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QUANTITATIVE ASSESSMENT OF VISIBILITY OF MODIFIED LOCOMOTIVE LIGHTING

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EXECUTIVE SUMMARY

The Office of the National Rail Safety Regulator (ONRSR) has engaged the Monash Institute of Railway Technology (Monash IRT) to conduct a quantitative assessment of the visual conspicuity of freight trains. This project addresses one critical component of road/rail safety at passive level crossings through improving the visibility of locomotives. Freight locomotives can be visually less conspicuous due to limited onboard lighting and external factors such as the surrounding environment. The visual conspicuity of a freight locomotive depends not only on its brightness or shininess (quantified by its luminance value), but also on the average luminance of the surrounding background and viewing circumstances (observation distance and angle). The intensity and colour of light emitted from the locomotive including the effects of livery, cleanliness, viewing settings, etc influence the luminance of the locomotive. The visibility is also dependent on the natural light characteristics, weather condition, sun direction and ambient condition.

Previous trials have assessed the efficacies of solutions such as converting headlights from SEALED beam to LED and installing flashing beacons on the frontal brow of the locomotive when traversing level crossings. This study is an extension of the work completed in WA, and builds upon the findings and the methodology developed by Monash IRT. The base case in the current assessment is a locomotive with SEALED beam headlight and with no beacon lights or side marker lights.

The focus of the current study is to assess the effects of additional lighting on locomotive visibility, particularly examining flashing LED beacon lights mounted on the brow and side marker lights mounted along both side sills of the locomotive. However, the study did not consider any health implications or safety improvements due to the additional lighting.

This investigation, conducted through a field experimental program for various predefined scenarios at a railway yard, independently assessed the trials based on scientific principles. Test plans were developed through design of experiments methodology, ensuring comprehensive data collection across various scenarios. Over 500 luminance measurements were gathered, considering scenarios like vegetation obscurity, simulated weather, and different daylight and night-time conditions. All measurements were conducted while the locomotive was stationary. The trial testing of the lighting systems was conducted at sites near Pacific National (PN) Trip Shed at Port Waratah and Progress Rail Port Kooragang in Newcastle, New South Wales (NSW).

In this assessment, the locomotive with its additional light fittings on the front and side is the target while the region near and around a locomotive is considered as the background. The Opticam luminance camera provided validated and calibrated data for assessing the effects of additional lighting on locomotive conspicuity. The relative luminance (i.e., the luminance contrast) between the locomotive and its surrounding background is used as a quantifiable visibility index.

The luminance contrast levels measured for daytime and night time differed significantly for the same locomotive and lighting fixtures, indicating that locomotives would be more visible at night. This may partially explain the large difference in the number of recorded level crossing collisions during the day in comparison to night. Hence, the industry efforts should focus on alternative ways to increase the luminance contrast during day time, or explore alternative strategies for safety improvements in conjunction with additional enhancements to the level crossing interface with road authorities and rail infrastructure managers.

> *Key findings indicate that in clear daylight conditions or dense vegetation, the addition of beacon lights and side marker lights has little or no enhancement in locomotive conspicuity. Conversely, during night time assessments, significant enhancements are observed on the overall locomotive conspicuity, especially with side marker lights.*

Visibility improvement in clear daylight is highly interrelated to a combination of headlight state, viewing circumstances, and sunlight direction. The headlight, particularly in high beam during the day, significantly improves frontal locomotive conspicuity, especially at longer distances. The visibility improvement reduces when the locomotive is viewed at an angle.

Viewing circumstances, such as observation angle and distance, can be associated with level crossing design, crossing angle and minimum distance for road vehicles to stop before arriving at the level crossing. The arrangement of passive level crossings means that locomotive conspicuity viewed from angles up to 90° is one of the most important aspects to visibility to enable drivers to make safe judgements.

> *The suggested recommendations to enhance locomotive conspicuity during daytime operations when observed at an angle and from different distances include having the headlight on high beam at level crossings with sharp angles and exploring the feasibility of a headlight that radiates the light beam over a wider angle.*

In simulated misty conditions, both the beacon light and the side marker light had an impact on locomotive visibility. The colour of the side marker light has shown a significant effect in simulated misty conditions. Further trials are recommended for side marker lights, exploring higher luminous intensity and alternative fitting angles to understand its impact on locomotive visibility. The health effects of the additional lighting and light pollution effects were not considered in the current study. Health and safety implications of the additional lighting, including higher luminance or flashing lights, should be assessed, benchmarking against international regulations to understand the effects of light pollution on locomotive drivers, road vehicle users and those remaining or living adjacent to the track.

The study proposes investigating the use of Daytime Running Lights independently or in conjunction with side marker lights. Adaptive lighting systems and light lens protective covers that dynamically adjust to environmental conditions are suggested for assessment.

Reflective materials on the locomotive's front and sides can be used as a means to enhance locomotive’s conspicuity. Vegetation clearance at level crossings, along with trackside sirens or horns and mandatory locomotive horn requirements, should be considered for locations with visual obstructions. The study further suggests assessing the feasibility of integrating laser-initiated light technology, as part of a broader level crossing study, for improved detectability in visually obscured situations.

One of the limitations of the current Australian Standard for Rolling stock lighting and visibility (AS 7531) is that it does not specify acceptable luminance contrast levels for locomotives visual conspicuity. A future review of AS 7531 should include a list of reference background luminance values, taking into account diverse scenarios such as variation in weather and environment. The AS standard should additionally specify a reference or threshold visibility value, indicating when the locomotive is considered visible at wide view angles up to 90˚. This requirement can be used by the industry in the choice of lighting, lighting colour and locomotive livery.

While daylight improvements appear limited using the trialled additional lighting solutions, significant visibility enhancements are achievable at night and in misty conditions from the measured base case.

In conclusion, the findings stress the need for an alternative approach for safety improvements at regional level crossings. This could include factors beyond locomotive visual conspicuity improvement through auxiliary lighting, such as signage conspicuity and conspicuity of the level crossing infrastructure through way side lighting on the approach to level crossings. Furthermore, developing dedicated sections on the National Level Crossing Portal or relevant local government websites, providing comprehensive information about level crossings including details on orientation, types of crossings, safety guidelines, and any ongoing enhancements or modifications, can be considered to improve public awareness and safety at level crossings. A similar approach is employed in the USA to furnish relevant information to citizens, industry, data users, and policymakers. These recommendations aim to create an alternative strategy to enhance freight train visibility as well as enhancing the visibility of the level crossing itself, enabling greater potential safety for level crossing users at regional level crossings.

DISCLOSURE NOTICE

(Please read before reading report)

PURPOSE:

This report presents the findings and quantitative assessment results pertaining to trials of visibility of a locomotive modified with additional lighting.

AUDIENCE:

The work described in this report was carried out for Office of the National Rail Safety Regulator (ONRSR).

ASSUMPTIONS/QUALIFICATIONS:

The findings, assessments, discussion and recommendations made in this report are based on an analysis/assessment of information obtained from on-site measurement, public domain and provided by ONRSR.

FURTHER INFORMATION:

Further information can be obtained from Professor Ravi Ravitharan at Monash Institute of Railway Technology.

EXTERNAL SOURCE MATERIALS:

Monash Institute of Railway Technology (IRT) and/or Monash University do not accept responsibility for the validity or accuracy of any source material, measurements or data used in this study that was not generated by Monash IRT.

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ACRONYMS AND DEFINITIONS

Acronyms

AS	Australian standard
DoE	Design of experiment
FORG	Freight On Rail Group
FRA	Federal Railroad Administration
IRT	Monash Institute of Railway Technology
LC	Level crossing
LED	Light-Emitting Diodes
NSW	New South Wales
ONRSR	Office of the National Rail Safety Regulator
PN	Pacific National
PN9035	PN locomotive 90 Class number 35, typically described as 9035 Class
RISSB	Railway Industry Safety and Standards Board
ROI	Region of Interest
VI	Visibility index
WA	Western Australia

Glossary

Beacon lights	Lights mounted on the brow of a locomotive displaying flashes of light (white or coloured) to warn road users and other motorists
Conspicuity	The attribute that ensures an object attracts attention in its surroundings
Ditch lights (Visibility lights)	Also known as visibility lights, auxiliary lights or crossing lights used to make trains easier to spot, for safety
Front marker lights	Lights mounted on the front of a locomotive to indicate the front of a train or the direction of the train movement
Headlights	A powerful light mounted at the front of a locomotive or cab that are positioned at the top of the cab to illuminate the railway track ahead
Illuminance	The amount of light falling on a surface from a light source and is typically expressed in lux measurements

Interaction effect	The amount a response is influenced by the level of two or more factors
Light pollution	The negative effects of any unwanted, inappropriate, or excessive artificial lighting on the surrounding people, wildlife and vegetation
Livery	The exterior colour scheme and markings of the locomotive
Luminance	The intensity of light emitting from a source or surface per unit area in a given direction and measured in candela per meter square (cd/m^2)
Luminance Contrast	The relative luminance level of an object to that of a background surrounding the object
Main effect	The amount a response is influenced by the level of a single factor
Passive LC	An unprotected level crossing with no warning system
Side marker lights	Lights mounted on the side sill of a locomotive to improve side visibility or detection of locomotives
Viewing angle	The angle the camera (observer) view towards the front of the locomotive cab end
Viewing distance	The distance between the camera (observer) and the locomotive
Viewing circumstance	Refers to the observation distance and angle between the observer and the locomotive
Visibility	The ability of an object to be seen and is often tied to properties of the object itself such as size, colour, contrast and brightness
Visibility index	A physical measure for visibility performance (rather than absolute visibility) of locomotive and its light fittings

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

As part of the consolidated Freight on Rail Group (FORG)/ Office of the National Rail Safety Regulator (ONRSR) train visibility working group, Pacific National (PN) has initiated a locomotive visibility improvement trial, installing both LED beacon lights on the front and side marker lights onto locomotive PN9035 for the trial phase. The locomotive image is shown in Figure 1. The ONRSR has engaged the Monash Institute of Railway Technology (IRT) to conduct a quantitative assessment of these trials.

FIGURE 1. BEACON LIGHTS ON THE FRONT OF LOCOMOTIVE (TOP), AND SIDE MARKER LIGHTS ALONG BOTH SIDE SILLS OF THE LOCOMOTIVE (BOTTOM)

1.2 PURPOSE

The objective of this project is to assess the change in freight train visual conspicuity resulting from luminance scheme alterations, including:

- Installation of LED beacon lights on the front as per Aurizon CBH trial [1]; and
- Installation of side marker lights.

Based on light measurements considering a number of scenarios including the base case, the project aims to determine the effects of the additional lighting modifications on locomotive's overall conspicuity during daylight and night time, especially when varying observation angles up to 90˚. The effects of the colour of the side marker lights are assessed considering different ambient lighting conditions. Additionally, the effects of the added lighting concerning different surrounding backgrounds are evaluated. Key recommendations are provided based on the findings of the assessment. Additional recommendations for further consideration to improve the locomotive conspicuity, not considered in the current trial, are also given.

1.3 LIMITATIONS OF THE STUDY

The assessment is limited only to the two lighting modifications and their efficacy on visual conspicuity of a locomotive during day and night time. The consequences of these additional lightings, including light pollution effects to the surrounding and to the train crew are not considered in the current study. Light pollution refers to the negative effects of any unwanted, inappropriate, or excessive artificial lighting, during the day or night, that disturbs the surrounding residents, wildlife and vegetation growth [2]. Health effects and safety benefit of the additional lighting are beyond the scope of this work. Furthermore, factors such as livery, shape, and form of the locomotive body are not considered in the current locomotive visibility assessment.

1.4 SCOPE OF WORK

The scope of works encompasses three stages:

Stage 1 – Field Experimental Design

- Defining of quantities to be measured;
- Planning of field measurements at proposed site;
- Consideration of variables affecting locomotive visibility; and
- Utilization of Design of Experiment (DoE) methodology for an effective experimental plan.

Stage 2 – Collection of Data

- Predefine observation locations and angles at each test site;
- Collection of reference data from the predefined locations;
- Gathering extensive measurement data at various sites with different viewing circumstances and environmental condition; and
- Measurement conducted under simulated variable weather conditions, e.g., simulated light rain.

Stage 3 – Data Analysis

- Analysis of data gathered from the field trial;
- Defining regions of interest for the visibility analysis;
- Defining reference visibility quantity; and
- Quantify the effects of the variables on the result using the DoE methodology.

1.5 PROJECT EXECUTION STEPS

A project team, comprising ONRSR, Aurizon, PN, Rail Industry Safety and Standards Board (RISSB), and Monash IRT, was formed to discuss the detailed scope of the current project. Meetings were held continuously with the project team to discuss activities throughout the duration of the project. The adopted approach was an extension of the work completed in WA [1] and the scope of works to conduct the trial assessment were built upon the previous findings and proposed to ONRSR and the FORG members during the project inception period and were mutually agreed.

A detailed test plan and test scenarios for the field trial testing of the lighting systems were prepared for sites at PN Trip Shed, Port Waratah and Progress Rail Port Kooragang in Newcastle, New South Wales (NSW). Sample sizes, variable combinations, testing setups, and limitations were discussed and agreed upon. A design of experimental methodology was followed to prepare the experimental planning. PN installed beacon lights and side marker lights onto locomotive PN9035 for the trials. The locomotive used at the trial is a PN 90 Class locomotive with sequential number 35. Trial tests were conducted, and data were collected using different apparatus. Measurements were conducted both in day and night times. Members of the project team (ONRSR, PN, and Monash IRT) were involved in the field experimental design and data collection conducted in Newcastle, NSW.

2 METHODOLOGY

A measurement-based assessment was used to evaluate the visibility of locomotives with additional lights. The base case in the current assessment was a locomotive with SEALED beam headlight and with no beacon lights or side marker lights. This method aims to capture the relative conspicuity or improvement in visual conspicuity using a quantitative standard unit, providing a universal quantitative expression. This approach was employed in a trial conducted in Aurizon in Western Australia (WA) in 2022 [1].

Traditionally, and in numerous previous conspicuity assessments, locomotives were positioned against various backgrounds, at different viewing distances and angles. Observers (participants) were then asked to identify the locomotive under various ambient light conditions. However, this approach necessitates multiple arrangements of the locomotive, involves a large and diverse group of observers, and is often time-consuming, costly, and complex. Moreover, visual perception by observers may vary across different situations, rendering assessments using human visual observation less representative and potentially inconsistent. The reliability of such assessments is further compromised by factors such as prior knowledge of the scene, observer familiarity with the environment, and individual differences among observers, including attentiveness, age, experience, awareness of the subject matter, and intellectual level.

In contrast, measurement-based assessment provides a universal and effective approach to quantify the visual conspicuity of locomotives under various lighting arrangements and in any natural scene, without the need for extensive prior knowledge of the environment. This was demonstrated in a trial conducted by Monash IRT in Western Australia (WA) in 2022, where measurements could be easily and quickly performed in the field or complex environments without mobilizing a large number of observers [1]. Based on the results from the Aurizon WA assessment, it is understood that three main attributes, namely viewing circumstances, object-related factors, and environment, are interrelated in terms of their effect on locomotive conspicuity. Further discussions and details about the methodology employed in the current trial, along with information about the measurement apparatus and approach, can be found in the preceding report [1].

2.1 VARIABLES AFFECTING LOCOMOTIVE VISIBILITY

In the earlier study, several variables were examined to evaluate their effects on locomotive visibility [1]. The study focused on the effects of the locomotive's front lighting, including headlights and their types, beacon lights, and ditch lights (visibility lights). Consideration was given to potential variables influencing luminance measurements. However, there were noticeable limitations in terms of the measured parameters and assessed effects due to ambient conditions such as sun direction and overall light conditions. The earlier assessment solely considered the frontal visibility, without considering the locomotive's overall wide-angle visibility.

In the current trials, the investigation included the effects of side marker lights' intensity and colour, as well as beacon lights. Additionally, the effect of front marker lights' intensity and colour was assessed. Figure 2 and Figure 3 show the lighting configurations fitted in the trial locomotive PN9035. All lighting fixtures fitted to the front view of the locomotive are shown in Figure 2 while images of the side marker lights are shown in Figure 3. Table 1 lists all relevant variables, including the modified lighting, affecting the visibility of both the front and side views of a locomotive. The variables are categorised under the three main aspects, i.e., viewing conditions, object-related factors, and environment considerations.

TABLE 1. LIST OF POSSIBLE VARIABLES (FACTORS) INCLUDED IN THE FIELD TRIALS

Variables	Categories
Viewing distance (position)	Viewing conditions
Level crossing design (viewing angle)	
Head light state	Object related
Beacon light	
Ditch (visibility) light	
Side marker light	
Front marker light	
Ambient light condition	Environment
Vegetation coverage	
Sun direction	
Weather condition	

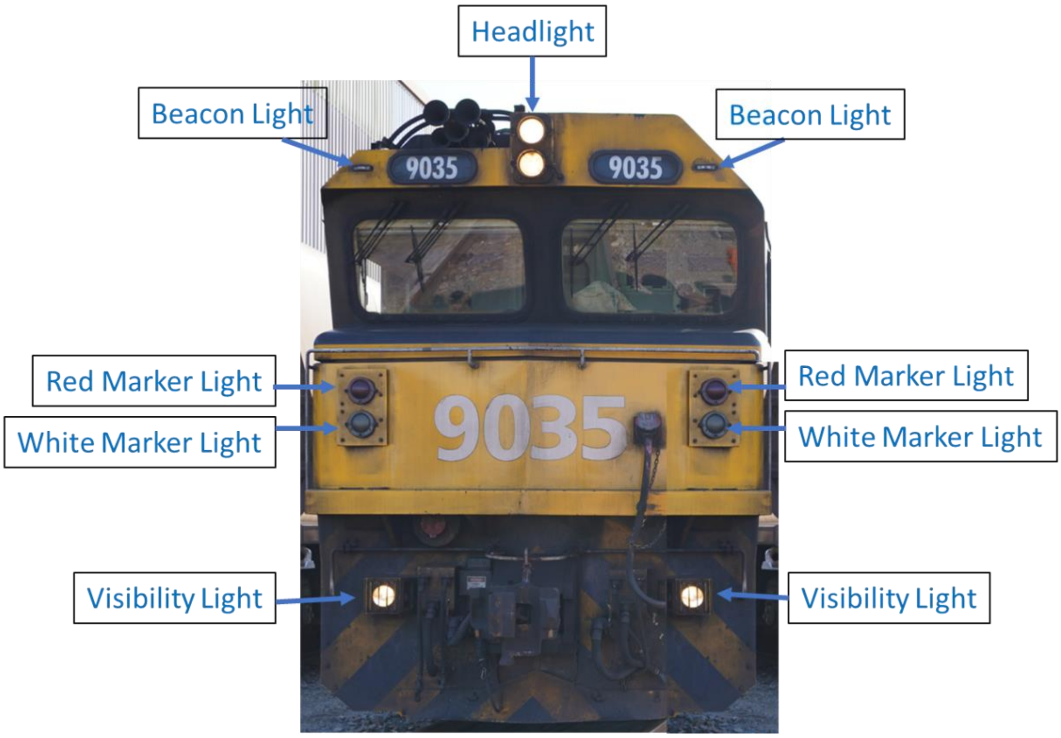

FIGURE 2. FRONT OF THE MODIFIED LOCOMOTIVE PN9035

FIGURE 3. AMBER SIDE MARKER LIGHTS (TOP) AND WHITE SIDE MARKER LIGHTS (BOTTOM) ALONG THE SIDE SILLS OF THE LOCOMOTIVE

Based on the earlier assessment in Aurizon WA [1], the variables categorised under viewing circumstances, object-related factors, and environmental conditions have interrelated effects and influence on the visibility of the locomotive. In order to understand the effects of modified locomotive lighting on its visibility, it is crucial to determine whether there are interrelated or combined effects involving one or more variables that may significantly affect the locomotive's visibility. This analysis will offer physical explanations for the effects of these variables, providing valuable information for decision-making in the design of lighting improvements to enhance locomotive visibility.

2.1.1 VIEWING CIRCUMSTANCES

Viewing circumstances encompass a range of factors that influence how an individual perceives a locomotive within its surroundings. These factors include angle and distance of observation, as illustrated in Figure 4. These variables can be related to level crossing design, crossing angle and minimum distance for road vehicles to stop before arriving at the level crossing. Note that the minimum stopping distance for road vehicle depends on the speed of the road vehicle. Assessing visibility from various angles from 0˚ (frontal visibility) up to 90˚ (side visibility) under different distances provide insights into how the locomotive visibility changes when viewed from different viewing circumstances, especially in varying environmental conditions. The outcome of the effects of the viewing circumstances can be employed for assessments aimed at improving the design of the level crossing layout.

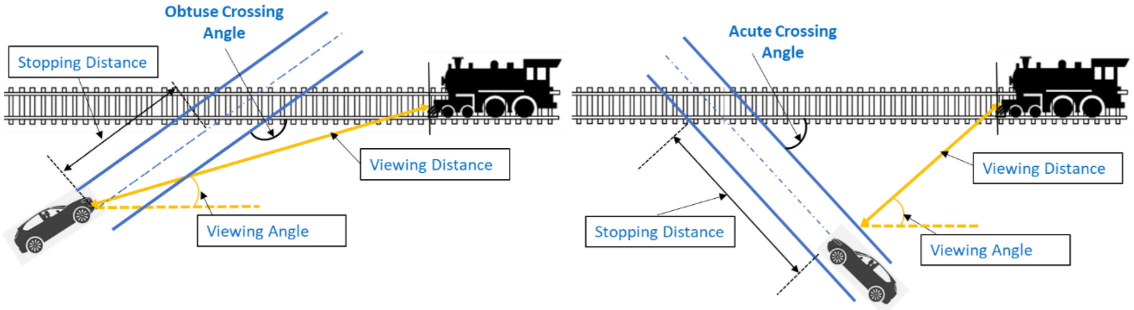

FIGURE 4. ILLUSTRATION OF VIEWING CIRCUMSTANCES FOR TWO DIFFERENT LEVEL CROSSING LAYOUT DESIGNS: (LEFT) OBTUSE ANGLE AND (RIGHT) ACUTE ANGLE

2.1.2 OBJECT-RELATED FACTORS

Locomotive-related attributes play a significant role in its visibility. Factors include lighting arrangement, intensity, lighting colour, and type of lighting, such as beacon lights and visibility lights, etc. which impact the locomotive's visibility during daylight hours and night time. Evaluating the efficacy of additional lighting aids in understanding their contributions to visibility enhancement. Factors such as locomotive livery, livery cleanliness and other non-lighting related factors are discounted here, but are included in later discussions and recommendations.

2.1.3 ENVIRONMENT

Environmental variables, such as weather conditions, affect the visibility of a locomotive. Various weather conditions, including rain, fog, or glare from sunlight, significantly influence locomotive visibility. Further, the complexity and diversity of the background affect the locomotive visibility. Evaluating visibility against different background types, such as clear view and dense vegetation, aids in understanding how a locomotive with a modified lighting fixture stands out in specific settings. In the current trials, locomotive visibility was assessed under simulated weather conditions to obtain an understanding of how these factors impact detection and recognition of the locomotive under the modified lighting.

2.2 DATA COLLECTION AND ANALYSIS METHOD

2.2.1 APPARATUS

Measurements of the object's luminance[1] and the ambient background under various viewing and environmental conditions are considered to understand the effects of the additional lighting. The GL OptiCam 3.0, an imaging luminance camera, was utilised to measure the luminance distribution of a selected region of interest in an image [6]. It provides both the luminance value of the object viewed and the overall luminance of the entire scene. The methodology employing this luminance camera has been previously validated in previous measurements conducted in WA [1].

Survey instruments were employed to set up various positions and measurement angles prior to the luminance measurements. Additionally, a range finder was used to locate the experimental settings and collect distance readings. A light intensity meter (lux meter) was used to measure the illuminance of the ambient condition/ light from the surrounding light sources falling on a locomotive side during the night time measurement.

A detailed discussion of the measurement equipment used in the current trials is available in the preceding report [1].

2.2.2 DESIGN OF EXPERIMENT (DOE) METHODOLOGY

A Design of Experiment (DoE) methodology [3] was applied to systematically collect data from the field trials, encompassing a combination of the identified possible variables. A factorial experiment, with full factorial, is found to be the most economic and statistical based methodology to conduct trial experiments with several identified variables considered. The variables (design factors) for the current experiment are detailed in Table 2. These factors were set to two levels of variations and the effect of these variations in the response was assessed. The response values used in the effect analysis for this assessment are the luminance contrast and the luminance ratio at each experimental run. Luminance contrast and luminance ratio are defined and explained in the next section, Section 2.2.3.

In this analysis, one variable alone may have a significant effect on the response(s), or the effect may become significant when one variable is combined with another. The variables or factors analysed can be either quantitative, as in case of viewing angle (e.g., 22.5˚or 45˚), or qualitative, as seen in the case of colour of side marker lights (e.g., Amber or White). The DoE methodology efficiently studies the influence of two or more independent variables whether quantitative or qualitative, on one or multiple outputs (responses).

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[1] Luminance: is the measure of light emitting from a source and measure in candela per meter square (cd/m²).

The influence of locomotive's beacon lights and side marker lights are studied at two levels of variation. The levels of variation are shown in Table 2. The influence of the change of state of side marker lights cannot be separated from the influence of the ditch lights as both are wired to a similar switch and they change simultaneously. Consequently, the effect of the intensity of the side marker lights may not be captured independently of the ditch lights for some of the measurement trials. To assess the effect of the side marker lights colour and intensity, trial measurements were conducted only viewing the side of the locomotive, at a viewing angle of 90°.

However, the effect of the change in colour of the side marker lights can be captured as an independent variable in most of the experimental trials. The effect of beacon lights was also studied at two levels. Although the beacon light is a flashing light for 60 seconds, the two-levels design of experiment considers beacon light setting, 'ON' or 'OFF' state. As a result of flashing light, the measured luminance may fluctuate depending on the frequency of the flashing light. For 'ON' state, the average measured luminance during the flashing cycles can be taken as the highest level. For this scenario, tests are replicated to examine the variation due to the flashing arrangement and for determination of measurement error. When the state of the light is OFF, that can be considered as the second level 'OFF' state. The effect of the frequency of the variation of the fluctuating luminance is not considered in the current assessment.

Various other factors may affect the response, including viewing circumstances, direction of sun, ambient light condition, weather condition, and vegetation. The effects of these variables, or the interaction effects with the locomotive's lighting can be studied using the current methodology. The amount a response is influenced by the level of a single factor is called the *main effect*. The joint effect of two or more factors which change simultaneously is called an *interaction effect*. A two-level factorial design is used to investigate the joint effect of all possible combinations of the factor levels. Using a DoE methodology, it is possible to evaluate the effects of the factors or interaction effects with fewer number of trials compared to the method of varying one-factor-at-a-time. Based on the possible variables listed in Table 2, experimental design was planned for three different trials, with two levels of variation for each variable. The details of all the variables and their levels are tabulated in Table 2. All other potential variables are considered to be constant. The headlight setting was kept consistent in all trials unless specifically studying the effect of the headlight state. Only a SEALED beam headlight was considered in the current trials. The type of headlight (LED versus SEALED beam) was not a factor considered in the current experimental design. The effect of the type of headlight has been assessed in the earlier trial conducted in WA [1].

2.2.3 DEFINITION OF LUMINANCE CONTRAST/ LUMINANCE RATIO AND VISIBILITY INDEX

A comprehensive study by Blackwell [4] discusses quantitative method for prediction of visibility as a function of luminance. Luminance is the intensity of light from a source or surface per unit area in a given direction and it is given in cd/m^2. In general, luminance refers to the intensity of light entering human eyes. The study by Kim et.al., examined the correlation between measured luminance and distance of measurement from the light source [5]. The study found that the luminance changes with measurement distance.

Table 2. Possible Design Variables (Factors) and Their Variation Levels Used at the Different Trials During Daylight Hour

Term	**Variables to Consider (Factors)**	**Levels**	
		Low (-1)	**High (1)**
X1	Viewing angle (Level crossing angle)	22.5°	45°
X2	Colour of side marker lights	Amber	White
X3	Sun direction	Afternoon	Morning
		Facing	Behind
X4	Beacon light	Off	On
X5	Ditch light/ Side marker lights	Off	On
X6	Weather condition	Clear	Rainy (Mist)
X7	Time of the day (Ambient light condition)	Dawn	Dusk
		Overcast	Daylight
X8	Vegetation coverage	None	Dense
X9*	Viewing distance	105 m	240 m
X10$^+$	Headlight	Low beam	High beam
X11*	Front marker light	Red	White

Note:

X9* viewing distance and X11* front marker light, are considered only in day time frontal visibility.

X10$^+$ headlight is considered as variable only in frontal visibility. Only a SEALED beam headlight was considered. The type of headlight (LED versus SEALED beam) is not a factor considered in the experimental design.

In the current assessment, the *visibility index* is defined as a function of the luminance of a target (object) and the luminance of a background around the target. In this assessment, the locomotive with its light fittings on the front and side is the target while the region near and around a locomotive is considered as the background.

In the previous assessment of locomotive lighting for locomotive's frontal visibility, the front of the locomotive was defined as the object while two background regions were defined, namely immediate background and wider background [1]. The immediate background describes the region around the target within the field of view, ranging from 1.5° to 3.5°. This range depends on the viewing distance between the observer (luminance camera) and the target (front of the locomotive), as illustrated in Figure 5. The wider background covers a field of view ranging from 7° to 10°, depending on the observer's distance from the target.

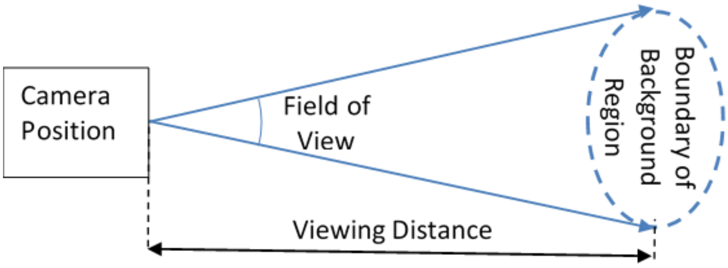


FIGURE 5. ILLUSTRATION OF FIELD OF VIEW AND BOUNDARY OF BACKGROUND REGION

The current assessment is for locomotive’s visibility from a wider view angle. Unlike the earlier assessment, both the front and the side of the locomotive are used to define the locomotive boundary. The background regions are the areas near and around the locomotive body boundary.

Figure 6 shows a description for the boundaries of the object (target) and the immediate and wider background. Here, the PN9035 trial locomotive is oriented at 45° from the direction of the observer.

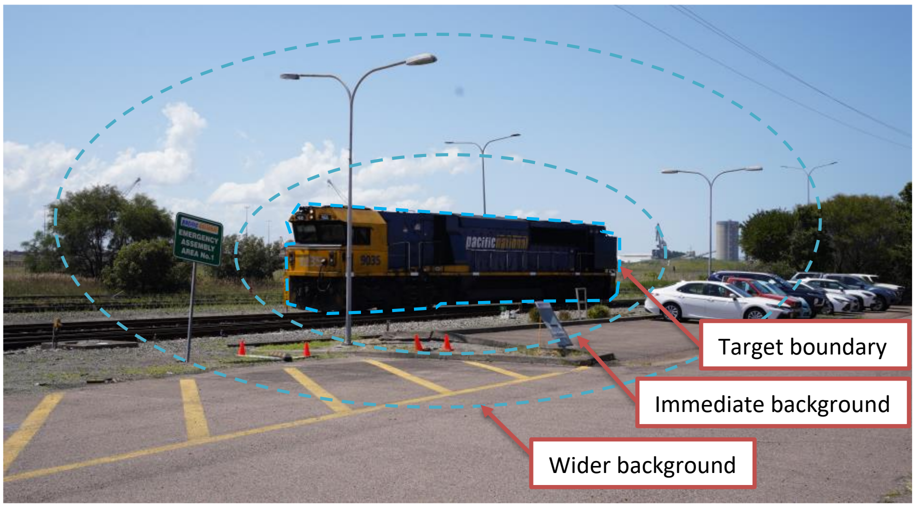


FIGURE 6. ILLUSTRATION OF REGION OF INTEREST FOR LUMINANCE CONTRAST CALCULATION WITH THE BOUNDARY OF THE TARGET, IMMEDIATE BACKGROUND AROUND THE TARGET AND THE WIDER BACKGROUND WITH A LARGER VIEW AREA

The larger the difference in luminance between a locomotive and its background, the easier it is for an individual to detect the locomotive. Factors such as livery, shape and form of the locomotive also contributes to its visibility. However, the current visibility assessment focuses solely on measured luminance as a quantitative value. A more detailed discussion of the models adopted for the locomotive visibility assessment can be found in the preceding report [1].

The measured luminance values are utilized to calculate the luminance contrast and luminance ratio between the locomotive and the background, and used as visibility indicators for assessing the efficacy of the proposed trial implementation. The equations for these calculations are as follows:

$$C = \frac{L_O - L_B}{L_B} \tag{1}$$

$$C_r = \frac{L_O}{L_B} \tag{2}$$

where,

C = luminance contrast between average luminance of target and background;

C_r = luminance ratio between average luminance of target and background;

L_O = average luminance (cd/m^2) of the target; and

L_B = average luminance (cd/m^2) of the background.

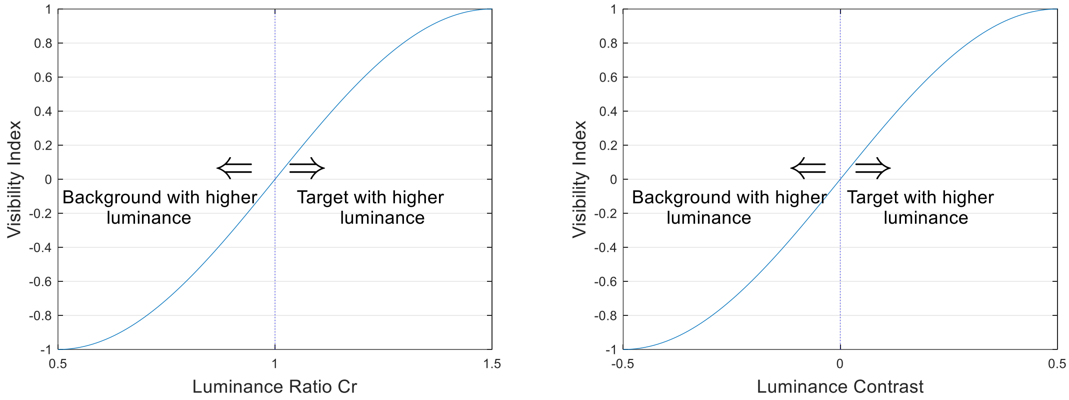


FIGURE 7. RELATIONSHIP BETWEEN LUMINANCE RATIO (LEFT) AND LUMINANCE CONTRAST (RIGHT), AND VISIBILITY INDEX

The relationships between luminance contrast, luminance ratio and visibility index are shown in Figure 7. If the luminance contrast is zero, it signifies no distinction between the luminance values of the target and the background, resulting in zero visibility index (refer to eq.1). This indicates that the background luminance fully masks the object. Similarly, if the luminance ratio between the object and the background is 1, it signifies no distinction between the luminance values of the target and the background and the visibility index is zero (refer to eq.2). When the luminance of the object is 50% higher than the background, the object can easily be distinguishable and the visibility can be considered 100%. The corresponding visibility index is 1 when the luminance contrast is 0.5 or the luminance ratio is 1.5.

According to Blackwell [4], visibility is defined as the ratio between the luminance contrast C and the reference threshold contrast, $\bar{C}_{ref}$, which is a function of reference luminance $L_{o,ref}$, as:

$$V = \frac{C}{\bar{C}_{ref}} \tag{3}$$

where,

V = visibility;

C = luminance contrast; and

$\bar{C}_{ref}$= reference threshold contrast empirically determined as a function of reference luminance $L_{o,ref}$.

The current trial involves defining reference luminance contrast for daytime visibility assessment. Reference measurements were conducted to set a luminance contrast value for zero visibility index above which the locomotive is considered visible. Additionally, a threshold luminance contrast was established for a visibility index value of 0.75 (75% visibility), which signifies that the object is fully conspicuous in day time conditions. This relationship is solely based on luminance values and may not be valid for cases and conditions other than in day time conditions defined for the current testing scenario.

2.3 CONSTRAINTS OF THE CURRENT TRIAL ASSESSMENT

2.3.1 FIELD TRIAL CONSTRAINTS

The field experiment was constrained by the yard environment and the static measurement of the luminance camera system. The current assessment is for visibility in a stationary situation, without taking into consideration the impact of both train and road vehicle speed. All measurements were taken while the locomotive was stationary at a predefined position, thus not considering luminance variation within the target or background areas. Furthermore, the luminance values were taken at a given instant of time and no consideration was made for the transient adaptation.

2.3.2 VISIBILITY MODEL CONSTRAINTS

The visibility index model, which is based on the luminance contrast between the target and the background, does not consider the effects of natural light variation on visibility. The model only considers the average luminance of the target and the background area at a given instant. It is designed to indicate visibility in a stationary situation, where there is no transient change in luminance of the target or background. Additionally, the adopted model indicates relative visibility (visibility improvement) rather than absolute visibility. Therefore, an accurate visibility model that considers not only luminance contrast but also contrast sensitivity, glare effect and transient factor is critical.

3 FIELD EXPERIMENTAL DESIGN AND MEASUREMENT PLAN

To evaluate the effect on additional lighting on the modified locomotive PN9035, a field experiment was conducted. This involved collecting field data considering three primary attributes: viewing circumstances, object-related factors, and environmental conditions.

The primary goal was to assess whether the additional lighting has improved the locomotive's visibility, particularly when observed from wide angles of up to 90˚.

3.1 FIELD SETTING AND MEASUREMENT LOCATIONS

To ensure minimal disruption to normal train/freight operations and accommodate different shunting routes of the modified PN9035, two locations were selected: PN Trip Shed, Port Waratah and Progress Rail Port Kooragang, both located in NSW. The choice of relevant parameters was based on the three primary attributes mentioned earlier. Parameters such as the colour of side marker lights, status of beacon lights and side marker lights, viewing angles, weather conditions, and vegetation coverage were varied and tested under daylight, overcast and night-time ambient conditions. Additionally, the factor of sun direction, facing and behind the locomotive, was also taken into account. These parameters are summarized in Table 2.

3.2 MEASUREMENT PROCEDURE

The measurement process involved assessing the luminance of objects and ambient backgrounds under various viewing and environmental conditions. Survey instruments and a range finder were employed to determine different angles and distances for identifying potential testing locations.

First, survey instruments and a range finder were employed to determine different angles and distances for identifying potential testing locations. For reference measurement trials in daylight, markers were set at 105 m and 240 m locations in front of the locomotive cab position. Further, markings were set at 90˚ to the track about 28 - 35 m distance from the side of the locomotive. Then, the GL OptiCam 3.0 [6], an imaging luminance camera, was positioned at these marking locations to capture luminance data of the objects and ambient backgrounds. The luminance camera was positioned facing the locomotive front or side to capture luminance data of the front view or side view of the locomotive and the background. Baseline reference measurements were conducted to quantify the results of the subsequent measurements.

For daylight measurement trials encompassing several viewing circumstances, markers were set at 22.5˚ and 45˚ viewing angles from the track alignment (locomotive orientation). The luminance measuring equipment was located at about 60 m - 80 m from the front of the locomotive depending on the test site for the 22.5˚ viewing angle. The testing equipment was positioned at about 28m - 40 m from the front of the locomotive for the 45˚ viewing angle.

For night-time trials, measurements were conducted from the frontal view at approximately 100 m, from the side view at approximately 30 m and from wide locomotive view at an angle of 22.5˚ and 45˚.

3.3 LOCOMOTIVE LIGHTING CONFIGURATION

The locomotive PN9035 was equipped with various lighting components, including a headlight, front marker lights, and visibility lights (ditch lights) at the frontal section. The two headlight bulbs are centrally located above the windscreen, one on top of the other. The headlight setting is able to change the intensity between low beam and high beam. The front of the locomotive was also fitted with two beacon lights positioned on the brow (at both the left and right top front) (refer to Figure 2). These beacon lights are activated and flash for 60 seconds when the horn was sounded.

In the middle section of the frontal view of the locomotive, both on the left and right sides, there are white marker lights that illuminate when the locomotive is leading and red marker lights that illuminate when it is trailing. Moreover, the modified locomotive, as shown in Figure 3, has been fitted with five 44 Series Marker lights, white colour marker lights along one side and amber along the other side sills of the locomotive. The operation of the side marker lights was coupled to ditch (visibility) lights operation. The detail specification of the current lighting setting is listed in Table A.1 of Appendix A1. The results of the current trial are limited to the effects of the locomotive lighting based on the current configuration.

3.4 TEST PLAN

The test plan comprised three primary field measurement activities conducted at PN Trip Shed and Progress Rail Port Kooragang. Prior to the commencement of actual field measurements, three potential sites, as depicted in Figure 8, were pre-identified by PN representatives and mutually agreed upon by the working group.

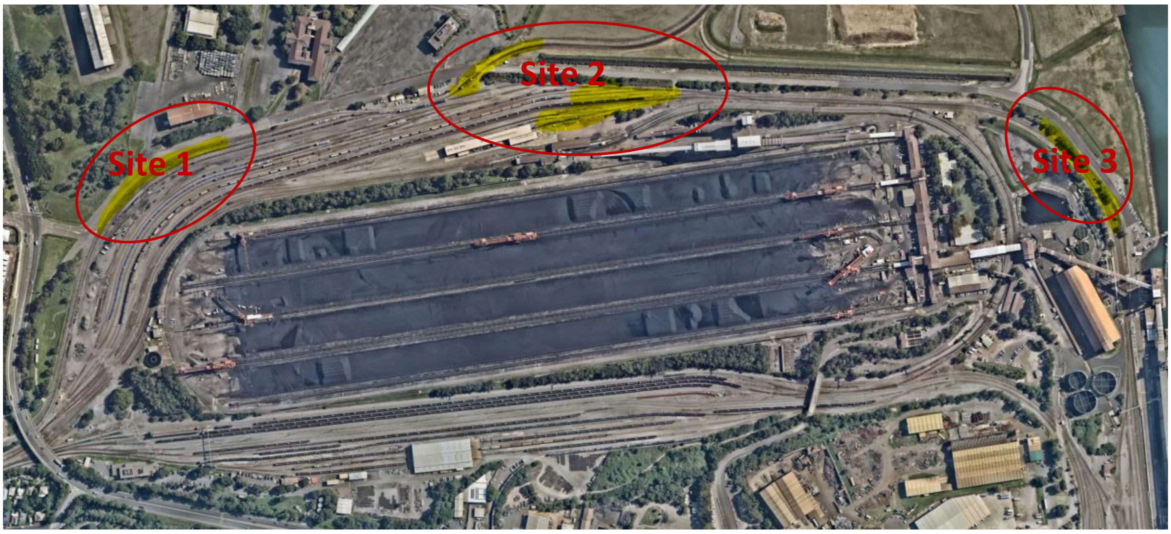


FIGURE 8. SITE OPTIONS FOR THE FIELD MEASUREMENT IN DAYTIME AT PORT WARATAH

Testing procedure, measurement apparatus, data to be collected, measurement times, etc, were detailed in the test plan [7], and are summarized in Appendix A2. The test plan consists of three primary activities. These are:

- Test plan I - Reference measurements
- Test plan II - Day time measurement (involving various parameters)
- Test plan III - Night time measurement (was originally an optional test plan)

A detailed time plan for the three activities was prepared and the weather forecast for the three measurement days (10th Oct – 12th Oct) was also added.
The reference measurement was planned and conducted for the following arrangements:

- The locomotive front was facing the testing equipment (luminance camera) at approximately 100 m and 240 m distances to conduct frontal view reference measurements.
- The testing equipment located at about 30 m from the side of the locomotive, both sides, perpendicular to the track.

A pictorial representation of the testing arrangement for the reference measurement is shown in Figure 9. The reference measurement was conducted during daytime between 2:30 pm and 4:30 pm under clear weather conditions at PN Trip Shed, at Site 2 as shown in Figure 8. This reference data serves as a baseline dataset, providing reference luminance or threshold luminance contrast for subsequent measurements.

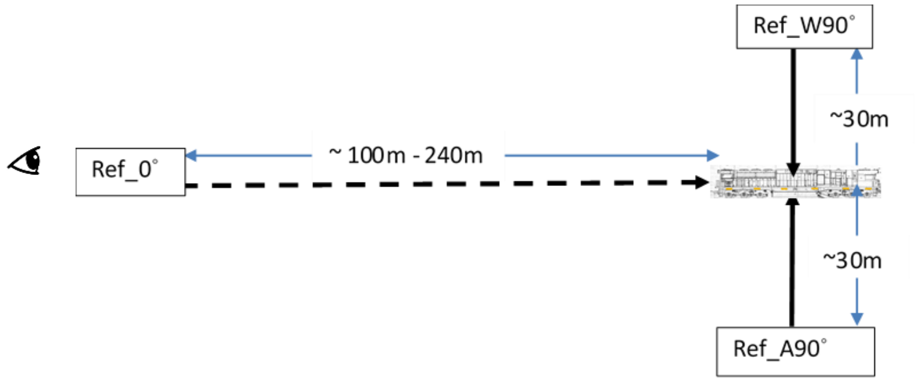


Figure 9. Illustration of the Testing Arrangement for Reference Testing - Test Plan I. The Boxes Ref_0°, Ref_A90° and Ref_W90° Refers to the Locations of the Luminance Camera

Day time testing involved various measurements to assess the effect of additional beacon lights and side marker lights (white and amber) on visibility improvements under different parameters during full daylight. These measurements included variations in viewing circumstances, weather conditions, and backgrounds. Viewing angles of 22.5° and 45° were considered at distances, approximately 60 m-80 m and 30 m-40 m, respectively for clear day measurements. Figure 10 illustrates an example of possible testing arrangement and locomotive position for test plan II. A22.5° and A45° in Figure 10 indicate measurements taken from the locomotive side with amber side marker lights at 22.5° and 45° viewing angles from the locomotive front view, respectively. W22.5° and W45° indicate measurements taken on the side of white side marker lights at 22.5° and 45° viewing angles, respectively. Additionally, luminance measurements were conducted during sunrise and sunset conditions, and under obstructed views caused by vegetation and simulated light rain conditions.

The night-time measurement was planned and conducted in Progress Rail Port Kooragang, as depicted in Figure 11, under clear weather conditions without any vegetation obstruction. Its purpose was to assess the effects of the additional lights on visibility in a night-time environment. Similar to the daytime measurement, frontal view at 100 m distance and viewing angles of 22.5°, 45°, and 90° were utilized in the setup.

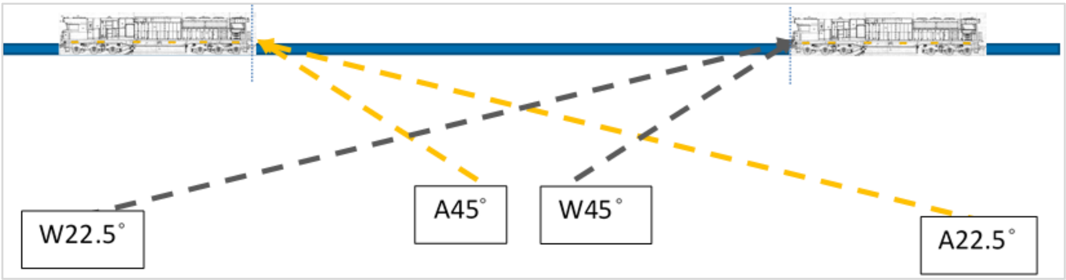


FIGURE 10. AN EXAMPLE OF A POSSIBLE TESTING ARRANGEMENT AND LOCOMOTIVE POSITION FOR TEST PLAN II FOR 22.5° AND 45° VIEWING ANGLES. THE BOXES W22.5°, W45°, A22.5° AND A45° REFER TO THE LOCATIONS OF THE LUMINANCE CAMERA

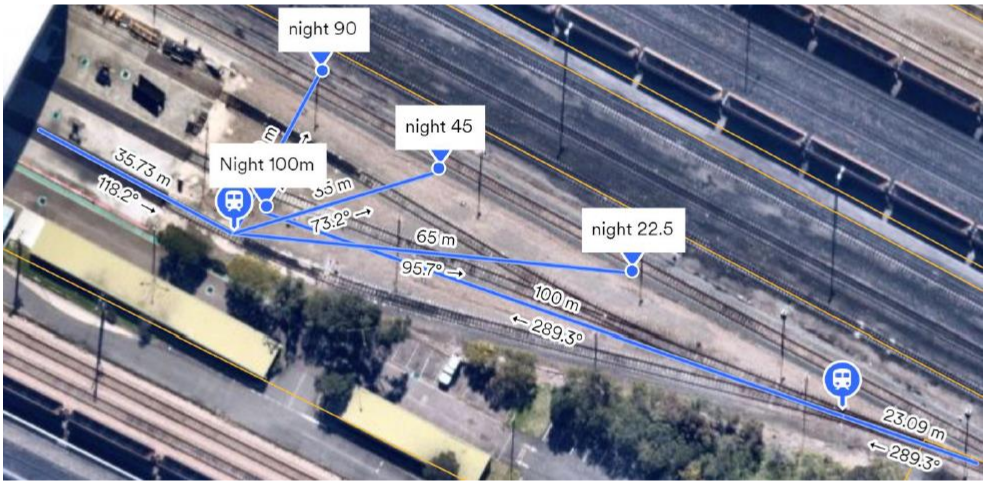


FIGURE 11. SITE FOR NIGHT-TIME MEASUREMENTS AT PROGRESS RAIL PORT KOORAGANG

4 FIELD DATA COLLECTION

Field data collection was a critical phase within this study, essential for capturing data and evaluating the effects of additional lighting on locomotive visibility. This section discusses the methodologies employed on-site and describes the diverse environmental conditions under which data was systematically collected. It offers an insight into the measurement processes conducted throughout the study

4.1 PREDEFINED VIEW LOCATIONS AND ANGLES

During the onsite visit, while prioritising minimal disruption to normal train/freight operations, specific sections of site 2 and site 3 within the predetermined locations at PN Trip Shed, depicted in Figure 8, were chosen for conducting reference and daytime measurements. For the night-time measurements, the designated measurement location remained consistent at Progress Rail Port Kooragang, as originally planned. Preceding the field measurements, survey equipment and a range finder, as depicted in Figure 12, were employed to predefine testing locations and precise angles for both daytime and night-time measurements. Minor adjustments to the measurement plan were made to ensure clear view condition, appropriate vegetation obstruction, and other on-site conditions were adequately accommodated.


(A)

(B)

FIGURE 12. (A) ESTABLISHING THE MEASUREMENT LOCATIONS IN DAYTIME AT PN TRIP SHED, AND (B) NIGHT-TIME AT PROGRESS RAIL PORT KOORAGANG

4.2 COLLECTING MEASUREMENT DATA

4.2.1 REFERENCE MEASUREMENTS

Two reference measurements were conducted in daylight and clear weather condition. The imaging luminance camera, GL OptiCam 3.0, was positioned at a distance of 105 m and 240 m, facing the front of the locomotive at 0° angle. Figure 13 illustrates the perspective from the 240 m reference measurement. Both reference measurements were captured under varying parameters outlined in Table 3. The purpose of measuring these parameters was to establish the baseline dataset essential for subsequent analysis. During the 240 m measurement, front marker lights were considered as additional variable and data pertaining to this lighting configuration was also captured.

TABLE 3. PARAMETERS MEASURED IN REFERENCE MEASUREMENT

Distance	**Headlight**	**Beacon Light**	**Side Marker Light and Ditch Light**	**Front Marker Light**
240 m	On/ Off	On/ Off	On/ Off	Red/ White/ Off
105 m	On/ Off	On/ Off	On/ Off	-
The operation of side marker lights and ditch (visibility) lights were coupled for the current trial.				

FIGURE 13. REFERENCE MEASUREMENT – VIEWING FROM 240 M

4.2.2 DAYTIME MEASUREMENT

To assess the daytime effects of beacon lights and side marker lights in both white and amber colours, various viewing angles and distances were identified for measurement. An illustration of on-site measurements in different viewing angles is depicted in Figure 14. Distances and angles between the imaging luminance camera and the locomotive were set at 65 m at a 22.5° angle and 28 m at a 45° angle for measurements of the white side marker lights. For the amber side marker lights, the distances were 65 m at a 22.5° angle and 40 m at a 45° angle. These measurements were conducted under clear weather conditions without any viewing obstructions and the parameters outlined in Table 4.

TABLE 4. PARAMETERS MEASURED IN DAYTIME MEASUREMENT

Parameters Measured		
Headlight	On	Off
Beacon Light	On	Off
Side Marker Light	On	Off
Side Marker Light Colour	White	Amber

Additionally, measurements were carried out during both dawn and dusk periods under clear weather conditions, employing 22.5° and 45° viewing angles to understand any effects of the additional lighting under different sun directions. Site measurement photos are presented in Figure 15. Due to limited morning and evening twilight duration, measurements were solely conducted on the locomotive side with installed white side marker lights. The parameters measured aligned with those in Table 4, with the only variation being the side marker light colour.

Figure 14. Field Measurement at Varying Viewing Angles: 22.5°, 45° and 90°

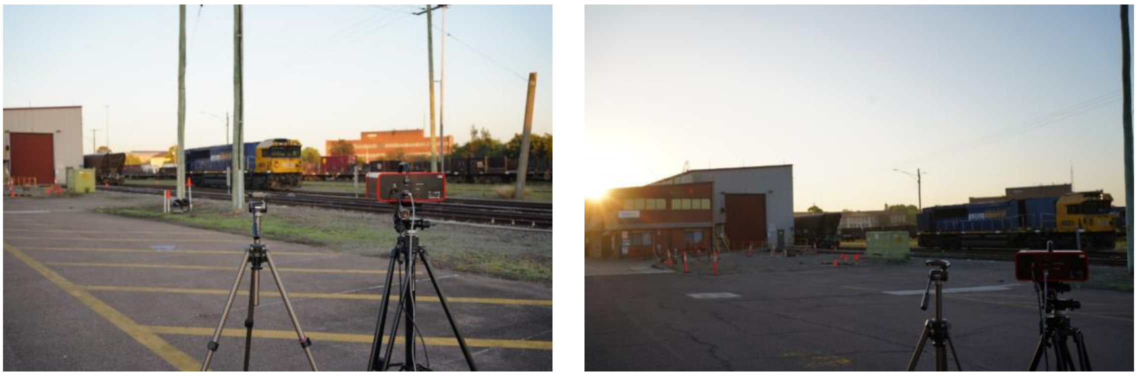


Figure 15. Conducting Measurements During Dawn (Left) and Dusk (Right)

In order to assess the influence of beacon and side marker lights across a range of environmental conditions, luminance values were recorded for these lighting components under simulated light rain and vegetation at viewing angles of 22.5° and 45°, following the parameters outlined in Table 4. To replicate light rain conditions, mist was introduced in front of the imaging luminance camera simulating the visual obstruction effect of rainfall on the locomotive. Figure 16 depicts images of the locomotive and the surrounding taken under both simulated light rain conditions and vegetation.

This daytime measurement was conducted to provide insights into the effect of the additional lighting and how their efficacy is influenced in various scenarios, particularly within diverse environmental settings.

FIGURE 16. MEASUREMENT TAKEN UNDER LIGHT RAIN CONDITION (LEFT) AND VEGETATION (RIGHT)

4.2.3 NIGHT TIME MEASUREMENT

To determine the effects of the additional lights on night-time visibility, night-time measurements were conducted in Progress Rail Port Kooragang under clear weather conditions without obscurity. An illustration of the on-site measurements at different viewing angles is shown in Figure 17. The distances and angles between the imaging luminance camera and the locomotive were set at 70 m with a 22.5° angle, 32 m with a 45° angle and 30 m with a 90° angle. In addition, reference measurements directly facing the front of locomotive at a 0° angle with a distance of 100 m was carried out and is depicted in Figure 18. Parameters measured during night-time measurements included the on and off states of the headlight, beacon lights, side marker lights, and colours of side marker lights. The parameters recorded during the night-time measurement are outlined in Table 5.

TABLE 5. PARAMETERS MEASURED IN NIGHT-TIME MEASUREMENT

Parameters Taken		
Headlight	On (High/ Low)	Off
Beacon Light	On	Off
Side Marker Light	On	Off
Side Marker Light Colour	White	Amber

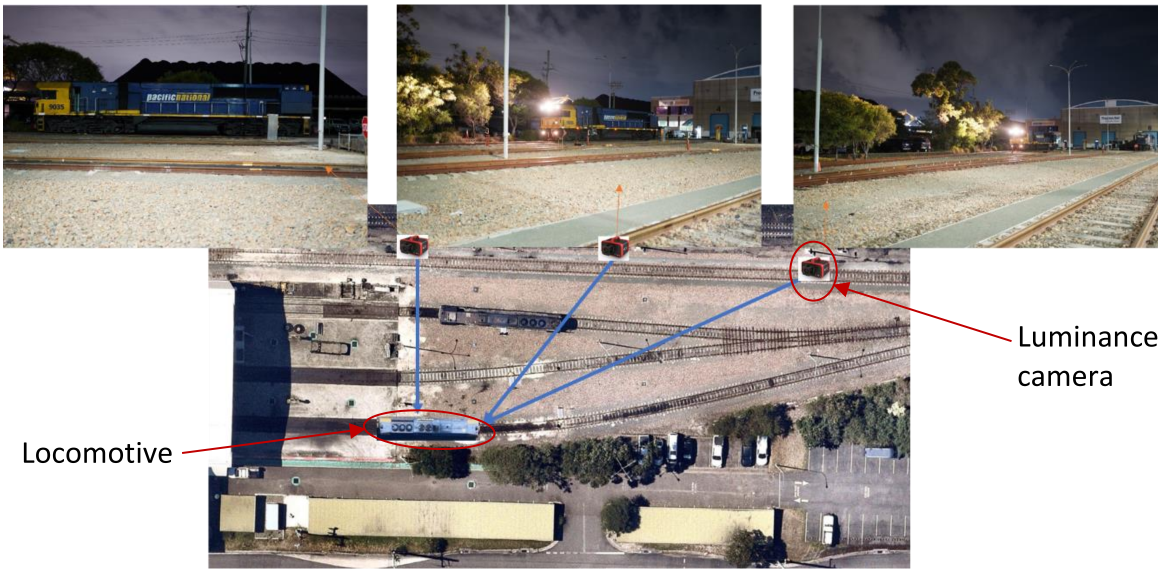


FIGURE 17. NIGHT-TIME MEASUREMENT OF AMBER SIDE MARKER LIGHTS AT ANGLES 22.5°, 45° AND 90°

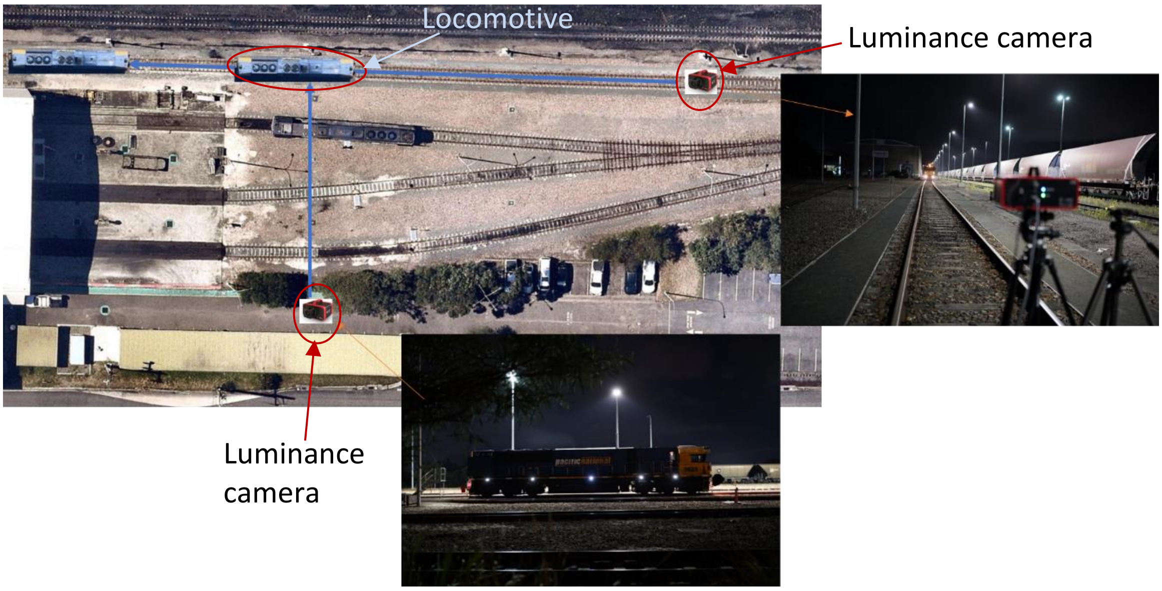


FIGURE 18. NIGHT-TIME MEASUREMENT WITH ANGLES 0° AND 90°

5 RESULTS ANALYSIS AND FINDINGS

Under different scenarios, more than 500 datasets were collected for all measurements. In the case where flashing beacon lights were turned on, the measurement runs were repeated at least two times. Also, measurements were taken twice for the same test run in some of the investigated scenarios. In such cases, the average of all repetitions was considered in the analysis. The repetition and the difference between repeated measurements for the same test case (object, environment, and viewing condition) were used to calculate the standard error margin in the effect analysis.

Consolidation and filtering of this data were necessary to make it more reasonable and understandable. The data were categorised under the investigated lighting related parameters, viewing circumstances or environmental parameters and the effects of the additional lighting were analysed for each of the categories.

5.1 DEFINING REGION OF INTEREST

Definition of visibility index requires the luminance quantities of the object and the surrounding background. It is based on the contrast between the luminance of the two. Two regions of interest are needed for each of the contrast, the object, defining the boundaries of the locomotive body, and the background region, surrounding the object, within a field of view ranging from 2° to 11.5°, depending of the observation distance and the physical size of the object.

To gain a comprehensive understanding of the results in different circumstances, regions of interest (ROI) for different scenarios were defined. Figure 19 shows the 105 m viewing distance with different lighting setups. While discussing the ROI, it is understood that the background/ambient environment would play a crucial role in terms of result interpretations. The object, i.e., locomotive PN9035 in this case, needed to be outlined in the image first and excluded for background calculation.

An example in Figure 20 (top) illustrates how the object, immediate background, and wider background are defined at a viewing distance of 105 m. The background was more complex when taking the 240 m measurement due to a train set running on the adjacent track. Figure 20 (bottom) shows another locomotive and freight wagons beside the target object. Exclusion of irrelevant background information was also conducted.

FIGURE 19. DIFFERENT LIGHTING SETUPS VIEWING FROM 105 M DISTANCE: (LEFT) ALL LIGHTS OFF, (MIDDLE) ONLY HEADLIGHT ON, AND (RIGHT) HEADLIGHT, BEACON AND DITCH LIGHT ON

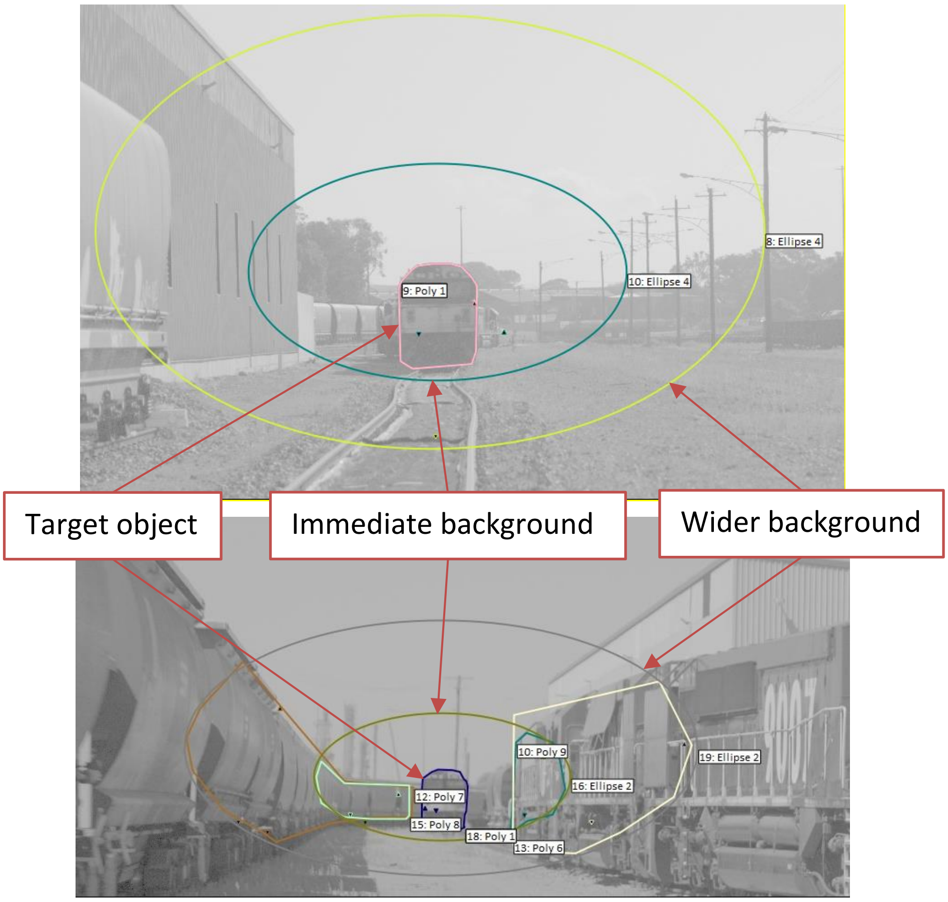


FIGURE 20. AN EXAMPLE OF DEFINING ROI AT OBSERVATION DISTANCE: (TOP) 105 M AND (BOTTOM) 240 M

The current assessment includes both the frontal and side visibility of the locomotive. The ROI for the object boundary covers the visible boundaries of the locomotive for a wider view angle up to 90°. Figure 21 shows images of the side of the locomotive with the defined boundary ROI for both white and amber side marker lights. By combining the two images, the full side view of the locomotive and the surrounding background ROI are defined. Due to the close range of the measurement location, about 30 m distance, the immediate background was only considered.

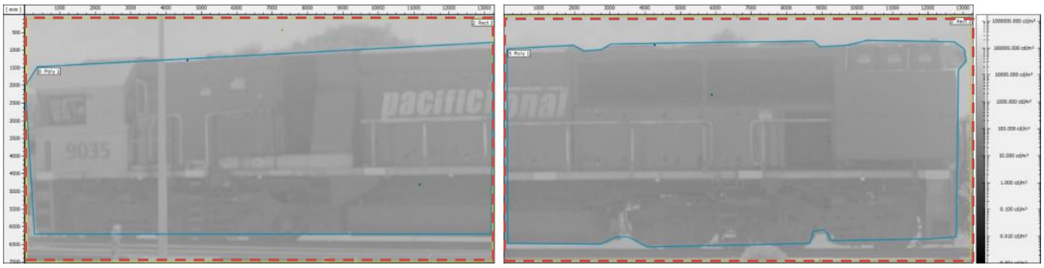


FIGURE 21 : AN EXAMPLE OF DEFINING ROI AT 90° VIEW ANGLE. THE POLYGON SURROUNDING THE LOCOMOTIVE SIDE VIEW REPRESENT THE OBJECT ROI WHILE THE BROKEN RED RECTANGLES REPRESENT THE BACKGROUND ROI

An example of the boundary for the object and the background ROIs for 45° view angle is shown in Figure 22. Due to the close distance between the camera and the object, about 30 m - 40 m distance, only the immediate background around the locomotive is defined. Figure 23 shows the locomotive viewed at 22.5° view angle. The polygon line surrounding the outer edge of the locomotive represents the object ROI. All the visible view of the locomotive (front and side view) are included in the object definition. The two ellipses surrounding the locomotive represent the boundaries of the immediate background ROI defined by a field of view in the range of 3.5° - 5° and the wide background ROI defined by a field of view in the range of 7.5° - 11°.

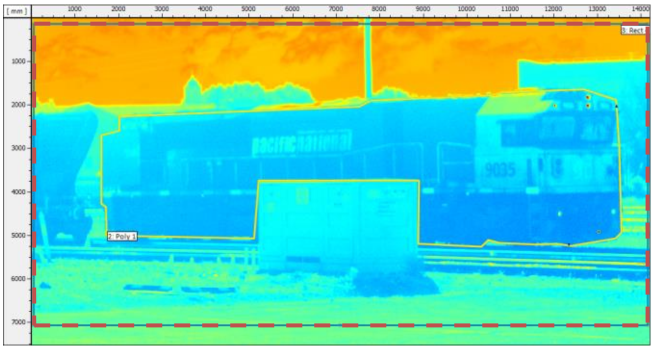


Figure 22. An Example of Defining ROI At 45° View Angle. The Polygon Surrounding the Locomotive Front and Side is the Object ROI, while the Broken Red Rectangle Represents the Boundary for the Background ROI

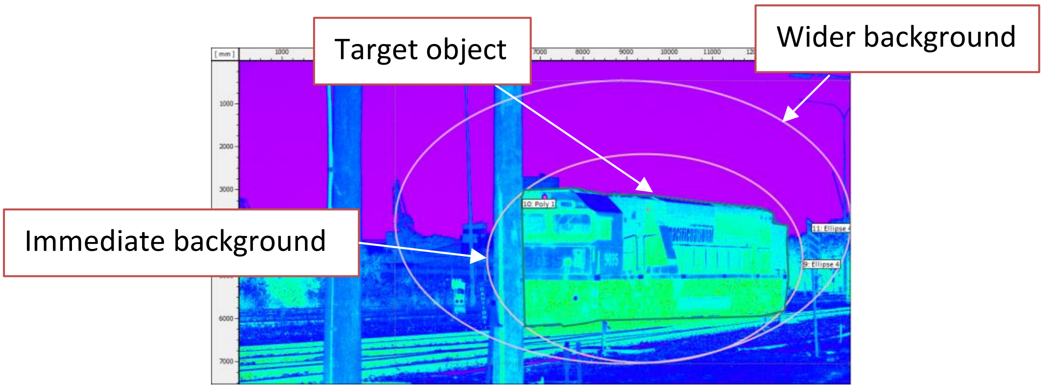


Figure 23. An Example of ROI at 22.5° View Angle. The Polygon Line Surrounding the Locomotive Visible View is the Object ROI. The Ellipses Represent the Boundaries for the Immediate And Wide Background ROIs

A consistent approach to defining the ROI was also applied in all other scenarios during both daytime and night-time measurements. Figure 24 (Left) provides an example defining the region of interest under dense vegetation conditions. In the original image, displayed in Figure 24 (Right), a locomotive was positioned behind the vegetation, and light-coloured tree trunks and poles between the fences were present, potentially affecting the analysis results. Analysis of the results took into account various factors and excluded irrelevant areas. During night-time measurements, it was not possible to turn off the lighting for the main operating running line. The ROI in night-time measurements is illustrated in Figure

25 (Left), while Figure 25 (Right) displays the images at a distance of 100 m with mainline lighting. The street lights were excluded from the background ROI.

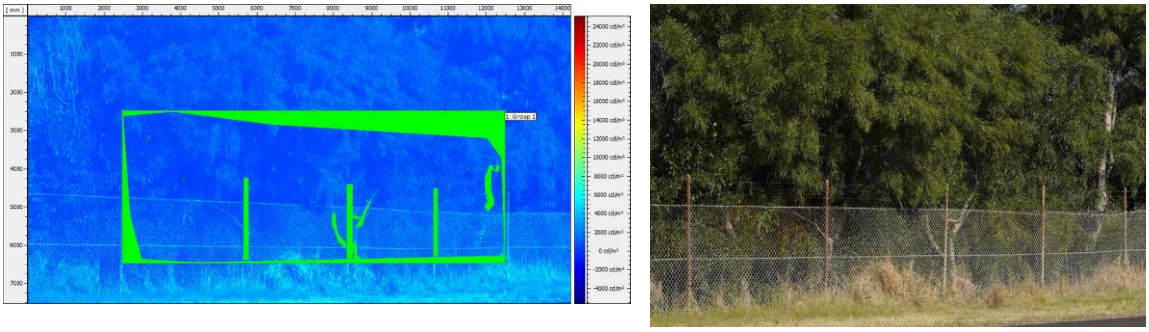


FIGURE 24. AN EXAMPLE OF DEFINING ROI OF THE OBJECT IN DENSE VEGETATION: (LEFT) LUMINANCE CAMERA IMAGE AND (RIGHT) ORIGINAL IMAGE

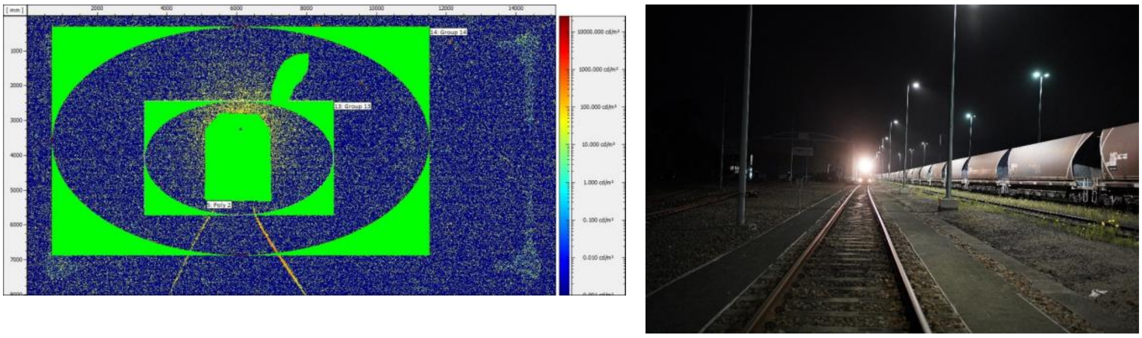


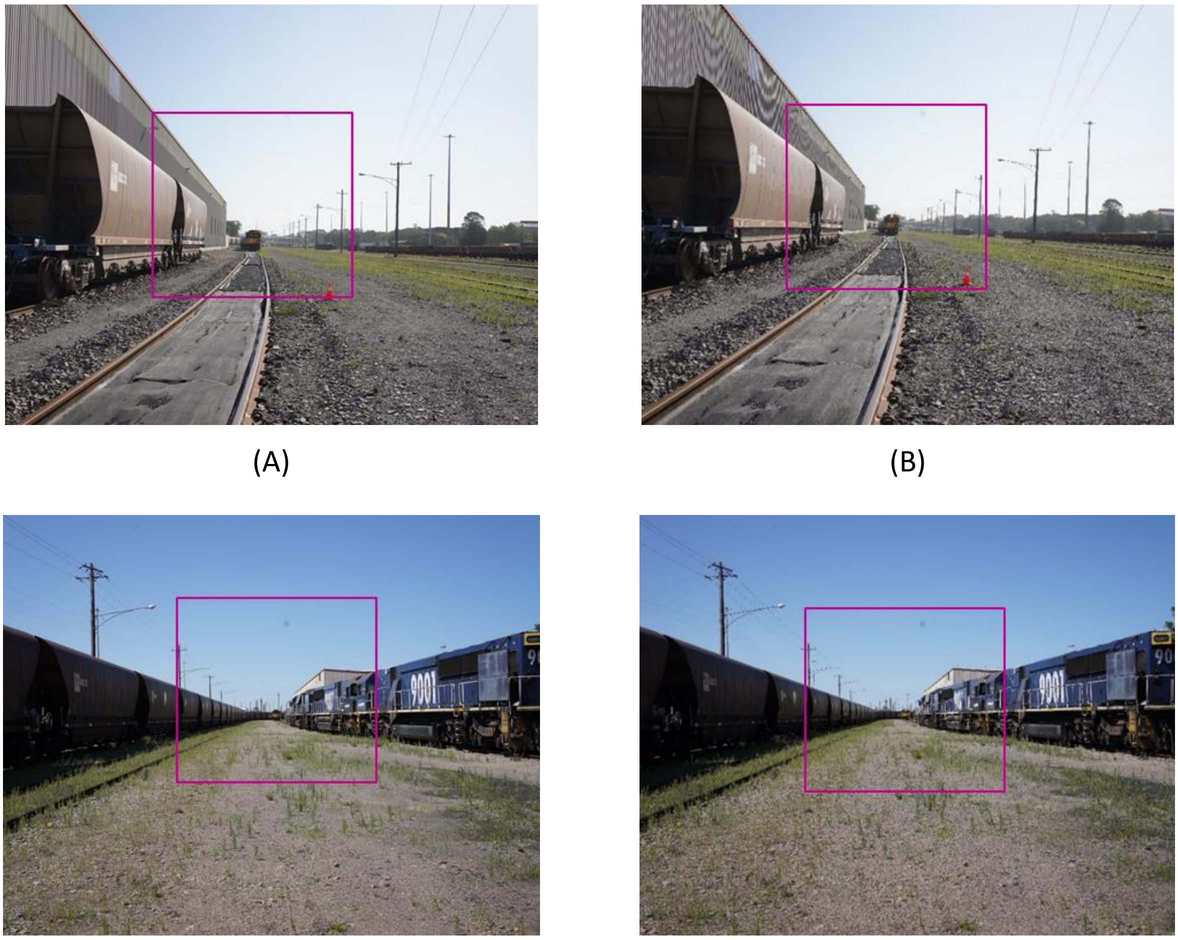
FIGURE 25. AN EXAMPLE OF DEFINING ROIS IN NIGHT-TIME MEASUREMENT: (LEFT) LUMINANCE IMAGE WITH DEFINED ROIS AND (RIGHT) ORIGINAL IMAGE

5.2 REFERENCE MEASUREMENTS

Luminance measurements were collected to assess the frontal view visibility of the locomotive at two locations. Both measurements were conducted during daylight hours between 2:30 pm and 4:30 pm, when the ambient light was relatively high. The objective of the reference measurement was to define the reference luminance contrast or reference luminance ratio to use as threshold values for the subsequent measurements.

The first measurement was taken at a distance of 105 m from the front of the locomotive cab. The direction of the sun was towards the measurement camera, resulting in sun glare and less illumination on the front face of the locomotive. The second measurement was conducted at a distance of 240 m from the front of the locomotive cab, with the sun glaring towards the locomotive's front view. In this measurement, a significant portion of the front face of the locomotive was well illuminated. Figure 26 displays images of the locomotive at both 105 m and 240 m distances. All the images were taken with identical camera settings.

As the locomotive was not clearly distinguishable in these images, the images were cropped to better fill the frame and accurately position ROIs, as depicted in Figure 27. The closer view allows for a clear examination of the background features and the brightness of the background and the locomotive. The images were taken when all the locomotive lighting was off and when all the locomotive lighting was on. The headlight, beacon light and ditch lights are clearly distinguishable in the cropped and zoomed images in Figure 27.



(A) (B) (C) (D)

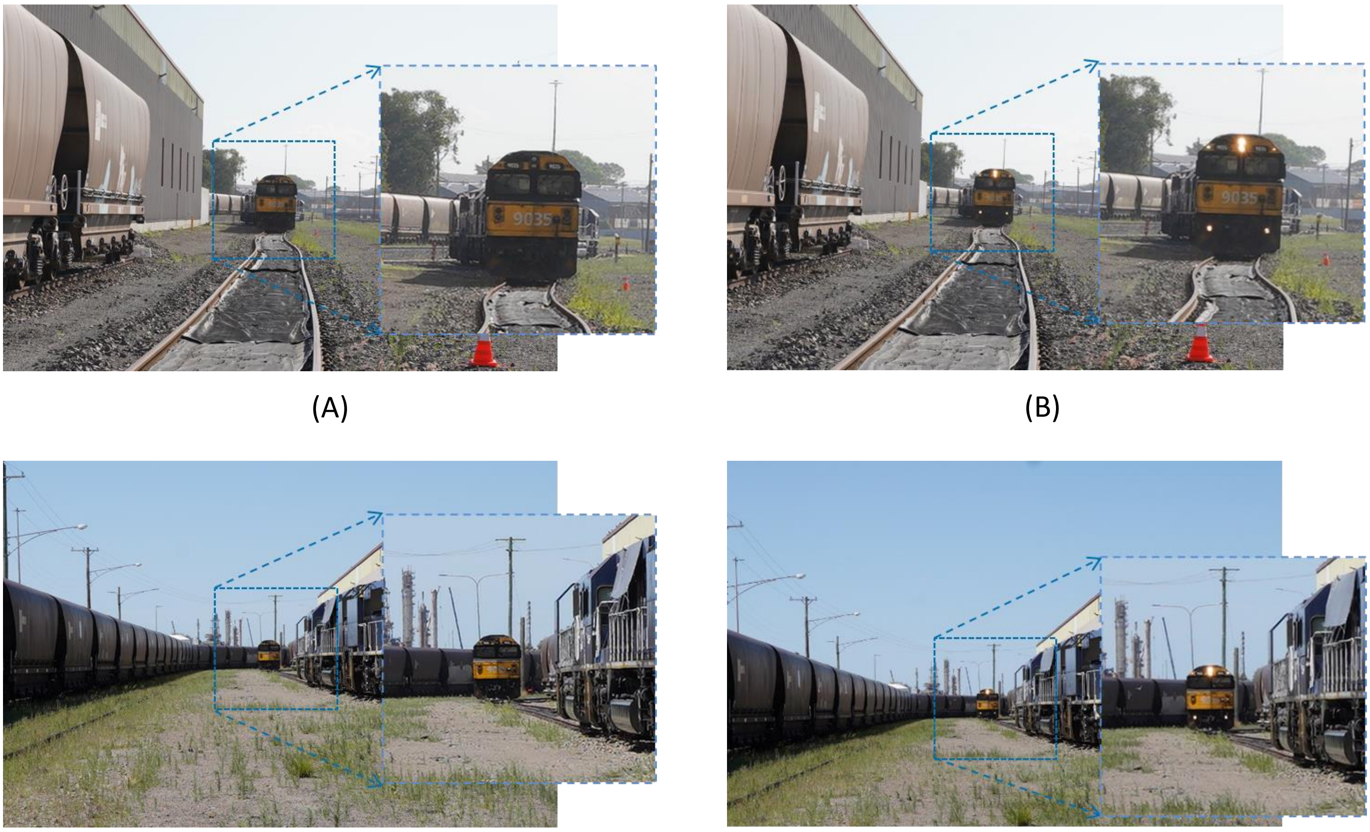
Figure 26. Images of the Locomotive and the Background: (A) At 105 m Distance with All Lights Off, (B) At 105 m Distance with All Lights On, (C) At 240 m Distance with All Lights Off, and (D) At 240 m Distance with All Lights On

In the current assessment, luminance contrast threshold and luminance ratio threshold were established using the reference measurements. First, various regions of interest (ROI) were defined, including the boundary outlined by the front view of the locomotive and the areas near and surrounding the locomotive's front. The mean luminance values within these defined ROI were analysed.

5.2.1 Defining Threshold Luminance Contrast

5.2.1.1 Regions of Interest for the Reference Measurements

Four background boundaries were defined to analyse their effect on the locomotive visibility assessment. These boundaries correspond to regions subtended by fields of views of 2°, 4°, 8°, and 11.5°.



(A) (B)

(C) (D)

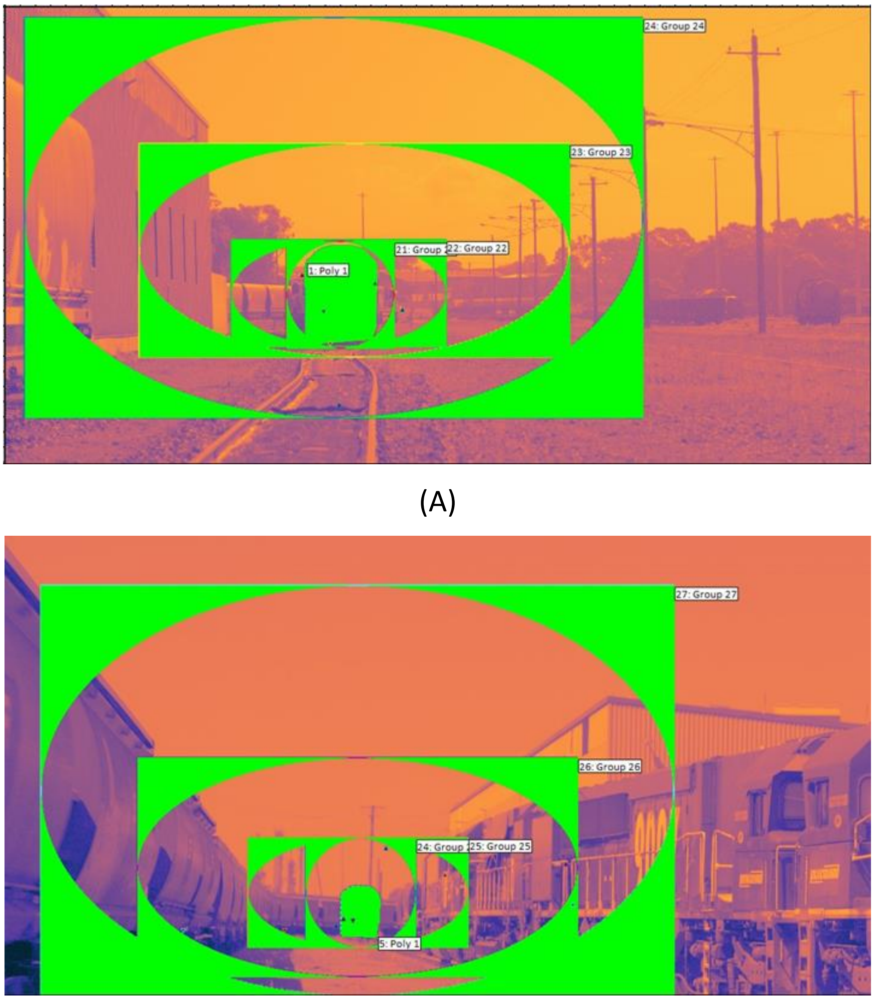
FIGURE 27. CLOSER VIEW OF THE LOCOMOTIVE AND THE BACKGROUND. (A) AT 105 M DISTANCE WITH ALL LIGHTS OFF, (B) AT 105 M DISTANCE WITH ALL LIGHTS ON, (C) AT 240 M DISTANCE WITH ALL LIGHTS OFF, AND (D) AT 240 M DISTANCE WITH ALL LIGHTS ON

Table 6 lists the horizontal and vertical angles subtending the ROIs for the reference measurements. Luminance contrast was calculated between the mean luminance of the object and the mean luminance of the background region. Four luminance contrasts were calculated for each of the four defined boundaries.

TABLE 6. REGIONS OF INTEREST (ROI) FOR THE REFERENCE MEASUREMENTS

Regions of Interest	**Angular size of the boundaries of ROIs**	
	Angular width (degree)	**Angular height (degree)**
Locomotive front at 105 m distance	1.3	1.8
Locomotive front at 240 m distance	0.7	0.9
Background at 2° field of view	2	2
Background at 4° field of view	4	2
Background at 8° field of view	8	4
Background at 11.5° field of view	11.5	7.5

The boundaries of the ROIs for the reference measurements at 105 m and 240 m locations are shown in Figure 28. The background ROIs comprise the areas subtended by the ellipse around the locomotive front view.



(A)

(B)

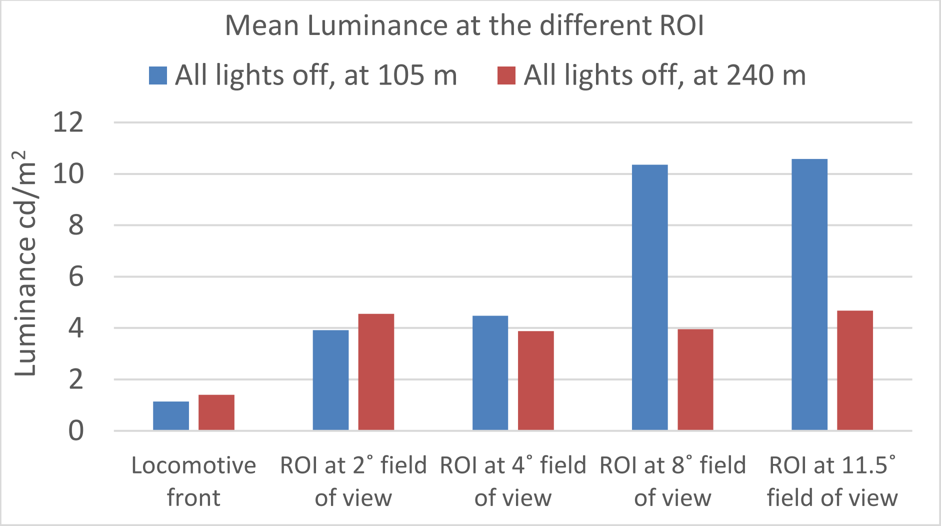
FIGURE 28. OBJECT AND BACKGROUND BOUNDARIES ROI FOR REFERENCE MEASUREMENT: (A) AT 105 M VIEWING DISTANCE, AND (B) AT 240 M VIEWING DISTANCE

The mean luminance values for various ROI are shown in Figure 29. In the base scenario, with all locomotive lighting off, the luminance measurement at the front of the locomotive at 240 m is slightly higher than the corresponding measurement at 105 m, despite the more than doubling in distance. In addition to the distance factor, visibility of locomotives can be affected by the direction of the sunlight.

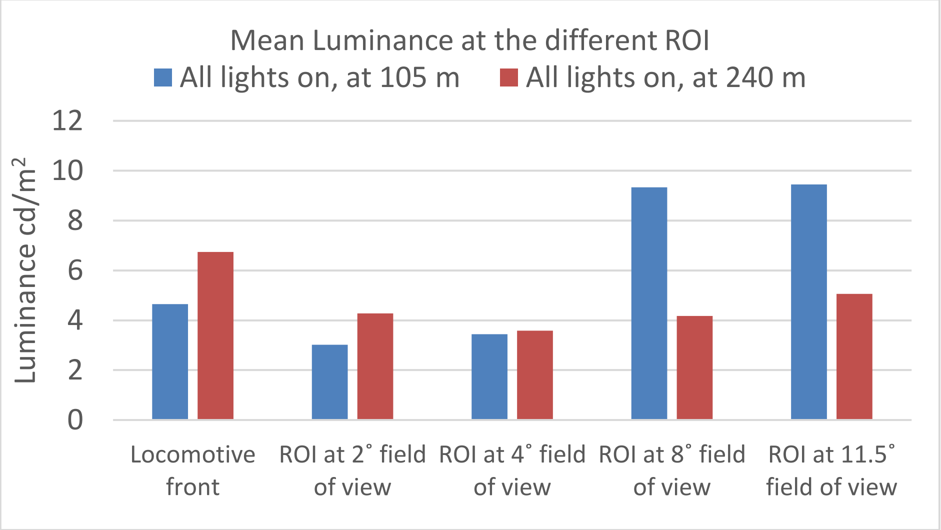
Figure 29 (A) shows the mean luminance values of the different ROIs for the base scenario, with all the locomotive lighting off. The corresponding mean luminance values of the different ROIs, with the locomotive lighting on, are shown in Figure 29 (B).

The mean luminance values of the background regions for the 240 m location ranges between 3.9 to 4.7 cd/m^2, which is relatively similar across all background ROIs. It is important to note that the mean luminance measurement of the background and the object changes due to the transient nature of the ambient light; however, the effect of the transient ambient light is not accounted for in the current assessment methodology.

The mean luminance of the background for the 105 m location is relatively consistent up to a 4° field of view (3.9 - 4.57 cd/m^2). However, a significant increase in the mean luminance of the background occurs for the 105 m when considering 8° and 11.5° field of views for the ROI. This can be explained by the larger area of the clear sky in the background for measurements at the 105 m location, while the proportion of the clear sky at the 240 m location remains relatively the same, as depicted in Figure 28.



(A)



(B)

FIGURE 29. MEAN LUMINANCE VALUES FOR VARIOUS ROI AT 105 M AND 240 M: (A) ALL LOCOMOTIVE LIGHTS OFF, AND (B) ALL LOCOMOTIVE LIGHTS ON

The mean luminance values of the front of the locomotive at 240 m distance are slightly higher than the corresponding measurements at 105 m, even when all the lights are on, as depicted in Figure 29 (B). Despite the distance more than doubling, two factors contribute to the increase in the mean luminance at 240 m location. First, as explained earlier in the base scenario, with all locomotive lighting off, the locomotive front view was well illuminated at 240 m distance due to sun glare. Second, the headlight beam is more concentrated towards the 240 m location than the 105 m location, as illustrated in Figure 30. According to the AS 7531:2015 standard [8], *“the centerline of each headlamp beam should be aimed at a point at center of track level at least 240 m ahead and in front of the headlight.”* The intensity of the headlight is concentrated in the direction of the beam to illuminate the track ahead. The measured properties of the headlight, physical size and luminance properties are presented in Table A.3 of Appendix A3.

The luminance values of all pixels within the boundary of the headlight were extracted. The maximum luminance of the headlight was 6459 cd/m^2 and 1931 cd/m^2 measured at 105 m and 240 m locations, respectively. The proportion aligns with the expectation, considering luminance decreases with distance [5]. However, the mean luminance of the headlight was 382 cd/m^2 and 274 cd/m^2 measured at 105 m and 240 m locations, respectively. This proportion is not aligned with the proportion of the maximum luminance measurements. The standard deviation of the luminance measurement of all pixels within the boundary of the headlight was 874 cd/m^2 and 411 cd/m^2 at 105 m and 240 m, respectively. The reduced variation at 240 m measurement location confirms that the headlight beam is concentrated and aimed at 240 m distance, although it may also radiate with decreasing intensity.

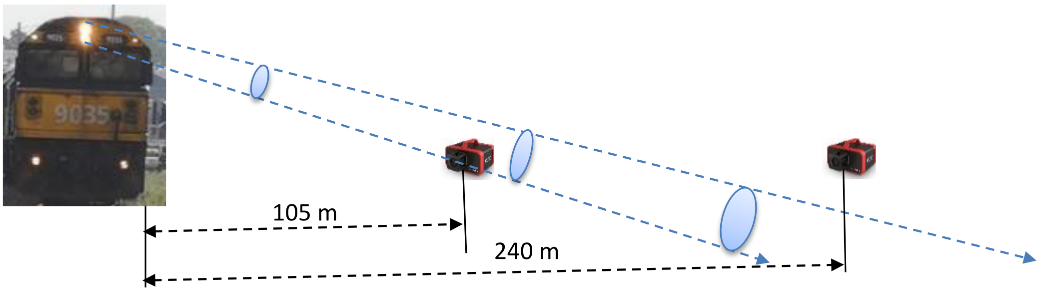


FIGURE 30. ILLUSTRATION OF HEADLIGHT BEAM DISTRIBUTION

To provide additional clarification regarding the headlight beam, the work conducted by the US Department of Transportation (US DOT) on compliance testing of locomotive lights [10] illustrates the bird’s eye view of illuminance maps for various types of lamp samples, as shown in Figure 31. These illuminance maps represent the amount of light falling on ground from a set of lamps installed on a locomotive using lux measurements. The outer most edge represents a cut-off threshold of 0.3 lux. As can be seen from the map, the light beams are concentrated to a specified beam angle, and the intensity reduces towards the outer edges.

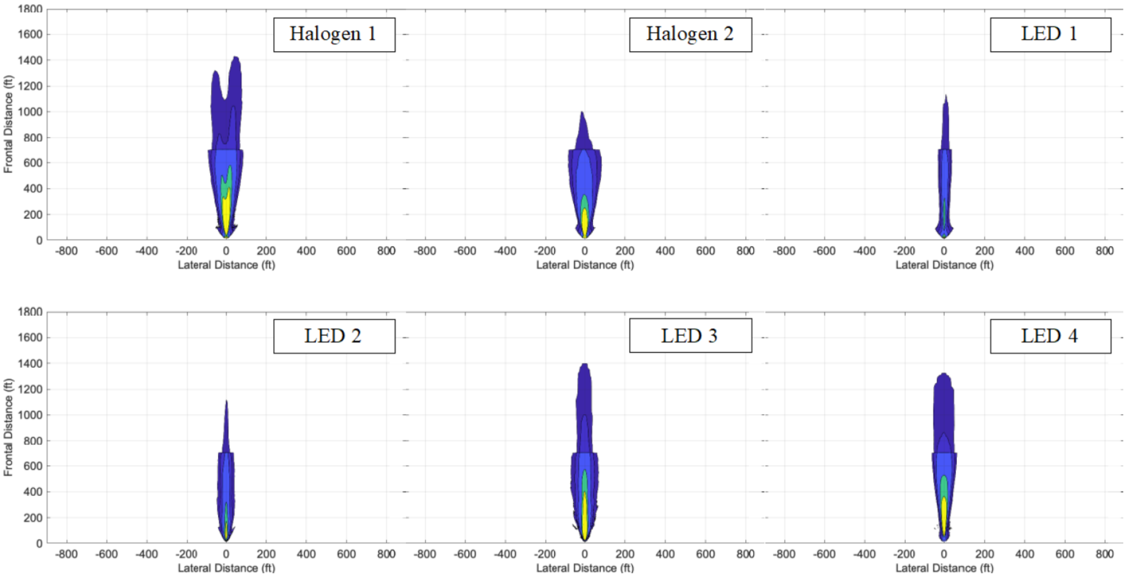


FIGURE 31. ILLUMINANCE MAPS OF LAMP SAMPLES [10]

5.2.1.2 REFERENCE LUMINANCE AND THRESHOLD LUMINANCE CONTRAST

According to Blackwell [4], the visibility index is defined as a function of reference luminance or threshold luminance. This index represents the ratio between luminance contrast and a threshold luminance contrast. Based on reference luminance measurements of the locomotive and the background ROIs, luminance ratio and luminance contrast values are calculated.

Figure 32 illustrates the luminance ratio between the front of the locomotive and the different background regions. As can be seen clearly, when the locomotive lighting was turned off, the background mean luminance exceeded the mean luminance of the locomotive across all defined background regions. At the 240 m location, with the locomotive lighting turned on, the luminance ratio was greater than 1, indicating enhanced visibility. For the 105 m location, a luminance ratio greater than 1 was observed only for the ROIs defined by 2° and 4° field of views.

Figure 33 presents luminance contrast values for the reference measurements. Negative values are indicative of situations where the background luminance is higher than that of the target object. Higher luminance contrast values signify easier detection of the object from the background region without requiring extensive searching. With the locomotive lighting on, positive luminance contrast values indicate the locomotive front can easily be noticed from its background. At the 240 m location, luminance contrast values exceed 0.25 when the lighting is on, whereas at the 105 m location, this occurs only for the immediate background, with 2° and 4° fields of views. The luminance contrast is negative when 8° and 11.5° fields of views were considered.

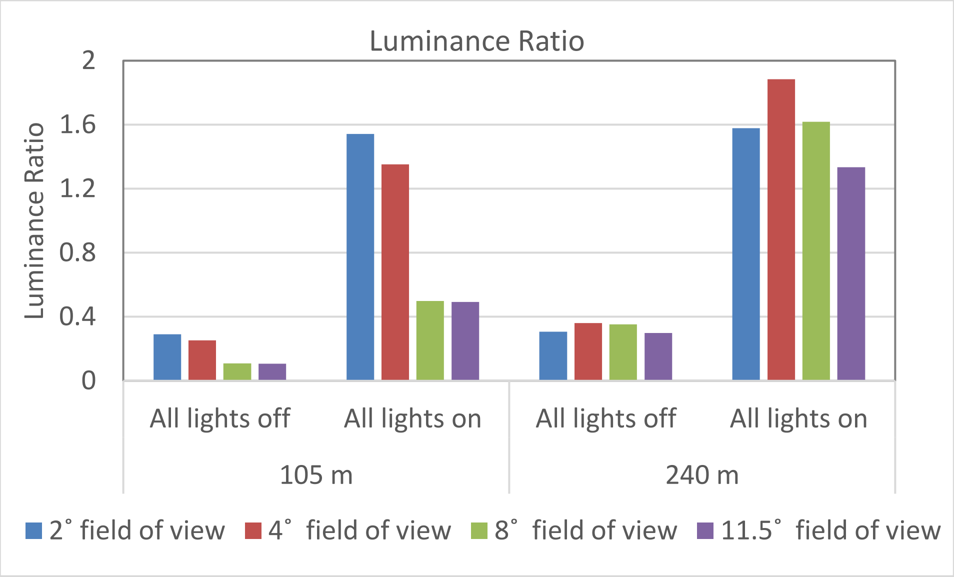


FIGURE 32. LUMINANCE RATIO BETWEEN THE FRONT OF THE LOCOMOTIVE AND THE VARIOUS BACKGROUND ROIS AT REFERENCE MEASUREMENTS

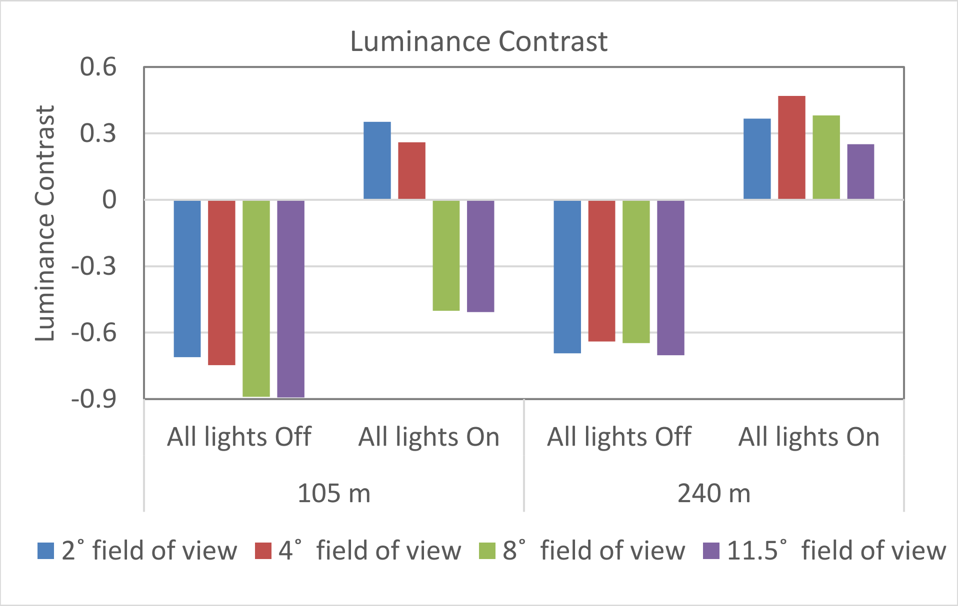


FIGURE 33. LUMINANCE CONTRAST FOR THE REFERENCE MEASUREMENTS BETWEEN THE FRONT OF THE LOCOMOTIVE AND THE VARIOUS BACKGROUND ROIS

The visibility index curves in Figure 34 map the luminance contrast and luminance ratio, with threshold values determined at a visibility of at least 75% or a visibility index of 0.75. A luminance ratio of about 1.25 can be taken as a threshold value beyond which the locomotive front is easily distinguishable from the defined background. In terms of luminance contrast, a value of 0.25 and above can be considered as a threshold luminance contrast for frontal locomotive visibility, indicating that the luminance of the locomotive is 25% higher than the background region. The luminance contrast threshold values should be valiadted through psychphysical methods, considering various senarios and background conditions.

Further analysis of luminance contrast and luminance ratio values reveals that the 2° and 4° fields of view can be classified as immediate background ROI, while the 8° and 11.5° can be categorised as wider background ROI depending on the observation distance. For measurements at the 105 m location, the 4° field of view is designated as the immediate background, whereas the 8° and 11.5° can considered the wider background. In contrast, for measurements at the 240 m location, the 2° field of view is regarded as immediate background ROI, while the 4° and 8° are categorised as the wider background. This distinction in classifying field of views assists in defining the background regions impacting locomotive visibility during assessments at different viewing circumstances.

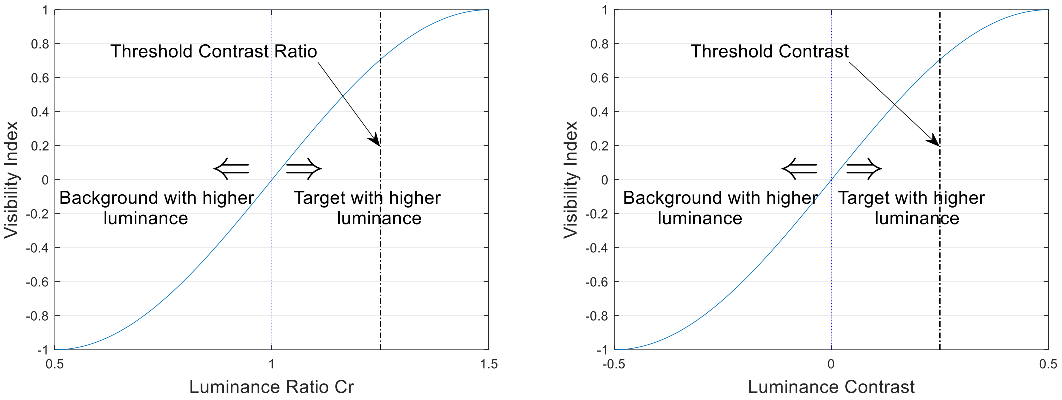


Figure 34. Threshold Luminance Ratio (Left) and Threshold Luminance Contrast (Right) in the Visibility Index

5.2.2 Effect of Front Marker Lights on Frontal Visibility

The effect of the front marker light on the visibility of the locomotive's front view was assessed based on the luminance measurements taken at the 240 m location. Both red and white front marker lights were evaluated.

The calculated luminance contrast for both the immediate background and wider background is shown in Figure 35. The luminance contrast showed no significant change when only the front marker lights are turned on, regardless of the front marker light colour. The luminance of the locomotive, with front marker lights off, was about 70 % less than the luminance of the background region around the locomotive. The luminance did not show any noticeable change when the front marker lights were turned on. The resulting luminance contrast values and the luminance ratios remained well below the threshold limits.

As a comparison, when the headlight was turned on, the luminance contrast of the locomotive increased by over 117%, as shown in Figure 35. This suggest that the effect of front marker light on locomotive visibility is negligible. It is important to note that the objective of the current assessment is mainly to assess the effects of locomotive lighting on its overall visibility. The visibility of the marker lights itself was not assessed in the current assessment.

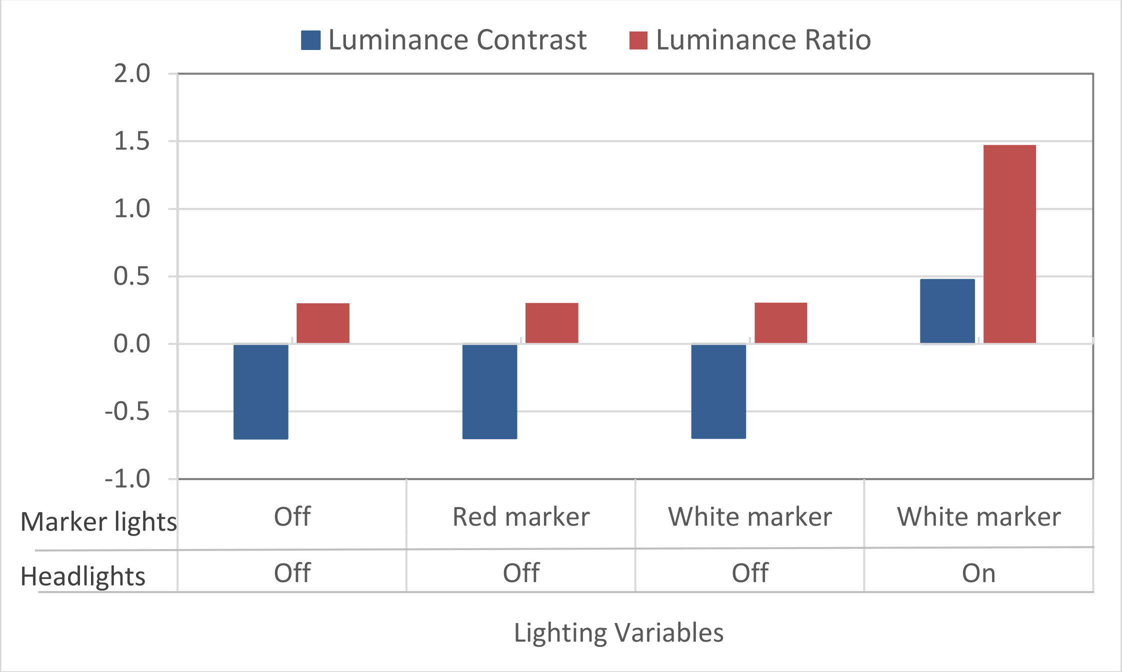


FIGURE 35. LUMINANCE CONTRAST AND LUMINANCE RATIO CHANG DUE TO FRONT MARKER LIGHTS AT 240 M LOCATION

5.2.3 EFFECT OF SIDE MARKER LIGHTS ON SIDE VISIBILITY

The effect of the side marker light on the visibility of the locomotive's side view was evaluated based on the luminance measurements taken at about 30 m distance, perpendicular to the side of the locomotive (90° view angle). The trial assessment included two different colours of the side marker lights, amber marker lights on one side and white marker lights on the other side of the locomotive.

The effects of sun direction, distance and other environmental factors remained relatively consistent. Measurements were conducted in a similar background scenery and under relatively similar ambient daylight conditions between 1:30 pm and 3:30 pm. The side profile, the proportion of side livery, and the proportion of reflectors on both sides of the locomotive were relatively similar, as depicted in the images of the locomotive sides at the measurement spot in Figure 36(A) and (B). When the side marker lights were off, the difference in the mean luminance between the two sides of the locomotive was approximately 7%.

(A)

(B)

FIGURE 36. IMAGES OF THE SIDE OF THE LOCOMOTIVE FITTED WITH: (A) WHITE SIDE MARKER LIGHTS AND (B) AMBER SIDE MARKER LIGHTS

The luminance contrast for the immediate background was calculated for both sides as shown in Figure 37. The calculated luminance contrast values are observed to be below the threshold luminance contrast. This can be explained by the clear sky background, that measures luminance levels about 7 - 15 times higher than that of the locomotive side view. It is to be noted that the current visibility index definition relies solely on luminance measurements as a quantitative value, without taking into account shape, form, colour and other factors that might affect visual conspicuity.

When the side lights were off, the side with white side marker lights showed approximately 15% higher luminance contrast compared to the side with amber marker lights. However, when the side lights were turned on, the locomotive side with amber marker lights demonstrated a 3% increase in the luminance contrast. Conversely, the white side marker lights, when the lights were turned on, resulted in a reduction in the luminance contrast by about 9%. This variation could occur due to the transient ambient light variation during the measurement. Based on the current configuration of the side marker lights, it appears that the side marker lights may not contribute to visibility improvement during clear daylight hours.

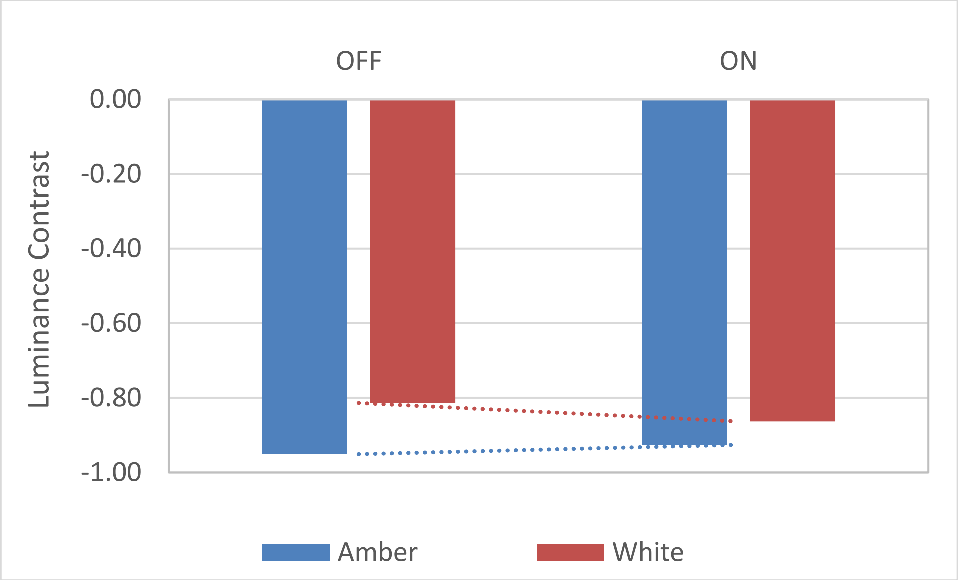


FIGURE 37. LUMINANCE CONTRAST OF LOCOMOTIVE SIDE VIEW DUE TO SIDE MARKER LIGHTS

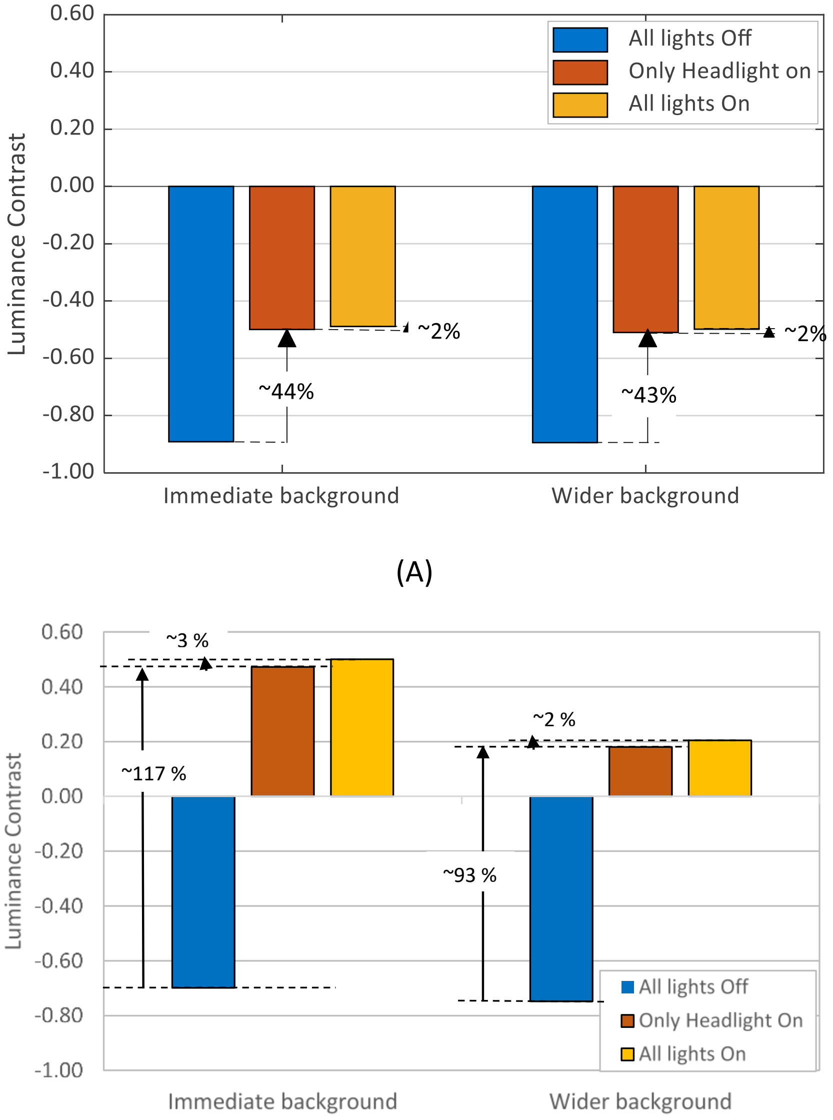
5.2.4 EFFECT OF BEACON LIGHT ON FRONTAL VISIBILITY

The effect of the beacon light on the visibility of the locomotive's front view was also evaluated by measuring the luminance of the locomotive and the background ROIs. Luminance contrast and luminance ratios were then calculated. In this evaluation, an immediate background ROI, subtended by a 4° field of view, and a wider background ROI, subtended by an 8° field of view, were considered. The three locomotive lighting setting variations considered are listed in Table 7. Measurement data were collected at a distance of 105 m and 240 m in daylight, around 4:30 pm and 2:30 pm, respectively.

The luminance contrast for the three lighting settings when viewing the locomotive front at 105 m and 240 m locations are shown in Figure 38(A) and Figure 38(B), respectively. It is evident from Figure 38 that the locomotive lighting significantly affects the locomotive's frontal visibility.

TABLE 7. LOCOMOTIVE LIGHTING SETTINGS FOR FRONTAL VISIBILITY

Measurement #	Headlight	Beacon lights	Visibility (Ditch) lights
All lights Off	Off	Off	Off
Headlight On	On	Off	Off
All lights On	On	On	On



(A)

(B)

FIGURE 38. LUMINANCE CONTRASTS CONSIDERING IMMEDIATE AND WIDER BACKGROUND ROI WITH DIFFERENT LIGHTING SETTINGS: (A) AT 105 M LOCATION, AND (B) AT 240 M LOCATION

The luminance contrast was below the threshold value when all the locomotive lighting was turned off. When all the locomotive lighting was turned on, the frontal visibility improved by about 46% and 120% for 105 m and 240 m locations, respectively, when the immediate background ROI was considered. For the wider background ROI, the corresponding improvements were 45% and 95% for 105 m and 240 m locations, respectively.

The visibility improvement due to the headlight alone, compared to the base scenario with all lighting off, was about 43% - 44% for the 105 m measurement location, as shown in Figure 38(A). There was a further 2% - 3% improvement when both beacon lights and ditch lights were turned on. Although the headlight alone or combined with the beacon and ditch lights improved visibility by about 46%, the luminance contrast remained below the threshold value.

In contrast, for 240 m location, the luminance contrast value corresponds to a visibility index of 1, or full visibility, when immediate background ROI was considered. The luminance contrast was close to the threshold value, corresponding to 75% visibility, when the wider background ROI was considered. In all these cases, the principal improvement in visibility is achieved due to the headlight alone.

While the visibility improvement due to headlight is very significant, the contribution from the other lighting is almost negligible, in the order of about 2% - 3%. Figure 39 shows the luminance contrast of the front of the locomotive measured at 240 m when an immediate background ROI was considered. In the base scenario with all lighting off, the luminance contrast was -0.7. When only the headlight setting was turned on, the contrast increased to 0.47, equivalent to an increase in 117%. When the visibility lights setting were turned on, keeping the headlight on, the luminance contrast increased further by about 2.5%. By keeping the headlight on and varying only the beacon lights while the visibility light was off, there was about a 1% increase in the luminance contrast. The combined effect of visibility and beacon lights was about 3%. Note that, the headlight setting was only on high beam during the measurements at 105 m and 240 m locations.

The above findings indicate that the effect of beacon light on the frontal visibility improvement is insignificant in comparison to the effect of the headlight for the considered testing conditions. A similar finding was observed from the trial conducted in WA for frontal visibility assessment, where the contribution of beacon lights and ditch lights was about 5%, despite the differences in the locomotive livery and background conditions with the current trial.

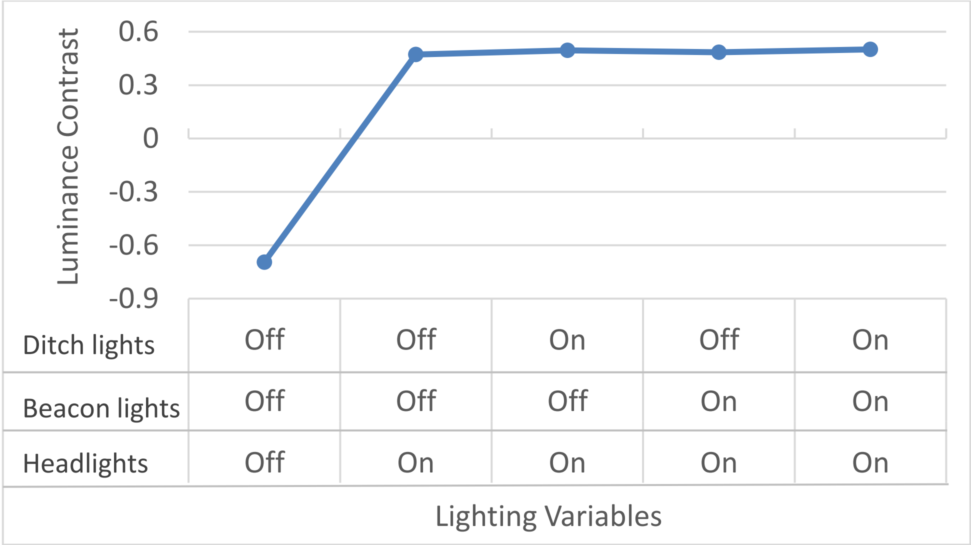


FIGURE 39. LUMINANCE CONTRASTS CONSIDERING IMMEDIATE BACKGROUND AS ROI MEASURED AT 240 M LOCATION WITH DIFFERENT LIGHTING SETTINGS

5.2.5 EFFECTS OF VIEWING DISTANCE AND SUN DIRECTION ON FRONTAL VISIBILITY

The difference in visibility improvement at the 105 m and 240 m locations suggests that the viewing location (viewing distance) significantly influences the effect of the headlight. The effect of the headlight is particularly noticeable at the 240 m location. As previously explained in Section 5.2.1.1, the mean luminance of the locomotive front measured at 240 m location was about 26% higher than the corresponding measurement at 105 m when all the lights were off, refer to Figure 29(A). The difference in the luminance contrast was about 22% when the immediate background ROI was considered while it was 16% when the wide background ROI was considered, refer to Figure 38. This difference is solely due to the sun direction illuminating the locomotive front during the measurements at 240 m.

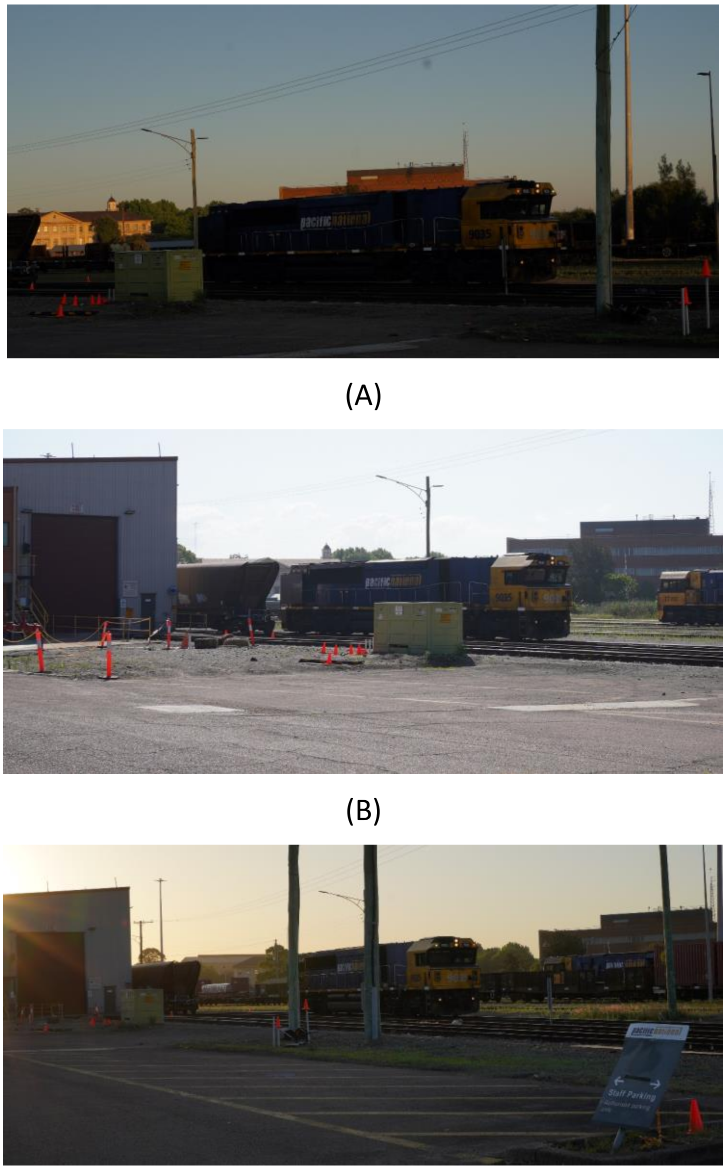
On the other hand, when all the lights were on, the mean luminance of the locomotive front measured at 240 m location was about 44% higher than the corresponding measurement at 105 m, refer to Figure 29(B). The difference in the luminance contrast for this case was about 200% when the immediate background ROI was considered while it was 140% when the wide background ROI was considered, refer to Figure 38.

These differences in the luminance contrast (visibility index values) between measurements at 105 m and 240 m location can be explained as partially by the headlight beam aiming distance (refer to Figure 30) and partially by the direction of the sun. The front face of the locomotive at the 105 m location was less exposed to direct sunlight. These results infer that the visibility improvement is a combination of headlight, viewing locations, and the direction of the sun. While it is beyond the scope of the current assessment to study the light interference effect of the sun light on the headlight beam, the results indicate that the ambient surrounding light has an effect on the visibility of the locomotive.

5.3 DAY TIME MEASUREMENTS

Measurements were conducted at different times of the day, including dawn, morning, midday, afternoon and dusk, to assess the effect of the lighting on daytime locomotive visibility. Locomotive lighting variables, such as beacon lights and side marker lights were varied at two-levels (on and off states). Environmental factors such as weather and ambient light were also varied at two-levels, and their individual effects and their interaction effects with the lighting variables were assessed. Additionally, the effect of the lighting variables was compared in clear and vegetation-obscured scenarios.

Figure 40 shows images of a locomotive captured from the measurement location under clear weather conditions but at different times of the day. The images were taken with similar camera setting around 6:00 am (sunrise), 3:30 pm (afternoon) and 7:30 pm (sunset). Differences in ambient light and the general visibility are evident in the images. Also, locomotive visibility can be significantly affected by the direction of the sun and the ambient light conditions. Measurements were conducted for view angles of 22.5° and 45° under both clear weather and mist conditions.



(A)

(B)

(C)

Figure 40. Images of a Locomotive Viewed at Different Times of the Day in Clear Weather Conditions: (A) Around 6:00 am (Sunrise) (B) Around 3:30 pm and (C) Around 7:00 pm (Sunset)

5.3.1 Visibility at Different Times of the Day

There is a clear difference in the luminance contrast values of the measurements taken at different times of the day, as shown in Figure 41. This change is more distinct for measurements at 22.5° view angle than for measurements at 45° view angle. The change in the calculated luminance contrast values due to the two different side marker light colours can also be seen. In all measurements at 22.5° view angle, amber side marker lights appear to give slightly higher luminance contrast than white side marker lights. At 45° view angle, white side marker lights appear to give slightly higher luminance for measurements in morning time, while amber side marker lights give slightly higher luminance contrast than white side marker lights for measurements in the afternoon. There are several other variables than the colour of the side marker lights leading to the difference in luminance contrasts. To quantitatively assess the effects of the individual variables and to determine if there are interaction effects between two- or three-variables, effect analysis was conducted based on all the test runs. A full factorial design with five factors was employed for the effect analysis.

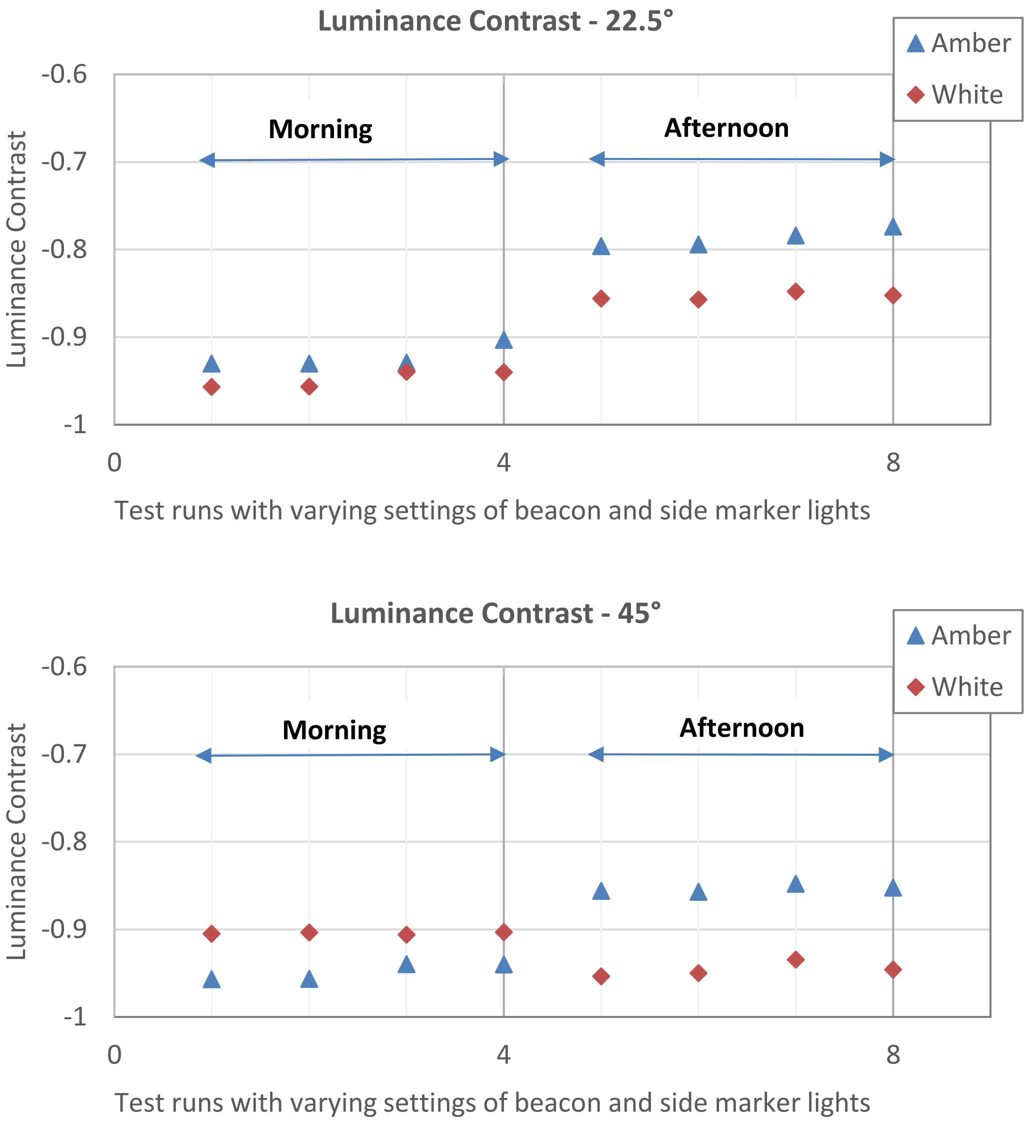


FIGURE 41. LUMINANCE CONTRASTS VALUES FOR MEASUREMENTS AT DIFFERENT TIMES OF THE DAY AND WITH DIFFERENT SETTINGS OF BEACON AND SIDE MARKER LIGHTS WHEN LOCOMOTIVE IS VIEWED: (TOP) AT 22.5° VIEW ANGLE AND (BOTTOM) AT 45° VIEW ANGLE

Table 8 lists the design variables (factors) and the two-levels of variation coded as -1 (for low levels) and +1 (for high levels) considered in the daylight visibility assessment at different times of the day. A full factorial design with $2^5 = 32$ runs was used to identify the main effects from the less important effects and assess the effects of additional lighting on the visibility improvements.

The full factorial design matrix for the 2^5 factorial design is shown in Table A.7 of Appendix A3, including main factor and two-, three-, four-, and five-factor interactions. Each row in the design matrix is independent of the others, ensuring that each estimated effect is unaffected by the values and levels of the others. Luminance contrast values were computed for each of the 32 independent runs.

TABLE 8. DESIGN VARIABLES (FACTORS) AND THEIR VARIATION LEVELS CODED AS LOW (-1) AND HIGH (1)

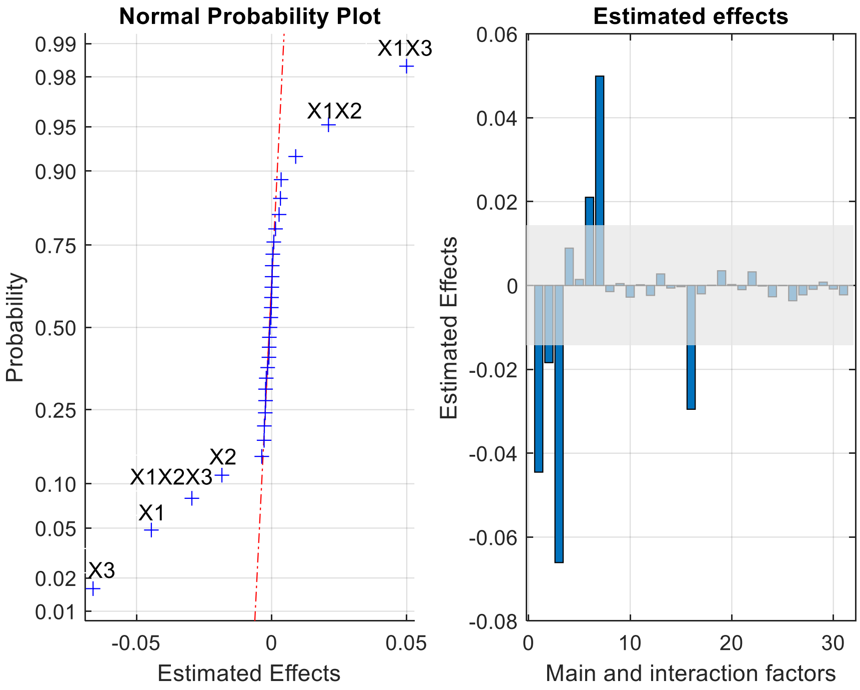
Term	**Variables to Consider (Factors)**	**Levels**	
		Low (-1)	**High (1)**
X1	View angle	22.5°	45°
X2	Colour of side marker light	Amber	White
X3	Sun direction (times of the day)	Afternoon	Morning
		Facing	Behind
X4	Beacon light	Off	ON
X5	Ditch light/ Side marker light	Off	ON

Figure 42 shows all estimated effects for the range of variations of the five factors. The effects are presented in a normal probability plot. Alternatively, the calculated effects can be illustrated on a bar chart, as shown in Figure 42. The 31 effects obtained from the measurements are plotted and the normal distributions centred at zero would form a straight line. As seen from the normal probability plots of effect estimates in Figure 42, main effects X1, X2, X3, and interaction effects of X1X2, X1X3 and X1X2X3 are outside of the normal probability line, indicating significant effect. All the other main effects, namely main effects of X4 and X5, and the interaction effects are within the normal probability line, indicating no significant effect.

X1 represents the effect of viewing angle, X2 represents the effect of colour of the side marker light, and X3 signifies the effect of time of the day (ambient light) and direction of sun. X4 and X5 represent the effects of beacon and side marker lights, respectively. X1X2 represents the interaction effect of viewing angle and colour of the side marker light, while X1X3 represents the interaction effect of viewing angle and ambient light. X1X2X3 represents the interaction of the three factors viewing angle, colour of the side marker light and ambient light. The bar chart in Figure 42 also highlights the main factors and interaction factors with highest estimated effects.

A reasonable assumption was made to estimate the standard error by considering the four- and five-factors interactions as largely due to noise, providing a reference for the remaining lower-order interaction and main effects. The shaded part in the bar chart of Figure 42 signifies the standard error, and the estimates of main and interaction effects within the range of the estimated error are considered insignificant.

The effects of viewing angle (X1), colour of the side marker light (X2), and time of the day (X3) cannot be interpreted separately due to the large two- and three-factor interactions. These three factors have the highest main effect, but as there are interaction effects, the effects of the three factors cannot be explained without considering the interaction effects. Given significant interaction effects of the viewing angle with colour and ambient light, the effects are analysed separately for the two viewing angles.

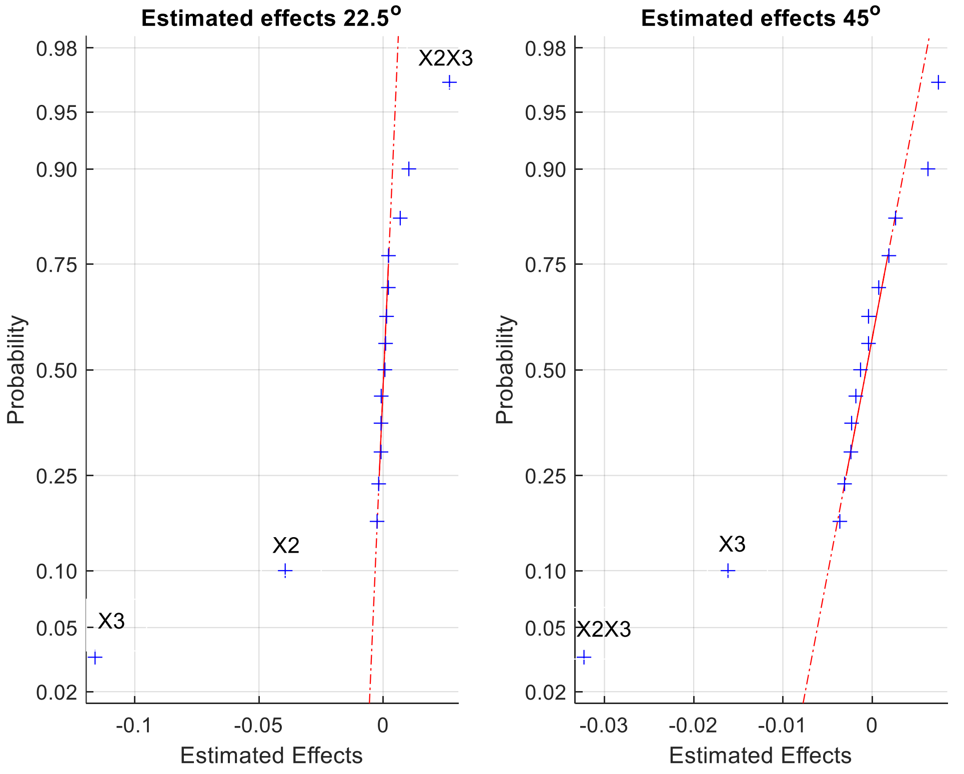


(A) (B)

FIGURE 42. EFFECTS ESTIMATES FOR MEASUREMENTS AT DIFFERENT TIMES OF THE DAY: (A) NORMAL PROBABILITY PLOT, AND (B) BAR CHART OF ESTIMATED EFFECTS

The experimental design was analysed separately for the two viewing angles, 22.5° and 45°. Each of the 16 runs was considered independently to exclude the effect of viewing angle (X1) variation in the effect analysis. Figure 43 shows the effect estimates for view angles 22.5° and 45° separately. Notably, the main effects of X2 (colour of the side marker light) and X3 (time of the day), as well as interaction effect of X2X3, are significant for the 22.5° view angle. Only main factors X3 and interaction effects of X2X3 are significant for the 45° view angle.

This analysis conclusively demonstrates that the colour of the side marker lights has significant effect on luminance contrast and the visibility of the locomotive, particularly at a 22.5° view angle. However, the effects of beacon lights, and the intensity of the marker lights/ditch lights are considered insignificant during daylight hours and in clear weather condition and cannot be distinguished from the standard error. Another important finding of this analysis is the highest interaction effect X1X3 (the interaction effect of viewing angle and time of day), which confirms that visibility is significantly affected by a combination of view angle and ambient day light.



(A) (B)

FIGURE 43. NORMAL PROBABILITY PLOT OF ESTIMATED EFFECTS FOR MEASUREMENTS AT VIEWING ANGLES OF (A) 22.5° AND (B) 45°

5.3.2 VISIBILITY IN VARIOUS WEATHER CONDITION

A light rain (mist) condition was simulated, and measurements were conducted to assess the effects of additional lighting when ambient visibility is reduced. Figure 44 show images of a locomotive captured from the measurement location in clear and misty weather conditions. Note the reduced visibility of the locomotive and the surrounding background due to the simulated mist condition. Measurements were conducted for view angles of 22.5° and 45° to compare the effects of additional lighting in clear weather condition and misty weather condition.

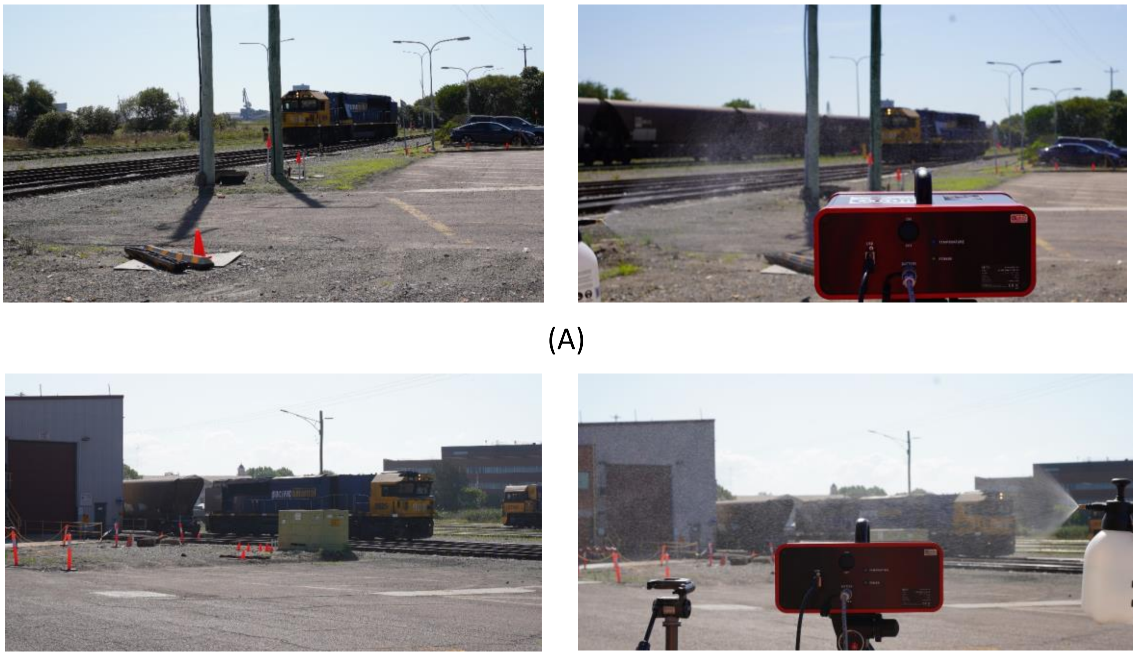
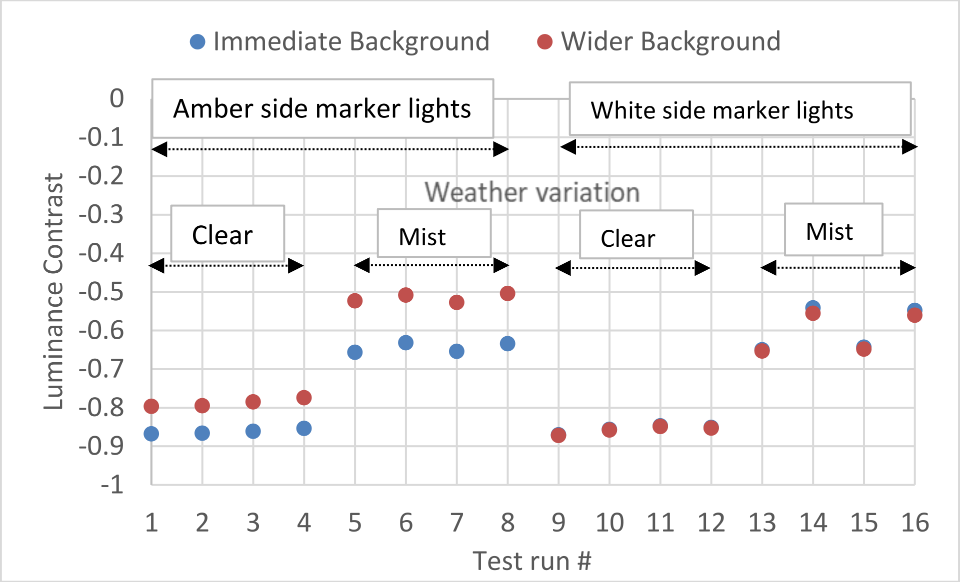


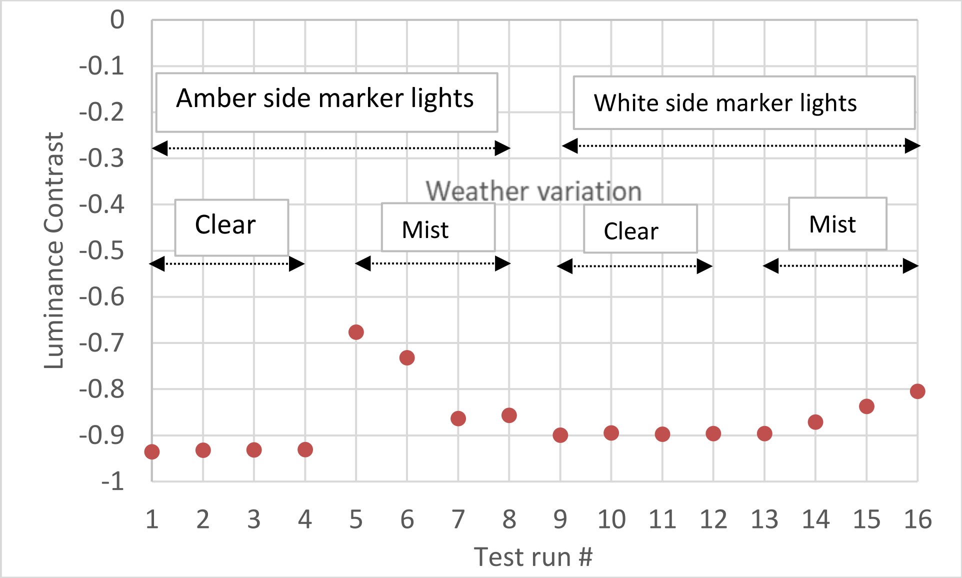
FIGURE 44. IMAGES OF A LOCOMOTIVE VIEWED FROM THE MEASUREMENT LOCATION IN CLEAR (LEFT) AND SIMULATED MIST (RIGHT) WEATHER CONDITION VIEWED AT VIEW ANGLES OF (A) 22.5° AND (B) 45°

Figure 45 shows the luminance contrast values for the 22.5° and 45° view angles for clear and misty condition. From the results it can be seen that the luminance contrast has increased in the misty conditions compared to the clear weather condition due to the locomotive lighting. For the 22.5° view angle, the luminance contrasts seem to be improved by 20% - 30% in misty conditions compared to clear weather condition, for both white and amber side marker lights. For the 45° view angle, the luminance contrasts seem to be improved by about 20% in misty conditions compared to clear weather condition for amber side marker lights. However, the luminance contrast seems to be improved by only 5% in misty conditions compared to clear weather condition when white side marker lights were used. To quantify the effects of the side marker light and the beacon light, the effects were analysed using a full factorial experimental design for the range of changes in the variables considered.

Again, a full factorial design with $2^5 = 32$ runs was used to analyse the effects additional lights in misty conditions. To exclude the effect of the change in sun direction (time of the day), experiments conducted under similar ambient light condition and sun direction were only considered. Table 9 lists the design variables (factors) and the two-levels of variation coded as -1 (for low levels) and +1 (for high levels) considered in the daylight visibility assessment with two levels of weather condition, i.e., clear and mist.



(A)



(B)

FIGURE 45. LUMINANCE CONTRAST VALUES FOR CLEAR AND MIST CONDITIONS WHEN LOCOMOTIVE VIEWED AT: (A) 22.5° ANGLE AND (B) 45° ANGLE. THE MEASUREMENTS INCLUDE FOR VARIATION IN BEACON LIGHT AND DITCH/SIDE MARKER LIGHT SETTING

A full factorial 2^5 design for the five factors, including the higher order interactions, was used for the analysis. Based on this design, with 32 independent runs, luminance contrast values were computed for each of the runs. The design variables (factors) and their variation levels are listed in Table A.8 of Appendix A3. The full factorial design in coded form for the $2^5 = 32$ independent combinations is included in Table A.9 of Appendix A3.

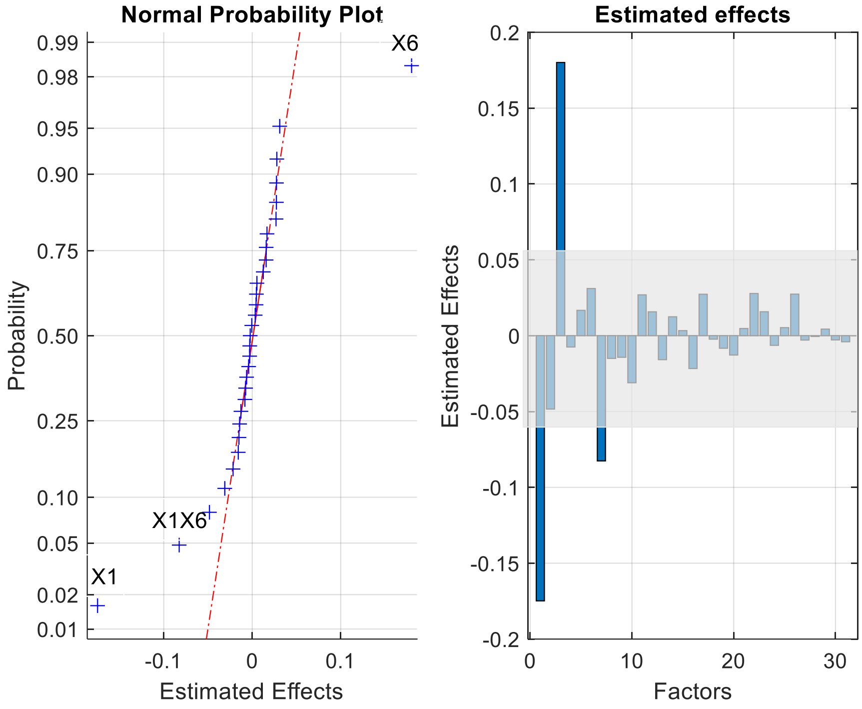
Table 9. DESIGN VARIABLES (FACTORS) AND THEIR VARIATION LEVELS CODED AS LOW (-1) AND HIGH (1) FOR VARIABLE WEATHER CONDITION

Term	Variables to Consider (Factors)	Levels	
		Low (-1)	High (1)
X1	Viewing angle	22.5˚	45˚
X2	Colour of side marker lights	Amber	White
X4	Beacon light	Off	On
X5	Ditch light/ Side marker light	Off	On
X6	Weather condition	Clear	Rain (Mist)

Figure 46 shows effect estimates for measurements at different weather conditions in terms of a normal probability plot and bar chart (refer to Tables A.8 and A.9 of Appendix A3 for details of 'Main Factors' and "Two-Factor Interaction"). There is a clear indication that the main effect X1 (viewing angle) and main effect X6 (weather condition), and interaction effect X1X6 (combined effect of view angle and weather condition) are significant, whereas the other effects are less significant. This could be due to the highest effect of the view angle and weather condition, undermining the effects of the lighting.

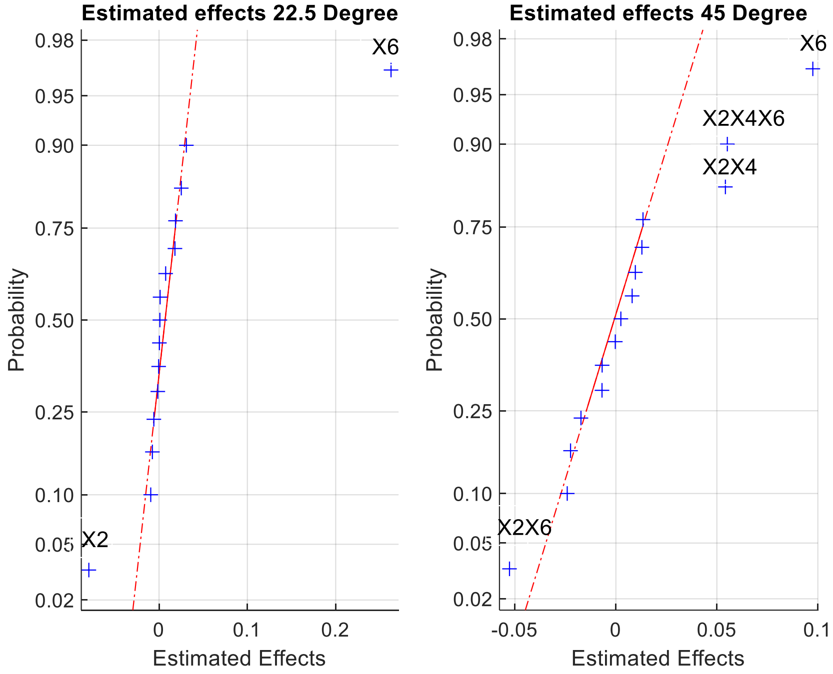
Further, the effect of the lighting at two different weather conditions was assessed, excluding the view angle from the variables. Figure 47 shows the effect analysis plots separately for measurements at 22.5˚ and 45˚ view angles. For 22.5˚ view angle, the colour of the side marker lights (X2) and the weather condition (X4) have the highest effects while the others have an insignificant effect. Notably, in misty weather conditions, the effect of changing the side marker light colour (X2) from white to amber colour improves the luminance contrast and hence the locomotive visibility by about 0.1 units, and this is approximately irrespective of the change of the other variables.

For the 45˚ view angle, in addition to the highest effect due to the weather condition (X6), there are interaction effects of side marker light colour and weather (X2X6), side marker light colour and beacon lights (X2X4), as well as three-factor interaction of side marker light colour, beacon light and weather (X2X4X6), which are relatively significant. The effect of beacon light for the 22.5˚ view angle is insignificant, whereas the result for 45˚ view angle indicates that the beacon light tends to affect the luminance contrast. The highest improvement in the luminance contrast can be obtained in misty conditions when the beacon light is on together with the amber side marker light.



(A) (B)

Figure 46. Effect Estimates for Measurements at Different Weather Condition: (A) Normal Probability Plot and (B) Bar Chart of Estimated Effects



(A) (B)

Figure 47. Normal Probability Plot of Estimated Effects with Two Levels of Weather Condition Measured at (A) 22.5° Viewing Angle, and (B) 45° Viewing Angle

The main effect of a factor should be individually interpreted only if there is no evidence indicating that the factor interacts with other factors. However, when there is evidence of one or more such interactions, the interacting variables must be considered jointly. From the effect analysis, the two-factor interaction effects of side marker light colour and weather (X2X6), and side marker light colour and beacon light (X2X4), as well as three-factor interaction of side marker light colour, beacon light and weather (X2X4X6), are found to be relatively significant.

To assess the effects of beacon light and side marker lights, for a specific scenario, the change in luminance contrast in clear and misty conditions was compared, as shown in Figure 48. For clear weather, the visibility improvement due to beacon lights and ditch/side marker lights is only 3%. About 20 % visibility improvement was obtained due to beacon lights only while 10% improvement was obtained due to ditch and white side marker lights, in misty condition.

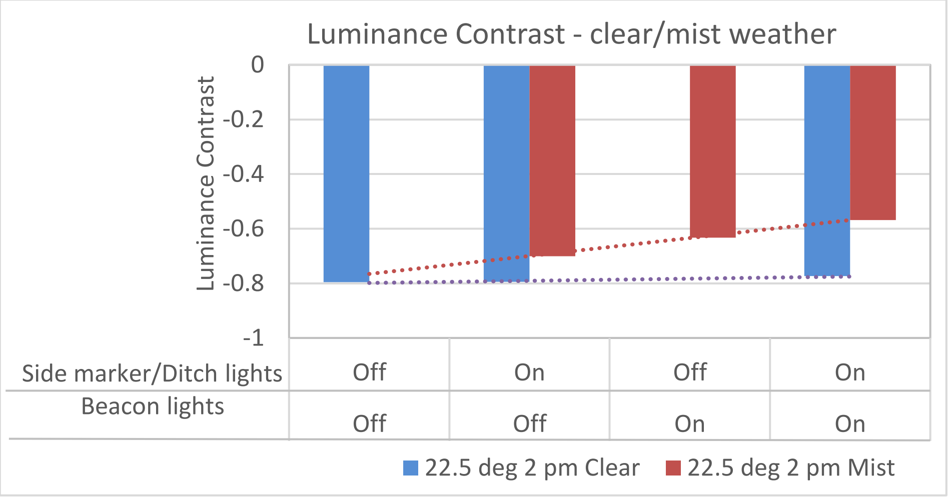


FIGURE 48. LUMINANCE CONTRAST IN MISTY AND CLEAR WEATHER CONDITIONS

5.3.3 VISIBILITY WITH VEGETATION OBSCURITY

The effects of beacon lights and side marker lights/ditch lights in a dense vegetation environment have also been evaluated. Variations in sun direction (time of day) and weather conditions have been excluded from the design variables. Experimental runs under similar ambient light condition and clear day were considered in the assessment. Table 10 lists the design variables (factors) and the two-levels of variation coded as -1 (for low levels) and +1 (for high levels) considered for visibility assessment in dense vegetation environment.

TABLE 10. DESIGN VARIABLES (FACTORS) AND THEIR VARIATION LEVELS CODED AS LOW (-1) AND HIGH (1) FOR VISIBILITY IN DENSE VEGETATION OBSCURITY

Term	**Variables to Consider (Factors)**	**Levels**	
		Low (-1)	**High (1)**
X1	Viewing angle	22.5˚	45˚
X2	Colour of side marker light	Amber	White
X4	Beacon light	Off	ON
X5	Ditch light	Off	ON
X8	Vegetation coverage	None	Dense

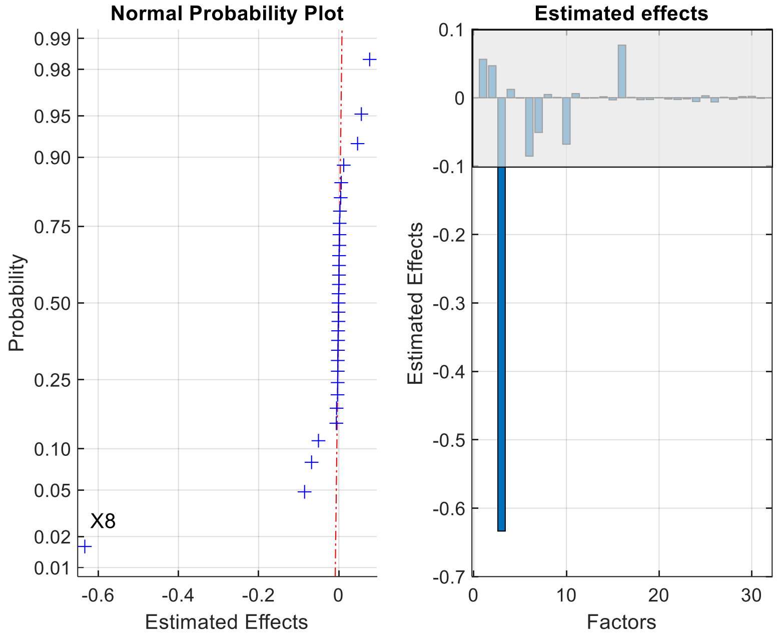
Again, for this scenario with five design variables, a $2^5 = 32$ full factorial design was used to analyse the effects of additional lights in dense vegetation obscurity. The design variables (factors) including obscurity factor and their variation levels are listed in Table A.10 of Appendix A3. The full factorial design for 5 variables with two levels of variation, $2^5 = 32$ is included in Table A.11 of Appendix A3.

All estimated effects based on the 32 independent measurement runs are shown in Figure 49. Using the design of experiment effect analysis, it is possible to determine which effects are significant and which effects are insignificant and can be explained by chance variation. Effects that are less than or equal to the standard error estimates can be explained as variation by chance alone or due to noise.

From the results of the duplicate runs, the standard deviation of the response was calculated and from which the standard error was approximated. Estimated main and interaction effects for the response luminance contrast are presented in normal probability plot in Figure 49. Effects least likely to be due to noise are outside of the shaded zone, which represents the estimated standard error. From the bar chart of Figure 49, the main effect X8 (vegetation coverage) seems to be convincingly higher than all the other main and interaction effects, and this effect cannot be explained by measurement error or noise.

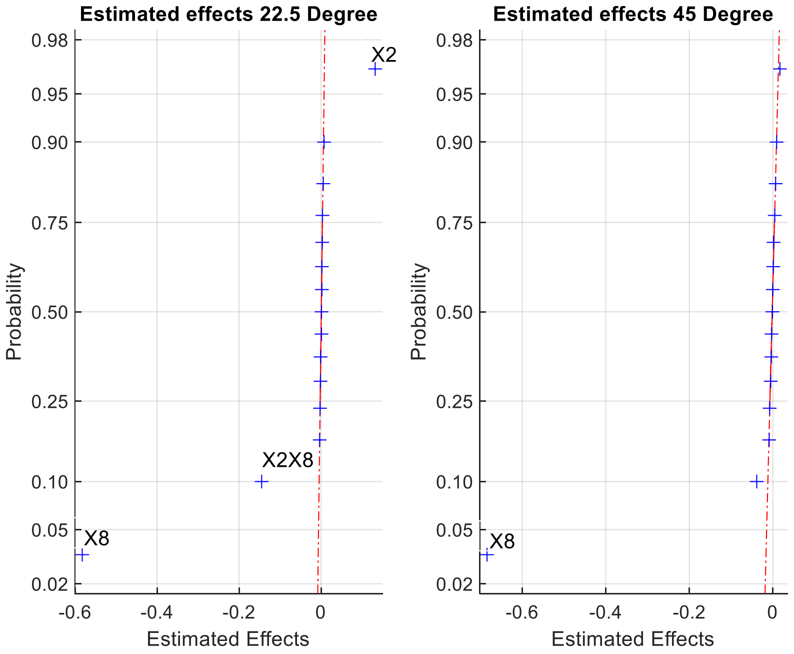
Alternatively, the effect analysis can be illustrated by plotting the calculated effects on a normal probability plot, as shown in Figure 49. The 31 effects obtained from the luminance measurement are plotted and the normal distributions centred at zero would form a straight line. Only the main effect X8 (vegetation coverage) is distinctly outside of the normal probability line. This is an obvious outcome, in the sense that dense vegetation physically obscures locomotive visibility. From the effect analysis, it can be concluded that the main effect of vegetation coverage is the only dominant effect, while the other main and interaction effects can be considered as insignificant.

The effect of the lighting in vegetation and clear condition is shown in Figure 50, separately for the two viewing angles. It can be clearly seen that vegetation obscurity has the highest and the only effect when viewed at 45˚ angle, while the colour of the side marker light (X2) has shown to have some effect when the 22.5˚ view angle was considered. The effect of the colour of the side marker light cannot be interpreted alone since there is evidence that it interacts with vegetation density (X2X8). However, the estimated effect of colour of the side marker light is considerably low, and it can be explained as variation by chance alone.



(A) (B)

Figure 49. Effects estimates for measurements at different vegetation density: (A) Normal Probability plot, and (B) Bar chart of estimated effects



(A) (B)

Figure 50. Normal Probability Plot of Estimated Effects Measured at (A) 22.5° Viewing Angle, and (B) 45° Viewing Angle

Further exploration was conducted to provide a physical interpretation of the effects of additional lighting in vegetation obscured condition. Measurements conducted at two separate locations with different levels of vegetation density (veg 1 and veg 2) and at two different times of the day (morning and afternoon) were used to assess the effects of lighting on visibility, as illustrated in Figure 51. Irrespective of the viewing angles, time of the day, and level of vegetation density, there seems to be no change in the luminance contrast due to change in the locomotive lighting setting. Hence, for vegetation obscurity scenario, the effect of side marker light and beacon light on locomotive visibility at all viewing angles are negligible.

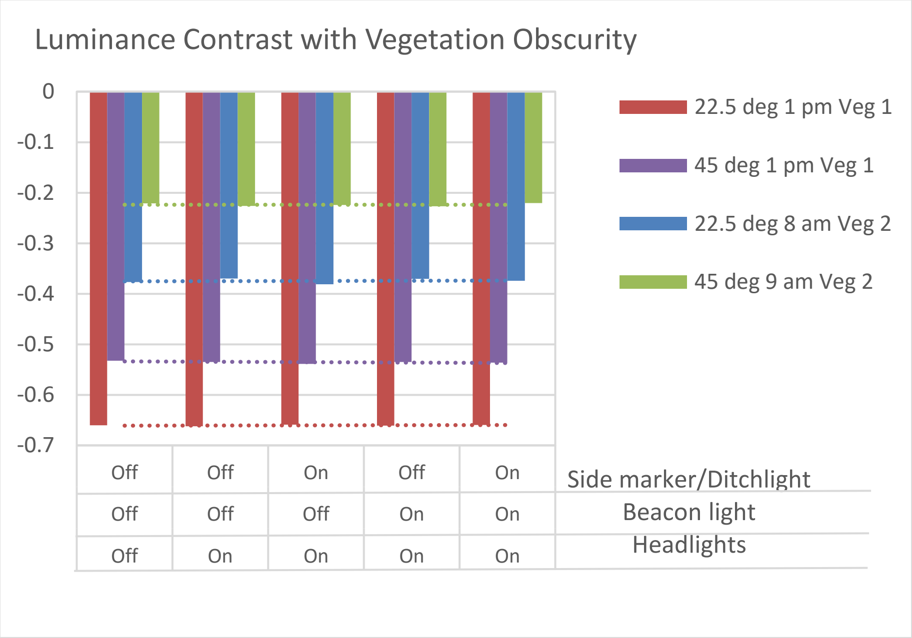


FIGURE 51. LUMINANCE CONTRAST AT TWO DIFFERENT LEVELS OF VEGETATION DENSITY

5.3.4 VISIBILITY AT SUNRISE AND SUNSET

The effects of beacon lights and side marker lights/ditch lights have been evaluated considering sunset and sunrise lighting condition. For this assessment, only white side marker lights were considered. The design variables and the range of variations in two levels for this scenario are listed in Table 11.

TABLE 11. DESIGN VARIABLES (FACTORS) AND THEIR VARIATION LEVELS CODED AS LOW (-1) AND HIGH (1) FOR VISIBILITY AT DUSK AND DAWN

Term	Variables to Consider (Factors)	Levels	
		Low (-1)	High (1)
X1	Viewing angle	22.5˚	45˚
X4	Beacon light	Off	On
X5	Ditch light/ Side marker lights	Off	On
X7	Time of the day (Ambient light condition)	Dawn	Dusk

The design variables (factors) and their variation levels for measurements at dawn and dusk are listed in Table A.12 of Appendix A3. The full factorial design for 4 variables with two levels of variation, $2^4 = 16$ is included in Table A.13 of Appendix A3.

Visibility of the locomotive is lower at dusk (sunset) and higher at dawn (sunrise), as shown in Figure 52. This could be due to the direction of the sun and the amount of the ambient light. The effect of the colour of the side marker lights was not considered but the effect of changing the side marker light between ‘on’ and ‘off’ states was evaluated.

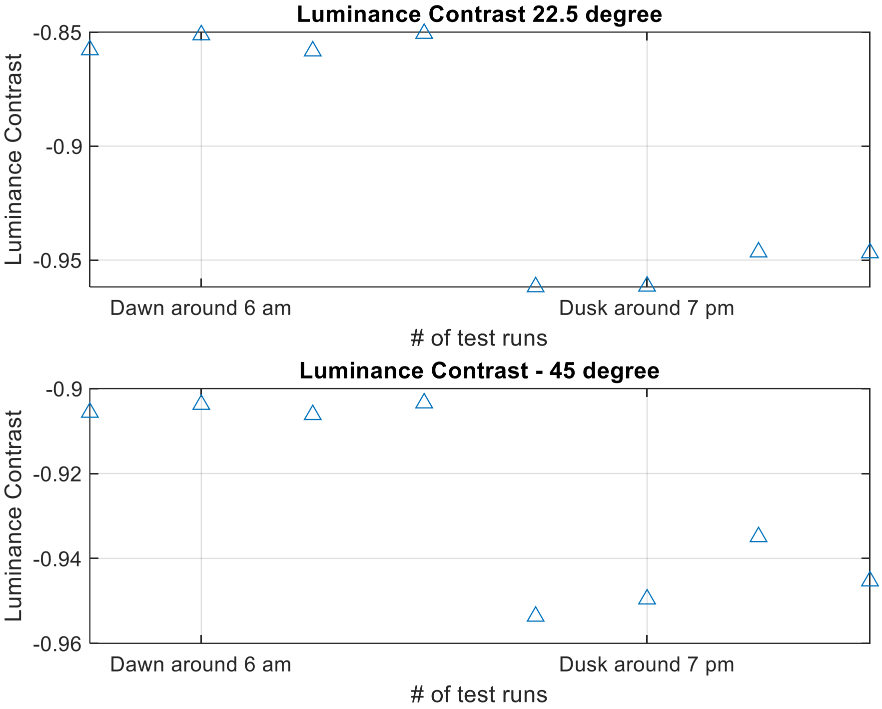
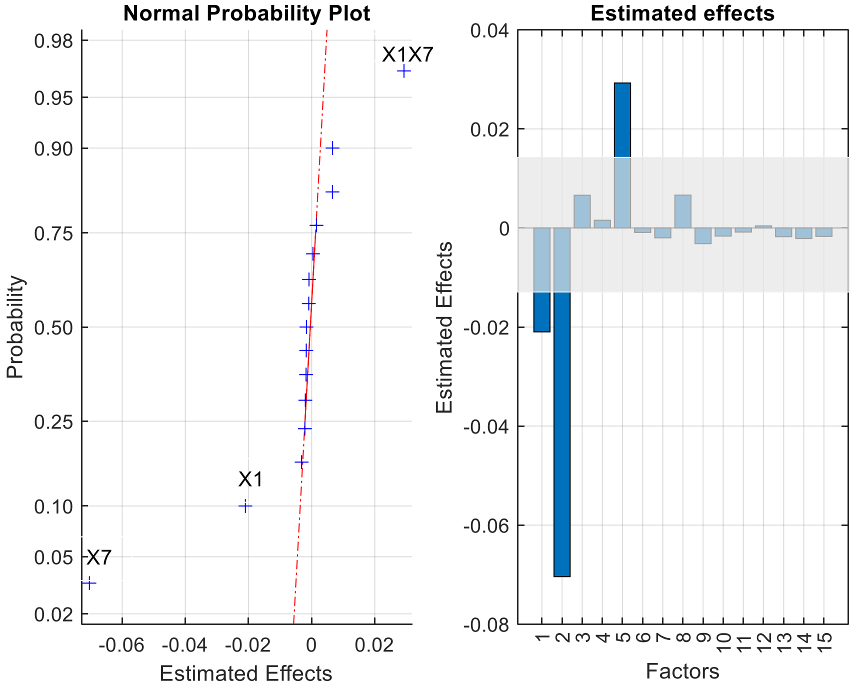


Figure 52. Luminance Contrasts Values for Measurements at Sunrise and Sunset When the Locomotive was Viewed at: (Top) 22.5° Viewing Angle and (Bottom) 45° Viewing Angle. The Measurements Include for Variation in Beacon Light and Ditch/Side Marker Light Settings

The results of the effect analysis are presented in Figure 53. There is a significant main effect of X1 (viewing angle) and X7 (ambient light), along with an interaction effect of X1X7. It is evident from the effect analysis in Figure 53 that there is no significant effect of beacon lights (X4) and side marker lights/ditch lights (X5) on locomotive visibility when viewed from both 22.5° and 45° angles. A similar observation was obtained for measurements conducted at different times of the day, as discussed in Section 5.3.1. The interaction effect of viewing angle and time the day (X1X3) was significant while the effects of beacon light and side marker light were negligible. The findings from the analysis considering the sunrise and sunset align with the results obtained when different times of the day was considered.

The following statement can be drawn from the effect analysis under different ambient light condition. Regardless of the additional lighting setting, for a given ambient light condition, the visibility of the locomotive can be worse at one viewing angle compared to the other. To give a physical interpretation of the results, locomotive visibility becomes worse at dusk when the locomotive is observed at a 45˚ view angle, while the same locomotive visibility improves at dawn and when viewed at 22.5˚ angle.



(A) (B)

FIGURE 53. EFFECTS ESTIMATES FOR MEASUREMENTS AT DIFFERENT AMBIENT LIGHT CONDITION: (A) NORMAL PROBABILITY PLOT, AND (B) BAR CHART OF ESTIMATED EFFECTS

5.4 NIGHT TIME MEASUREMENTS

The purpose of the night-time measurement was to assess the effects of additional lighting on locomotive visibility at night-time. The following aspects were assessed during the night-time measurement for frontal view, side view and at wider viewing angles:

- Effect of beacon light;
- Effect of side marker light; and
- Effect of side marker light colour.

For the measurement of white colour side marker lights, the yard light was positioned behind the locomotive side being measured, and the ambient light on the locomotive side was 0.15 lux, see Figure 54. In the case of amber side marker light measurement, the locomotive side was exposed to the yard light, and the measured ambient light was approximately 4.15 lux, see Figure 55. As can be seen from the images of Figure 54 and Figure 55, one side of the locomotive was illuminated due to yard lights. This difference in the ambient light was accounted in the subsequent analyses.

As discussed earlier, the background and target object (side of the locomotive) were defined, and the mean luminance for the defined ROIs were determined. Given the close range of the measurement location to the locomotive side (about 30 m distance), only the immediate background was considered (refer to Figure 21). The luminance contrast, calculated based on the mean luminance of the object and the background, for various lighting configurations tested at night-time is shown in Table 12.

(A) (B)

FIGURE 54. LOCOMOTIVE SIDE WITH WHITE SIDE MARKER LIGHTS (A) OFF, AND (B) ON. THE YARD FLOOD LIGHTS ARE BEHIND THE LOCOMOTIVE

(A) (B)

FIGURE 55. LOCOMOTIVE SIDE WITH AMBER SIDE MARKER LIGHTS: (A) OFF, AND (B) ON. NOTE THAT THE SIDE OF THE LOCOMOTIVE IS WELL-ILLUMINATED DUE TO THE YARD FLOOD LIGHT

TABLE 12. NIGHT TIME MEASUREMENT VARIABLES AND CALCULATED LUMINANCE CONTRASTS

Viewing circumstances (angle - distance)	**Headlight**	**Beacon light**	**Ditch and side marker lights**	**Side marker light's colour**	**Luminance Contrast**		**Ambient light (lux)**
					Immediate background	**Wide background**	
22.5˚ - 70 m	Low	Off	On	Amber	12.7	9.4	
22.5˚ - 70 m	High	Off	On	Amber	122.0	103.2	
22.5˚ - 70 m	Low	Off	Off	Amber	6	4.8	
22.5˚ - 70 m	High	On	On	Amber	123.5	104.2	
22.5˚ - 70 m	High	On	Off	Amber	151.1	128	
45˚ - 32 m	Low	On	Off	Amber	2.5		

45˚ - 32 m	High	On	Off	Amber	7.1		
45˚ - 32 m	Low	Off	On	Amber	1.6		
45˚ - 32 m	High	On	On	Amber	8.0		
45˚ - 32 m	High	Off	On	Amber	3.3		
0˚ - 100 m	Off	Off	Off	Amber	0.3	0.1	
0˚ - 100 m	Low	Off	Off	Amber	49.3	70.3	
0˚ - 100 m	High	Off	Off	Amber	53.3	79.3	
0˚ - 100 m	Low	On	On	Amber	23.3	23.2	
0˚ - 100 m	High	On	On	Amber	53.5	79.5	
90˚ ~ 30 m	Off	Off	Off	Amber	1.6		4.2
90˚ ~ 30 m	Off	Off	Off	White	-0.4		0.2
90˚ ~ 30 m	Off	Off	On	Amber	2.6		
90˚ ~ 30 m	Off	Off	On	White	15.23		

5.4.1 Effect of Lighting on Side Visibility

The locomotive was fitted with five side marker lights on each side, and the effects of side marker light intensity and colour on night-time visibility were assessed. Measurements were taken at a distance of about 30 m, viewing the side of the locomotive, in both ‘on’ and ‘off’ states of the side marker light.

It is evident that the effect of side marker lights becomes significant in low ambient light condition. Figure 56 shows the calculated luminance contrast of the side visibility for various lighting configurations. Due to variation in ambient light (background light) from the yard on the two sides of the locomotive, the luminance contrast values differ, despite the side marker lights were off for both cases, as seen in Figure 56. Images of the locomotive reveal that when all locomotive lights were off, one side was illuminated by the yard floodlight (see Figure 55(A)), while the other side (as shown in Figure 54(A)) was not. Thus, the luminance contrast of one side was 3.6 times higher than the other only due to the difference in ambient light conditions.

Measurement indicates an improvement in locomotive side visibility with the use of side marker lights. When the white side marker lights were on, the luminance contrast increased from -0.44 to about 15, equivalent to 34 times increase in side visibility. On the other hand, when the amber side marker lights were on, the luminance contrast increased from about 1.6 to about 2.6, resulting in merely 1.6 times increase in side visibility. There is a clear difference in the effects of the two different side marker light colours, although the impact of the ambient light is considerable. It is to be noted that the ambient light measurement on the side of the locomotive due to the yard floodlight was only 4 lux, while the intensity of the side marker light was 20 lux, as detailed in the lighting specifications in Table A.1.

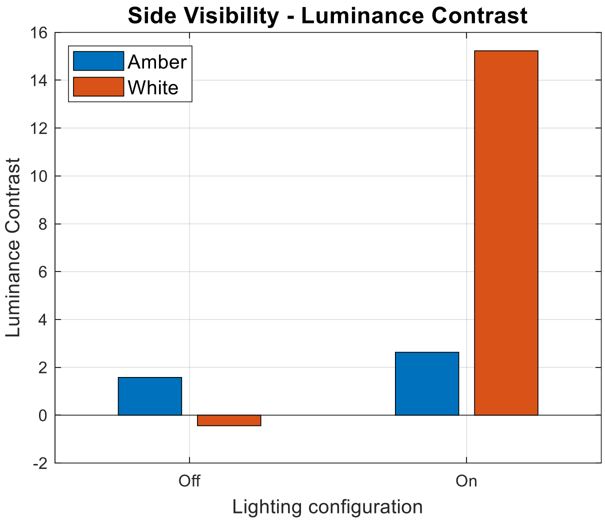


FIGURE 56. NIGHT-TIME SIDE VISIBILITY DUE TO SIDE MARKER LIGHTS

5.4.2 EFFECT OF LIGHTING ON FRONTAL VISIBILITY

The effect of beacon lights on frontal visibility was also assessed. The results discussed are only valid for the lighting configuration fitted at the time of the trial (refer to Table A.1 for the lighting specifications).

Figure 57 shows the luminance contrast for immediate and wider background ROIs when the locomotive was viewed at about 100 m distance from the front of the locomotive cab. The headlight setting varied (off, low beam, or high beam) and the beacon light configuration changed (off or flashing on) during the measurement to assess the effects of these lighting conditions on locomotive frontal visibility.

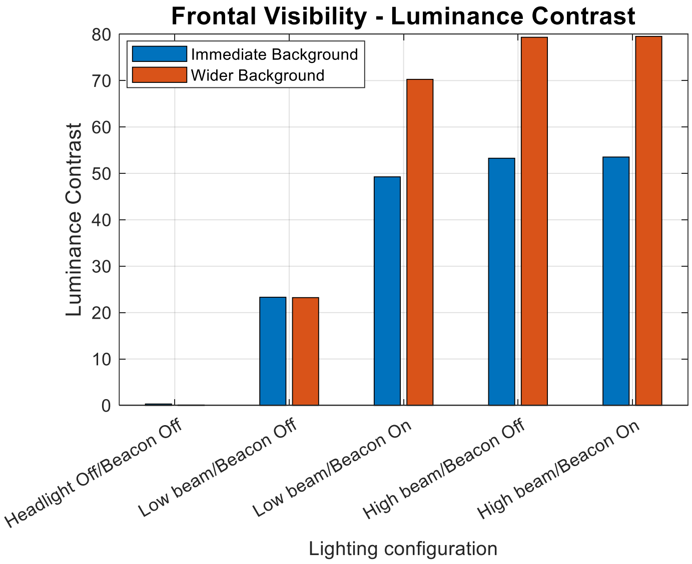


FIGURE 57. LUMINANCE CONTRAST VALUES FOR DIFFERENT LIGHTING CONFIGURATIONS FOR NIGHT-TIME FRONTAL VISIBILITY

When all the locomotive lighting was off, the luminance contrast, considering both immediate and wide background ROIs, was almost zero. It can be seen from Figure 57 that the headlight and beacon lights have an effect on the luminance contrast during night-time ambient lighting condition. The effect of the headlight is clearly more significant compared to the effect of the beacon lights. The locomotive frontal visibility increased by over 20 when the headlight was in low beam and the beacon light was off, while it increased by about 55 times more when the headlight was in high beam (refer to Table 12). These values consider the immediate background ROI when calculating the luminance contrast. The luminance contrast increased from about 23 to about 80 when the headlight was changed from low beam to high beam when a wider background ROI was considered. This is equivalent to an increment of 3.5 times more due to the change in the headlight beam setting.

The effect of the beacon lights is also considerable, as depicted in Figure 57. When the headlight was on low beam and beacon lights off, the luminance contrast was about 23. The value increased to about 70 when the beacon lights were on, simultaneously with the headlight on low beam. This is equivalent to an increase of 3 times due to the beacon lights only. However, the visibility increment due to beacon lights is almost nil when the headlight is in high beam. It can be concluded that the improvement in frontal visibility at night-time due to beacon light is almost the same as due to changing the headlight to high beam.

5.4.3 EFFECT OF LIGHTING ON VISIBILITY AT DIFFERENT VIEW ANGLES

The visibility improvement of the locomotive when viewed from different viewing angles was evaluated. Measurements were taken at 22.5° and 45° viewing angles, considering only amber side marker lights. The measurements at 22.5° viewing angle were taken from approximately 70 m distance from the front of the locomotive, while those at the 45° viewing angle were taken at a distance of about 32m.

A two-level fractional factorial design $2^{(4-1)}$ was developed to plan for eight independent runs in the night-time measurement. The results of each run were used to analyse the effects of the four considered factors on the visibility of locomotive at different viewing angles. Table 13 lists the design variables and their variation for the night-time measurements. The fractional factorial design in coded form for 4 variables with two levels of variation, with resolution III, $2_{III}^{(4-1)} = 8$ independent combinations is included in Table A.15 of Appendix A4.

TABLE 13. NIGHT TIME EXPERIMENTAL DESIGN FACTORS (VARIABLES) AND THEIR CORRESPONDING LEVELS OF VARIATION

Coded levels	Viewing angle	Beacon light	Ditch/side marker lights	Headlight
	X1	X4	X5	X10
-1	22.5°	Off	Off	Low beam
1	45°	On	On	High beam

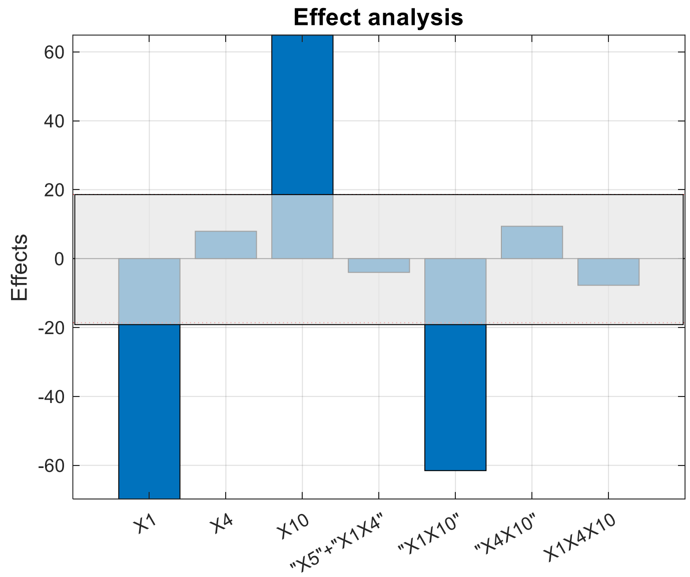


FIGURE 58. BAR CHART OF ESTIMATED EFFECTS DUE TO THE VARIATION IN THE DESIGN VARIABLES

Based on the results of the eight experimental runs, the main effects and interaction effects were estimated. Each experimental run was repeated, and the average of the two replicated runs was used as a response value, i.e., luminance contrast value.

Figure 58 shows the bar chart illustrating the effect estimates based on the eight independent runs. The effect of changing the viewing angle (X1) from 22.5˚ to 45˚, the headlight (X10) from low beam to high beam, and changing both simultaneously (X1X10) seem to give similar effects. The two main effects (X1 and X10) and the interaction effect (X1X10) are clearly distinguishable from the other effects and can be considered significant. However, the main effects of the beacon light and side marker lights, as well as their interaction effects with other factors, are not significant. The shaded area indicates the region where the estimated effects of factors and interaction effects are insignificant.

Alternatively, the effects of these parameters can be illustrated in the dot plot shown in Figure 59. The effect estimates marked by red ellipses are remarkably higher compared to the effect estimates of other factors or interactions.

The main observations from the above findings are that the estimated main effects of viewing angle (X1) and headlight (X10) are significant but also there is a significant X1X10 two-factor interaction effects. Changing the viewing angle to 22.5˚ while the headlight is changed to high beam will result in the highest effect, whereas changing the viewing angle to 45˚ while the headlight is changed to low beam will produce the lowest effect. A 22.5˚ view angle and headlight at low beam gives about the same visibility if the locomotive was viewed at 45˚ while the headlight is on high. This indicates that the headlight should be on high beam at level crossing with sharp angles.

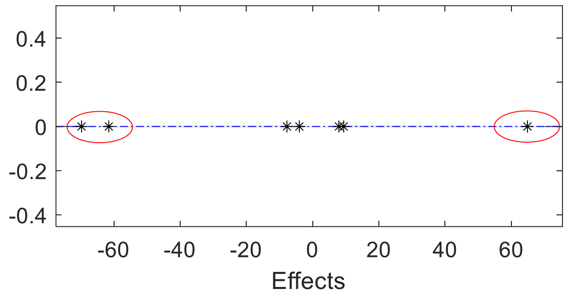


FIGURE 59. DOT PLOT OF THE EFFECTS FROM THE NIGHT TIME MEASUREMENTS

5.4.4 EFFECTS OF BEACON LIGHTS AND SIDE MARKER LIGHTS UNDER BROADER VIEWING CIRCUMSTANCES

The effects of the beacon lights and side marker lights were evaluated with the headlight kept in low beam for broader viewing circumstances, including frontal, side, and 22.5° and 45° viewing angles. Figure 60 illustrates the variation in luminance contrast for combinations of beacon lights and ditch/side marker lights. Only amber colour side marker lights were considered. The locomotive visibility is above a threshold luminance contrast value for all viewing circumstances and lighting combinations, due to the dark ambient background light.

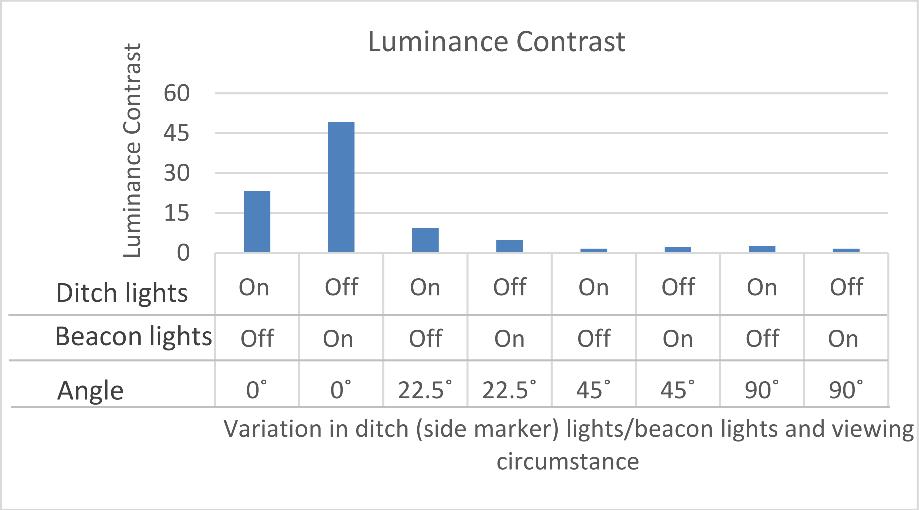


FIGURE 60. LUMINANCE CONTRAST VARIATION FOR COMBINATION OF BEACON AND SIDE MARKER LIGHTS UNDER BROADER VIEWING CIRCUMSTANCES IN NIGHT-TIME

The effect of the beacon light is more than twice that of the visibility (ditch) lights for frontal view (0° view angle), with luminance contrast around 49 for the beacon lights compared to approximately 23 for the visibility lights. It is to be noted that this effect becomes insignificant when the headlight is in high beam.

On the contrary, the effect of the ditch /side marker lights is significantly higher than that of the beacon lights at a 22.5° viewing angle. According to AS 7531 [8], visibility lights (ditch lights) shall be aimed between 7.5 and 15 degrees to the longitudinal centreline of the vehicle, producing at least 400 candela intensity at an angle of 20° from the centreline of the locomotive. The observed effect of the ditch/side marker lights at a 22.5° viewing angle aligns with these expectations.

However, at a 45° viewing angle, the effect of the beacon lights is approximately 40% higher compared to the effect of the ditch/side marker lights. Changing the view angle to 90° increases the effect of the ditch/side marker lights, resulting in the same level of visibility (luminance contrast) obtained at a 45° viewing angle due to the combined effect of the headlight at low beam, beacon lights, and ditch/side marker lights, see Figure 60.

This trial indicates that the side marker light improves locomotive's side visibility at night-time, providing a similar level of visibility as the 45° viewing angle. For the night time observations during the trials, there appears to be no significant light disturbance and no negative effect on the measurement crew due to the side marker lights in their current configuration over the range of factors considered in the trial.

6 SUMMARY

Improving the visual conspicuity of freight trains is one possible aspect to improve safety at passive level crossings. Freight locomotives often have less onboard lighting which may affect their conspicuity. Previous trials have assessed the improvement of freight locomotives' conspicuity through additional lighting or converting the type of head light from SEALED beam (halogen) to LED, with practical applications already in place. This assessment extends the previous field trials, which focused solely on LED headlights and frontal beacons, to include an assessment of the effects of additional lighting on both the front and sides of the locomotive, as well as its overall conspicuity from wider viewing angles.

The visual conspicuity of the locomotive depends on the actual luminance value of the locomotive as well as the luminance of the surrounding background. Viewing circumstances, such as distance to the locomotive and viewing angles, also influence visual conspicuity. Furthermore, the luminance of the locomotive is influenced by various factors, including ambient light, the direction of sun glare, intensity and colour of light emitted from the locomotive, livery and patterns of the locomotive, cleanliness of the locomotive visible surface, amount of reflectors, viewing conditions, etc. As the visual conspicuity of the locomotive is a relative factor (contrast) with respect to the background; the surrounding environment, natural light characteristics, and weather condition will also influence the conspicuity of the locomotive.

In consideration of an additional lighting scheme, trials have been conducted to evaluate the impact of installing flashing LED lights (beacon lights) on the front of locomotives, along with marker lights on each side of the locomotive, aimed at enhancing train visibility. An extensive field experiment was conducted to assess the effects of these two additional lighting features, involving various scenarios such as variations in ambient light, time of day, sun direction, weather conditions, physical obscurity due to vegetation, and viewing circumstances.

The assessment followed a three-stage approach. First, a test plan for three different field experiments was prepared using a design of experiment. Then, data were collected from the field for all three-test plans. Based on the collected photometric quantity, the effect of the additional lighting on locomotive conspicuity was assessed. The experimental plan, including the number of variations, trialled scenarios, and trial locations, was developed in consultation with the project team. The actual data collection was conducted collaboratively together with the project team, consisted of representatives from PN, ONRSR and Monash IRT.

The trial assessments used the change in luminance contrast as a physical measure of the relative visibility improvements due to the additional lighting rather than the absolute visibility of locomotive and its light fittings. One limitation of the current methodology is that it is based on static measurements, which do not consider the contrast sensitivity, the transient nature of ambient light, or the effect of the locomotive's speed.

The results and important outcomes from the trial assessment are summarised in this section. The key findings are presented in Table 14 and Table 15.

- Trials of locomotive PN9035 fitted with flashing LED lights (beacon lights) and side marker lights have been tested in both day time and night time conditions.
- In this investigation, visibility of a locomotive is defined in a measurable photometric quantity, luminance. Luminance is the amount of light emitted or reflected from a locomotive in a given direction and entering human eyes, and it is given in cd/m^2.
- A GL Opticam luminance camera was used in the current study to measure luminance quantities. This device has been validated and calibrated in the earlier trial at WA.
- Over 500 luminance measurements were collected in various scenarios, with various lighting settings and at different times of a day. The scenarios included dense vegetation condition, simulated misty weather condition, different daylight conditions including sunrise and sunset, and night-time measurements.
- The measured luminance value was used as the visual conspicuity quantity of a locomotive in various lighting arrangements. A term "visibility index (conspicuity index)" is developed to describe improvement or reduction in visual conspicuity of a locomotive. It is based on the luminance quantities of the object and surrounding background, emphasizing the contrast between the two. This is a relative value for a given setting and it is not an absolute value of how much better or worse the conspicuity of the locomotive is. It rather gives an indication whether the conspicuity has improved or worsened.
- Regions of interest (ROIs) for the background and the locomotive boundary were defined for the contrast analysis. Different fields of view were assessed, and immediate and wider background ROIs were defined, considering different fields of view and observation distances.
- Visibility at frontal, side and broad viewing angles, up to 90˚ view angle of the locomotive were assessed, using consistent ROI definition during both day and night measurements.

Reference Testing during Daylight

- Reference measurements were conducted at 105 m and 240 m distances to define luminance contrast and luminance ratio thresholds to use in the subsequent visibility assessments. A luminance ratio of 1.25 and a luminance contrast of 0.25 is considered as the threshold value for frontal locomotive visibility, equivalent to visibility index of 0.75 for optimal visibility of the locomotive.

- Luminance values showed variations based on locomotive's lighting conditions, ambient light, observation distances, and background ROIs. The effect of the transient ambient light is not accounted for in the current assessment methodology.
- Negative luminance contrast values are indicative of situations where the background luminance is higher than that of the locomotive. Higher luminance contrast values mean higher visibility indices which signify easier detection of the locomotive from the background region. With the locomotive lighting on, positive luminance contrast values indicate the locomotive can easily be noticed without requiring extensive searching.
- Ambient light has a strong influence in both night and daytime measurements, and sun direction affected locomotive visibility.
- The effects of various lighting configurations on the visibility of a locomotive's front and side views have been assessed.
- Viewing distance demonstrates an effect in frontal visibility, as visibility improvement was more pronounced at 240 m compared to 105 m.

Day-time Testing

- The headlight (SEALED beam) contributed to a substantial improvement of the frontal visibility, over 100% visibility improvement, while visibility lights (ditch lights) had a minor effect.
- At 105 m distance, the luminance contrast increased from about -0.9 to about -0.5, approximately a 44% increase, when the headlight setup changed from off to high beam. In contrast, at 240 m distance, the luminance contrast increased from about -0.7 to about 0.47, approximately a 117% increase, when the headlight setup changed from off to high beam.
- The beacon light does not have any effect on visibility improvement in daylight hours under clear conditions. However, when ambient light changes, and the weather is in a simulated misty condition, there is a considerable effect from the beacon lights.
- Side marker lights showed minimal visibility improvement during clear daylight condition.
- The colour of the side marker light showed a significant difference both during night measurements and in daytime during reduced visibility. Amber side marker lights give better locomotive visibility than white side marker lights under simulated misty condition.
- Front marker lights showed negligible effects on visibility, with no significant change in luminance contrast.

Night-time Testing

- The night-time assessment covers frontal, side, and wider viewing angles, to assess the effects of beacon lights, side marker lights, and colour of side marker light.

- Side marker lights, especially white colour lights, gives a significant improvement in side visibility at night, improving the visibility by about 12 fold. This improvement is achieved without significant light pollution at the current lighting configuration.
- The headlight and beacon light configurations have a substantial effect on frontal visibility at night. When considering broader view angles, the effect of headlight is significantly influenced by the viewing angle.
- There is a significant difference in the luminance contrast values between day time and night time measurements. For example, at 105 m distance, the day time measurement indicates that the luminance contrast increased from about -0.9 to about -0.5 when the headlight setup changed from off to high beam, which is approximately a 44% increase in the luminance contrast. Note that the current trial considers SEALED beam headlights only. In comparison, during night measurements at about 100 m distance, the luminance contrast increased from about 0.1 to 79 when the headlight setup changed from off to high beam, representing about a 790-fold increase in the luminance contrast. The above data indicates a significant difference in the luminance contrast between the day and night time measurements due to the lighting effect, with locomotives being more visible at night. This could contribute to the lower number of level crossing collisions at night.
- Beacon lights have a significant effect on frontal visibility when the headlight is in low beam, while the effect becomes less significant as the viewing angle increases. The beacon light is more significant than visibility light when the viewing angle is 45˚.

Beacon Lights

- Have an insignificant effect in daylight at 105 m and across all viewing angles when the headlight is in high beam.
- Provide an improved visibility in simulated misty conditions, but with no observed effect in dense vegetation.
- Significantly enhance frontal visibility in night time when the headlight is in low beam setting, while the effect is negligible when the headlight is in high beam.
- Have a significant effect at night when the observation angle is 45˚, irrespective of the headlight setting.

Side Marker Lights

- Provide a strong effect during night-time.
- Provide improved visibility in simulated misty conditions, but with no observed effect in dense vegetation.
- White coloured side marker lights showed a higher visibility during night measurements than the amber colour. Note that the locomotive and the surrounding were illuminated by flood lights for the case of the amber side marker light trials.
- Amber coloured lights have a slightly higher effect in simulated misty conditions but the colour of the side marker lights has little effect during clear daylight.

Front Marker Lights

- Provide no significant improvement in daytime visibility.
- There is no significant difference based on the colour of the front marker lights.

Headlight

- Provides a significant effect in visibility with up to about 117% increase in visibility when the headlight is on high beam. The headlight used in the current trial is SEALED beam.

Table 14. Summary of the Measurement Results During Daytime

Viewing circumstances	Lighting Type			
	Beacon Light	**Side Marker Light**	**Front Marker Light**	**Headlight**
240 m (clear condition)	Less effect (Headlight low beam)	N.A	No effect	Significant effect (high beam)
105 m (clear condition)	Less effect (Headlight low beam)	N.A	N.A	Less effect (high beam)
22.5° (clear condition)	No effect	No effect	N.A	Significant effect (high beam)
22.5° (Mist Condition)	Less effect	Less effect (Amber colour)	N.A	Significant effect (high beam)
45° (clear condition)	No effect	No effect	N.A	Less effect (high beam)
45° (Mist Condition)	Less effect	Less effect (Amber colour)	N.A	Less effect (high beam)
90° (clear condition)	No effect	Less effect (Amber colour)	N.A	N.A
Vegetation	No effect	No effect	N.A	No effect

Table 15. Summary of the Measurement Results During Night Measurement

Viewing circumstances	Lighting Type			
	Beacon Light	**Side Marker Light**	**Visibility Light**	**Headlight**
100 m	Significant effect (Headlight low beam)	N.A	Significant effect (Headlight low beam)	Significant effect (Headlight high or low beam)
22.5°	Less effect (Headlight low beam)	Less effect	Significant effect (Headlight low beam)	Significant effect (Headlight high or low beam)
45°	Significant effect (Headlight high or low beam)	Less effect	Less effect (Headlight low beam)	Significant effect (Headlight high beam)
90	N.A	Significant effect (White colour)	N.A	N.A

The important findings above means that there is no significant locomotive conspicuity improvement in clear daylight due to the addition of beacon lights or side marker lights, irrespective of the colour of the side market lights. However, the additional lighting has an effect during simulated misty weather conditions. These daylight results suggest that visibility improvement is influenced by a combination of headlight state, viewing circumstances (distance and angle), the direction of the sun and the ambient surrounding light. This implies that the trialled lighting solution may have a different effect depending on the layout design of the level crossing considered. Hence, the headlight should be on high beam at level crossings with sharp angles. In cases where the rolling stock operators' procedures require high beam not to be used for operational reasons, beacon lights may be considered to achieve a similar visibility level.

At night, the luminance contrast measurements confirm the obvious and expected effect of lighting on improving visibility. The current study reveals another perspective on the relationship between visibility and safety improvement at level crossings. The locomotive lighting significantly improves visibility at night, consistent with data showing that most level crossing collisions happen during the day [9]. This suggests a basis for the industry to focus on increasing luminance contrast during day time.

This finding is solely based on analysing the photometric quantity by measuring the luminance of the locomotive and the surrounding environment. However, additional factors such as locomotive livery, shape and form of the locomotive, not included in the current trial, may have significant effect on locomotive visual conspicuity in daylight hours. Future trials should include these factors including the effects due to varying lighting colour and pattern. Further, the safety benefit and the health effect of the additional lighting on locomotive drivers and other level crossing users, not been looked at in this trial, have to be evaluated.

7 CONCLUSIONS

This project aimed to assess the effect of the additional lighting, such as beacon lights and side marker lights, as well as existing locomotive lighting such as front marker light, visibility light and headlight, on locomotive visibility, primarily during daylight but also at night. The assessment focussed on the effects of frontal beacon lights and side marker lights in different environmental and ambient light conditions. An extensive field experiment was conducted to assess the effects of the two additional lights.

The effects of the trialled lighting on the visual conspicuity of a locomotive are assessed based on scientific principles and statistical procedure. The assessment used a measurement procedure to quantify the visual conspicuity of a locomotive in various lighting arrangements. This method allows the visual conspicuity or visibility of the locomotive, for any change in the colour or lighting, to be easily and quickly evaluated without a need for human observers. Only the photometric quantity luminance of the object and the surrounding background were considered as measurable quantities. The accuracy of the current method has been validated through a comparison in previous trials conducted in WA at Aurizon facilities.

From the lighting perspective, the visual conspicuity of the locomotive depends on the actual luminance value of the locomotive as well as the luminance of the surrounding background. Luminance is the amount of light emitted or reflected from an object in a given direction and entering human eyes, and it is given in cd/m^2. The measured luminance value was used as the visual conspicuity quantity of a locomotive in various lighting arrangements and under various background environments.

Over 500 luminance measurement datasets were gathered under different scenarios, with various lighting settings, and measurements repeated at least two times when the flashing beacon light setting was turned on. The current assessment includes visibility at frontal, side and broad viewing angles, up to 90˚ view angle. The scenarios assessed in the current trial includes dense vegetation condition, simulated misty weather condition, different daylight conditions including sunrise and sunset, and night-time measurements.

Based on the measured luminance values, the relative luminance (luminance contrast) was determined as a visibility indicator. Regions of interest (ROI) for the locomotive boundary and the background boundary were defined, and luminance contrast between the two ROIs was computed for each dataset. It is important to note that the luminance measurement of the background and the object can change due to the transient nature of the ambient light (e.g., due to cloud cover); however, the effect of transient ambient light was not accounted for in the current assessment. All measurements were considered as static. Hence, future assessments may need to consider the transient factor as well as the effect of moving targets (objects).

Higher luminance contrast values signify easier detection of the locomotive from the background region in comparison to the case with no additional lighting. Negative luminance contrast values are indicative of situations where the background luminance is higher than that of the locomotive. With the locomotive lighting on, positive luminance contrast values mean that the locomotive is conspicuous against the background which indicate that the locomotive can easily be discerned by an individual. One of the limitations of the current AS 7531 is that it does not specify acceptable luminance contrast levels for locomotives visual conspicuity. A future review of AS 7531 should include a list of reference background luminance values. This should take into account diverse scenarios such as variations in weather and environment. The aim is to specify luminous intensity requirements of locomotive lighting, considering the efficacy the lighting has on rolling stock visibility viewed at wide view angles up to 90˚. The Australian Standard should additionally specify a reference or threshold visibility value, indicating when the locomotive is considered visible. This will assist locomotive lighting designers in selecting lighting that will achieve the necessary visibility output.

One approach to defining a visibility index, a physical measure for visibility performance, is the ratio between the luminance contrast and a reference threshold luminance contrast, without needing to account for relative contrast sensitivity or disability glare factor. This threshold luminance contrast value can define the perception of an object's visibility, with the minimum threshold marking the boundary between visible and less visible luminance contrast levels. Objects that do not reach contrast threshold cannot be perceived. Achieving a minimum luminance contrast under various environmental, weather and ambient light conditions is crucial for locomotive lighting and livery design to ensure optimal visibility. Thus, the study underscores the importance of incorporating acceptable threshold limits for luminance contrast for locomotive visibility considerations. These threshold luminance values can be developed and validated through psychophysical and psychological tests involving various scenarios and test cases.

The visibility model adopted in the current analysis is based on the relative luminance of the locomotive and the surrounding background. To have a consistent definition and analysis model, the definitions of luminance contrast, the range of field of view for the background region, and other relevant visibility analysis models need to be addressed in the Australian Standard. Furthermore, AS 7531 should specify viewing angles and measurement distances that the luminance values should be measured, also considering the Australian Level Crossing Assessment Model (ALCAM) conditions. AS 7531 should also include a method for measuring the luminosity of the lighting and contribution of the livery of the locomotive in relation to locomotive conspicuity.

The Opticam system and luminance measurements have not been used in railway visibility studies, except for this specific set of trials, earlier in WA and currently at the trial in NSW. The Opticam system was specifically introduced to Australia especially for the purpose of this trial, to provide quantitative data across a wide field of view. It is highly recommended to benchmark the measurements and the adopted methodology against well-advanced and established use cases, such as those in road marking, road lighting and tunnel entrance visibility.

The frontal visibility of the locomotive at about 100 m observation distance improved by only 1.8 times during day time due to the locomotive lighting, while the improvement was 790 times greater during night. This discrepancy is expected given the significantly lower ambient light at night. Nevertheless, this data is significant as it provides insight into the relationship between locomotive visibility and level crossing safety.

As reported in the 2009 update to the Train Illumination Report [9], between 75% and 94% of all level crossing collisions occur in daylight hours. This can be largely attributed to the higher traffic levels experienced during daytime operation. However, the current study reveals another perspective, indicating that locomotive lighting significantly improved visibility at night. This finding aligns with data showing that most level crossing collisions happen during the day. This may indicate the need for the industry to focus on ways to increase daytime luminance contrast.

Consistent with previous findings from trials in WA on a CBH class locomotive, the effect of beacon lighting, in its current configuration, on locomotive visibility under clear daylight conditions is insignificant. It is important to note that the results from front beacon light testing canot be directly compared to the previous report on measurements in WA due to differences in beacon light installation. The CBH class locomotive has a tapered brow above the windscreen, whereas on the PN 90 Class, the brow is flat.

The current trial revealed a significant effect from the beacon light in simulated misty conditions when general ambient visibility is low. Additionally, the effect of the beacon light was considerable at night when the headlight is on low beam. Locomotive frontal visibility increased by threefold due to the beacon lights alone. However, the visibility increment due to beacon lights is almost negligible when the headlight is on high beam. It is important to note that the headlight in the PN9035 locomotive is a SEALED beam headlight, not an LED headlight. The beacon light proved particularly significant in wider view angles. Comparable visibility improvement is obtained with the beacon light at night, as with the headlight on high beam when the observation angle is at 45°, and the headlight on low beam at frontal visibility and 22.5˚ view angle. It can be concluded that the beacon light proves effective in improving locomotive visibility at night and in misty conditions, particularly when viewed at 22.5˚ and 45˚ angles. Therefore, in rail networks where the standard practice is to use the headlight on low beam when approaching level crossings, the beacon light can provide a similar level of visibility as that achieved with the headlight on high beam.

Although the intensity of the side marker lights is low, and the operation of the side marker lights was coupled with the ditch lights during the trial, the side marker lights demonstrated an effect in simulated misty conditions and a very significant effect at night. No improvement is observed due to the side marker lights in dense vegetation and in clear daytime. The colour of the side marker light has shown a significant effect both in misty conditions and at night. White side marker lights increased the luminance contrast by about 6 times more than the amber colour; nonetheless, the night time visibility improvements due to amber colour is still very significant. Note that the ambient light was different during the two locomotive side visibility measurements at night. In daylight conditions, amber side marker lights showed a slightly higher effect than the white side marker lights, despite the lights' low intensity. Hence, it can be concluded that amber side marker lighting gives better locomotive visibility. A light lens protective cover that adapts and changes colour in daytime and night time operation could be effective.

Further trials can be conducted using side marker lights with higher luminous intensity than the ones currently trialled to determine the light intensity level that may lead to improved side visibility without significant effects on health and light pollution to the surrounding. Adaptive lighting that increases intensity in daytime operation and misty weather conditions while reducing for night operations may reduce the light pollution effects during night that may occur due to side marker lights. Additionally, side marker light trials can include different fitting angles to illuminate the locomotive body and assess their impact on visibility improvements.

The study concludes that there is no significant improvement in locomotive conspicuity in clear daylight due to the addition of beacon lights and side marker lights at their current configurations, regardless of the colour of the side marker lights. However, there is a significant improvement in locomotive conspicuity during the night. The additional lighting has also enhanced locomotive conspicuity in simulated misty weather conditions. Hence, any future review of AS 7531 should consider the effects of the beacon lights and side marker lights for the potential visibility improvement during night and misty weather conditions.

The effect of the front marker light, in its current configuration, on locomotive visibility is negligible. It is important to note that the objective of the current assessment is mainly to evaluate the effects of locomotive lighting on its overall visibility. The assessement considered the relative luminance between the locomotive with its lighting and the surrounding background. The visibility of the marker lights themselves was not assessed in the current evaluation. The definition of the object and background as well as the viewing circumstances would be different for the assessment of the visibility of the marker lights. However, the luminance measurements do not show any difference between the two front marker lights. The colour of the front marker lights was also indistinguishable during the daytime measurements from a distance of 240 meters. According to AS 7531, locomotives shall have red tail and white marker lights fitted as high and wide as practical, at both sides of each end. The purpose of the marker light is to indicate which direction the train is travelling. The visibility of the front marker lights, especially the red marker, in its current configuration, need further assessment, also with higher intensity front marker lights.

The glare and spill effects of the beacon and side marker lights on adjacent locomotives' drivers cabs and into the surrounding neighbourhood have not been investigated. From the trials, both in daytime and night time, there appears to be no significant light pollution due to the addition of beacon lights and side marker lights. However, the health effects of the additional lighting to the train crew, light pollution effects on the surroundings, and the potential to "dazzle" road users need to be assessed.

The current trial focuses solely on lighting solutions, with the assessment based on analysing luminance contrast. However, factors such as livery, shape, and form of the locomotive body are not considered in the current visibility assessment. Further trials and assessments are necessary, incorporating livery design, colour with texture, patterns, lighting arrangements, or other alternative designs to evaluate their effect on locomotive conspicuity. These assessments should also take into account colour designs for road users with colour vision deficiencies.

8 RECOMMENDATIONS

8.1 KEY RECOMMENDATIONS

The following are key recommendations based on the assessment conducted during the lighting trials:

- The assessment for daylight conditions indicates that visibility improvement is a combination of main headlight state, viewing circumstances (observation distance and angle), and the direction of the sun. Locomotive visibility is low when the observation angle is large and the headlight is in low beam. Comparative visibility improvement is achieved when the headlight is in high beam. This implies that, for level crossings with sharp angles headlights on “high beam” can improve locomotive visibility.
- The assessment at night condition indicates that the efficacy of the beacon light is significant when the headlight is on low beam, particularly in wider view angles. In situations where the rolling stock operators' procedures restrict the use of high beam for operational reasons (such as avoiding potential dazzling effect on oncoming road or rail traffic), beacon lights can improve the luminance contrast levels (visibility) of locomotives.
- The side marker lights demonstrated an insignificant effect during clear daytime conditions due to the low intensity lights used in the current trials. If the side marker lights are used, it is recommended to use higher luminous intensity than currently trialled to improve luminance contrast levels (visibility) of locomotives.
- Due to the increased efficacy the additional lighting has on locomotive conspicuity during the night at wide view angles and in simulated misty weather conditions, the industry should consider the use of beacon and side marker lights as a means to improve the luminance contrast levels (visibility) of locomotives.
- In line with the above remarks, the next review of AS 7531 should consider beacon lights and side marker lights with higher light intensity than currently trialled, as a means to

improve the luminance contrast levels (visibility) of locomotives, subject to impact assessment on road users and other rail traffic.

- One of the limitations of the current AS 7531 is that it does not specify acceptable luminance contrast levels for locomotives visual conspicuity. A future review of AS 7531 should include a list of reference background luminance values, that consider diverse variations in weather and environmental conditions. AS 7531 should additionally specify a reference or threshold visibility value at which the locomotive is considered visible, which can be used by the industry in the choice of lighting, lighting colour and locomotive livery.
- AS 7531 should also include a method for measuring the luminance of the lighting and the contribution of the livery of the locomotive in relation to locomotive conspicuity.
- In level crossings with dense vegetation or other visual obstruction, the measurement results of the additional lighting solutions suggest low or no efficacy on locomotive visibility improvement. Therefore, the following recommendations are proposed:
    - Clear vegetation to remove visual obstructions.
    - Incorporate into the design of level crossings requirements for clear visual observation of oncoming trains by road traffic users.
- Assess the potential impact of the additional lighting on human factors and health, especially considering the introduction of lights with higher luminance or flashing. Consider benchmarking with other countries, such as the Code of Federal Regulations [14, 15], to ensure that any enhancements do not compromise safety or result in significant discomfort and light pollution to train drivers, observers, and the general public.
- The current trial was conducted with a cleaned livery. As deliberated during the earlier trials at WA, the cleanliness of the livery has a significant effect on its conspicuity. Therefore, it is recommended to conduct locomotive cleaning as a means to improve the luminance contrast levels (visibility) of locomotives.
- There is no significant improvement in locomotive conspicuity in clear daylight due to the addition of beacon lights and side marker lights at their current configurations, regardless of the colour of the side marker lights. The findings stress the need for an alternative approach to safety improvements in daytime at regional level crossings. This should consider factors beyond locomotive visual conspicuity improvement through auxiliary lighting.

8.2 RECOMMENDATIONS FOR FURTHER CONSIDERATION

The following are additional recommendations for further consideration:

- The headlight in low beam during night time operation proves to offer sufficient visibility. However, as stated above, the headlight on high beam enhances locomotive conspicuity in daylight conditions. The improvement is more pronounced at 240 m distance than at 105 m. This is due to the focused or concentrated nature of the headlight beam toward a specific distance (240 m ahead). The visibility improvement reduces when viewed at an angle. Consideration may be given to assessing the effectiveness of a headlight that radiates the light beam over a wider angle (rather than a concentrated beam in one direction) during daytime operation as a means to enhance conspicuity when observed at an angle and from different distances.
- In the current trial, the side marker lights were fitted at 90˚. Further trials with

    - alternative fitting configuration of the side marker lights to illuminate a larger surface area of the side of the locomotive,
    - side marker lights at alternative angles and adjusting luminous intensity, or
    - optimum colour of the side lights,

  may prove beneficial to improve locomotive visibility.
- Furthermore, the luminance contrast change will be dynamic with a flashing light. Therefore, it is advisable to set up the side marker lights to flash in time (synchronously) with the front visibility and beacon lights. The above suggestions may contribute to improved visibility under various conditions.
- In dense vegetation or other visual obstruction, assess the effectiveness of the following suggestions to improve locomotive's conspicuity at level crossings:
    - Evaluate the feasibility of laser light technology integrated into the locomotive's lighting system to enhance detectability in visually obscured situations, such as vegetation, fog, heavy rain, or landscape.
    - Explore the placement of laser lights on both sides of the locomotive's top (the brow) with the lights angled to avoid interference with other rail or road users.
    - Explore the use of trackside sirens (horns) and mandatory requirements of locomotive horn in conjunction with lighting when approaching a level crossing with visual obstructions.
- The current trial focuses solely on lighting solutions. The effect of the locomotive livery design, colour designs considering users with colour vision deficiencies, patterns, lighting arrangements, or other alternative designs on locomotive conspicuity in daylight and night time should be considered in future trials as a means to improving the luminance contrast levels (visibility) of locomotives.
- Research [10, 11] suggests that incorporating Daytime Running Lights can mitigate the overall likelihood of being part of a non-night-time multi-vehicle collision in road vehicles. Explore the trial of utilization of similar specification Daytime Running Lights independently along the side sills or in conjunction with Side Marker Lights to assess whether a synergistic effect exists, leading to an increase in luminance contrast and enhancement in overall visibility.
- Investigate the feasibility of adaptive lighting systems that can dynamically adjust to environmental conditions. This may include technologies that respond to factors like ambient light, weather and obstruction [12, 13]. Investigate feasibility of light lens protective cover that adapts and changes colour in daytime and night time operation.
- Investigate the use of reflectorised materials to enhance conspicuity both during night time and daytime. This includes exploring the amount of reflectorised material per surface area and the location of mounting the reflectorised material on front and side of the locomotive.
- Finally, locomotive conspicuity enhancement using lighting solutions for safety improvement at LCs may be limited due to possible adverse health and safety effects. It is advisable to explore other safety improvement schemes for regional-level crossings, such as improving signage visibility and implementing lighting solutions on level crossing infrastructure, in conjunction with locomotive conspicuity improvement solutions during day time. Furthermore, developing dedicated sections on relevant local government websites, such as the National Level Crossing Portal, providing

comprehensive information about level crossings including details on orientation, types of crossings, safety guidelines, and any ongoing enhancements or modifications, can be considered to bolster public awareness and safety at level crossings. A similar approach is employed in the USA [17] to furnish relevant information to citizens, industry, data users, and policymakers.

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APPENDIX A1

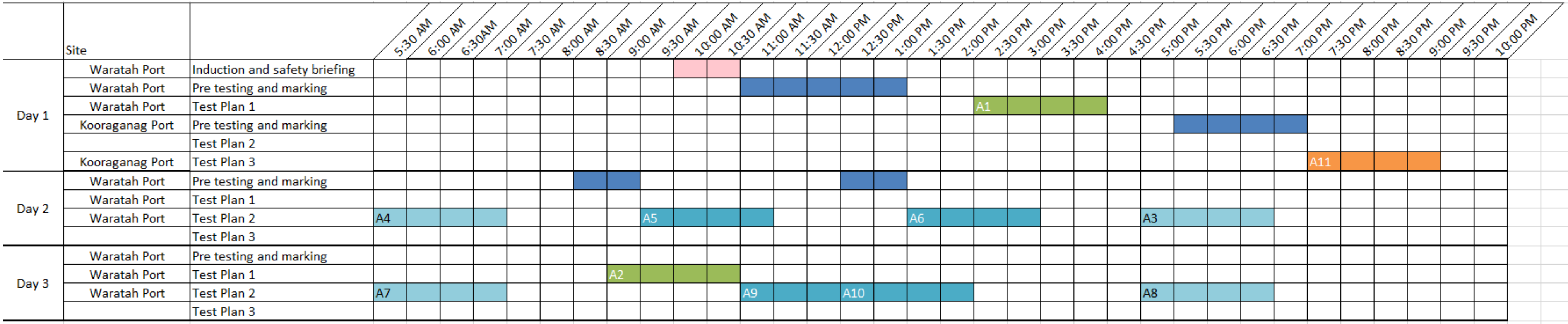
TABLE A.1. SPECIFICATIONS OF LIGHTING FITTED ON PN9035 LOCOMOTIVE

Head Light	Ditch Light
Brand: Amglo (Round) Type: K21 - Halogen Voltage:74VDC Current: 4.72A Wattage: 350W Age profile/ Last replaced: 06/11/2022	Brand: Hella Type: H3 - Halogen Voltage: 24VDC Current: 2.91A Age profile/ Last replaced: 23/05/2021

Front Beacon Light	Side Marker Light
• Deemed as a Class 1 specification = 18,000 cd-s/m • Front beacon lights are connected to a bespoke designed and built control box (note still in the testing phase) • The control box is used to activate ECCO flashing LED lights mounted on the front of locomotives • The flashing rate is currently set to 15 secs when the horn is activated.	• Local internal measurement with luminous intensity of one light at 1m was 20 Lux / 20 Candella.

APPENDIX A2

TABLE A.2. SUMMARY OF THE PLANNED MEASUREMENT TIMES FOR THE VARIOUS ACTIVITIES



	Site		5:30 AM	6:00 AM	6:30AM	7:00 AM	7:30 AM	8:00 AM	8:30 AM	9:00 AM	9:30 AM	10:00 AM	10:30 AM	11:00 AM	11:30 AM	12:00 PM	12:30 PM	1:00 PM	1:30 PM	2:00 PM	2:30 PM	3:00 PM	3:30 PM	4:00 PM	4:30 PM	5:00 PM	5:30 PM	6:00 PM	6:30 PM	7:00 PM	7:30 PM	8:00 PM	8:30 PM	9:00 PM	9:30 PM	10:00 PM
Day 1	Waratah Port	Induction and safety briefing										🟥	🟥																							
	Waratah Port	Pre testing and marking												🟦	🟦	🟦	🟦	🟦																		
	Waratah Port	Test Plan 1																		A1	🟩	🟩	🟩													
	Kooraganag Port	Pre testing and marking																									🟦	🟦	🟦	🟦						
		Test Plan 2																																		
	Kooraganag Port	Test Plan 3																													A11	🟧	🟧	🟧		
Day 2	Waratah Port	Pre testing and marking							🟦	🟦							🟦	🟦																		
	Waratah Port	Test Plan 1																																		
	Waratah Port	Test Plan 2	A4	🟦	🟦	🟦					A5	🟦	🟦	🟦					A6	🟦	🟦	🟦				A3	🟦	🟦	🟦							
		Test Plan 3																																		
Day 3	Waratah Port	Pre testing and marking																																		
	Waratah Port	Test Plan 1								A2	🟩	🟩	🟩																							
	Waratah Port	Test Plan 2	A7	🟦	🟦	🟦								A9	🟦	🟦	A10	🟦	🟦	🟦						A8	🟦	🟦	🟦							
		Test Plan 3																																		

Test Equipment used During the Testing

- Light intensity meter (Lux meter) – For measuring ambient condition;
- Luminsnce camera – For luminance measurements;
- Digital cameras – for data collection;
- Range finder, survey instruments – for horizontal distance, height and angle measurement

Data to be recorded

1. The luminance of the loco with the light(s) ON/OFF (in cd/m^2);
2. The ambient lighting value in lux. (lux meter)
3. Images of all the testing by digital camera/luminance camera.
    - Details of the locomotives including types, shapes and forms of locos
    - Colour and any reflective and position of the lighting fittings.

Background information to be recorded

- Type of head lights and ditch lights
- Date of installment of the head lights and ditch lights
- Colour of Ditch lights
- Distance and angle from the measuring camera to the front of locomotive
- Beacon lights status
- Side marker lights colour
- Side marker lights status
- Weather condition
- Vegetation info
- Locomotive livery
- Time of measurement

APPENDIX A3

Reference Measurement during daylight

TABLE A.3. PHYSICAL SIZES AND LUMINANCE PROPERTIES OF THE HEADLIGHTS MEASURED AT 105 M AND 240 M VIEWING DISTANCES

Distance	Mean	SD	Max	RMS contrast	Physical size (mm x mm)	Angular width	Angular height
240 m	273.9	411.4	1931	1.502	74.22 x 152.49	0.07	0.15
105 m	381	865.1	6459	2.271	93.29 x 186.75	0.11	0.21

TABLE A.4. LUMINANCE CONTRAST AND LUMINANCE RATIO DUE TO FRONT MARKER LIGHTS AT 240 M LOCATION

View circumstance	Headlight	Front marker	Luminance Contrast	Luminance Ratio
Front view_240 m	Off	Off	-0.699	0.301
Front view_240 m	Off	Red marker	-0.697	0.303
Front view_240 m	Off	White marker	-0.695	0.305
Front view_240 m	On	White marker	0.473	1.473

TABLE A.5. LUMINANCE CONTRAST AND LUMINANCE RATIO AT 105 M AND 240 M LOCATION

View circumstance	Headlight	Beacon light	Ditch/ Side Marker Light	Luminance Contrast		Luminance Ratio	
				Immediate Background	Wide Background	Immediate Background	Wide Background
Front view_105 m	Off	Off	Off	-0.89	-0.89	0.11	0.11
Front view_240 m	Off	Off	Off	-0.7	-0.75	0.3	0.25
Front view_105 m	On	Off	Off	-0.5	-0.51	0.5	0.49
Front view_240 m	On	Off	Off	0.47	0.18	1.47	1.18
Front view_105 m	On	On	On	-0.49	-0.5	0.51	0.5
Front view_240 m	On	On	On	0.5	0.2	1.5	1.2

Daytime measurement at different times of the day

Table A.6. Design Variables (Factors) and Their Variation Levels Coded as Low (-1) and High (1)

Term	Variables to Consider (Factors)	Coded levels	
		Low (-1)	High (1)
X1	View angle	22.5˚	45˚
X2	Colour of side marker light	Amber	White
X3	Sun direction (times of the day)	Afternoon	Morning
		Facing	Behind
X4	Beacon light	Off	ON
X5	Ditch light/ Side marker light	Off	ON

Table A.7. A two-Level Full Factorial Design $2^5 = 32$ for Five Factors Day-Time Measurement at Different Times of the Day

	Main Factors					Two-factor interaction										Luminance Contrast
Runs	Viewing angle	Side marker light colour	Sun direction (times of day)	Beacon lights	Ditch/side marker lights											
	X1	X2	X3	X4	X5	X1X2	X1X3	X1X4	X1X5	X2X3	X2X4	X2X5	X3X4	X3X5	X4X5	Wide background
1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	-0.796
2	-1	-1	-1	-1	1	1	1	1	-1	1	1	-1	1	-1	-1	-0.794
3	-1	-1	-1	1	-1	1	1	-1	1	1	-1	1	-1	1	-1	-0.785
4	-1	-1	-1	1	1	1	1	-1	-1	1	-1	-1	-1	-1	1	-0.774
5	-1	-1	1	-1	-1	1	-1	1	1	-1	1	1	-1	-1	1	-0.930
6	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	-1	1	-1	-0.930

7	-1	-1	1	1	-1	1	-1	-1	1	-1	-1	1	1	-1	-1	-0.930
8	-1	-1	1	1	1	1	-1	-1	-1	-1	-1	-1	1	1	1	-0.929
9	-1	1	-1	-1	-1	-1	1	1	1	-1	-1	-1	1	1	1	-0.856
10	-1	1	-1	-1	1	-1	1	1	-1	-1	-1	1	1	-1	-1	-0.857
11	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	-1	1	-1	-0.848
12	-1	1	-1	1	1	-1	1	-1	-1	-1	1	1	-1	-1	1	-0.852
13	-1	1	1	-1	-1	-1	-1	1	1	1	-1	-1	-1	-1	1	-0.952
14	-1	1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	-1	-0.952
15	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	1	-1	-1	-0.933
16	-1	1	1	1	1	-1	-1	-1	-1	1	1	1	1	1	1	-0.934
17	1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	-0.935
18	1	-1	-1	-1	1	-1	-1	-1	1	1	1	-1	1	-1	-1	-0.932
19	1	-1	-1	1	-1	-1	-1	1	-1	1	-1	1	-1	1	-1	-0.931
20	1	-1	-1	1	1	-1	-1	1	1	1	-1	-1	-1	-1	1	-0.931
21	1	-1	1	-1	-1	-1	1	-1	-1	-1	1	1	-1	-1	1	-0.924
22	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	-1	1	-1	-0.924
23	1	-1	1	1	-1	-1	1	1	-1	-1	-1	1	1	-1	-1	-0.914
24	1	-1	1	1	1	-1	1	1	1	-1	-1	-1	1	1	1	-0.902
25	1	1	-1	-1	-1	1	-1	-1	-1	-1	-1	-1	1	1	1	-0.900
26	1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1	-1	-1	-0.895
27	1	1	-1	1	-1	1	-1	1	-1	-1	1	-1	-1	1	-1	-0.897
28	1	1	-1	1	1	1	-1	1	1	-1	1	1	-1	-1	1	-0.898
29	1	1	1	-1	-1	1	1	-1	-1	1	-1	-1	-1	-1	1	-0.954
30	1	1	1	-1	1	1	1	-1	1	1	-1	1	-1	1	-1	-0.950
31	1	1	1	1	-1	1	1	1	-1	1	1	-1	1	-1	-1	-0.935
32	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-0.945

Daytime measurement for variable weather condition

TABLE A.8. DESIGN VARIABLES (FACTORS) AND THEIR VARIATION LEVELS CODED AS LOW (-1) AND HIGH (1) FOR VARIABLE WEATHER CONDITION

Term	Variables to Consider (Factors)	Coded levels	
		Low (-1)	High (1)
X1	Viewing angle	22.5˚	45˚
X2	Colour of side marker lights	Amber	White
X4	Beacon light	Off	ON
X5	Ditch light/ Side marker light	Off	ON
X6	Weather condition	Clear	Rainy (Mist)

TABLE A.9. A TWO-LEVEL FULL FACTORIAL DESIGN $2^5 = 32$ FOR FIVE FACTORS DAY-TIME MEASUREMENT FOR VARIABLE WEATHER CONDITION

	Main factors					Two-factor interaction										Three-factor interaction	
	Viewing angle	Side marker light colour	Beacon lights	Ditch/side marker lights	Weather condition												
Runs	X1	X2	X4	X5	X6	X1X2	X1X4	X1X5	X1X6	X2X4	X2X5	X2X6	X4X5	X4X6	X5X6	X1X2X4	X1X2X5
1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	-1	-1
2	-1	-1	-1	-1	1	1	1	1	-1	1	1	-1	1	-1	-1	-1	-1
3	-1	-1	-1	1	-1	1	1	-1	1	1	-1	1	-1	1	-1	-1	1
4	-1	-1	-1	1	1	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	1
5	-1	-1	1	-1	-1	1	-1	1	1	-1	1	1	-1	-1	1	1	-1
6	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	-1	1	-1	1	-1
7	-1	-1	1	1	-1	1	-1	-1	1	-1	-1	1	1	-1	-1	1	1
8	-1	-1	1	1	1	1	-1	-1	-1	-1	-1	-1	1	1	1	1	1
9	-1	1	-1	-1	-1	-1	1	1	1	-1	-1	-1	1	1	1	1	1
10	-1	1	-1	-1	1	-1	1	1	-1	-1	-1	1	1	-1	-1	1	1

11	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1
12	-1	1	-1	1	1	-1	1	-1	-1	-1	1	1	-1	-1	1	1	-1
13	-1	1	1	-1	-1	-1	-1	1	1	1	-1	-1	-1	-1	1	-1	1
14	-1	1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	-1	-1	1
15	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	-1
16	-1	1	1	1	1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1
17	1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1
18	1	-1	-1	-1	1	-1	-1	-1	1	1	1	-1	1	-1	-1	1	1
19	1	-1	-1	1	-1	-1	-1	1	-1	1	-1	1	-1	1	-1	1	-1
20	1	-1	-1	1	1	-1	-1	1	1	1	-1	-1	-1	-1	1	1	-1
21	1	-1	1	-1	-1	-1	1	-1	-1	-1	1	1	-1	-1	1	-1	1
22	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	-1	1	-1	-1	1
23	1	-1	1	1	-1	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	-1
24	1	-1	1	1	1	-1	1	1	1	-1	-1	-1	1	1	1	-1	-1
25	1	1	-1	-1	-1	1	-1	-1	-1	-1	-1	-1	1	1	1	-1	-1
26	1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1	-1	-1	-1	-1
27	1	1	-1	1	-1	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1
28	1	1	-1	1	1	1	-1	1	1	-1	1	1	-1	-1	1	-1	1
29	1	1	1	-1	-1	1	1	-1	-1	1	-1	-1	-1	-1	1	1	-1
30	1	1	1	-1	1	1	1	-1	1	1	-1	1	-1	1	-1	1	-1
31	1	1	1	1	-1	1	1	1	-1	1	1	-1	1	-1	-1	1	1
32	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Daytime measurement for variable vegetation obscurity

TABLE A.10. DESIGN VARIABLES (FACTORS) AND THEIR VARIATION LEVELS CODED AS LOW (-1) AND HIGH (1) FOR VARIABLE VEGETATION OBCURITY

Term	Variables to Consider (Factors)	Coded levels	
		Low (-1)	High (1)
X1	Viewing angle	22.5°	45°
X2	Colour of side marker light	Amber	White
X4	Beacon light	Off	ON
X5	Ditch light	Off	ON
X8	Vegetation coverage	None	Dense

TABLE A.11. A TWO-LEVEL FULL FACTORIAL DESIGN $2^5 = 32$ FOR FIVE FACTORS DAY-TIME MEASUREMENT FOR VARIABLE VEGETATION OBSCURITY

Runs	Main factors					Two-factor interaction										Three-factor interaction	
	Viewing angle	Side marker light colour	Beacon lights	Ditch/side marker lights	Vegetation coverage												
	X1	X2	X4	X5	X8	X1X2	X1X4	X1X5	X1X8	X2X4	X2X5	X2X8	X4X5	X4X8	X5X8	X1X2X4	X1X2X5
1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	-1	-1
2	-1	-1	-1	-1	1	1	1	1	-1	1	1	-1	1	-1	-1	-1	-1
3	-1	-1	-1	1	-1	1	1	-1	1	1	-1	1	-1	1	-1	-1	1
4	-1	-1	-1	1	1	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	1
5	-1	-1	1	-1	-1	1	-1	1	1	-1	1	1	-1	-1	1	1	-1
6	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	-1	1	-1	1	-1
7	-1	-1	1	1	-1	1	-1	-1	1	-1	-1	1	1	-1	-1	1	1
8	-1	-1	1	1	1	1	-1	-1	-1	-1	-1	-1	1	1	1	1	1
9	-1	1	-1	-1	-1	-1	1	1	1	-1	-1	-1	1	1	1	1	1
10	-1	1	-1	-1	1	-1	1	1	-1	-1	-1	1	1	-1	-1	1	1

11	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1
12	-1	1	-1	1	1	-1	1	-1	-1	-1	1	1	-1	-1	1	1	-1
13	-1	1	1	-1	-1	-1	-1	1	1	1	-1	-1	-1	-1	1	-1	1
14	-1	1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	-1	-1	1
15	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	-1
16	-1	1	1	1	1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1
17	1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1
18	1	-1	-1	-1	1	-1	-1	-1	1	1	1	-1	1	-1	-1	1	1
19	1	-1	-1	1	-1	-1	-1	1	-1	1	-1	1	-1	1	-1	1	-1
20	1	-1	-1	1	1	-1	-1	1	1	1	-1	-1	-1	-1	1	1	-1
21	1	-1	1	-1	-1	-1	1	-1	-1	-1	1	1	-1	-1	1	-1	1
22	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	-1	1	-1	-1	1
23	1	-1	1	1	-1	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	-1
24	1	-1	1	1	1	-1	1	1	1	-1	-1	-1	1	1	1	-1	-1
25	1	1	-1	-1	-1	1	-1	-1	-1	-1	-1	-1	1	1	1	-1	-1
26	1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1	-1	-1	-1	-1
27	1	1	-1	1	-1	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1
28	1	1	-1	1	1	1	-1	1	1	-1	1	1	-1	-1	1	-1	1
29	1	1	1	-1	-1	1	1	-1	-1	1	-1	-1	-1	-1	1	1	-1
30	1	1	1	-1	1	1	1	-1	1	1	-1	1	-1	1	-1	1	-1
31	1	1	1	1	-1	1	1	1	-1	1	1	-1	1	-1	-1	1	1
32	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Measurement at dusk and dawn

TABLE A.12. DESIGN VARIABLES (FACTORS) AND THEIR VARIATION LEVELS CODED AS LOW (-1) AND HIGH (1) FOR VISIBILITY AT DUSK AND DAWN

Term	**Variables to Consider (Factors)**	**Levels**	
		Low (-1)	**High (1)**
X1	Viewing angle	22.5°	45°
X4	Beacon light	Off	On
X5	Ditch light/ Side marker lights	Off	On
X7	Time of the day (Ambient light condition)	Dawn	Dusk

TABLE A.13. A TWO-LEVEL FULL FACTORIAL DESIGN $2^4 = 16$ FOR MEASUREMNETS AT DUSK AND DAWN

	Main factors				**Two-factor interaction**						**Three-factor interaction**				**Four-factor interaction**
Runs	**Viewing angle**	**Beacon lights**	**Ditch/side marker lights**	**Time of the day**											
	X1	**X4**	**X5**	**X7**	**X1X4**	**X1X5**	**X1X7**	**X4X5**	**X4X7**	**X5X7**	**X1X4X5**	**X1X4X7**	**X1X5X7**	**X4X5X7**	**X1X4X5X7**
1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	-1	-1	1
2	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	1	1	1	-1
3	-1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	1	-1
4	-1	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	-1	1
5	-1	1	-1	-1	-1	1	1	-1	-1	1	1	1	-1	1	-1
6	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1

7	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	1	1	-1	1
8	-1	1	1	1	-1	-1	-1	1	1	1	-1	-1	-1	1	-1
9	1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1
10	1	-1	-1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1
11	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	1	1
12	1	-1	1	1	-1	1	1	-1	-1	1	-1	-1	1	-1	-1
13	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	-1	1	1	1
14	1	1	-1	1	1	-1	1	-1	1	-1	-1	1	-1	-1	-1
15	1	1	1	-1	1	1	-1	1	-1	-1	1	-1	-1	-1	-1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

APPENDIX A4

Measurement during night time

Table A.14. Night Time Experimental Design Factors (Variables) and Their Corresponding Levels of Variation

Term	**Variables to Consider (Factors)**	**Levels**	
		Low (-1)	**High (1)**
X1	Viewing angle	22.5˚	45˚
X4	Beacon light	Off	On
X5	Ditch light/ Side marker lights	Off	On
X10	Headlight	Low beam	High beam

Table A.15. A Two-Level Fractional Factorial Design $2^{(4-1)} = 8$ for Four Factors Night-Time Measurement

	Viewing angle	**Beacon lights**	**Headlight**	**Ditch/side marker lights**	**Two-factor interactions**		**Three-factor interaction**
Runs	**X1**	**X4**	**X10**	**X5 + “X1X4”**	**X5 = “X1X10”**	**X6 = “X4X10”**	**X7 = “X1X4X10”**
1	-1	-1	-1	1	1	1	-1
2	-1	-1	1	1	-1	-1	1
3	-1	1	-1	-1	1	-1	1
4	-1	1	1	-1	-1	1	-1
5	1	-1	-1	-1	-1	1	1
6	1	-1	1	-1	1	-1	-1
7	1	1	-1	1	-1	-1	-1
8	1	1	1	1	1	1	1