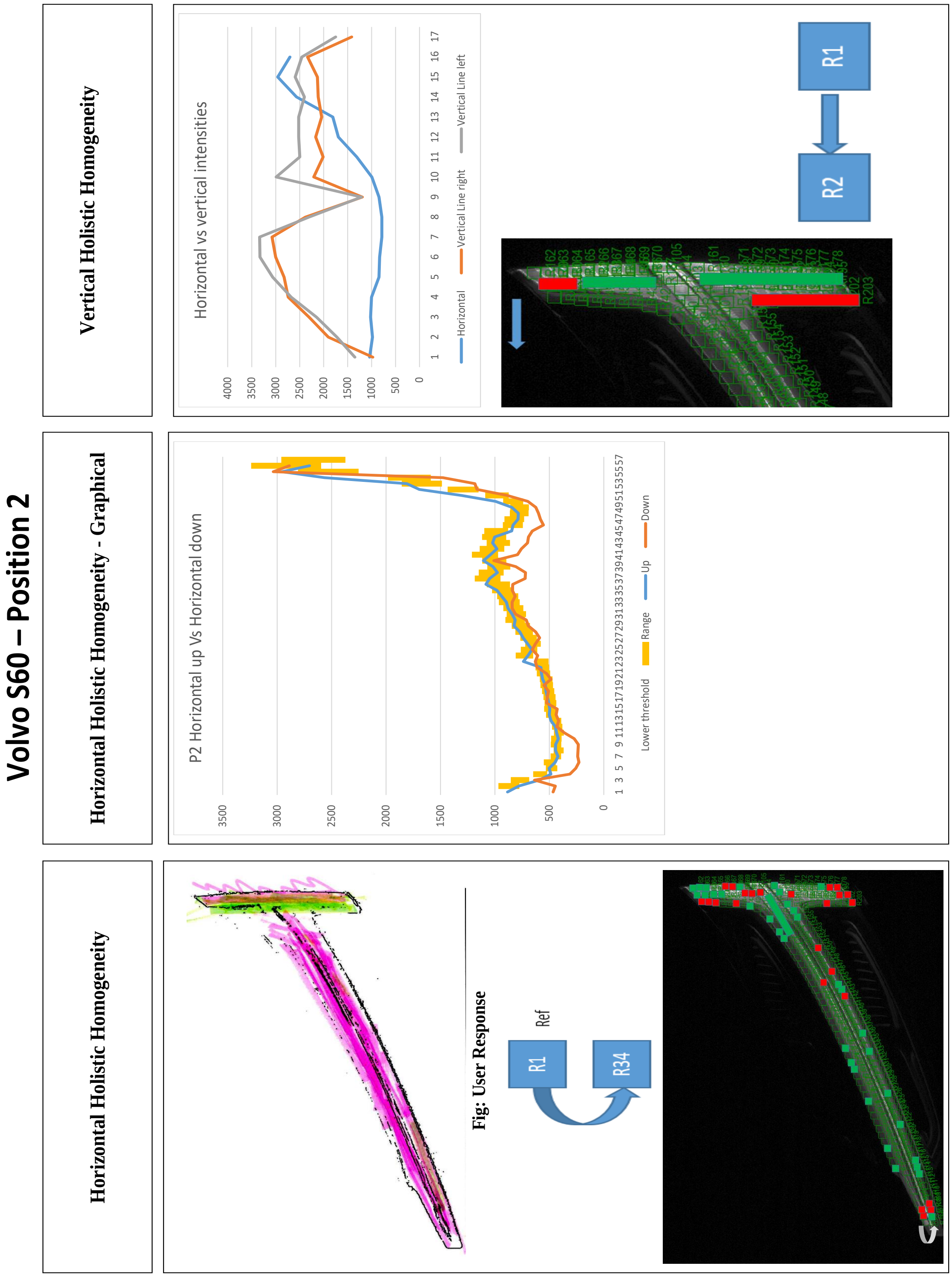
A

Analysis of Volvo S60

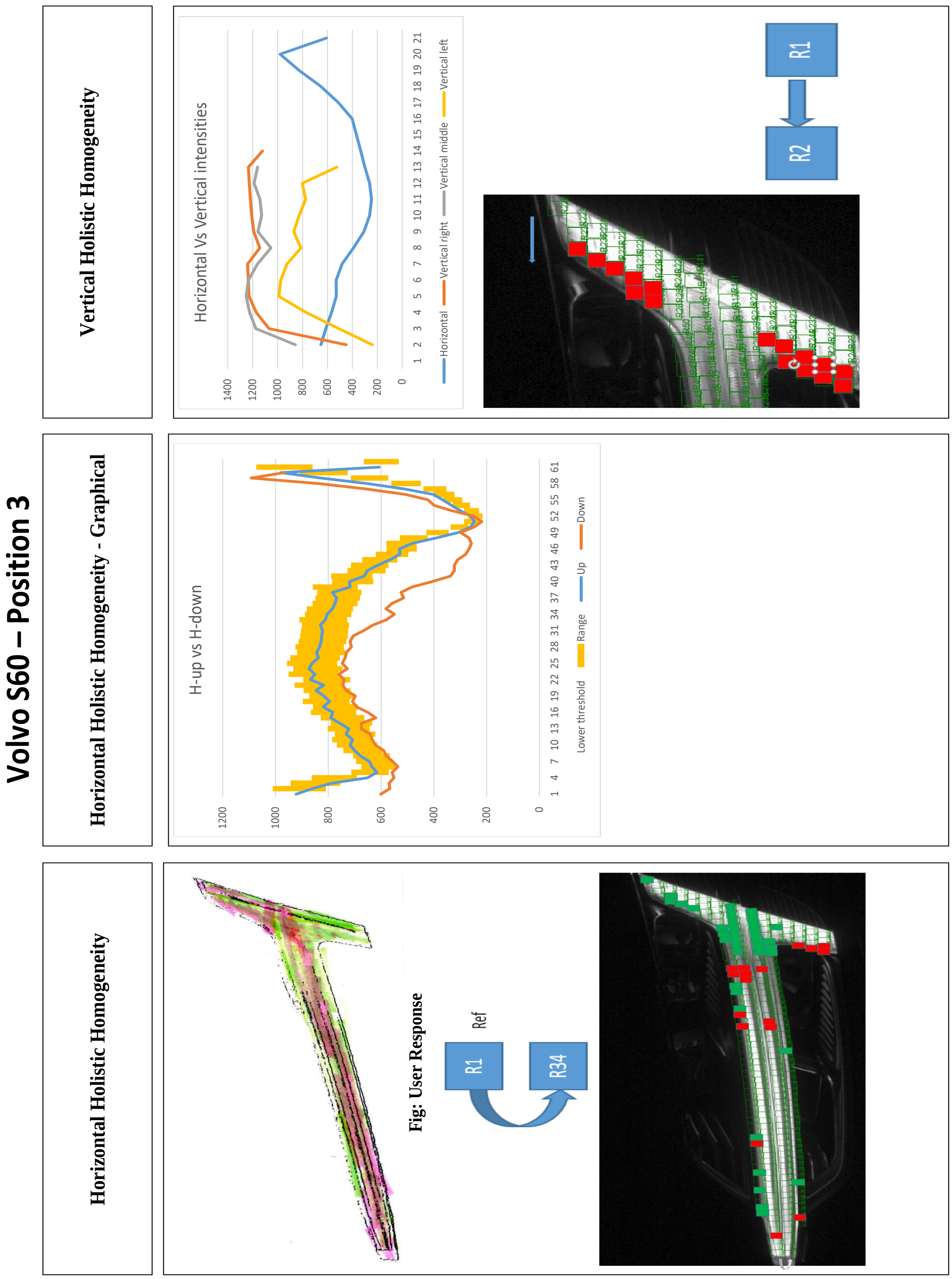
A.1 Position 1 - Seating (H0V0)



A.2 Position 2 - Standing (H0Veyelevel)



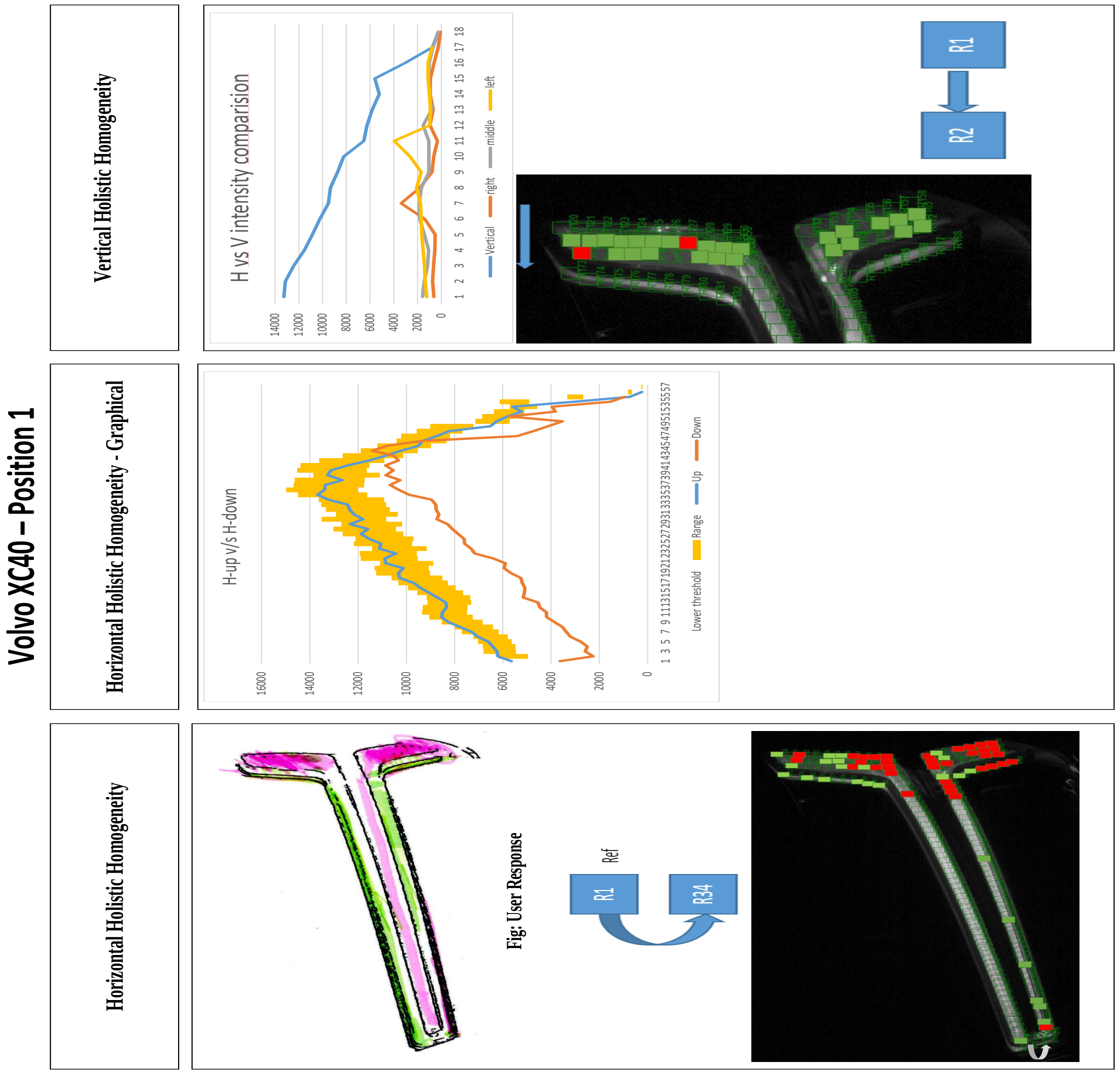
A.3 Position 3 - Standing (H22.5Veyelevel)



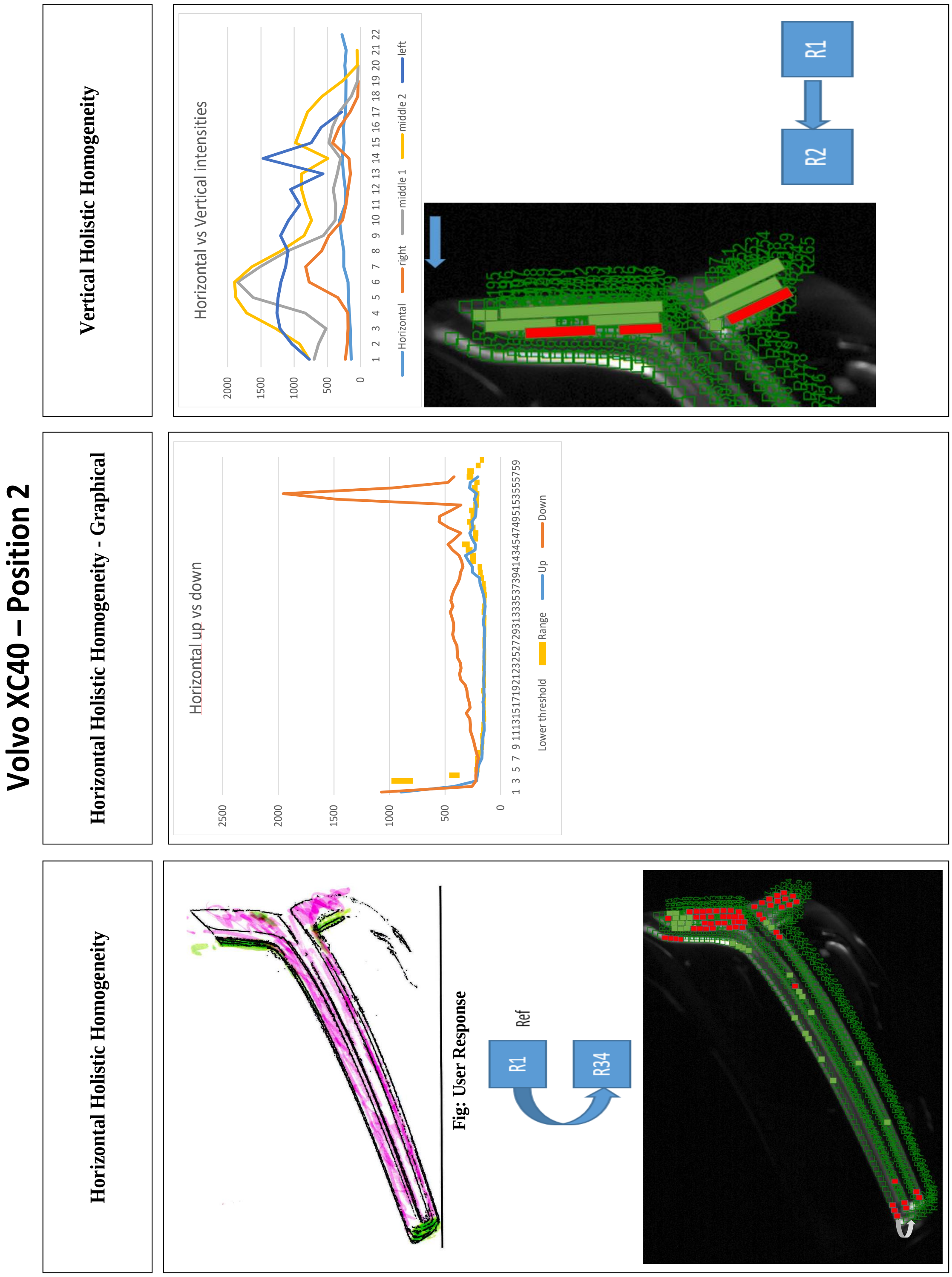
B

Analysis of Volvo XC40

B.1 Position 1 - Seating (H0V0)



B.2 Position 2 - Standing (H0Veyelevel)



C

JND Calculations

C.1 user response

		Participant 1 €		Participant 2 €		Participant 3		Participant 4		Participant 5 €		Participant 6 €		Participant 7 €		Participant 8 €		Participant 9 €		Participant 10	
Lower	Upper	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2
80%	L	623	426	614	600	620	730	660	500	600	555	570	380	600	520	600	300	600	580	580	450
40%	H	320	300	350	310	300	350	310	380	300	350	340	400	320	360	340	350	340	280	320	380
60%	H	490	480	450	390	400	330	400	340	480	400	480	420	490	500	490	500	490	550	480	450
20%	L	140	120	150	200	110	134	163	220	120	124	140	100	134	145	130	95	137	220	140	120
100%	L	720	550	712	580	713	690	714	680	700	713	700	550	710	670	714	480	710	520	720	630
20%	H	100	80	158	140	209	250	144	133	110	150	144	130	145	130	160	90	139	90	136	160
60%	L	500	340	480	390	430	300	484	410	450	380	450	470	460	380	470	380	480	490	460	430
80%	H	600	450	602	623	540	600	549	558	590	500	580	490	580	490	600	690	580	540	580	530
40%	L	360	230	340	300	380	300	334	411	350	300	330	340	340	280	320	250	340	320	331	300

		Participant 11 €		Participant 12		Participant 13		Participant 14		Participant 15 €		Participant 16 €		Participant 17 €		Participant 18 €		Participant 19		Participant 20	
Lower	Upper	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2	X1	X2
80%	L	590	450	590	490	570	450	572	400	640	700	637	440	630	463	640	300	600	470	620	500
40%	H	320	320	320	330	300	220	300	450	350	370	350	490	340	351	341	400	320	300	340	590
60%	H	460	350	472	460	475	428	470	445	500	490	511	350	460	400	465	665	480	370	500	550
20%	L	130	120	123	158	145	138	139	180	120	93	183	204	140	125	140	126	142	185	123	142
100%	L	712	600	710	720	717	550	705	620	754	756	762	510	735	593	762	480	740	700	758	459
20%	H	130	100	155	250	151	183	144	250	126	200	130	182	117	165	138	220	140	128	158	248
60%	L	453	450	453	460	459	435	457	475	496	570	500	350	451	340	470	378	460	500	475	400
80%	H	580	520	590	530	597	440	600	550	640	750	644	820	570	563	600	547	615	690	617	731
40%	L	325	290	325	381	300	310	300	321	324	376	329	265	308	304	327	290	300	338	334	280

C.2 Organized user response

Reference intensity	User response	Log of user response
140	120	4.787491743
140	80	4.382026635
140	200	5.298317367
140	140	4.941642423
140	124	4.820281566
140	150	5.010635294
140	100	4.605170186
140	130	4.86753445
140	145	4.976733742
140	130	4.86753445
140	95	4.553876892
140	90	4.49980967
140	220	5.393627546
140	90	4.49980967
140	120	4.787491743
140	100	4.605170186
140	93	4.532599493
140	200	5.298317367
140	204	5.318119994
140	182	5.204006687
140	125	4.828313737
140	165	5.105945474
140	126	4.836281907
140	220	5.393627546
330	300	5.703782475
330	230	5.438079309
330	310	5.736572297
330	300	5.703782475
330	350	5.857933154
330	300	5.703782475
330	400	5.991464547
330	340	5.828945618
330	360	5.886104031
330	280	5.634789603
330	350	5.857933154
330	250	5.521460918
330	280	5.634789603
330	320	5.768320996
330	320	5.768320996
330	290	5.669880923
330	370	5.913503006
330	376	5.929589143
330	490	6.194405391
330	265	5.579729826
330	351	5.860786223

330	304	5.717027701
330	400	5.991464547
330	290	5.669880923
470	480	6.173786104
470	340	5.828945618
470	390	5.966146739
470	390	5.966146739
470	400	5.991464547
470	380	5.940171253
470	420	6.040254711
470	470	6.152732695
470	500	6.214608098
470	380	5.940171253
470	500	6.214608098
470	380	5.940171253
470	550	6.309918278
470	490	6.194405391
470	350	5.857933154
470	450	6.109247583
470	490	6.194405391
470	570	6.345636361
470	350	5.857933154
470	350	5.857933154
470	400	5.991464547
470	340	5.828945618
470	665	6.499787041
470	378	5.934894196
600	426	6.054439346
600	450	6.109247583
600	600	6.396929655
600	623	6.434546519
600	555	6.318968114
600	500	6.214608098
600	380	5.940171253
600	490	6.194405391
600	520	6.253828812
600	490	6.194405391
600	300	5.703782475
600	690	6.536691598
600	580	6.363028104
600	540	6.29156914
600	450	6.109247583
600	520	6.253828812
600	700	6.551080335
600	750	6.620073207
600	440	6.086774727
600	820	6.70930434

600	463	6.137727054
600	563	6.333279628
600	300	5.703782475
600	547	6.304448802
723	550	6.309918278
723	580	6.363028104
723	713	6.56948142
723	550	6.309918278
723	670	6.507277712
723	480	6.173786104
723	520	6.253828812
723	600	6.396929655
723	756	6.628041376
723	510	6.234410726
723	593	6.385194399
723	480	6.173786104

C.3 Segregated based on intensity level

C.3.1 20 percent

Reference intensity 140cd/sq.m

20% Negative		20% Positive	
Lower Intensity cd/sq.m	Log of intensity	Higher Intensity cd/sq.m	Log of intensity
80	4.382026635	165	5.105945474
90	4.49980967	182	5.204006687
90	4.49980967	200	5.298317367
93	4.532599493	200	5.298317367
95	4.553876892	204	5.318119994
100	4.605170186	220	5.393627546
100	4.605170186	220	5.393627546
120	4.787491743	145	4.976733742
120	4.787491743	150	5.010635294
124	4.820281566	142	4.955827058
125	4.828313737	158	5.062595033
126	4.836281907	160	5.075173815
130	4.86753445	180	5.192956851
130	4.86753445	183	5.209486153
140	4.941642423	185	5.220355825
120	4.787491743	220	5.393627546
128	4.852030264	248	5.513428746
133	4.890349128	250	5.521460918
134	4.8978398	250	5.521460918
138	4.927253685	250	5.521460918
Averaged value	4.782	Averaged value	5.222

C.3.2 40 percent

Reference intensity 330 cd/sq.m

40% Negative

Lower Intensity cd/sq.m	Log of intensity
230	5.438079309
250	5.521460918
265	5.579729826
280	5.634789603
280	5.634789603
290	5.669880923
290	5.669880923
300	5.703782475
300	5.703782475
300	5.703782475
304	5.717027701
310	5.736572297
320	5.768320996
320	5.768320996
220	5.393627546
280	5.634789603
300	5.703782475
300	5.703782475
300	5.703782475
310	5.736572297
321	5.771441123
330	5.799092654
338	5.823045895
Averaged value	5.675

40% Positive

Higher Intensity cd/sq.m	Log of intensity
340	5.828945618
350	5.857933154
350	5.857933154
351	5.860786223
360	5.886104031
370	5.913503006
376	5.929589143
400	5.991464547
400	5.991464547
490	6.194405391
350	5.857933154
380	5.940171253
380	5.940171253
381	5.942799375
411	6.018593214
450	6.109247583
590	6.380122537
Averaged value	5.931

C.3.3 60 percent

Reference intensity 470 cd/sq.m

60% Negative

Lower Intensity cd/sq.m	Log of intensity
340	5.828945618
340	5.828945618
350	5.857933154
350	5.857933154
350	5.857933154
378	5.934894196
380	5.940171253
380	5.940171253
380	5.940171253
390	5.966146739
390	5.966146739
400	5.991464547
400	5.991464547
420	6.040254711
450	6.109247583
300	5.703782475
330	5.799092654
340	5.828945618
370	5.913503006
400	5.991464547
410	6.01615716
428	6.059123196
430	6.063785209
435	6.075346031
445	6.098074282
450	6.109247583
460	6.131226489
460	6.131226489
Averaged value	5.964

60% Positive

Higher Intensity cd/sq.m	Log of intensity
470	6.152732695
480	6.173786104
490	6.194405391
490	6.194405391
500	6.214608098
500	6.214608098
550	6.309918278
570	6.345636361
665	6.499787041
475	6.163314804
500	6.214608098
550	6.309918278
Averaged value	6.255

C.3.4 80 percent

Reference intensity	600 cd/sq.m

80% Negative

Lower Intensity cd/sq.m	Log of intensity
300	5.703782475
300	5.703782475
380	5.940171253
426	6.054439346
440	6.086774727
450	6.109247583
450	6.109247583
463	6.137727054
490	6.194405391
490	6.194405391
500	6.214608098
520	6.253828812
520	6.253828812
540	6.29156914
547	6.304448802
555	6.318968114
563	6.333279628
580	6.363028104
600	6.396929655
400	5.991464547
440	6.086774727
450	6.109247583
450	6.109247583
470	6.152732695
490	6.194405391
500	6.214608098
500	6.214608098
530	6.272877007
530	6.272877007
550	6.309918278
558	6.324358962
600	6.396929655
Averaged value	6.179

80% Positive

Higher Intensity cd/sq.m	Log of intensity
623	6.434546519
690	6.536691598
700	6.551080335
750	6.620073207
820	6.70930434
690	6.536691598
730	6.593044534
731	6.59441346
Averaged value	6.572

C.4 Final Calculations

C.4.1 Lower Threshold

Equation of logarithmic curve: $Y = 0.8249\ln(X) + 0.9576$

Sl. No.	Lower response values in Log Y	Solving for X X	Intensity of reference strip (cd/sq.m) E = Exponent of X	Reference intensity cd/sq.m R	D = R - E	Log R-Log(R-D)
20%	4.782	4.636198327	108.3090258	125.1768127	16.86778693	0.144738748
40%	5.675	5.718753788	319.7514427	353.9214654	34.17002268	0.101531087
60%	5.9645	6.069705419	454.1809028	543.4046669	89.22376414	0.179358702
80%	6.1795	6.330343072	589.4166011	729.8208749	140.4042738	0.213665891
					Delta RI	0.16297902
					Adding 20% error	0.130383216

C.4.2 Upper Threshold

Sl. No.	Higher response values in Log Y	Solving for X X	Intensity of reference strip (cd/sq.m) E = Exponent of X	Reference intensity cd/sq.m R	D = E - R	Log(R+D)-Log R
20%	5.222	5.169596315	167.0516457	125.1768127	41.87483298	0.28575781
40%	5.931	6.029094436	394.5718059	353.9214654	40.65034052	0.108726102
60%	6.2555	6.422475452	584.7486853	543.4046669	41.34401838	0.073327872
80%	6.5703	6.804097466	856.4570512	729.8208749	126.6361763	0.160005045
					Delta Rh	0.114019673
					Removing 20% error	0.091215738

D

Defined Grading scale

Criteria	Grading Scale
Fit to size	5 - Perfectly covers the entire region in a single box (neither upper nor lower portion of the horizontal) 4 - Near to perfection 3 - Slightly exceed or fall behind 2 - Either very larger or too small 1 - Not ok to be accepted
Human error	5 - Negligible error 4 - Low error 3 - Medium error 2 - High error 1 - Very high error
Degree of closeness	5 - Completely matches the subjective results 4 - Good match between obtained results and the subjective results 3 - Fair level of closeness 2 - Poor closeness 1 - Do not match the subjective reults
Threshold magnitude	5 - 0 cd 4 - 10 cd 3 - 20 cd 2 - 30 cd 1 - 40 cd
Holistic comparision	5 - Completely compariable 4 - Good comparision 3 - Fairly compariable 2 - Barely compariable 1 - Poorly compariable
Time to generate	5 - 5 mins 4 - 10 mins 3 - 15 mins 2 - 20 mins 1 - 25 mins or more

E

Calculation

E.1 Finding the Rate of Response

For Lower response value at 20% of reference intensity :-

Averaged lower response at 20% intensity = 4.782 = Y

Equation of Logarithmic curve :-

$$Y = 0.8249 \ln(x) + 0.9576$$

solving for x in the above equation :-

$$\ln(x) = \frac{Y - 0.9576}{0.8249}$$

Replacing 'Y' by the 20% intensity value :-

$$\ln(x) = \frac{4.782 - 0.9576}{0.8249}$$

$$\ln(x) = 4.636$$

$$x = e^{4.636}$$

$$x = 108.309 \ cd/m^2$$

Reference intensity for the considered 20% response = 125.17 cd/m²

Using equation of lower threshold of Weber-Fechner's equation :-

$$\Delta R_L = \log(I) - \log(I - \Delta I)$$

where :- $I = 125.17 \ cd/m^2$

$$I - \Delta I = 125.17 - 108.309$$

$$= 16.86$$

$$\Delta R_L = \log(125.17) - \log(16.86)$$

$$\Delta R_L = 0.1447$$

Similarly on averaging with intensities of 40%, 60% and 80%

$\Delta R_L = 0.16$, with 20% error :- $\boxed{\Delta R_L = 0.13}$

E.2 Finding Intensity based on Response Range

Calculation to find intensity based on response range :-
(Incorporated into macro)

We know $\Delta R_L = 0.13$

Weber-Fechner's equation for Lower threshold calculation:-

$$\Delta R_L = \log(I) - \log(I - \Delta I) \quad — ①.$$

Assuming 1000 cd/m² as the intensity to which the threshold range of intensities has to be determined.

For solving in equation ① :-

$$I = 1000 \text{ cd/m}^2$$

$$\log I = 6.907$$

Rearranging eq ① :-

$$\Delta I = I - e^{(\log(I) - \Delta R)}$$

$$\Delta I = 1000 - e^{(\log 1000 - 0.13)}$$

$$\Delta I = 139.26 \text{ cd/m}^2$$

∴ Magnitude of lower intensity threshold :-

$$I - \Delta I = 1000 - 139.26$$

$$= \underline{860.73 \text{ cd/m}^2}$$

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