Camera-based indirect vision systems for heavy duty vehicles: phase I

Mcwha, T.; Desouza, F.

https://doi.org/10.4224/23000736

National Research Council Canada

Conseil National de Recherches Canada

Automotive and Surface Transportation

Automobile et transports de surface

NRC·CNRC

Camera-Based Indirect Vision Systems for Heavy Duty Vehicles – Phase I

Prepared for:

ecoTECHNOLOGY for Vehicles
Stewardship and Sustainable Transportation Programs
Transport Canada
330 Sparks St.
Ottawa, ON K1A 0N5
Canada

Prepared by:

T. McWha, P.Eng.
F. Desouza, Ph.D.

Project A1-001055

ST-GV-TR-0001

August 8, 2013

UNLIMITED
UNCLASSIFIED

Canada

CAMERA-BASED INDIRECT VISION SYSTEMS FOR HEAVY DUTY VEHICLES – PHASE I

Prepared for:

ecoTECHNOLOGY for Vehicles
Stewardship and Sustainable Transportation Programs
Transport Canada
330 Sparks St.
Ottawa, ON K1A 0N5
Canada

National Research Council Canada
Automotive and Surface Transportation
2320 Lester Rd.
Ottawa, ON K1V 1S2
Canada

Technical Report

ST-GV-TR-0001

CHANGE CONTROL

Revision	Date	Description	Author
A	March 28, 2013	Initial release	T. McWha
B	August 8, 2013	Abstract and executive summary added	T. McWha

DISCLAIMER

ABSTRACT

Indirect vision systems are used by drivers to identify objects that do not fall directly within their line of sight. This can be accomplished through the use of a conventional mirror-based indirect vision system or by a camera-based indirect vision system. The purpose of this study is to evaluate the design factors surrounding the use of camera-based indirect vision systems, quantify the possible fuel savings which may be achieved through the use of such systems and to identify and quantify any secondary effects related to their use.

The design factors were separated into human design considerations and equipment design considerations. The two categories of design factors were evaluated through a literature review of past similar studies as well as other pertinent journal articles and texts.

The possible fuel savings which may be realized through the use of a camera-based indirect vision system were quantified by performing full-scale component testing in a 2 m by 3 m wind tunnel. The results of the component testing were compared to previously performed full-scale vehicle testing in order to determine the overall reduction in the vehicle drag coefficient expected through the use of a camera-based indirect vision system and, in turn, the possible fuel savings.

EXECUTIVE SUMMARY

Indirect vision systems are used by drivers to identify objects that do not fall directly within their line of sight. This can be accomplished through the use of a conventional mirror-based indirect vision system or by a camera-based indirect vision system. The presence of mirror-based indirect vision systems on highway tractors is a significant source of aerodynamic drag. The replacement of such systems in favour of camera-based indirect vision systems can reduce the overall drag coefficient of the vehicle, and in turn reduce fuel consumption.

The purpose of this study is to evaluate the design factors surrounding the use of camera-based indirect vision systems, quantify the possible fuel savings which may be achieved through the removal of conventional mirrors and to identify and quantify any secondary effects related to their use.

The study consists of two phases. Phase I involves a literature review concerning the current state of technology and the human factors associated with the use of a camera-based indirect vision system. Phase I also involves the design and installation of a prototype system on a subject vehicle. Phase II, not described within this report, will consist of field testing of the prototype system designed in Phase I. The field testing will consist of both closed course and highway use of the prototype system by drivers with a range of age and experience.

The realization of the possible fuel savings and the associated reduction in greenhouse gas emissions has led to research into the development of camera-based indirect vision systems to replace conventional mirror systems. Several previous studies have evaluated the design requirements of camera-based indirect vision systems. Additional studies have evaluated the use of camera systems on city buses with the aim of reducing blind spots to minimize the number of side crash events. To date, the majority of research has been focused on the development of driver vision enhancement systems rather than the use of camera systems to replace mirrors.

A camera-based indirect vision system consists mainly of cameras and monitors. Video data captured by the cameras will be displayed on monitors located within the vehicle. It is therefore important to understand how the eye is used to gather visual information when designing a camera-based indirect vision system for use on heavy duty vehicles to ensure that the system does not put undue stress on the eye or distract from other visible sensory information required to operate the vehicle in an efficient manner. Visual acuity, temporal acuity, the visual field, accommodation, presbyopia, brightness, contrast, ciliary muscle fatigue, depth perception, information processing and colour blindness must all be considered when designing a camera-based indirect vision system.

In addition to the human factors design considerations, there are numerous equipment factors which must be investigated and evaluated in order to design a camera-based indirect vision system. The camera fields of view, camera location, image resolution, monitor location, monitor size, image reversal, infrared capabilities, screen brightness, the use of colour, power consumption, system mass, environmental concerns, vibrations, redundant systems, polarization of light, vehicle width, wide loads, and the limitations of present-day camera technology must all be taken into consideration when designing such a system.

The use of a camera-based indirect vision system will allow for processing of the captured video data to extract meaningful information that may assist drivers to operate their vehicle in a more efficient manner. However, when considering how the visual data may be processed, one must keep in mind that data processing takes time which will induce a certain amount of lag in the system, which is undesirable. The camera-based indirect vision system may be used to identify

targets, monitor the angle of the trailer, assist in staying in one's lane as well as use infrared light to detect targets in complete darkness.

The basic design goal for the camera-based indirect vision system was that the same visual information available through the use of a conventional mirror-based indirect vision system was available through the use of the camera-based system. The subject vehicle on which the camera-based indirect vision system was installed was a Volvo VN780. The subject vehicle had two west coast mirrors on either side of the vehicle, two fender-mounted convex mirrors and a look-down mirror on the passenger side. All four of the mirrors were replaced by cameras and monitors in an attempt to replicate the available field of view.

In order to determine the required field of view of the camera-based indirect vision system, the fields of view of the conventional mirror-based system were quantified. This was accomplished by connecting a 53 foot trailer to the subject vehicle, and having a driver of average height sit in the driver seat of the subject vehicle, adjust his mirrors as he would for normal driving and describe his field of view to the test engineer. In addition to the indirect visibility measurements, measurements of the direct visibility of the driver were also taken. These were used later to compare the visual obstruction of the mirrors to the visual obstruction of the monitors.

Interior vehicle measurements allowed for the calculation of the maximum required system resolution, taking into account normal visual acuity as well as the distance between the vehicle operator's eyes and the A-pillars.

Several different cameras from various manufacturers were reviewed based on the manufacturer's specifications. Both standard definition (SD) analog and high definition (HD) digital cameras were considered for use in the system. However, the majority of the HD cameras surveyed required data compression to transmit the captured video. The compression of the data takes time, inducing noticeable lag between the time the image was captured and the time the image was displayed on the monitor. Lag in a camera-based indirect vision system is undesirable, therefore HD cameras were deemed inappropriate for use in the prototype system. The camera selected for the prototype camera-based indirect vision system was a Panasonic WV-CP624 which has a good combination of image resolution and day and nighttime viewing characteristics. The selected lens for the camera was a Panasonic PLZ5-50DN with a variable field of view from 5° to 50°. The variable field of view capabilities of the lens allowed for the use of a single camera and lens solution for all four cameras.

Several different monitors from various manufacturers were reviewed based on the specifications provided on their data sheets. The monitors selected for use in the prototype camera-based indirect vision system are manufactured by ToteVision. Three different sizes were selected for the four monitors: 142 mm (5.6 in), 163 mm (6.4 in) and 213 mm (8.4 in).

It was important to determine the overall change in aerodynamic drag coefficients through the use of a camera-based indirect vision system to determine the change in vehicle fuel consumption that could be realized through the use of such systems. In order to perform the aerodynamic testing, two separate camera fairings were designed. One of the camera fairings was designed to be placed in the front fender location. The other camera fairing was designed to be mounted in the location where the mirrors are conventionally placed as there are a few camera-based indirect vision systems under development which have the cameras placed in such a location. It was deemed important to test a similar fairing in order to determine the possible fuels savings through the use of such a camera location.

It was determined that the optimal location for the cameras was on the front fender of the subject vehicle. There are two cameras mounted on either side of the vehicle, one on top of the other. The camera in the uppermost position was used as the convex mirror surrogate camera. The camera in the lowermost position was used as the flat mirror surrogate camera.

It was determined that the ideal locations for the monitors are on the left and right A-pillars. The monitors mounted on the left A-pillar were a ToteVision LCD-562 mounted above a ToteVision LCD-642. The monitors mounted on the right A-pillar were a ToteVision LCD-642 mounted above a ToteVision LCD-842HD.

Since the camera-based indirect vision system was replicating a mirror-based system, it was necessary to mirror the images captured by the cameras. A Colorado Video NVVN420CS mirror box was used to perform the mirroring operation.

In addition to the cameras and monitors, an IR illuminator was mounted to the side of the subject vehicle to provide additional IR lighting during nighttime driving conditions. The selection of the IR mode on the cameras as well as the powering of the IR illuminator for the prototype system was performed via a toggle switch accessible by the driver of the vehicle.

The camera system field of view was configured using the variable field of view lenses to replicate the field of view provided by the mirror-based system. The camera system field of view for the flat mirror surrogates is slightly larger than that provided by the flat mirrors themselves to account for driver head movements.

The visual obstruction of the mirror-based indirect vision system was compared to those of the camera-based system. The visual obstruction angles of the mirror-based system include both the west coast mirrors, the fender mounted convex mirrors and the A-pillars. The visual obstruction angles of the camera-based system only include the visual obstruction of the largest monitor located on the A-pillar. The total visual obstruction angles were less for the camera-based indirect vision system than for the mirror-based indirect vision system.

The power consumption of the prototype camera-based indirect vision system was used to calculate the approximate fuel required to power the system. Based on a system power consumption of 94.0 W and some assumptions concerning vehicle efficiencies and duration of system use per year, the prototype camera-based indirect vision system was expected to consume roughly 87.2 L of fuel each year.

An electrically powered, electronic camera-based indirect vision system may be subject to failure at a higher rate than a conventional mirror-based system. Assuming the vehicle operates for roughly 2500 hours per year, the system mean time to failure was calculated to be about 5.4 years.

The mass of the system will have an impact on the fuel consumption of the vehicle. Overall, there is a net decrease in mass of 5.26 kg when using the prototype camera-based indirect vision system instead of the mirror-based system. Based upon the overall mass decrease of the vehicle, the yearly estimated fuel savings due to a decrease in overall vehicle mass is roughly 1.8 L per year.

The cost of the prototype camera-based indirect vision system was approximately $8,980. Comparing this to the replacement cost of the mirror-based indirect vision system of approximately $2,316, the camera-based indirect vision system costs approximately $6,664 more than a mirror-based system. However, the prototype system was purchased on a component basis and it was assumed that a production level system would cost significantly less.

In order to quantify the fuel savings which could be realized through the use of a camera-based indirect vision system it was important to quantify the gains in aerodynamic efficiency as a result of using such a system. To do so, full-scale testing of the camera-based indirect vision system components were tested in NRC-IAR's 2 m by 3 m wind tunnel. Because wind tunnel testing was performed on a full-scale component basis only, the mirrors of the subject vehicle also had to be tested. The testing of the mirrors allowed for the comparison of data from previous full-scale vehicle testing.

The results of the aerodynamic testing revealed a possible fuel savings of roughly 1,902 L per year.

Canadian Motor Vehicle Safety Standards (CMVSS) only requires a unit magnification mirror with 325 cm^2 of reflective area on both sides of the vehicle. However, the subject vehicle had total of 1,107 cm^2 of reflective area on each side of the vehicle due to the west coast mirrors, or roughly 340% the required amount. By assuming the smaller CMVSS minimums mirror has the same general shape as the tested mirror, and scaling the aerodynamic testing data, it is estimated that a yearly fuel savings of about 1,896 L could be realized by using only the two small unit magnification mirrors as required by CMVSS instead of the stock mirrors.

By combining the change in fuel consumption associated with the power draw of the system, the change in vehicle mass and the change in aerodynamic efficiencies, the use of a camera-based indirect vision system is expected to save roughly 1,817 L of fuel per year. Using an estimated fuel price of $1.20 per liter, the estimated payback period for the use of the prototype camera-based indirect vision system is approximately 4.1 years. This payback period is based upon the prototype system only and may be different for mass production level systems.

By multiplying the estimated fuel savings of 1,817 L by a factor of 2.69 kg of CO_2 released per liter of diesel fuel burned, the use of the prototype camera-based indirect vision system has the capability of reducing CO_2 emissions by roughly 4,888 kg per year per vehicle. If camera-based indirect vision systems were to be installed on all of the highway tractors operating on Canadian highways, it is estimated that the yearly reduction in CO_2 emissions would be roughly 1,109,600 tonnes.

It is necessary that extensive testing be performed on the use of camera-based indirect vision systems to determine all of the human factors issues which may arise through the use of such systems. Although this report attempted to address all human factors issues, it is very likely that additional issues will arise during field testing. It will be important to perform both closed course and highway testing of the prototype camera-based indirect vision system. Drivers selected for the testing should be of various age and gender and have varying levels of experience. Ideally, a large number of drivers should be used during the testing phase. For highway testing, it will be important that the mirror-based indirect vision system be removed from the vehicle while testing the camera-based indirect vision system. This will require permits to operate on Ontario highways without mirrors as required by CMVSS 111. Thorough testing of the system is required as it is of utmost importance that the use of camera-based indirect vision systems as a replacement for conventional mirror-based systems does not result in a degradation in the driver's ability to operate their vehicle effectively.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Purpose

Indirect vision systems are used by drivers to identify objects that do not fall directly within their line of sight. This can be accomplished through the use of a conventional mirror-based indirect vision system or by a camera-based indirect vision system.

Conventional mirror-based indirect vision systems require large structures to be placed in the airflow passing the vehicle creating a significant amount of drag. The use of a camera-based indirect vision system requires smaller support structures, thereby reducing the overall drag coefficient of the vehicle on which they are mounted. The reduction in drag results in fuel savings and a corresponding reduction in harmful emissions.

The purpose of this study is to evaluate the design factors surrounding the use of camera-based indirect vision systems, quantify the possible fuel savings which may be achieved through the use of such systems and to identify and quantify any secondary effects related to their use. To evaluate the preceding, a prototype camera-based indirect vision system will be designed and installed on a subject vehicle in replacement of the conventional mirror-based system.

1.2 Background

CMVSS 111 [1] stipulates that all vehicles weighing 4,536 kg or more must be fitted with unit magnification side view mirrors which are adjustable in the horizontal and vertical directions with no less than 325 cm^2 (50 in^2) of reflective surface on either side of the vehicle. However, there is a significant and measurable increase in vehicle aerodynamic drag caused by the addition of the mandatory side view mirrors required by CMVSS 111. The placement in the airstream and the blunt body area of the mirrors remain the principal factors when considering aerodynamic losses. Technological advances have made it possible to replace the rear view mirrors with cameras, thus reducing aerodynamic drag. [2]

1.3 Scope

The use of a camera-based indirect vision system as a replacement for conventional mirrors on highway tractors is to be evaluated to determine whether such systems are suitable for use on Canadian highways. The camera-based indirect vision systems will be studied to determine the potential benefits as well as associated risks involved with their use.

The project consists of two phases. Phase I involves a literature review concerning the current state of technology and the human factors associated with the use of a camera-based indirect vision system. Phase I also involves the design and installation of a prototype system on a subject vehicle.

Phase II consists of field testing of the prototype system designed in Phase I. The field testing will consist of both closed course and highway use of the prototype system by drivers with a range of age and experience.

2 LITERATURE REVIEW

2.1 Previous Research

Previous research conducted by the Institute for Aerospace Research (IAR) at the National Research Council (NRC) in their wind tunnel facilities has revealed that the removal of the indirect visions systems on a Volvo VN660 highway tractor can reduce the drag coefficient of the vehicle by 0.0254 while traveling at 27.8 m/s (100 km/h) [3]. The authors of the NRC-IAR report calculated that this decrease in drag coefficient relates to an annual fuel savings of roughly 1,526 liters per year. These findings suggest that a portion of these fuel savings could be realized through the replacement of conventional mirror-based indirect vision systems with camera-based indirect vision systems. It cannot be expected that all the fuel savings will be realized since camera-based systems would be required to protrude into the air stream, creating drag which would negate some of the fuel savings.

An additional study conducted by the NRC extrapolated the results of the IAR research to determine the net reduction in CO_2 production as a result of removing the mirror-based indirect vision systems [2]. By using the information in this report, it is expected that removing both the flat and convex mirrors from all highway tractors operating within Canada would result in a total yearly fuel savings of 347 million liters. This corresponds to a reduction of 914,500 tonnes of CO_2 released into the atmosphere.

The realization of the possible fuel savings and the associated reduction in greenhouse gasses has led to research into the development of camera-based indirect vision systems to replace conventional mirror systems. A general overview of the requirements a camera-based indirect vision system is provided by a Chalmers University of Technology thesis entitled Mirror Replacement in Trucks [4]. A more in depth evaluation of the requirements of camera-based indirect vision systems is provided by a series of reports published by the National Highway Traffic Safety Administration (NHTSA) in cooperation with the Virginia Tech Transportation Institute (VTTI). VTTI began their research into the development of camera-based indirect vision systems with the creation of a static test method for assessing the quality of indirect visibility on heavy trucks [5]. VTTI used their method for assessing the quality of indirect visibility to develop a performance specification for a camera/video imaging system (C/VIS) for use on heavy trucks [6], which was accompanied by the supporting research for the developed performance specification [7]. The performance specification included guidelines for the implementation of 11 different camera concepts divided into two distinct groups: surrogate camera systems and driver vision enhancement systems. The latter group, enhancements, focused on camera placements on heavy vehicles which provided additional visual information to the driver to enhance awareness of their surroundings. The surrogates group, consisting of only two of the eleven concepts, were meant as replacements to the conventional flat and convex mirror systems. It is only with the C/VIS surrogates that mirrors would be removed from the heavy vehicle and the fuel savings realized. VTTI designed, mounted and tested all 11 of their proposed concepts using 24 commercial drivers in three test groups. Testing was performed on a closed course using VTTI's Virginia Smart Road. The results of testing performed on the use of convex mirror surrogates revealed that driver performance was similar to that while using convex mirrors. The results of the testing performed on the simultaneous use of both flat and convex mirror surrogates revealed that driver performance was slower and less accurate and that drivers became more conservative in allowing clearance during passing. Drivers felt as though there would be a longer learning time associated with the use of surrogate vision systems than with enhanced vision systems.

VTTI, in conjunction with NHTSA, continued their development of their driver vision enhancement C/VIS systems [8]. The aim of developing their enhanced camera/video imaging system (E-C/VIS) was to increase the operational envelope of the previously developed system to extend operation into nighttime and inclement weather conditions. Testing was performed to determine the driver's ability to identify targets in nighttime and inclement weather situations. The results of testing indicated that E-C/VIS operators were able to detect and identify targets with greater ease than with the use of only mirrors. It should be noted that the E-C/VIS was a driver vision enhancement system, not a mirror surrogate, and as such the mirrors remained in place during testing.

The VTTI team again refined their design, developing the advanced camera/video imaging system (A-C/VIS), to perform user trials in typical highway conditions [9]. The A-C/VIS consisted of three driver vision enhancement cameras: one on either side of the vehicle and the third providing a view behind the vehicle's trailer. A commercially available camera system was also used in the user trials as a comparison to VTTI's system. Twelve commercial drivers were monitored for a period of four months as they used either the VTTI developed A-C/VIS or a commercially available camera system. Although the study was performed on driver vision enhancement systems, not surrogate systems, it is interesting to note that the results of the user trials revealed that drivers' involvement in safety critical events did not measurably worsen (or improve) while using the driver vision systems. It was also determined that there was no measurable degradation of the driver's visual attention to the forward roadway during the study.

To date most research has been focused on the development of driver vision enhancement systems rather than the use of camera systems to replace mirrors. An additional study performed by Center for Urban Transportation Research (CUTR) in conjunction with the Florida Department of Transportation studied the use of camera systems on city buses with the aim of reducing blind spots to minimize the number of side crash events [10]. The video system was tested in a controlled environment by 28 bus drivers. The study concluded that the designed system was beneficial in improving the drivers' situational awareness and generally increased the safety of the bus operation.

The focus on driver vision enhancement systems rather than mirror surrogate systems is likely due to the existing regulations which require the use of mirrors on vehicles operated on public roadways. CMVSS 111 in Canada [1] and FMVSS 111 in the United States [11] stipulate the minimum requirements for vehicle mirrors. Although much more study is required to substantiate an amendment to CMVSS 111 or FMVSS 111 to allow the use of a comparable camera-based indirect vision system, the International Organization for Standardization (ISO) is in the process of developing a standard which would set the minimum demands for the use of such technology in their ISO 16505 [12].

2.2 Existing Camera Systems

2.2.1 **Commercially Available Aftermarket Systems**

2.2.1.1 Motion Metrics International

Motion Metrics of Vancouver, British Columbia, offers their ViewMetrics system for Haul Trucks (VMHT). The VMHT system consists of two wide angle blind spot cameras and two monitors, one for each side of the vehicle. The system is advertised as a driver vision enhancement system and is to be used with the existing mirror-based indirect vision system. [13]

2.2.1.2 Zone Defense

Zone Defense of St. Petersburg, Florida, offers a large selection of cameras and monitors for use in vehicle applications. All cameras offered provide wide angle views and are not necessarily suitable for use in mirror surrogate systems. [14]

2.2.1.3 Jensen Heavy Duty

Jensen Heavy Duty offers a wide range of camera systems and components to decrease blind spots in heavy duty vehicles. Their camera systems offer only wide angle views and are not necessarily suitable for use in mirror surrogate systems. [15]

2.2.2 **OEM Prototype Systems**

There are two truck manufacturers that are currently advertising the development of a camera-based indirect vision system on their advanced prototype vehicles. MAN has developed their Concept S tractor, in conjunction with the Krone Aero Liner trailer, to reduce the overall drag coefficient of the tractor-trailer combination to less than 0.3, which is similar to levels achieved by passenger cars [16], [17]. The Concept S and Aero Liner are not expected to enter production in the near future due to restrictions placed on overall vehicle length as well as on the use of camera-based mirror systems.

Freightliner has developed their Revolution Innovation Truck with the aim of reducing fuel consumption. The Revolution Innovation Truck uses camera-based indirect vision systems to reduce the drag coefficient of the tractor and, as a result, decrease fuel consumption [18].

Neither the MAN Concept S or Freightliner Revolution Innovation Truck comply with current CMVSS regulations.

3 DESIGN CONSIDERATION

3.1 Human factors

3.1.1 Vision

It is estimated that 90% of the inputs perceived and acted upon by a driver are received by the eyes [19]. A camera-based indirect vision system consists mainly of cameras and monitors. Video data captured by the cameras will be displayed on monitors located within the vehicle. It is therefore important to understand how the eye is used to gather visual information when designing a camera-based indirect vision system for use on heavy duty vehicles to ensure that the system does not put undue stress on the eye or distract from other visible sensory information required to operate the vehicle in an efficient manner.

3.1.2 Basic Structure of the Eye

The eye is responsible for converting light, electromagnetic energy, into electrochemical neural energy which is transmitted via the optic nerve to the brain for interpretation. A schematic view of the eye may be seen in Figure 1. [20]

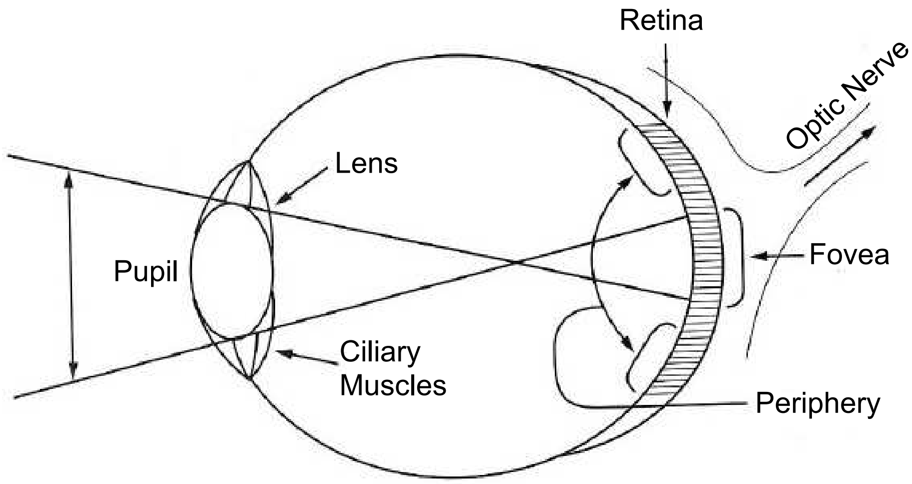

Figure 1: Schematic view of the eye (from [20])

The human eye is only sensitive to electromagnetic energy with wavelengths between 370 nm and 730 nm. Electromagnetic energy entering the eye which falls outside this range will not be interpreted by the brain. [21]

Light enters the eye through the pupil which will dilate (in dark environments) or constrict (in bright environments) to control the amount of light entering the eye. Light then passes through the lens and onto the retina. The shape of the lens is adjusted to bring the perceived image into precise focus on the retina. The shape change of the lens is controlled by the ciliary muscles. [20]

The retina contains two major types of photoreceptive cells: cones and rods. The cone receptors are sensitive under daytime conditions and are responsible for colour vision. The rods are used primarily in nighttime conditions and are colour blind. The fovea, the central part of the retina centered about the visual axis, consists only of cones. The cone decreases rapidly as the angular distance from the visual axis increases. The periphery of the retina is composed mainly of rods. [19]

3.1.3 **Visual Acuity**

Visual acuity is generally described as the ability to resolve two distinct objects from one another. Various techniques may be employed to measure ones visual acuity. Vernier acuity tests require the subject to determine whether or not two line segments are parallel or slightly out of alignment. Landolt ring acuity tests require the subject to determine the location of a discontinuity in a presented ring. Snellen acuity tests, the most common measure of visual acuity, is a measurement of one's ability to resolve detail at a distance of 20 feet relative to the distance at which a normal observer can resolve the same detail. The results of a Snellen acuity test are provided by ratios such as 20/20, 20/40 and 20/200. The numerator of a Snellen result provides the distance from which the test subject can resolve details from the Snellen test chart; the denominator provides the distance from which a normal subject can resolve the same details. For example, a Snellen acuity test resulting in a subject having 20/40 vision is interpreted to mean that the subject can resolve objects at a distance of 20 feet that a normal observer would be able to resolve at 40 feet. [20] [19]

The human eye is equipped with photoreceptors which subtend approximately 0.5 arc minutes of visual angle [22]. This sampling rate corresponds to a normal visual acuity of roughly 1 arc minute of visual angle. This means that under normal conditions, a normal eye can resolve a high-contrast, repeating pattern of equal width bars and spaces, when each element of that pattern subtends an angle of no less than 1 arc minute to the eye [23].

Visual acuity is directly proportional to the cone density [19]. The ability to resolve detail will be greatest when the eye is pointed directly at the object of interest. Peripheral vision, relying mainly on rods, provides lessor visual acuity. Since the usefulness of cones decreases in nighttime conditions, one may also expect that one's ability to resolve spatial details will lessen as ambient light levels decrease.

To be licensed as a Class A driver within the province of Ontario, one must have a visual acuity, as measured by a Snellen acuity test, that is not poorer than 20/30, with both eyes open and examined together and not poorer than 20/100 in the weaker eye, with or without the aid of corrective lenses. [24]

3.1.4 **Temporal Acuity**

Temporal acuity is the ability to distinguish visual events in time. This is important for applications involving video displays as the eye may not perceive the provided image stream as a continuous sensory input if the refresh rate of the monitor falls below the critical flicker frequency. The critical flicker frequency is the highest rate of flicker which may be perceived by the human eye. The critical frequency depends on many factors including stimulus size, retinal location and level of surrounding illumination. The critical flicker frequency for large stimuli with high intensity can be as high as 60 Hz. [21]

Rods have a faster response time than cones [25]. As a result, they are more susceptible to flicker phenomena [21]. A video monitor viewed in the periphery may be perceived to flicker even though it does not do so when viewed using foveal vision.

3.1.5 **Visual Field**

The vertical visual plane is an imaginary vertical plane which is coincident with the body's sagittal plane when the head is held in a vertical manner with the eyes facing forward. The horizontal visual plane is an imaginary horizontal plane which passes through the two eyes and is parallel with the body's transverse plane when the head is held in an upright position. The forward visual line is the intersection of the visual vertical and horizontal visual planes. [26]

The normal human field of view for a single eye extends along the horizontal visual plane roughly 150°: 90° from the forward visual line towards the outside of the head, 60° from the visual line towards the inside of the head. The combination of both left and right eyes, the ambinocular field of view, extends along the horizontal visual plane a total of 180°. An additional 90° may be added to the visual field along the horizontal visual plane due to comfortable left-right head movements of the driver. [27]

The normal human ambinocular field of view extends along the vertical visual plane roughly 135°: 50° to 55° above the forward visual line, 60° to 70° below the forward visual line. An additional 110° may be added to the visual field along the vertical visual plane due to comfortable up-down head movements of the driver. [27]

To be licensed as a Class A driver within the province of Ontario one must have, with both eyes open and examined together, a continuous horizontal visual field of at least 150° along the horizontal visual plane and at least a 20° continuous vertical visual field both above and below the forward visual line [24].

It is important to take into consideration the visual fields of the driver when determining where to place the system monitors. The monitors should be located such that they do not require excessive head movements to view.

3.1.6 **Accommodation and Presbyopia**

The human eye has the ability to change the image focused on the retina by adjusting the shape of the lens using the ciliary muscles. This shape change is referred to as accommodation. [20]

Accommodation allows images from a large range of distances to be brought into sharp focus on the retina. A person with a normal range of accommodation can focus on items at distances ranging from as close as 90 mm from the eye to, essentially, infinity. [19]

Accommodation abilities decrease with age due to the hardening of the lens. After the age of 45, the closest distance on which a person can focus is about 80 cm [19]; after the age of 60, this distance increases to roughly 100 cm [21]. The hardening of the lens and resulting increase in minimal focal distance is referred to presbyopia.

Presbyopia can be counteracted through the use of corrective lenses. Half frame reading glasses or bifocals may be used to improve vision while driving. However, half frame reading glasses and bifocals are designed to bring into focus only items located below the horizontal visual plane. Persons suffering from presbyopia may have difficulty in viewing displays which are mounted along or above the horizontal visual plane. [19]

3.1.7 **Brightness**

Brightness is the measure of visual perception that most closely relates to the intensity of the stimulation of the eye. Brightness can be classified as illuminance, light falling on a surface, or luminance, light generated by a surface. Illuminance is measured in lumens per square meter (or lux); luminance is measured in candelas per square meter. [21]

The brightness of the environment determines what receptors of the eye are used to collect the visual data. Photopic vision involves only the use of cones and occurs in daytime lighting conditions (luminance levels greater than 3 cd/m^2). Mesopic vision involves the use of both rods and cones and occurs under dusk or dawn lighting conditions (luminance levels between 0.001 cd/m^2 to 3 cd/m^2). Finally, scotopic vision only involves the use of the rods and occurs under low lighting conditions (luminance levels between 0.000001 cd/m^2 to 0.001 cd/m^2). [19]

The ability of one's eyes to adapt to low levels of luminance is termed dark adaptation. When transitioning from photopic or mesopic viewing conditions into scotopic viewing conditions, it takes approximately 30 minutes for the eyes to fully adjust to the dark environment. Vision may be momentarily impaired when the eye is returned to photopic conditions after becoming dark adapted. The eyes of older adults tend to require a greater length of time to adapt to the light levels of the surrounding environment. [21]

Ideally, the brightness of the monitor used to display the camera images should be adjusted to match the environment brightness. When operating under very bright conditions, the monitors should be bright enough to provide a clear image from the cameras. When operating under low light conditions, the brightness of the monitors should be decreased to allow the eyes to dark adapt. If possible, while operating under low lighting conditions, any bright images recorded by the cameras should be reduced in intensity. Environments in which drivers are required to use their scotopic vision but are periodically exposed to bright lights can be particularly disruptive [20].

An alternative to brightness adjustment while operating in environments with low ambient lighting could be one of colour adjustment. The rods, responsible for scotopic vision, are not sensitive to longer wavelengths of light (i.e. red light) [20]. Since the infrared display offered by the camera is monochromatic, it is possible to substitute the white colour in the display with varying shades of red. In this manner, the dark adaptation would not be disrupted by the monitors while driving at night.

When adjusting either the brightness or the colour of the monitor to account for ambient lighting conditions, sufficient contrast must be maintained to allow for object detection.

3.1.8 **Contrast**

One of the basic capabilities of human vision is the ability to discern between varying levels of luminance. Contrast is a measure of the difference in luminance between two objects. For target recognition, contrast can be expressed in terms of the difference in luminance between the target and the background, divided by the luminance of the background. This is expressed mathematically in equation (1). [19]

$$C = \frac{|L_T - L_B|}{L_B} \qquad \textbf{(1)}$$

Where C: contrast

L_T: luminance of target

L_B: luminance of background

The visual contrast threshold for which an object may be detected depends on the contrast of the target against its background, the adaptation luminance, and the target size. The adaptation luminance is the luminance to which the eyes have adapted and is dependent upon the time in which the eyes are located in an environment of a specific brightness. The target size is the visual angle subtended by the target under scrutiny.

Various visual contrast threshold curves for different exposure times have been generated through the analysis of experimental results of human testing [28]. These curves can be used to determine the minimum contrast required for the recognition of a target of known size and luminance in a background of known luminance [19].

In general, the contrast required for target recognition increases as either the background luminance or the target size decrease.

3.1.9 **Ciliary Muscle Fatigue**

The lens, as shown in Figure 1, must change shape to bring images into focus on the retina. The amount of shape change required is dependent upon the distance between the observer and the object being viewed. The shape change of the lens is performed by the ciliary muscles.

Repeated focusing on distant objects (such as vehicles on the road) then on nearby objects (such as the mirror surrogate monitors) will require repeated contraction and relaxation of the ciliary muscles. Ciliary muscle fatigue may occur with prolonged use of a camera-based indirect vision system. [21]

3.1.10 Depth Perception

When using a reflective surface to view an object, the eye perceives a virtual image of the object which is located at the same line of sight distance from the observer that the actual object is located. In other words, the distance of the virtual image from the observer is the sum of the distance from the observer to the mirror and the distance from the mirror to the object.

There are many ways that the human eye can perceive depth. There are four main categories of depth perception cues: ocular (or physiological), kinetic, pictorial and stereopsis. A categorized list of depth perception cues is found in Table 1. The depth perception cues which may be considered the most important as they pertain to the use of monitors instead of mirrors are accommodation, convergence, motion parallax, interoptic velocity differences, size, texture gradients, and disparity.

Table 1: Depth perception cues (from [25])

Category	Depth Cue
Ocular	Accommodation Convergence
Kinetic	Motion parallax Optic flow Kinetic depth effect Interocular velocity differences
Pictorial	Perspective Size Texture gradients Aerial perspective Superposition Shading
Stereopsis	Disparity

Accommodation, as described in section 3.1.6, refers to the changing of the shape of the lens using the ciliary muscles to bring objects of varying distances from the observer into focus. When a shape change of the lens occurs, this information is relayed to the higher perceptual centers of the brain and used to estimate the distance of the object from the observer. Accommodation is a monocular depth cue which is only used for objects closer than about 3 m from the observer [20]. This may cause some difficulty in depth perception when the driver of a vehicle equipped with a camera-based indirect vision system uses accommodation to focus on the nearby monitor which is displaying a distant object. However, accommodation is considered a weak depth perception cue and can be overridden by other cues [21].

Convergence, a binocular depth perception cue, relates to the amount of inward rotation of the eyes when focusing on a nearby object. In a manner similar to accommodation, the muscles which rotate the eyes send a message to the brain as to the magnitude of the inward rotation, which the brain can then interpret to give a sense of distance to the object being viewed [20]. Convergence works within a distance range similar to that of accommodation and is also considered a weak depth perception cue [25].

Motion parallax refers to the fact that, while in motion, objects which are further away from the observer tend to move a smaller distance within the visual field [20]. The use of lateral head movements can provide an observer with a sense of distance to the object or objects being viewed [25]. Motion parallax can be used to determine distance with a conventional side view mirror, but not with a camera-based indirect vision system. The image on the monitor will remain the same despite the driver's head movements.

When an object being tracked by an observer moves either towards or away from the observer, the image focused on the retina of each eye will move at different velocities. The interocular velocity difference can be interpreted by the brain to provide a sense of distance from the observer to the object [25]. Once again, this depth cue can be used with a mirror but not with a monitor since the objects displayed on the monitor, regardless of whether they are approaching or retreating from the camera, will maintain at the same focal distance from the observer's eye and the location on the retina on which the image is focused will not change.

The perceived size of an object can be used to estimate the distance of the object from the observer. The smaller the object, the further away from the observer it is perceived to be. The use of size to estimate the distance of the object from the observer depends on the observer's assumptions of the true size of the object [21]. Studies have shown that smaller vehicles are at a greater risk of being the victim of a rear-end collision due to the smaller-than-expected retinal image of the small vehicle, resulting in delayed braking due to the perceived distance to the vehicle being smaller than the actual distance [29]. Although one may not account for the driver's mental perception of distance due to the size of a vehicle, the studies suggest that replicating a unit magnification mirror field of view with the camera system is important for judging the distance to a vehicle. If the field of view is slightly larger than that provided by a unit magnification mirror resulting in the vehicle being displayed slightly smaller than it truly is, the driver may not leave sufficient room for a lane change.

Textural gradients are also used as a method of perceiving depth. When viewing a textured surface, the texture becomes finer as the distance from the observer increases [20]. When designing a camera-based indirect vision system, it will be important to maintain a high enough resolution of the cameras and monitors to allow for the use of textural gradients as a depth perception cue.

Binocular disparity arises from the fact that the two eyes view objects from different locations. There exists an imaginary curved surface on which every point located on that surface, when viewed with both eyes, will produce an image at the same point on the retina of both the left and right eyes. This imaginary curved surface it termed the horopter. For objects not located on the horopter, the images will fall on disparate locations on the retinas. The brain is able use this disparity to calculate a distance of the object from the observer. This depth perception cue is arguably the most powerful of all depth perception cues and it will not be available when using a monitor instead of mirror. [25]

Depth perception cues are additive in nature [21]. Despite the lack of availability of the previously mentioned depth perception cues, the remaining cues could be sufficient to determine the distance to targets through a camera-based indirect vision system. To date there have been several studies involving the depth perception measurements while using a camera-based indirect vision system, the results of which suggest that distances to vehicles may be accurately judged through optimization of the camera field of view and monitor size parameters [22] [30] [31].

3.1.11 Information Processing

Information is processed by the human brain in a variety of ways. In general, the information gathered through the sensory faculties is compared to data previously gathered during past experiences in order to allow one to make a decision on how to react to the available data.

Data that is gathered by the lower levels of stimulus processing, for example the eyes, and then sent to the higher perceptual centers of the brain is referred to as bottom-up processing. Top-down processing can be thought of as the perception of an object based upon our previous knowledge and experiences. A combination of both bottom-up and top-down processing is used to evaluate our surrounding environments. [20]

When considering the placement of the monitors of a camera-based indirect vision system, one must take into account the driver’s expectations, or in other words, account for the occurrence of top-down processing. Drivers, especially experienced drivers, have a preconceived notion as to where the mirrors should be – on either side of the vehicle. If the monitors were to be placed in a different location within the cab, the driver may instinctively look where the mirrors are expected to be, and then have to search for the location of the monitors. [7]

It is for the reasons mentioned above that the monitors should be located in areas as close as possible to the expected location of the mirrors. In most vehicles, this location is the left and right A-pillars. As time progresses and camera-based indirect vision systems become increasingly common, the expectations of the location of the visual information will change, and the movement of the monitors from the A-pillar locations can be considered.

3.1.12 Colour Blindness

The inability to discern one colour from another is commonly referred to as colour blindness. Roughly 8% of the male population and 0.04% of the female population are colour deficient in one manner or another [25]. There are no restrictions concerning the operations of motor vehicles on those who are colour deficient in North America as colour processing can be replaced by location processing. In other words, those who cannot discern red from green know that, in Ontario, the green light is located below the red light in a standard traffic signal. This information may be used instead of colour to determine when one may legally pass through an intersection.

Despite there being no driving restrictions for those who are colour deficient, and the fact that the visual information presented on a monitor will be similar to that which may be viewed in a mirror, it is prudent to design a camera-based indirect vision system to account for such colour deficiencies [20]. This becomes particularly important when determining the colour for any kind of informative text, symbols or figures which may be displayed on the camera-based indirect vision system monitors.

3.2 Equipment Factors

3.2.1 Camera Fields of View

The selection of the field of view for each of the camera mirror-surrogates is important for maintaining the depth perception capabilities of the driver. Studies have shown that the field of view selected for the camera has a direct bearing on the driver's ability to perceive distances through a camera-based indirect vision system [7] [22] [30] [31]. One such study [30] compared the distances perceived by drivers of a passenger vehicle while using the left-hand rear view mirror and a camera system with two different fields of view. The two selected camera fields of view were identical to those of a mirror with unit magnification and mirror of 0.5 magnification. The study found that the 0.5 magnification field of view camera produced distance estimates that closely resembled the distance estimates obtained while using the left-hand mirror. The unit magnification mirror surrogate camera resulted in distance estimates that were greater than those achieved using the left-hand mirror. Additional studies have cited 1.25 as an appropriate magnification factor for the mirror-surrogate camera [32] while others have cited a magnification factor of 0.33 [22]. However, these studies did not take into account the size and location of the monitors or the location of the cameras in combination with the camera field of view as a key factor in distance perception abilities.

The key factor when determining the appropriate field of view for the mirror-surrogate cameras is that the mirror-surrogate system should provide the same visual information that is provided by the conventional mirrors. As long as the cameras and monitors are located as described in sections 3.2.2 and 3.2.4 respectively, the driver's ability to judge distance should be maintained. The camera fields of view should therefore be selected by measuring the fields of view provided by the mirrors, and then providing the same fields of view with the cameras. However, the driver of a vehicle can gain additional field of view coverage by moving the location of the eyes, thus changing the angles of reflection for the unit magnification mirrors. To account for this slightly increased field of view caused by driver head movement, it is recommended that 5° be added to the field of view of the driver side unit magnification mirror surrogate and 3° be added to the field of view of the passenger side unit magnification mirror surrogate [7].

Although mirror adjustment is necessary to alter the field of view to accommodate the varying sizes and eye positions of drivers, no similar adjustment is required when using a video system as the camera field of view, once set, is the same for all drivers [10]. However, there may be situations in which the driver will want to alter the orientation of the field of view provided by the cameras, such as for viewing the location of the rear of the trailer when turning tight corners where obstructions on the corner may be present. In such situations it may be prudent to allow the driver to change the orientation of the camera to allow for a different field of view. This would only be necessary on the unit magnification surrogate and could be accomplished through the use of a servo.

3.2.2 Camera Location

The location of the cameras is one of the most important factors when considering the design of a camera-based indirect vision system. The selected location for the cameras will influence the environmental conditions to which the cameras are subjected but may also have an effect on the operational performance of the vehicle's driver.

As the cameras are meant to replicate the fields of view provided by the mirrors, the cameras should be located on either side of the vehicle as are the mirrors. However, the decision must be made as to the vertical and longitudinal location of the cameras. A vertical location too close to the ground plane will increase the amount of soiling encountered by the camera fairing from precipitation kicked up from the road surface by other vehicles as well as other road debris such as rocks or other refuse. A vertical location too far from the ground plane or a longitudinal location too far aft from the vehicle grille may create additional blind spots in which pedestrians, cyclists or small vehicles may be lost. A longitudinal location too far forward from the driver may create the illusion of vehicles being further away from the driver than they actually are and create a dangerous situation when changing lanes.

To determine the optimal location for the cameras, one must consider that the unit magnification mirror surrogate camera will provide the vehicle operator with the information needed to make judgments on the distance of other vehicles. The convex mirror surrogate camera will provide a slightly distorted view and therefore will not provide accurate information as to the distance to other vehicles. Therefore, when considering camera placement, the optimal location of the cameras will be one where the unit magnification mirror surrogate camera will offer a field of view very similar, if not identical, to that provided by the unit magnification mirror. [7]

In order to determine the optimal camera location for the unit magnification mirror surrogate camera one must examine how objects are viewed through a mirror. Figure 2 shows an eye, located at point A, viewing an object, B, through a unit magnification reflective surface, C. The effect of viewing the object through a reflective surface is that the viewer sees a virtual image of the object located at point D, as shown in Figure 2.

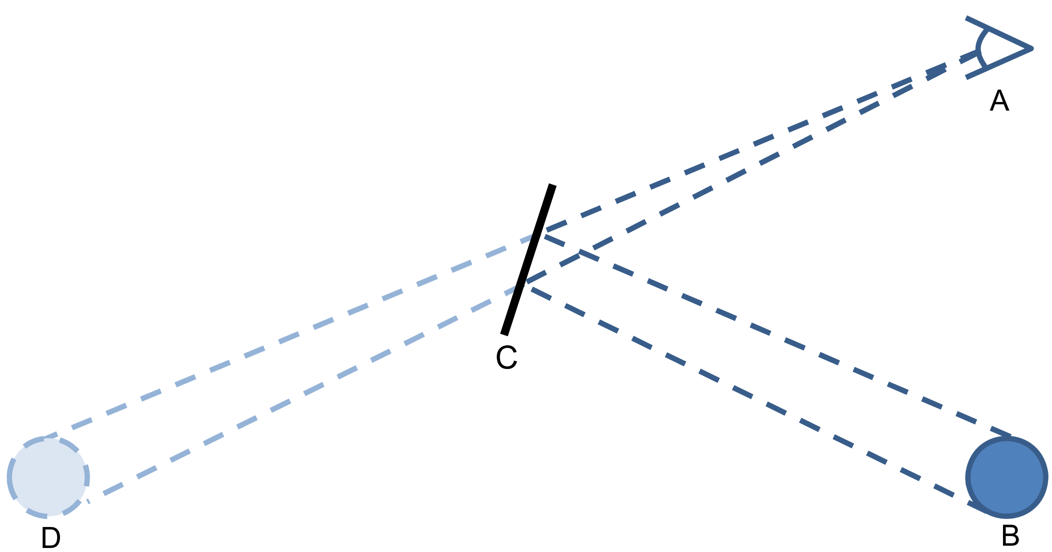

Figure 2: Viewing an object through a mirror (from [7])

If the concept of Figure 2 is extended so that the visual lines encompass the entire reflective surface, as shown in Figure 3, and the visual lines are extended to their point of convergence, that point of convergence, point E in Figure 3, would be the optimal location of a unit magnification mirror surrogate camera.

If the concept of Figure 2 and Figure 3 are extended to the unit magnification mirror located on the vehicle, as shown in Figure 4, and the visual lines extending from the unit magnification mirror are extended to their point of convergence, the optimal location of the unit magnification mirror surrogate camera would be located at point F in the figure. However, since the main purpose of the use of a camera-based indirect vision system is to reduce aerodynamic drag, the support structure for the camera should be minimized. This will result in locating the camera on the front fender location of the vehicle, as shown in Figure 5.

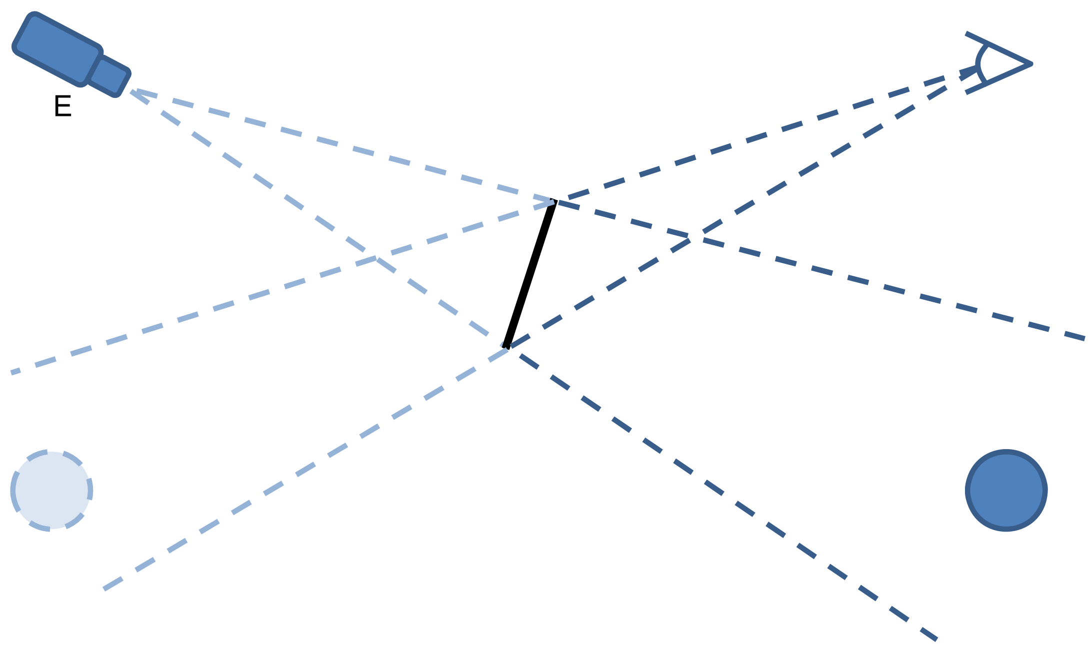

Figure 3: Theoretically optimal location of unit magnification mirror surrogate camera (from [7])

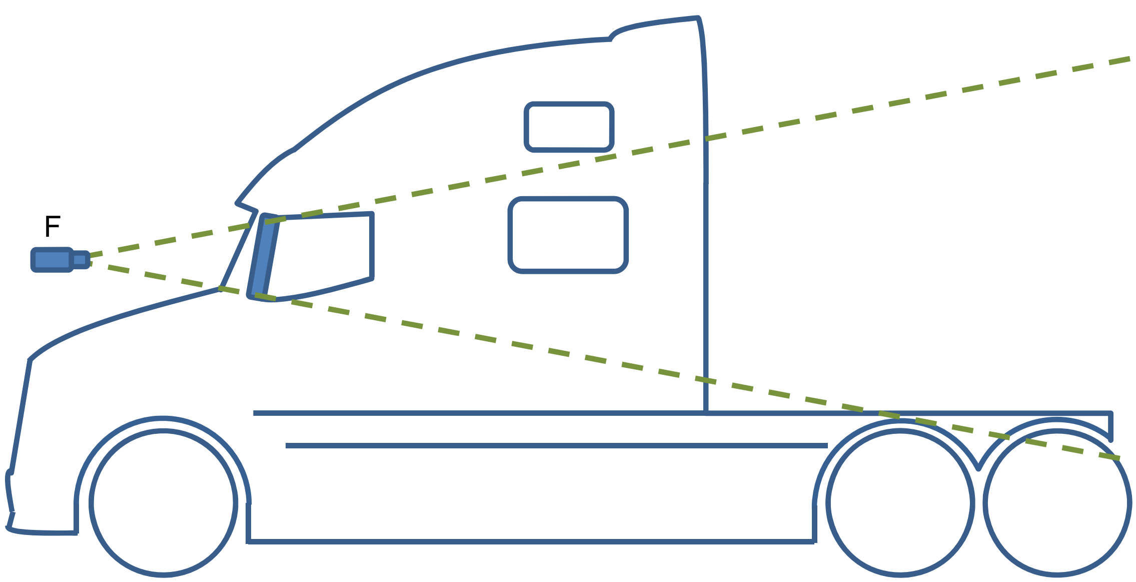

Figure 4: Optimal location of unit magnification mirror surrogate camera (from [7])

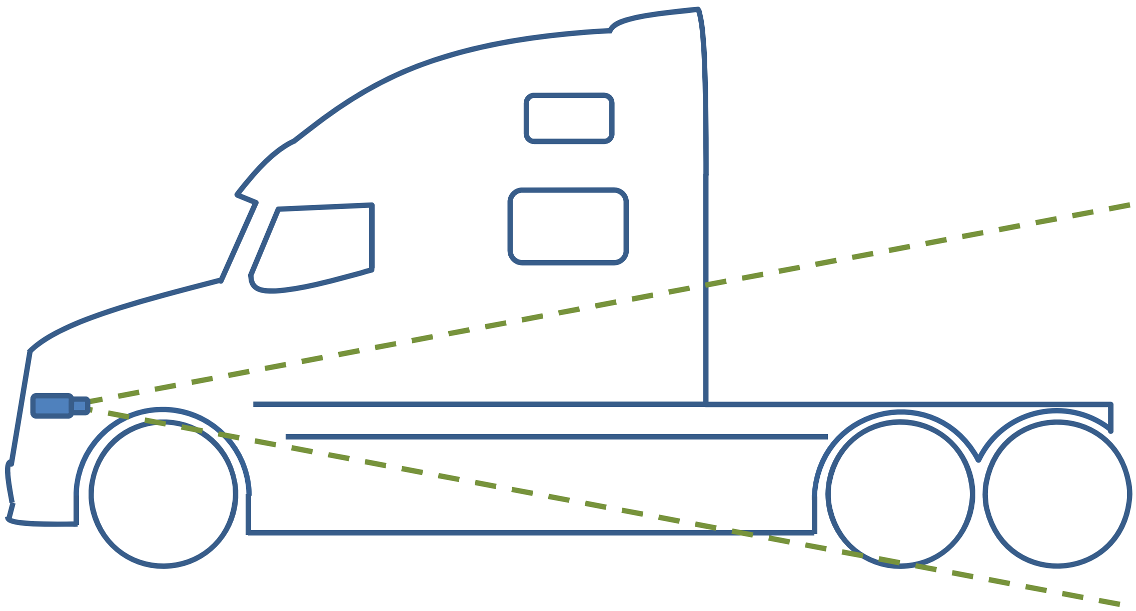

Figure 5: Selected location of unit magnification mirror surrogate camera

Further support for locating the cameras in the front fender location arises from the fact that the blind spot on the front passenger side of the vehicle will be reduced. Pedestrians, cyclists or small vehicles located in the right adjacent lane can easily be hidden in the blind spot on the front passenger side of the vehicle generated when using conventional mirrors [19]. Locating the cameras on the front fender of the vehicle will minimize this blind spot and allow drivers to identify targets in this area in a more efficient manner.

There are some designs under development which place the cameras in the conventional location of the mirrors. Both the Freightliner Revolution [18] and MAN Concept S [16] have located their camera-based indirect vision system cameras in such a location. However, the use of camera systems in the location could lead to difficulties with the driver's ability to determine distances to other vehicles.

3.2.3 Image Resolution

The resolution of the monitors should be selected such that a driver with normal vision (20/20 as defined by the Snellen acuity test) will not be able to discern individual pixels on the monitor. A resolution selected in such a manner will provide an image that is no less detailed than that provided by a mirror. The camera resolution should be selected such that it is of greater or equal resolution than that of the monitors.

As mentioned in section 3.1.3, a human eye with a 20/20 visual acuity, as measured by the Snellen acuity test, can resolve a repeating pattern of equal width bars and spaces, when each element of that pattern subtends an angle of no less than 1 arc minute to the eye. Therefore, to ensure that a driver cannot resolve the pixels from a monitor, the pixels should subtend a visual angle of less than 1 arc minute. Ideally, to make absolutely certain that individual pixels cannot be resolved while accounting for better than 20/20 vision, the monitor should have a resolution such that two pixels subtend a visual angle of 1 arc minute, as shown in Figure 6.

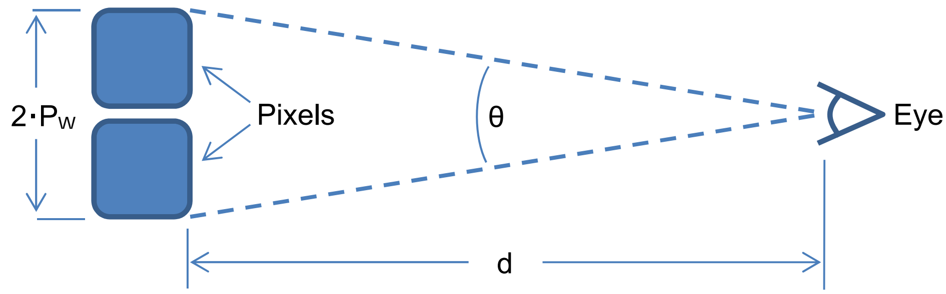

Figure 6: Maximum pixel size

In general, the pixel width, P_W, of the selected monitor should adhere to the equation presented in (2) with a visual angle, θ, of no less than 1 arc minute. As one can see from (2), as the distance from the eye to the monitor surface, d, increases, the required pixel width, P_W, decreases. This means that a monitor must have a higher resolution the closer it is to the driver.

$$P_W = d \cdot \tan\frac{\theta}{2} \quad \textbf{(2)}$$

Where θ: visual angle

d: distance from eye to monitor surface

P_W: pixel width

3.2.4 Monitor Location

The monitors for a camera-based indirect vision system can be placed anywhere within the cab. However, every effort should be made to allow the driver to maintain their visual attention to the front of the vehicle [27]. A typical driver will take roughly 0.8 seconds to 2.0 second glances at the mirror when making a lane change [19]. While traveling at 100 km/h, this equates to between 22 m and 56 m of distance travelled during mirror glances. It is important that the driver not waste any time searching for a mirror which has been replaced by a camera system. As described in section 3.1.11, the past experience of drivers' use of mirrors may cause the driver to look in the direction where they expect the mirrors (or equivalent system) to be. Therefore, it is recommended that the monitors be located in the same, or similar, line of sight that would otherwise be occupied by the mirrors.

It is recommended that the monitors for the unit magnification and convex mirror surrogate cameras be located on the A-pillars on either side of the vehicle. It is also recommended that the convex mirror surrogate camera monitor be placed above the unit magnification mirror surrogate camera monitor. The suggested location of the monitors may be seen in Figure 7. [6]

Additional consideration when determining the location of the monitors must be given to avoid, or minimize, possible reflections of the monitor image off of the windscreen during nighttime driving conditions. A reflection in the windscreen could cause undesired glare and driver distractions. [9]

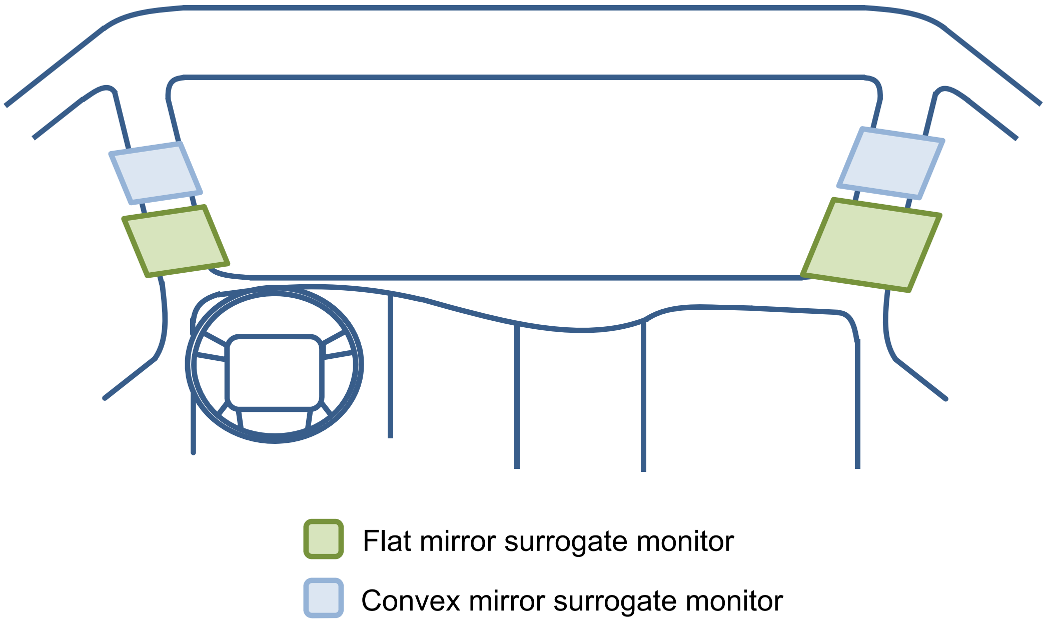

Figure 7: Monitor location on A-pillars

3.2.5 **Monitor Size**

The optimal monitor size is dependent upon the distance of the monitor to the driver. Figure 8, similar to Figure 3, presents the possible locations and sizes for the monitors by showing the visual angles experienced when viewing an object through a reflective surface. To maintain a good sense of depth perception, the monitors should be sized such that they subtend the same, or similar, visual arc that would normally be subtended when viewing the mirrors. As shown in Figure 8, the closer the monitor is to the viewer, the smaller it should be.

The relation between monitor size and distance from the viewer results in the monitors for the passenger side mirror surrogate cameras being larger than those of the driver side mirror surrogate cameras. The slightly larger monitors on the passenger side A-pillar may be seen in Figure 7.

Through user testing, it has been recommended that, when selecting commercially available monitors, the presented image be one of three predetermined sizes [6]. The recommended monitor image sizes are shown in Table 2.

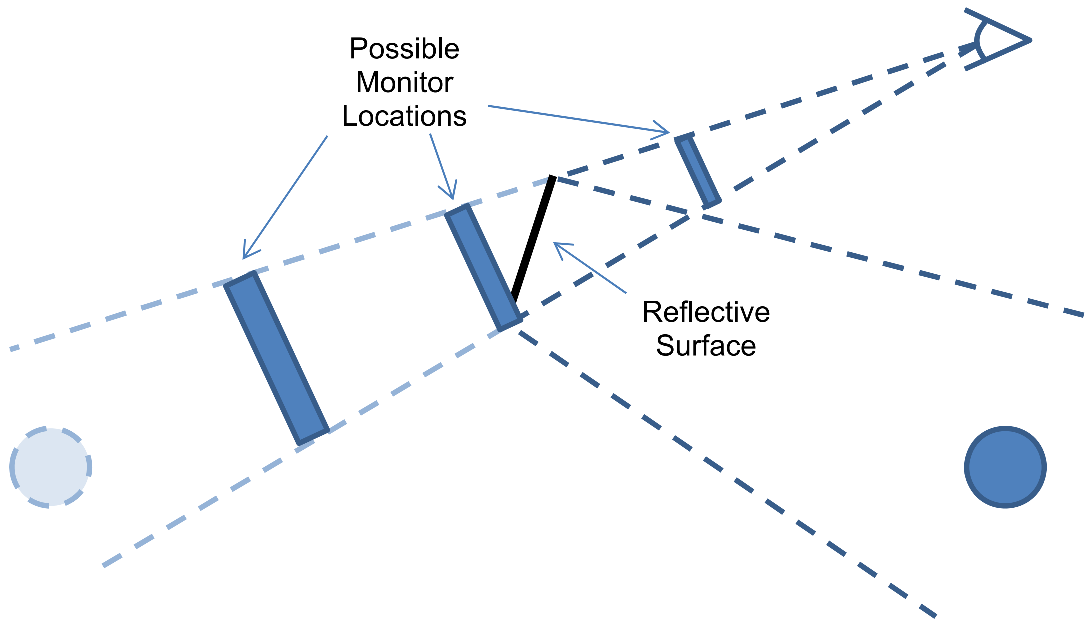

Figure 8: Monitor size in relation to distance from driver (from [7])

Table 2: Recommended monitor image sizes [6]

Size Designation	Height (mm)	Width (mm)	Diagonal (mm)
Size 1	84	113	141
Size 2	96	129	161
Size 3	128	170	213

3.2.6 Image Reversal

Motion viewed from a misrepresentative viewpoint can lead to disorientation [7]. Since the camera-based indirect vision system is replicating a mirror-based system, the image coming from the cameras must be reversed in the same fashion as would be done by a mirror to avoid confusion.

3.2.7 Infrared Capabilities

The camera-based indirect vision system must operate as effectively in nighttime driving conditions as it does during daytime driving conditions. Because there is little visible light available during nighttime driving, the cameras selected for the camera-based indirect vision system will require the ability to sense near infrared (IR) light. Near infrared light falls within the 750 nm to 1100 nm range of electromagnetic radiation wavelengths [33]. In addition to having cameras sensitive to near infrared light, in order to increase the visibility during nighttime operations, an IR illuminator should also be used. The use of IR illuminators, in combination with IR sensitive cameras, has proven to be more effective for object identification during nighttime viewing conditions than not using IR illuminators [8].

A concern with the use of IR illuminators to improve nighttime viewing capabilities is the possible interactions that such illumination may have with other vehicle systems such as adaptive cruise control or any kind of forward looking night vision systems.

3.2.8 Brightness

The selected monitors should be bright enough to be used in direct sunlight but be adjustable such that their brightness decreases when being used in nighttime driving conditions. A monitor that is not bright enough during operation in direct sunlight may result in a washed out or faded image. A monitor that is too bright during nighttime driving conditions may cause a visual distraction or even prevent the use of scotopic vision. It is important for the monitor brightness to have a large range of adjustability to allow for proper viewing during all lighting conditions encountered on the road. Ideally, there should be a mechanism for automatic monitor brightness control based upon the lighting of the surrounding environment to avoid the necessity of driver input.

3.2.9 Use of Colour

Colour can improve a driver’s ability to detect and identify targets. It is recommended that colour be used wherever possible in the design of a camera-based indirect vision system and that the colours displayed by the monitors accurately reflect the actual colours of the environment [7]. However, as discussed in section 3.1.12, it is important that the use of colour for any additional information displayed on the monitor take into account the possibility of a colour deficient operator.

3.2.10 Power Consumption

The power consumption of a camera-based indirect vision system must be considered since the additional power required by the system will add to the fuel consumption of the vehicle. The additional fuel consumption required to power the camera system will decrease the overall fuel savings realized through increases in aerodynamic efficiency.

In general, the volume of fuel required to power the camera system, V, may be calculated by knowing the power required by the system, P, the distance travelled by the tractor, d, the net calorific value of the fuel, E, the average speed of the tractor over the distance travelled, v, the density of diesel fuel, ρ_F, as well as the efficiencies of the engine, η_E, and the alternator, η_A.

The mass flow of the fuel required to power the system, $\dot{m}_F$, may be calculated as shown in equation (3).

$$\dot{m}_F = 1.0 \cdot 10^{-3} \cdot \frac{P}{\eta_E \cdot \eta_A \cdot E} \quad \textbf{(3)}$$

Where $\dot{m}_F$: mass flow of fuel (g/s)
P: power required by camera system (W)
η_E: efficiency of engine
η_A: efficiency of alternator
E: net calorific value of diesel fuel (MJ/kg)

The total mass of the fuel required to power the system, M_F, may be calculated as shown in equation (4).

$$M_F = \dot{m}_F \cdot t \quad \textbf{(4)}$$

Where M_F: mass of fuel required (g)
$\dot{m}_F$: mass flow of fuel (g/s)
t: duration of system use per year (s)

By dividing by the density of the fuel, $\rho_{F,}$ the total mass of the fuel required may be converted to a total volume of fuel required. Equation (5) combines equations and (4) to provide a calculation of the total volume of fuel required to power the camera system, V_F.

$$V_F = 3.6 \cdot 10^{-3} \cdot \frac{P \cdot t}{\eta_E \cdot \eta_A \cdot E \cdot \rho_F} \quad \textbf{(5)}$$

Where V_F: volume of fuel (L)
P: power required by camera system (W)
η_E: efficiency of engine
η_A: efficiency of alternator
E: net calorific value of diesel fuel (MJ/kg)
t: duration of system use per year (h)
ρ_F: density of fuel (kg/L)

3.2.11 Mass

The difference in mass of the camera-based indirect vision system compared to the mirror-based indirect vision system will have an impact on the fuel consumption of the vehicle on which the camera system is installed. Changes in vehicle mass changes the amount of energy required for acceleration, climbing of hills, and also alters the rolling resistance experienced by the tires.

The authors of a study performed in India calculated that the lightweighting of an Indian bus operating on a typical Indian duty cycle could result in an approximate fuel savings of $2.11 \cdot 10^{-5}$ L/kg of mass reduction for every kilometer traveled [34]. Another study which simulated the operation of a 4.9L V8 diesel engine with various vehicle masses, found that, while traveling at 96.6 km/h (60 mph), there was an approximate fuel savings of $2.16 \cdot 10^{-6}$ L/kg of mass reduction for every kilometer traveled at speed [35].

In order to estimate increases or decreases in fuel consumption in a conservative manner, the value of $2.11 \cdot 10^{-5}$ L/kg of mass reduction for every kilometer traveled will be used to calculate potential increases in fuel consumption due to an increase in overall weight, whereas the value of $2.16 \cdot 10^{-6}$ L/kg of mass reduction for every kilometer traveled will be used to calculate potential decreases in fuel consumption due to a decrease in overall weight.

The calculation of potential increases in fuel consumption on a yearly basis due to increased mass may be performed by using equation (6).

$$V = (2.11 \cdot 10^{-5} L/kg) \cdot \Delta m_i \cdot d \tag{6}$$

Where V: volume of fuel (L)

Δm_i: mass increase (kg)

d: distance travelled in a given year (km)

The calculation of potential decreases in fuel consumption on a yearly basis due to a decrease in mass may be performed by using equation (7).

$$V = (2.16 \cdot 10^{-6} L/kg) \cdot \Delta m_d \cdot d \tag{7}$$

Where V: volume of fuel (L)

Δm_d: mass decrease (kg)

d: distance travelled in a given year (km)

3.2.12 Environment

The environment in which the camera-based indirect vision system will operate is of major concern. While operating in Canada, the system can be expected to endure temperatures ranging from -46°C to 39°C [36], as well as a combination of snow, sleet, rain, hail, and wind. The camera-based system will also be exposed to large amounts of road salt used to maintain roads during the winter months. It is important that the housings containing the cameras be sufficiently rugged to protect the cameras from the elements and that they include provisions for cold weather operation, such as heating elements or redirected hot engine air. It may also be necessary to equip the monitors inside the cab with heating elements for cold weather operation if an extended warm up period is to be avoided during winter operation.

An additional environmental concern is that of debris collection on the camera lens or protective glass obstructing the camera's field of view [7]. Depending on where the cameras are located, the driver may not be able to reach the camera lens surface to clean the cameras. The camera housing should incorporate a means to clean the viewing port to avoid a possibly dangerous situation when one of the cameras becomes obstructed with debris. Another option to minimize the amount debris that accumulates on the surface of the camera lens would be to design the fairing such that airflows funnel debris away from the lens [9].

3.2.13 Vibrations

The area in which the cameras are mounted on the vehicle may be subject to vibrations due to the operation of the engine, interactions between the tires and the road surface, or buffeting caused by airflow around the vehicle. It is important that the system is designed such that the effects of such vibrations are minimized. For example, the selection of a camera with integrated image stabilization may aid with reducing the effect of vibration. Also, the design of the camera housing could include vibration dampening devices or be of sufficient mass to dampen out higher frequency vibrations. The monitors are also susceptible to the effects of vibration. A monitor vibrating at a frequency similar to that of the screen refresh rate could result in a strobe effect [7].

3.2.14 Redundant Systems

Although a mirror may fail during use through breakage, it may not be as likely to occur as a failure of a camera system. A vehicle power failure could result in the loss of all cameras and monitors, rendering the driver blind to traffic surrounding the vehicle. In the event of such a failure, a redundant mirror system should be kept on board the vehicle to aid in lane changes to the side of the road where the camera system failure can be addressed. An example of such a system is the Dead Angle Mirror System produced by B.D.S. [37]. This mirror could serve as a backup system to change lanes to the right towards the shoulder of the road in the event that the camera system fails.

In addition to redundant mirror systems, it is recommended that the camera-based indirect vision system is designed in such a manner that it is unlikely for all cameras to fail at one time. This can be achieved by ensuring that each camera and monitor system is as independent from other camera and monitor systems as possible. Of course, all onboard cameras and monitors share the same source of power, and if this were to fail, all cameras and monitors would also fail. However, in the event of an alternator or engine failure, the battery should provide sufficient power to keep the camera system operational for the short amount of time required to manoeuver the vehicle to the side of the road.

3.2.15 **Polarization**

The design of Liquid Crystal Displays (LCD) is such that the light radiating from the display is polarized. The orientation of the radiated polarized light is a result of the design of the particular display, and therefore the emitted light may be polarized at any angle the display designer may choose. [38]

If the environment in which the driver is operating the vehicle is too bright, it is very likely that sunglasses will be employed to ease with viewing of the road and the surrounding area. Polarized sunglasses are popular amongst the general population due to their ability to reduce glare. Polarized sunglasses are typically vertically polarized as the glare they are trying to eliminate is usually reflected from horizontal surfaces such as the road.

If the LCD monitor in use radiates horizontally polarized light, the use of polarized sunglasses will make the LCD monitor appear black. It is important that the polarization of light radiating from the selected monitor be taken into consideration to avoid such an event. If the monitor must be viewed in both the horizontal and vertical orientations, it would be important to have the light radiating from the monitor polarized at a 45° angle.

It should be noted that the majority of small scale Light Emitting Diode (LED) displays also use LCD technology to create onscreen images. In such LED displays, the LEDs are used to provide the backlighting and the LCD technology selects how the light is transmitted to the viewer.

3.2.16 **Vehicle Width**

The maximum allowable width of a vehicle traveling on roads and highways in Ontario is 2.6 m [39]. The mirrors are exempt from this requirement, but the design of a camera-based indirect vision system is not explicitly mentioned as exempt from this requirement. Other provinces within Canada have similar requirements pertaining to vehicle widths. It is recommended that the maximum width of a vehicle not exceed the 2.6 m limit including the installation of the camera-based indirect vision system until such time that CMVSS 111 is amended to include exemptions for camera-based indirect vision systems.

3.2.17 **Wide Loads**

In the event that the tractor on which a camera-based indirect vision system is hauling a wide load, the cameras will need to be placed further away from the body of the hauling vehicle to ensure that the driver can see around the wide load. To account for such a possibility, the camera-based indirect vision system camera fairing should have provisions for the addition of a spacer in between the camera fairing and the vehicle to move the cameras outboard so that the driver may see around the wide load being hauled. Alternatively, the system monitors could be configured to display images from remotely mounted cameras located elsewhere on the vehicle or hauled load to improve the driver’s situational awareness.

3.2.18 **Camera Limitations**

While operating under extreme conditions, cameras are susceptible to output distortions of the image that they capture. Blooming, overdriving and ghosting may occur with the use of a camera-based indirect vision system. These issues are not encountered with the use of a conventional mirror-based indirect vision system. [7]

Blooming occurs when there exists a particularly bright spot in the captured image, such as when a bright light is shone into the camera, resulting in an optical overload of one portion of the electronic image capturing device. The optical overload can result in vertical lines of brightness adjacent to, or a halo (bloom) surrounding the bright object. Anti-blooming techniques are employed in most modern cameras. However, one should expect that at least a small amount of bloom will occur when using an electronic camera. An example of blooming may be seen on the left side of Figure 9. [40]

Overdriving can occur when there exists a rapid change of lighting in the captured image. This could result when the vehicle equipped with a camera-based indirect vision system drives through a tunnel on a sunny day. The result of overdriving is a momentarily washed out image. Electronic correction can minimize this effect. [7]

Ghosting is caused by multi-path interference resulting in the captured image being displayed on the monitor twice, with the second, delayed occurrence of the image being slightly weaker than the first. The effect is that moving objects displayed on the monitor have ghostly traces. Ghosting can be minimized through the proper use of electronic mitigation strategies and proper elimination of interference sources. An example of ghosting may be seen on the right side of Figure 9. [41]

Although the above mentioned phenomena may be mitigated to a degree, they should be expected when using an electronic system. It is expected that the effects of such phenomena will decrease over time as camera technology improves.

Figure 9: Examples of blooming [42] (left) and ghosting [43] (right)

4 AUGMENTED SENSING CAPABILITIES

The use of a camera-based indirect vision system will allow for processing of the captured video data to extract meaningful information that may assist drivers to operate their vehicle in a more efficient manner. However, when considering how the visual data may be processed, one must keep in mind that data processing takes time which will induce a certain amount of lag in the system. It is recommended that the processing lag be less than 50 ms [6].

The following sections outline some of the possible processing techniques which could augment the driver's situational awareness and operational abilities.

4.1 Target Identification

While traveling on highways, the captured video data could be used to identify other vehicles. The type of vehicle, vehicle speed and distance to the vehicle could be calculated and the information provided to the driver. The vehicle path could be determined by the system processor and the driver alerted to any vehicle which may be considered a safety concern. For example, a calculated vehicle path could indicate a possible collision if the driver were changing lanes into the path of a fast moving vehicle. The system could also keep track of where surrounding vehicles are located and alert the driver if one of the vehicles was believed to be located within a known blind spot.

Taken one step further, facial mood recognition could be used to determine the emotional state or degree of mental alertness of nearby drivers. In the event that a driver that may pose a threat to the tractor-trailer is identified by the system, for example due to drowsiness or anger, the driver of the camera-system equipped vehicle could be alerted. It would be important that no facial recognition images be stored by the processing equipment to ensure the privacy of surrounding drivers.

4.2 Trailer Angle Monitoring

The camera-based indirect vision system could be used to calculate the angle of the trailer behind the tractor by processing the captured video data and identifying the outline of the trailer in the video image. The change in the outline of the trailer in the video data would be used to determine the angle of the trailer with the tractor.

Trailer monitoring could be useful in a variety of situations. Firstly, it could alert the driver to possible jackknife situations. If the angle of the trailer with the tractor increases as the driver applies brakes without steering input, the system could recognize a jackknife scenario before a driver and alert the driver to the developing situation. This method would most likely not be as effective as current electronic stability control methods, but it could be used to augment the sensing capabilities of such systems. Secondly, the trailer angle could be used for driver input when backing into a loading bay. Although backing is typically performed without much difficulty using mirrors, the display of the angle of the trailer with the tractor may aid the driver to perform this task. Finally, the monitoring of the trailer by the camera-based indirect vision system could allow for automatic field of view changes when the driver makes sharp turns. The system could recognize that the rear edge of the trailer is moving outside the camera's field of view, and then adjust the camera's field of view accordingly. Automatically adjusting the camera's field of view would allow the driver to determine whether the trailer will contact any obstructions which may be located on the corner.

4.3 Lane-Keeping Assist

The camera-based indirect vision system could identify the lane markers and adjust colour or contrast to present them more clearly to the driver on the system monitors. The system could also be used to alert the driver if they are about to depart their lane. If the system were to be tied into the steering system of the vehicle, a small amount of correction could be provided to the vehicle course if the vehicle were to approach the lane markers without the turn signal being activated.

4.4 Heat Sensing Capabilities

Although the use of IR sensing is required for detecting targets in low lighting conditions, the cameras used to do so generally operate in the near IR spectrum of light. This corresponds to a maximum electromagnetic radiation wavelength of roughly 1100 nm. The use of video capturing devices that operate in the midwave IR band (3 μm to 5 μm) and longwave IR band (7 μm to 14 μm) are capable of detecting heat radiating from objects. [33]

The use of a heat sensing camera could allow for the detection of objects and vehicles in complete darkness. No IR illuminator would be required for such a system. A heat sensing camera would be able to detect vehicles driving at night without headlights by using the heat generated by the engine or through road-wheel interactions.

5 PROTOTYPE SYSTEM

5.1 Design Goals

The basic design goal for the camera-based indirect vision system is that the same visual information available through the use of a conventional mirror-based indirect vision system is available through the use of the camera-based system. It is important that there be no hindrance to the ability of the driver to operate the vehicle in an effective manner when a camera-based system is used to replace the mirrors. It is essential that the fields of view provided by the camera-based system are equivalent to the fields of view provided by the conventional mirror system.

It is important that the design of the camera system ensures that all necessary components are installed solely on the tractor and that there are no components required on the trailer. With an estimated three trailers for every tractor operating within Canada (based upon a survey of the top 100 carriers in Canada [44]), having the system installed only on the tractor will cut down on installation costs of the systems. It will also eliminate the necessity of ensuring that a camera-based indirect vision system equipped tractor does not have to always be coupled with a trailer with the same capabilities.

In addition to the above, the camera-based indirect vision system should be low cost to decrease the payback period as well as easy to use to minimize driver input.

5.2 Subject Vehicle

The subject vehicle on which the camera-based indirect vision system was installed was a Volvo VN780 as shown in Figure 10. The subject vehicle had two west coast mirrors on either side of the vehicle consisting of a unit magnification mirror and a convex mirror located underneath the unit magnification mirror. The two west coast mirrors may be seen in Figure 11. In addition to the west coast mirror, the passenger side of the vehicle had a look-down mirror.

Figure 10: Subject vehicle

Figure 11: West coast mirrors on subject vehicle

The subject vehicle also had two fender-mounted convex mirrors as shown in Figure 12.

Figure 12: Fender-mounted convex mirrors on subject vehicle

The reflective area provided by the mirrors on the subject vehicle is provided in Table 3. As shown in Table 3, the reflective area provided by the unit magnification mirror is 819 cm^2, which is roughly 250% of what is required by CMVSS 111.

Table 3: Size of mirrors on subject vehicle

Mirror	Reflective Area (cm^2)
West coast – Flat mirror	819
West coast – Convex mirror	288
Fender mounted convex mirror	299

5.3 Vehicle Measurements

In order to determine the required field of view of the camera-based indirect vision system, the fields of view of the conventional mirror-based system had to be quantified. This was accomplished by connecting a 53 foot trailer to the subject vehicle, and having a 178 cm tall driver sit in the driver seat of the subject vehicle, adjust his mirrors as he would for normal driving and describe his field of view to the test engineer. The fields of view described by the driver are summarized in Table 4 and may be seen in Figure 13. The fields of view provided in Table 4 are ambinocular fields of view.

Table 4: Mirror field of view

Mirror	Field of View	
	Driver Side	Passenger Side
West coast – Flat mirror	18°	6°
West coast – Convex mirror	50°	42°
Fender mounted convex mirror	40°	53°

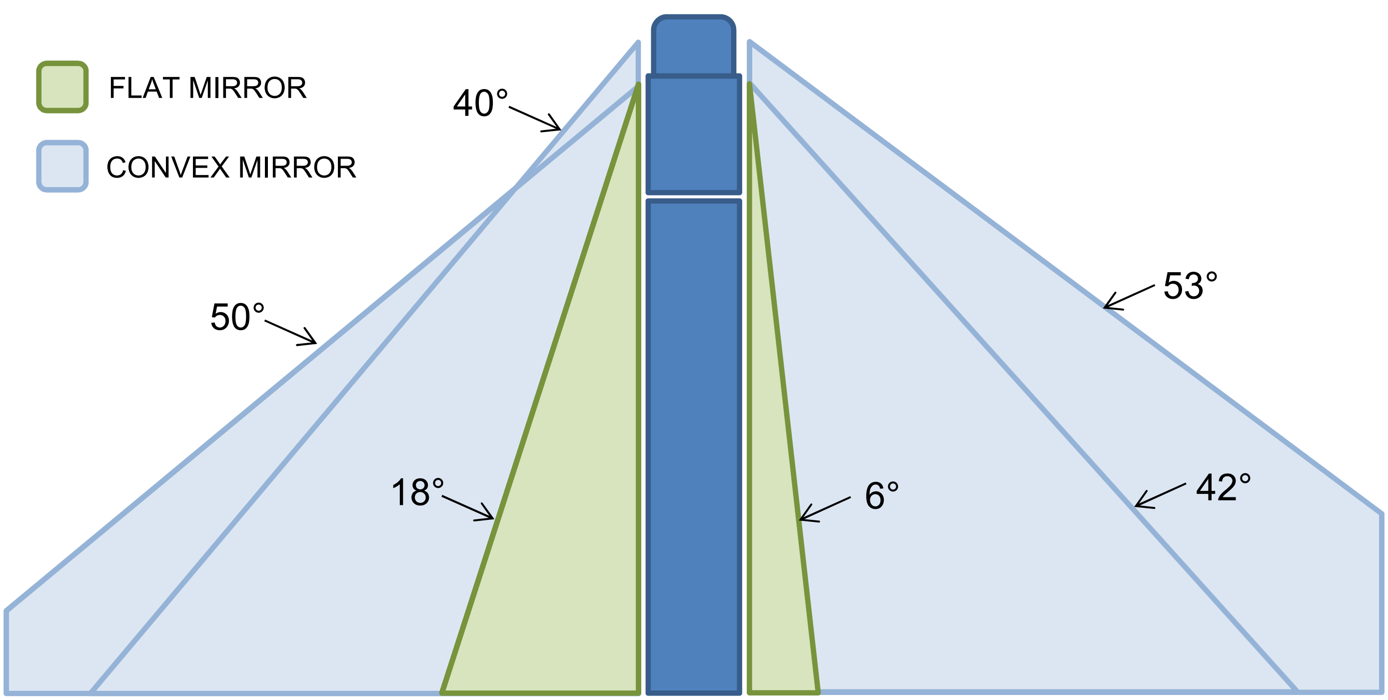

Figure 13: Mirror field of view for subject vehicle

The fields of view shown in Figure 13 represent the angles associated with each mirror field of view and do not necessarily represent areas in which targets may be successfully located and identified. The replication of the fields of view angles will allow for similar target detection capabilities in the camera-based system as would be available with the mirror-based system.

In addition to the indirect visibility measurements, measurements of the direct visibility of the driver were also taken. These were used later to compare the visual obstruction of the mirrors to the visual obstruction of the monitors. The direct visibility measurements were taken by locating the mid-eye centroid of the driver’s eyellipses for a male/female demographic of 90%/10% as described in SAE J941 [45]. An eyellipse is used to describe the statistical distribution of the eye locations in three-dimensional space within the vehicle. It is a contraction of the words “eye” and “ellipse”.

By locating the mid-eye centroid of the driver’s eyellipse, the field of view obstruction presented by the mirrors and the A-pillars was calculated in terms of the amount of visual angle subtended by the obstructing item. The visual angles of obstruction for the mirrors and the A-pillars are found in Table 5.

Table 5: Field of view obstructions

Item	Field of View Obstruction	
	Driver Side	Passenger Side
West coast mirror	11.6°	5.3°
Fender mounted convex mirror	4.8°	3.8°
A-pillars	7.2°	3.7°

5.4 Optimal System Resolution

The location of the driver's mid-eye eyellipse centroid in relation to the vehicle A-pillars allowed for the calculation of the maximum system resolution by using equation (2). The maximum required resolution for each recommended monitor size from section 3.2.5 is shown in Table 6. A camera or monitor resolution selected that is higher than the resolutions presented in Table 6 will offer no additional benefit to the clarity of images displayed on the monitors as the human eye will not be able to resolve individual pixels.

Table 6: Maximum required monitor resolutions

Size Designation	Diagonal Image Size (mm)	Maximum Resolution at Left A-Pillar (Mpx)	Maximum Resolution at Right A-Pillar (Mpx)
Size 1	141	0.58	0.15
Size 2	161	0.77	0.20
Size 3	213	1.34	0.35

5.5 Camera Selection

Previous studies evaluating the use of cameras for use in camera-based indirect vision systems recommended that a security camera be used as the image capturing device due to the requirements for both day and nighttime viewing [6]. Several different cameras from various manufacturers were reviewed based on the specifications provided on their data sheets.

Both standard definition (SD) analog and high definition (HD) digital cameras were considered for use in the system. However, the majority of the HD security cameras surveyed used an H.246 compression scheme to transmit the video data. The compression of the data takes time and would therefore induce noticeable lag between the time the image was captured and the time the image was displayed on the monitor. Lag in a camera-based indirect vision system is undesirable, therefore cameras which used an H.264 compression scheme were deemed inappropriate for use in the prototype system. There are a few cameras available which use SMPTE 292M, a non-compressive HD video transmission protocol, which may be suitable for use in a camera-based indirect vision system, but the cameras available with such a video transmission protocol did not have good nighttime viewing characteristics.

The use of an SD analog camera will provide a maximum resolution of 0.48 Mpx, which falls short of some of the calculated optimal resolutions shown in Table 6. However, the analog camera will not induce compression lag which was considered as a more important design factor.

The camera selected for the prototype camera-based indirect vision system was a Panasonic WV-CP624 which has a good combination of image resolution and day and nighttime viewing characteristics. The selected lens for the camera was a Panasonic PLZ5-50DN with a variable field of view from 5° to 50°. The variable field of view capabilities of the lens allowed for the use of a single camera and lens solution for all four surrogate cameras.

The selected camera and lens may be seen in Figure 14.

Figure 14: Selected camera and lens

5.6 Monitor Selection

Although the optimal monitor size is dependent upon the criteria described in section 3.2.5, only the monitor sizes presented in Table 2 were considered for use in the prototype camera-based indirect vision system. The monitor sizes presented in Table 2 are standard sizes provided by many monitor manufacturers.

Several different monitors from various manufacturers were reviewed based on the specifications provided on their data sheets. The monitors selected for use in the prototype camera-based indirect vision system are manufactured by ToteVision. Three different sizes of monitors were selected, corresponding to the sizes provided in Table 2. The selected monitors may be seen in Figure 15, the details of which are provided in Table 7.

Table 7: Selected monitors

Monitor	Diagonal Image Size (mm)	Resolution (Mpx)
ToteVision LCD-562	142	0.22
ToteVision LCD-642	163	0.22
ToteVision LCD-842HD	213	0.48

Figure 15: Selected monitors

Once again, the resolutions provided by the selected monitors fall short of some of the optimal resolutions presented in Table 6. However, the jump from SD to HD monitors would require the use of HD compatible cameras, which were deemed unsuitable for use in the prototype system as detailed in section 5.5.

5.7 Camera Fairings

It is important to determine the overall change in aerodynamic drag coefficients through the use of a camera-based indirect vision system to determine the change in vehicle fuel consumption that would be realized through the use of such systems. Some of the aerodynamic gains achieved by removing the mirrors will be negated by adding camera fairings. In order to perform the aerodynamic testing, two separate camera fairings were designed. The two camera fairings may be seen in Figure 16.

Figure 16: Camera fairings designed by NRC-AST

The camera fairing shown on the left in Figure 16 was designed to house the selected cameras and be located on the front fender of the subject vehicle. It was also designed to include a space claim for additionally required items such as a heater to maintain proper operating temperature of the cameras, servos to slightly alter the fields of view of the cameras, as well as space for a lens cleaning system that may be required to clean soiled lenses. The resulting camera fairing was considered a worst case situation. It is expected that a production version of a camera-based indirect vision system camera fairing would be no larger than the fairing shown on the left hand side of Figure 16.

The camera fairing shown on the right hand side of Figure 16 was designed to house only the cameras and mounted in the location where the mirrors are conventionally placed. There are a few camera-based indirect vision systems under development which have the cameras placed in such a location and it was important to test a similar fairing in order to determine the possible fuels savings through the use of such a camera location.

The location of each of the designed camera fairings may be seen in Figure 17.

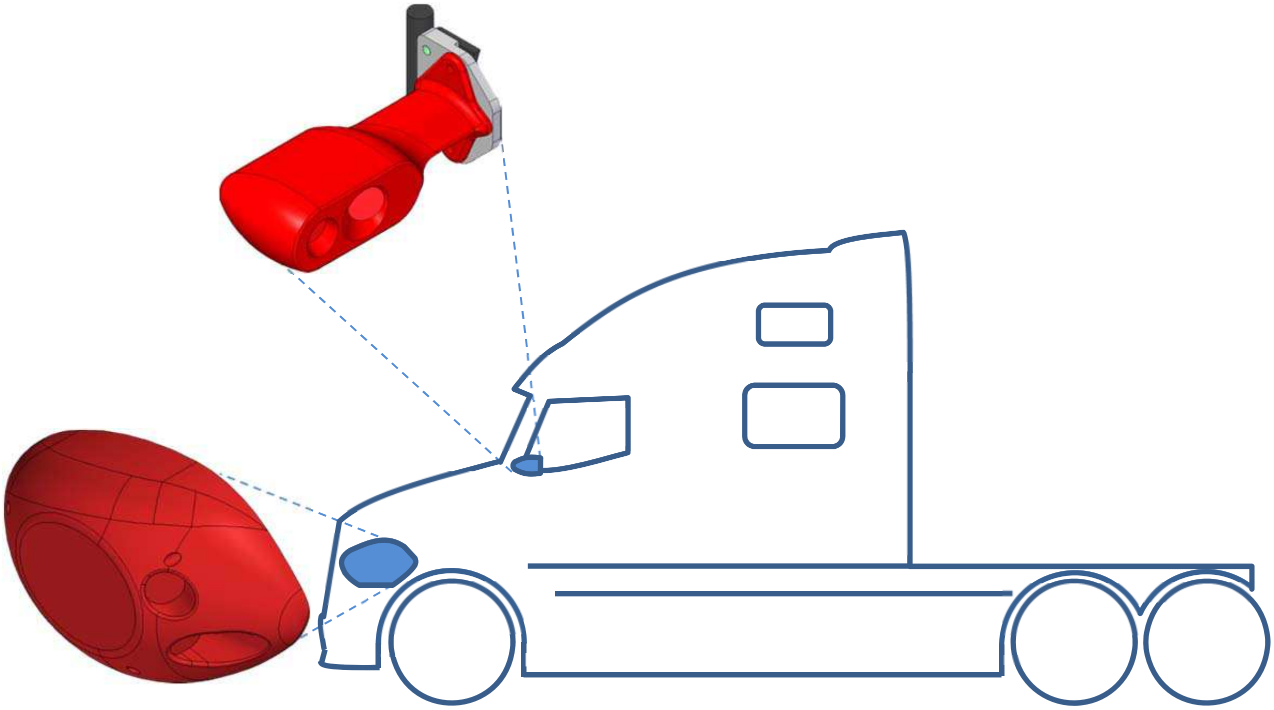

Figure 17: Location of prototype camera fairings on subject vehicle

5.8 Camera Location

As explained in section 3.2.2, the optimal location for the cameras is on the front fender of the subject vehicle. The mounting of the cameras on the front fender of the subject vehicle may be seen in Figure 18. There are two cameras mounted on either side of the vehicle. The camera in the uppermost position is used as the convex mirror surrogate camera. The camera in the lowermost position is used as the flat mirror surrogate camera.

Figure 18: Cameras mounted on subject vehicle

5.9 Monitor Location

As described in section 3.2.4, the ideal location for the monitors is on the left and right A-pillars. The monitors mounted on the left A-pillars of the subject vehicle may be seen in Figure 19 and the monitors mounted on the right A-pillars of the subject vehicle may be seen in Figure 20.

The monitors mounted on the left A-pillar were a ToteVision LCD-562 mounted above a ToteVision LCD-642. The top monitor provides the view from the driver side convex mirror surrogate camera and the bottom monitor provides the view from the driver side flat mirror surrogate camera.

The monitors mounted on the right A-pillar were a ToteVision LCD-642 mounted above a ToteVision LCD-842HD. The top monitor provides the view from the passenger side convex mirror surrogate camera and the bottom monitor provides the view from the passenger side flat mirror surrogate camera.

Figure 19: Monitors mounted in subject vehicle on left A-pillar

Figure 20: Monitors mounted in subject vehicle on right A-pillar

5.10 Mirror Box

Since the camera-based indirect vision system is replicating a mirror-based system, it is necessary to mirror the images captured by the cameras, as detailed in section 3.2.6. A Colorado Video NVVN420CS mirror box, as shown in Figure 21, was used to perform the mirroring operation.

Figure 21: Mirror box

5.11 IR Illuminator

In addition to the cameras and monitors, an IR illuminator was mounted to the side of the subject vehicle to provide additional IR lighting during nighttime driving conditions. The IR illuminator attached to the side of the subject vehicle is shown in Figure 22.

Figure 22: IR illuminator mounted on the side of the subject vehicle

5.12 IR selector

The selection of the IR mode on the cameras as well as the powering of the IR illuminator for the prototype system is performed via a toggle switch accessible by the driver of the vehicle. The IR selector may be seen in Figure 23. It is envisioned that a production camera-based indirect vision system would have automatic control of the IR capabilities and that no driver input would be required.

Figure 23: IR selector

5.13 Camera System Field of View

The camera system field of view was configured using the variable field of view lenses to replicate the field of view provided by the mirror based system. The fields of view provided by the camera-based system are summarized in Table 8 and shown in Figure 24.

Table 8: Camera-based indirect vision system field of view

Mirror	Field of View	
	Driver Side	Passenger Side
Flat mirror surrogate	23°	9°
Convex mirror surrogate	50°	50°

As can be seen in Figure 24, the camera system field of view for the flat mirror surrogates is slightly larger than that provided by the flat mirrors themselves, as shown in Figure 13. This is to account for the additionally available field of view provided by the driver's head movements, as described in section 3.2.1.

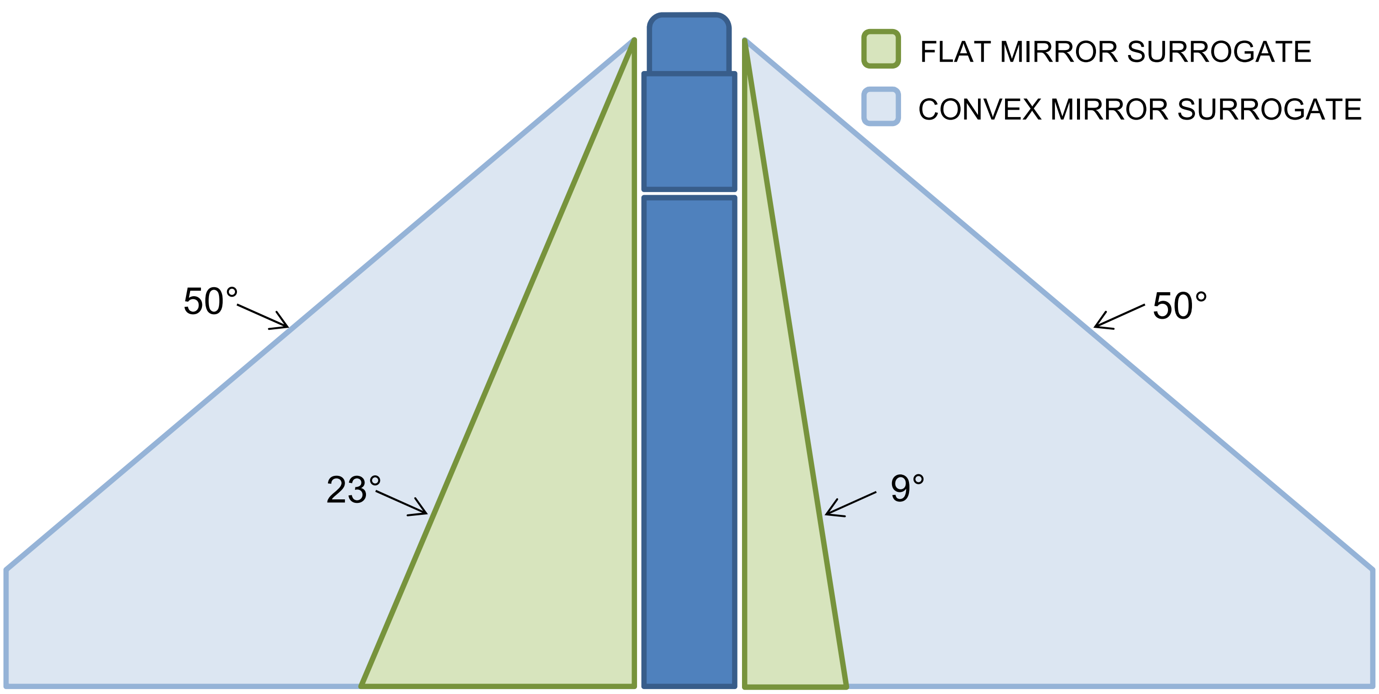

Figure 24: Camera-based indirect vision system field of view for subject vehicle

In addition to the indirect field of view measurements, the obstruction to the direct field of view to the driver due to the placement of the monitors on the A-pillars was also measured in terms of the amount of visual angle subtended by the obstructing item. The visual angles of obstruction for the monitors located on the A-pillars are found in Table 9.

Table 9: Field of view obstructions of monitors

Item	Field of View Obstruction	
	Driver Side	Passenger Side
Convex mirror surrogate monitor	11.5°	6.0°
Flat mirror surrogate monitor	13.3°	7.4°

5.14 Field of View Comparison

Figure 25 provides an overlay of the mirror field of view on top of the camera system field of view. As can be seen in Figure 25, there exists a small area on the passenger side of the vehicle which is covered by the mirror-based indirect vision system but is not visible through the camera-based system. This area subtends roughly 3° and will most likely not be readily apparent by the operator as a loss of indirect vision coverage. A human of average width would need to be approximately 10 m away from the vehicle before they would fit into the blind spot.

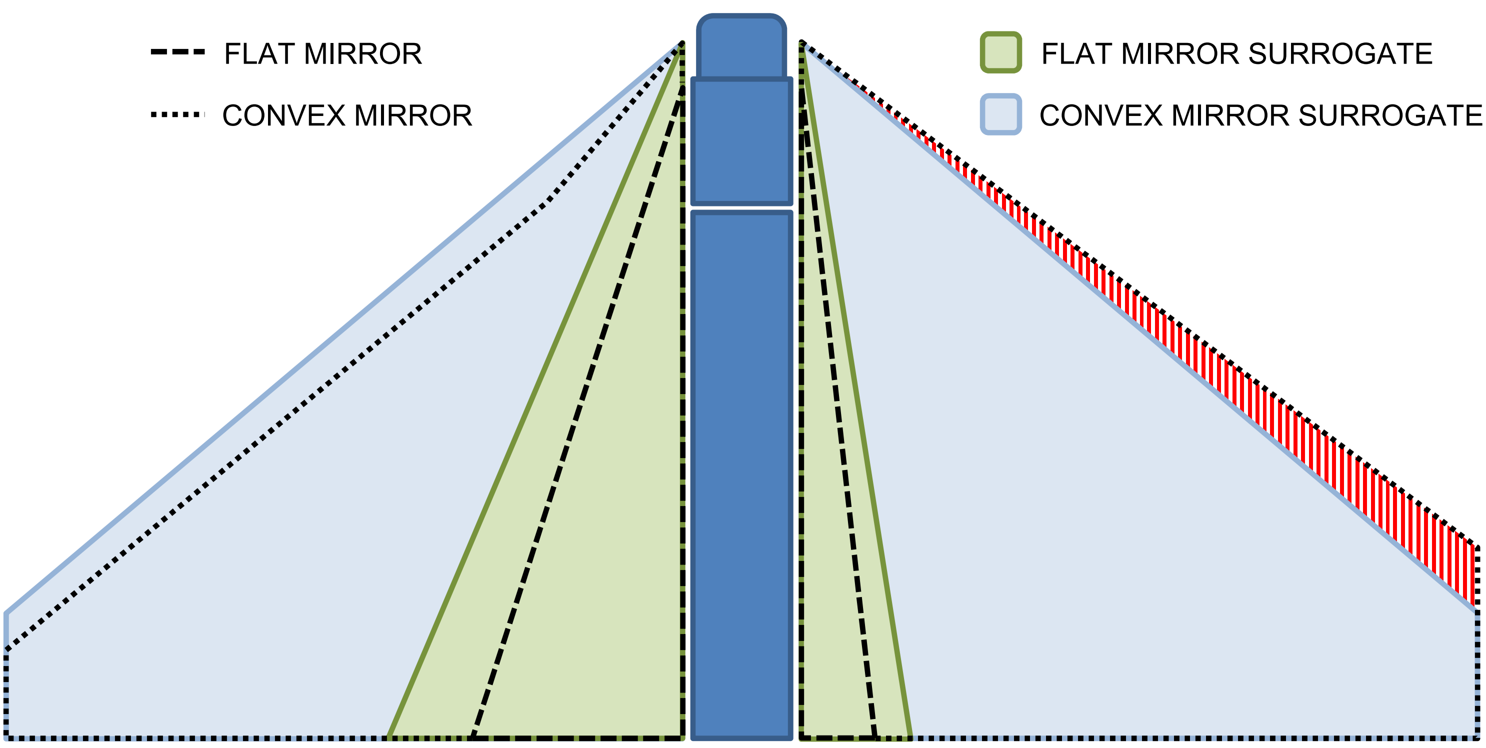

Figure 25: Comparison of mirror and camera-based indirect vision system fields of view

Figure 26 provides a side view of the passenger side of the vehicle. For comparison sake, both the fender mounted convex mirror and the camera-based indirect vision system are shown. It can be seen from Figure 26 that there exists an additional area of coverage while using the camera-based system that is not offered through the use of a fender mounted convex mirror. This additional coverage available with the camera-based system allows the driver to locate objects on the passenger side of the vehicle more easily than through the use of a fender mounted convex mirror.

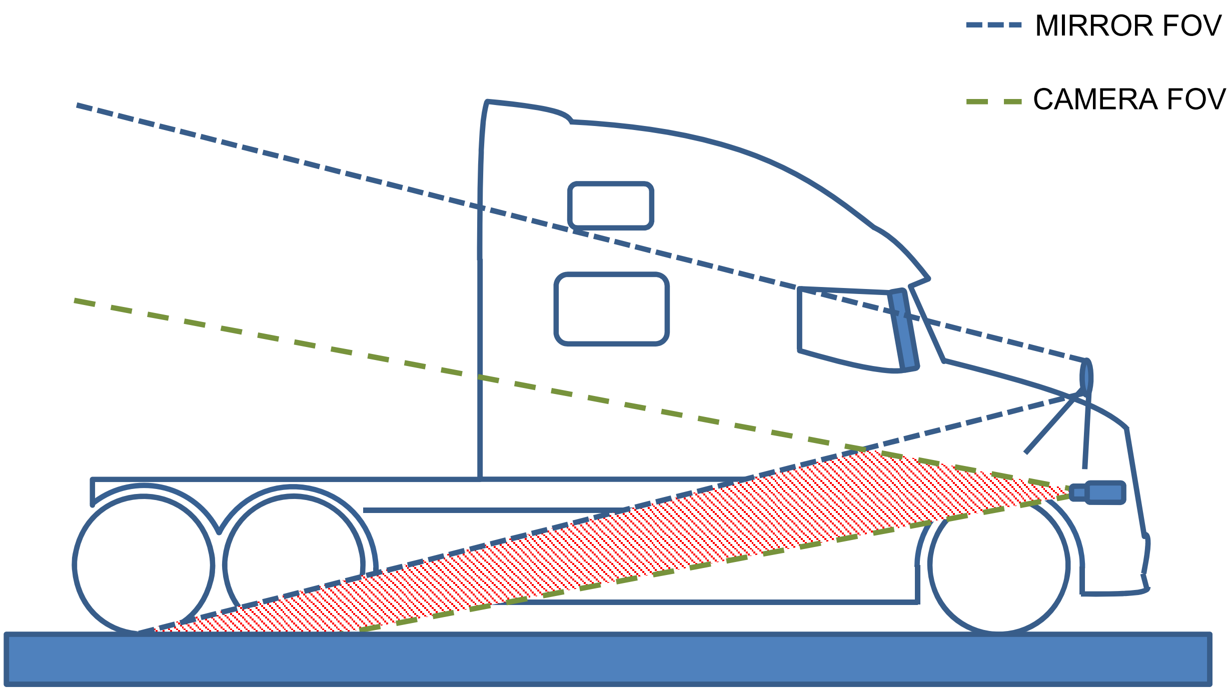

Figure 26: Comparision of camera-based indirect vision system to fender mounted convex mirror

Finally, the visual obstructions of the mirror-based indirect vision system can be compared to those of the camera-based system. By using the information presented in Table 5 and Table 9, the total visual angles of obstruction may be calculated. The visual obstruction angles of the mirror-based system include both the west coast mirrors, the fender mounted convex mirrors and the A-pillars. The visual obstruction angles of the camera-based system only include the visual obstruction of the largest monitor located on the A-pillar. The total visual obstruction angles are used for a comparison basis only. The results of such a comparison are found in Table 10.

Table 10: Comparison of field of view obstructions of mirrors and monitors

Parameter	Field of View Obstruction		
	Driver Side	Passenger Side	Total Obstruction
Mirror-based indirect vision system (and A-pillars)	23.6°	12.8°	36.4°
Camera-based indirect vision system	13.3°	7.4°	20.7°

As can be seen from Table 10, the camera-based system offers a slightly better unobstructed direct field of view for the driver.

5.15 Power Consumption

The power consumption of the prototype camera-based indirect vision system may be used to calculate the approximate fuel required to power the system as outlined in 3.2.10. The component based power consumption of each design item of the camera-based indirect vision system may be found in Table 11. Table 11 presents the rated power of each component as provided by the component specifications, as well as the experimentally measured voltage, current and power of each component.

Table 11: Component power consumption

Component	Rated Power (W)	Measured		
		Voltage (V)	Current (A)	Power (W)
Panasonic WV-CP624	2.6	12.00	0.172	2.06
ToteVision LCD-562	6.0	12.00	0.313	3.76
ToteVision LCD-642	12.0	12.00	0.526	6.31
ToteVision LCD-842HD	9.6	12.00	0.992	11.90
IR illuminator 15-IL05	12.0	15.00	0.657	9.86
Mirror Box NVVN420CS	5.0	5.00	0.341	1.71

The total system power requirements are presented in Table 12. Again, both rated power for the component specifications as well as measured power is included in Table 12.

Table 12: Total system power consumption

Component	Number of Specified Components	Component Basis		Total System Requirements	
		Rated Power (W)	Measured Power (W)	Rated Power (W)	Measured Power (W)
Panasonic WV-CP624	4	2.6	2.06	10.4	4.1
ToteVision LCD-562	1	6.0	3.76	6.0	3.8
ToteVision LCD-642	2	12.0	6.31	24.0	12.6
ToteVision LCD-842HD	1	9.6	11.90	9.6	11.9
IR illuminator 15-IL05	2	12.0	9.86	24.0	19.7
Mirror Box NVVN420CS	4	5.0	1.71	20.0	6.8
			TOTAL:	**94.0**	**58.9**

The data provided in Table 12 may be used to calculate the yearly fuel requirements to power the camera-based indirect vision system by using equation (5). Table 13 provides the assumptions used to perform the calculation. The engine efficiency noted in Table 13 was obtained from Volvo for their D12D-465 engine, the same engine that powers the subject vehicle.

Table 13: Assumptions for fuel required to power system calculations

Quantity	Assumed Value
Engine efficiency	39.4%
Alternator efficiency	70% [46]
Calorific value of diesel fuel	42.9 MJ/kg [46]
Duration of system use per year	2500 h
Density of fuel	0.820 kg/L [46]

Using equation (5) and the assumptions presented in Table 13, the fuel required to power the camera-based indirect vision system for one year at rated load is 87.2 L and at measured load is 54.6 L.

5.16 Mean Time To Failure

An electrically powered, electronic camera-based indirect vision system may be subject to failure at a higher rate than a conventional mirror-based system, as described in section 3.2.14. A block diagram of the major components of the camera-based system may be seen in Figure 27. Table 14 provides the estimated lifespan (and associated failure rates) of each of the major components of the camera-based indirect vision system. The life expectancies presented in Table 14 were collected through personal communication with the equipment manufacturers, except for that provided for the video cable which was calculated using MIL-HDBK-217F [47] using a temperature of 20°C, a mating/unmating factor of 1.5, an active connections factor of 1.4 and an environment factor of 1.0.

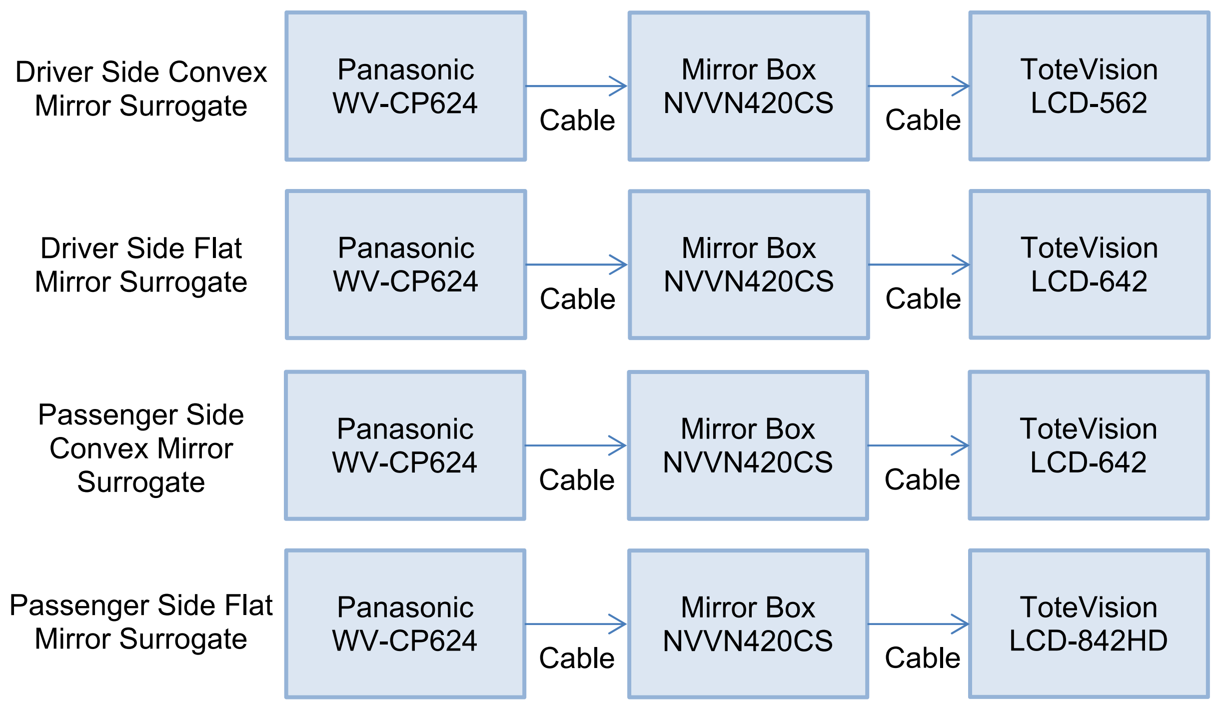

Figure 27: Block diagram of camera-based indirect vision system

Table 14: Life expectancy and failure rates of system components

Component	Life Expectancy (hours)	Failure Rate, λ (failures per 1000 hours)
Panasonic WV-CP624	270,029	$3.7 \cdot 10^{-3}$
ToteVision LCD-562	30,000	$3.3 \cdot 10^{-2}$
ToteVision LCD-642	30,000	$3.3 \cdot 10^{-2}$
ToteVision LCD-842HD	50,000	$2.0 \cdot 10^{-2}$
Mirror Box NVVN420CS	175,000	$5.7 \cdot 10^{-3}$
Cable	180,600,000	$5.5 \cdot 10^{-6}$

As can be seen in Figure 27, the camera-based indirect vision system is designed in such a way that all camera-to-mirror box-to-monitor paths are independent from one another. One may calculate the failure rate of any individual path by summing the failure rates for each component along that path [48]. The resultant failure rates and corresponding life expectancies for each mirror surrogate are presented in Table 15.

Table 15: Failure rates and life expectancies of mirror surrogates

Path	Failure Rate, λ (failures per 1000 hours)	Life Expectancy (hours)
Driver Side Convex Mirror Surrogate	$4.3 \cdot 10^{-2}$	23,385
Driver Side Flat Mirror Surrogate	$4.3 \cdot 10^{-2}$	23,385
Passenger Side Convex Mirror Surrogate	$4.3 \cdot 10^{-2}$	23,385
Passenger Side Flat Mirror Surrogate	$2.2 \cdot 10^{-2}$	33,980

Assuming that, for the system to be considered functional, at least three of the four available mirror surrogates need to be functional, the mean time to failure for the camera-based indirect vision system may be calculated by using equation (8) [48].

$$MTTF = \frac{1}{\lambda} \cdot \sum_{i=n}^{k} \frac{1}{i} \quad \textbf{(8)}$$

Where MTTF: mean time to failure

λ: failure rate

n: number of required functional paths

k: total number of paths

Since the camera-based indirect vision system requires three of the four mirror surrogates to be functional to consider the entire system as functional, n = 3 and k = 4 in equation (8). By using $\lambda = 4.3 \cdot 10^{-2}$ as a conservative value, the camera-based indirect vision system has a mean time to failure of roughly 13,570 hours. Assuming the vehicle operates for roughly 2500 hours per year, the system mean time to failure is about 5.4 years.

The calculation of a system mean time between failures is dependent upon how a system failure is resolved. The mean time between failure will be the same as the mean time to failure if, upon initial component failure, the entire system is replaced. However, it is more likely that only the failed component will be replaced. In the event that only the failed component is replaced, the mean time between failures will differ from the mean time to failure. In this situation, the mean time between failures is dependent upon how many hours of system time had elapsed before the failure occurred and the expected remaining lifetime of the components that were not replaced due to the failure.

5.17 System Mass

As described in section 3.2.11, the mass of the system will have an impact on the fuel consumption of the vehicle. The masses of the prototype camera-based indirect vision system components are provided in Table 16. For comparison, the masses of the mirrors removed from the vehicle are provided in Table 17.

Table 16: Mass of camera-based indirect vision system

Component	Quantity	Component Mass (kg)	Total Mass (kg)
Panasonic WV-CP624	4	0.259	1.036
ToteVision LCD-562	1	0.321	0.321
ToteVision LCD-642	2	0.476	0.952
ToteVision LCD-842HD	1	1.312	1.312
IR illuminator 15-IL05	2	0.259	0.518
Mirror Box NVVN420CS	4	0.301	1.204
Camera Mounting Bracket	2	1.415	2.830
Monitor Mounting Bracket	4	0.091	0.364
IR Illuminator Bracket	2	0.074	0.148
Video Cabling (per meter)	24.4	0.036	0.878
Video Cable Terminations	16	0.010	0.160
Power cable (per meter)	54.9	0.026	1.427
		TOTAL:	**11.150**

Table 17: Mass of mirror-based indirect vision system

Component	Quantity	Component Mass (kg)	Total Mass (kg)
West Coast Mirror	2	5.998	11.996
Lookdown Mirror	1	0.570	0.570
Fender Mounted Convex Mirror	2	1.923	3.846
		TOTAL:	**16.412**

By comparing the data provided in Table 16 and Table 17, one can see that the installation of the camera-based indirect vision system decreases the overall mass of the vehicle by roughly 5.26 kg. In order to calculate the potential fuel savings as a result of the weight decrease, equation (7) from section 3.2.11 will be used along with a travel distance of 130,000 km. Based on the results from equation (7), the yearly estimated fuel savings due to a decrease in overall vehicle mass is roughly 1.8 L per year.

5.18 Cost

The cost of each of the main components of the prototype camera-based indirect vision system, as well as the overall system cost, is provided in Table 18. The replacement cost of the mirror-based indirect vision system for the subject vehicle is provided in Table 19. As can be seen by comparing Table 18 and Table 19, the prototype camera-based indirect vision system costs roughly $6,663.84 more than the mirror-based indirect vision system.

Table 18: Cost of camera-based indirect vision system

Component	Quantity	Component Cost	Total Cost
Panasonic WV-CP624 (and lens)	4	$741.28	$2,965.12
ToteVision LCD-562	1	$449.73	$449.73
ToteVision LCD-642	2	$722.54	$1,445.08
ToteVision LCD-842HD	1	$1,115.81	$1,115.81
IR illuminator 15-IL05	2	$80.51	$161.02
Mirror Box NVVN420CS	4	$710.77	$2,843.08
		TOTAL:	**$8,979.84**

Table 19: Cost of mirror-based indirect vision system for subject vehicle

Component	Quantity	Component Cost	Total Cost
West coast mirror	2	$1,100.63	$2,201.26
Fender mounted convex mirror	2	$57.37	$114.74
		TOTAL:	**$2,316.00**

6 AERODYNAMIC TESTING

6.1 Description of Testing

In order to quantify the fuel savings which may be realized through the use of a camera-based indirect vision system it was important to quantify the gains in aerodynamic efficiency as a result of using such a system. To do so, full-scale component testing of the camera-based indirect vision system components were tested in NRC-IAR's 2 m by 3 m wind tunnel. In addition to the prototype camera fairings designed by NRC-AST, the camera housing designed by VTTI [9] was also tested. The VTTI camera housing is a small single camera housing which may be seen in Figure 28.

Figure 28: VTTI camera housing [9]

The large camera fairing designed by NRC-AST along with the small VTTI camera housing provided a best and worst case for the possible reduction in aerodynamic drag that could be expected when using a camera-based indirect vision system mounted on a front fender location. The worst case, the large dual-camera fairing designed by NRC-AST, included a space claim for things such as heating elements and lens cleaning systems. It is not expected that a camera housing would be much larger than that designed by NRC-AST. The best case, the VTTI designed small single-camera housing, housed only one camera and did not include any provisions for heating or cleaning. It is not expected that a camera housing would be much smaller than that designed by VTTI.

Because wind tunnel testing was performed on a full-scale component basis only, the mirrors of the subject vehicle also had to be tested. The testing of the mirrors allowed for the comparison of data from previous full-scale vehicle testing as described in [3]. The west coast mirror (with the lookdown mirror) being tested in the wind tunnel may be seen in Figure 29.

Figure 29: West coast mirror (with lookdown mirror) in wind tunnel

In addition to the camera fairings and the mirrors, it was also important to determine the contribution to aerodynamic drag due to the installation of an IR illuminator on the subject vehicle. NRC-IAR designed and built a prototype fairing to simulate an IR illuminator housing. The IR illuminator prototype fairing was composed of two different components: a leading component and a trailing component. The IR illuminator prototype fairing was tested with only the leading component (as shown on the left-hand side of Figure 30) and then again with both the leading and trailing components (as shown on the right-hand side of Figure 30).

Figure 30: IR illuminator prototype fairings in the wind tunnel

Table 20 provides a full list of all items tested in the wind tunnel.

Table 20: Components tested in the wind tunnel

Group	Component
Subject Vehicle Mirrors	West coast mirror (with lookdown mirror)
	West coast mirror (without lookdown mirror)
	Fender mounted convex mirror
Camera Fairings	Large fender mounted dual-camera fairing
	Small fender mounted single-camera fairing
	Mirror-location mounted dual-camera fairing
IR Illuminator Fairings	IR illuminator fairing (leading component only)
	IR illuminator fairing (leading and trailing components)

When mounted on the vehicle, the face of the unit magnification mirror housing made a 68° angle with the side of the vehicle. However, the airflows acting on the mirror while mounted on the vehicle are most likely not parallel to the longitudinal axis of the vehicle. To determine the sensitivity of the mirror drag coefficient to flow angle, the west coast mirror (with lookdown mirror) was mounted and tested at various angles. The truck-mounted angle of 68° was tested, but so were angles of 45° and 90°.

6.2 Results

The summarized results of the wind tunnel testing are provided in Table 21. The full results including all tested wind speeds may be found in Appendix A. The value of $C_D{\cdot}A$ given in Table 21 is the average drag coefficient of each component multiplied by the frontal area of the tested component over the range of speeds under which the component was tested.

Table 21: Results of wind tunnel testing

Group	Component	$C_D{\cdot}A$ (m^2)
Subject Vehicle Mirrors	West coast mirror (with lookdown mirror) – 90°	0.1677
	West coast mirror (with lookdown mirror) – 45°	0.0968
	West coast mirror (with lookdown mirror) – 68°	0.1296
	West coast mirror (without lookdown mirror) – 68°	0.1279
	Fender mounted convex mirror	0.0624
Camera Fairings	Large fender mounted dual-camera fairing	0.0079
	Small fender mounted single-camera fairing	0.0017
	Mirror-location mounted dual-camera fairing	0.0039
IR Illuminator Fairings	IR illuminator fairing (leading component only)	0.0107
	IR illuminator fairing (leading and trailing components)	0.0068

As previously mentioned, the wind tunnel testing was performed on a full-scale component basis only. In order to determine the change in the overall vehicle drag coefficient as a result of adding or removing the tested components, the $C_D{\cdot}A$ factors were divided by the frontal area of a full scale truck. The frontal area used for the calculations, 10.9 m^2, was the same as that used in previous full-scale wind tunnel testing [3]. The resulting changes in the overall vehicle drag coefficient as a result of removing the tested components from the vehicle, ΔC_D, are presented in Table 23. The change in overall drag coefficient was used to calculate the possible fuel savings which could be achieved by removing the component from the vehicle, as was done in previous full-scale aerodynamic testing [3]. Fuel savings were calculated by using equation (9) with the assumed values presented in Table 22. The results of the calculations are presented in Table 23.

$$V = 1.072 \cdot 10^{-5} \cdot \frac{\rho_A \cdot SFC \cdot v^2 \cdot \Delta C_D \cdot A_t \cdot d}{\eta_T} \tag{9}$$

Where V: volume of fuel saved per year (L)

ρ_A: density of air (kg/m^3)

SFC: specific fuel consumption of vehicle (L/kW·h)

v: velocity (km/h)

ΔC_D: change in drag coefficient

A_t: frontal area of truck (m^2)

d: distance travelled per year (km)

η_T: efficiency of transmission

Table 22: Assumptions for fuel savings calculations as a result of aerodynamic efficiency gains

Parameter	Assumed Value
Air density, ρ_A (at 15°C)	1.225 kg/m^3
Specific fuel consumption, SFC	0.275 L/kW·h
Vehicle velocity, v	100 km/h
Frontal area of truck, A_t	10.9 m^2
Distance travelled, d	130,000 km
Transmission efficiency, η_T	85%

Table 23: Calculated ΔC_D and fuel savings per component

Component	ΔC_D	Annual Change in Fuel Consumption (L)
West coast mirror (with lookdown mirror) – 90°	-0.0154	-927.1
West coast mirror (with lookdown mirror) – 45°	-0.0089	-535.8
West coast mirror (with lookdown mirror) – 68°	-0.0119	-716.4
West coast mirror (without lookdown mirror) – 68°	-0.0117	-704.4
Fender mounted convex mirror	-0.0057	-343.2
Large fender mounted dual-camera fairing	-0.0007	-42.1
Small fender mounted single-camera fairing	-0.0002	-12
Mirror-location mounted dual-camera fairing	-0.0004	-24.1
IR illuminator fairing (leading component only)	-0.0010	-60.2
IR illuminator fairing (leading and trailing components)	-0.0006	-36.1

It must be noted that the air density used in the calculations, as provided in Table 22, is that of air at 15°C and 101.3 kPa. As the air temperature decreases, its density increases. The increase in air density at colder temperatures will increase the fuel savings realized through the use of a camera-based indirect vision system. For example, the density of air at -25°C and 101.3 kPa is roughly 1.422 kg/m^3, increasing the expected fuel savings by roughly 16%.

By using the data presented in Table 23, one can calculate the net change in overall vehicle drag coefficient as well as the expected fuel savings for the prototype camera-based indirect vision system. The results of the calculations are presented in Table 24. As can be seen in Table 24, the net expected fuel savings through the use of the prototype camera-based indirect vision system on a yearly basis are roughly 1,902.4 L.

Table 24: Calculated ΔC_D and fuel savings for prototype system

Component	Number of Specified Components	ΔC_D per Component	Total ΔC_D	Total Annual Change in Fuel Consumption (L)
West coast mirror (with lookdown mirror) – 68°	1	-0.0119	-0.0119	-716.4
West coast mirror (without lookdown mirror) – 68°	1	-0.0117	-0.0117	-704.4
Fender mounted convex mirror	2	-0.0057	-0.0114	-686.3
Large fender mounted dual-camera fairing	2	0.0007	0.0014	84.3
IR illuminator fairing (leading component only)	2	0.0010	0.0020	120.4
		TOTAL:	-0.0316	-1,902.4 L

6.3 Aerodynamic Drag Associated with Mirrors Meeting CMVSS 111 Minimums

CMVSS 111 only requires a unit magnification mirror with 325 cm^2 of reflective area on both sides of the vehicle. However, as shown in Table 3, the subject vehicle had total of 1,107 cm^2 of reflective area on each side of the vehicle due to the west coast mirrors, or roughly 340% the required amount. This increases to 1,406 cm^2 of reflective area on each side of the vehicle, when including the front fender mirrors. It is of value to determine the possible fuel savings that could be realized through use of a mirror that met, but did not exceed, CMVSS 111 minimums.

The range of Reynolds number over which the west coast mirror was tested varied from about 380,000 to 690,000. There was relatively little variation in the drag coefficient of the west coast mirror over this range. For a mirror that is 3.4 times smaller, the Reynolds number falls to roughly 136,000 for a vehicle traveling at 100 km/h. It is expected that the drag coefficient would remain relatively constant over this new range of Reynolds numbers as well and that the data may be scaled to offer an estimate of fuel savings associated with the use of a smaller mirror.

By assuming the smaller CMVSS 111 minimums mirror has the same general shape as the tested mirror, the $C_D{\cdot}A$ factor presented in Table 21 for the west coast mirror may be scaled to estimate the ΔC_D of the smaller mirror. Scaling the $C_D{\cdot}A$ data by a factor of 3.4 results in an overall vehicle ΔC_D of 0.0035 for a mirror that meets the minimums of CMVSS 111. This translates to an estimated yearly fuel savings of about 1,896 L by using only the two small unit magnification mirrors as required by CMVSS instead of the stock mirrors.

Although the increased amount of reflective area on the subject vehicle may be necessary for adequate situational awareness, the removal of the additional reflective area could result in significant fuel savings. The situational awareness lost through the reduction of mirror size could be gained through the use of a much more aerodynamically efficient camera-based indirect vision system. The use of a combination of a mirror that meets CMVSS 111 minimums alongside a camera-based indirect vision system similar to the prototype system designed by NRC-AST would result in an estimated fuel savings of roughly 1,690 L.

6.4 Comparison With Previous Testing

The comparison of the change in overall vehicle drag coefficients and corresponding changes in fuel consumption may be seen in Table 25.

Table 25: Comparison of results of previous and current testing

Component	ΔC_D		Fuel Savings (L)	
	Previous Testing	Current Testing	Previous Testing	Current Testing
West coast mirrors	-0.016	-0.0236	938	1,423
Fender mounted convex mirror	-0.010	-0.0057	588	345

As can be seen in Table 25, there are some discrepancies between the values of previous and current testing. The results of previous testing indicated a lower fuel savings as a result of removing the west coast mirrors, but a higher fuel savings as a result of removing the fender mounted convex mirror. The difference in the results is attributable to the difference in the flows resulting from full-scale vehicle testing compared to those experienced with full-scale component testing. However, the data collected by full scale component testing is considered to offer a realistic estimation as to the fuel savings one may expect to realize through the use of a camera-based indirect vision system.

7 SUMMARY OF RESULTS

7.1 Fuel Savings

The changes in vehicle fuel consumption per year resulting from the power consumption, mass change, and change in vehicle drag coefficients as a result of the use of the prototype camera-based indirect vision system are provided in Table 26. One may calculate the overall change in vehicle fuel consumption over the period of one year by summing the individual changes in fuel consumption. As seen in Table 26, the use of a camera-based indirect vision system is expected to save roughly 1,817 L of fuel per year.

Table 26: Expected total fuel savings for prototype system

Factor	Total Annual Change in Fuel Consumption (L)
Fuel required to power system	87.2
Mass change	-1.8
Change in vehicle drag coefficient	-1,902.4
TOTAL:	-1,817.0

7.2 Payback Period

Based upon the information provided in Table 18 and Table 26 as well as an estimate of the current fuel price of $1.20 per liter, the estimated payback period for the use of the prototype camera-based indirect vision system is approximately 4.1 years. However, the price of fuel has increased over recent years and is expected to continue to rise. Also, the prototype system cost is expected to be higher than that of a production model system. Figure 31 provides a plot showing how the payback period of the camera-based indirect vision system varies as fuel prices increase and system costs decrease.

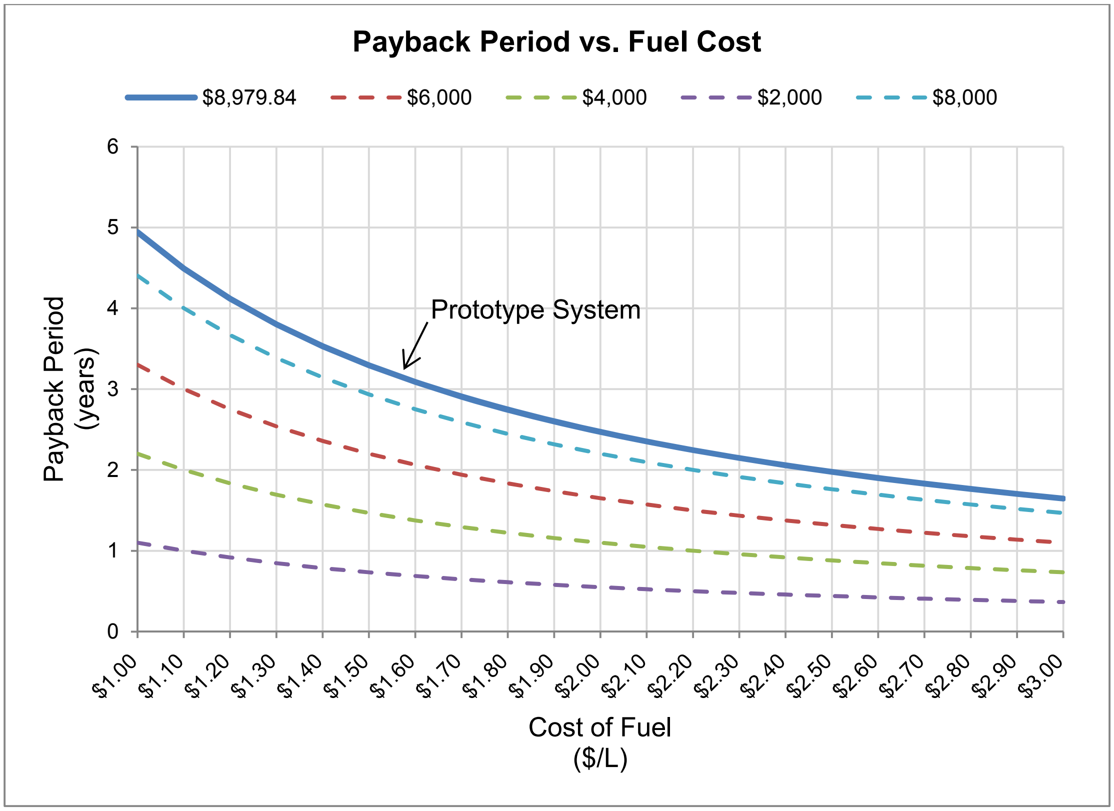

Figure 31: System payback period against fuel cost

7.3 Reduction in CO_2 Emissions

The estimated yearly fuel savings can be used to calculate an estimated yearly reduction in CO_2 emissions which may be realized through the use of a camera-based indirect vision system. By multiplying the estimated fuel savings of 1,817 L by a factor of 2.69 kg of CO_2 released per liter of diesel fuel burned [49], the use of the prototype camera-based indirect vision system has the capability of reducing CO_2 emissions by roughly 4,888 kg per year per vehicle.

It is estimated that there are roughly 227,000 highway tractors in operation on Canadian highways [2]. If camera-based indirect vision systems were to be installed on all of these vehicles, the yearly reduction in CO_2 emissions would be roughly 1,109,600 tonnes.

8 FUTURE WORK

8.1 Overview

Phase II of the current project involves the field testing of the prototype system developed in Phase I. It will be important to test how drivers react to the loss of their mirrors while using a camera-based indirect vision system. Phase II testing will involve both closed-course and on highway testing using a sample of heavy duty truck drivers.

8.2 Number of Drivers

Ideally, a large number of drivers should be included within Phase II testing in order to gain an appreciation for how the heavy duty truck population will react to the use of a camera-based indirect vision system and the corresponding loss of mirrors. However, due to restrictions on budget and project timeline it is unlikely that the sample population of drivers will contain more than ten drivers, but it should consist of no less than eight drivers.

8.3 Driver Experience

A variety of driver experience levels should be included within the sample population. Both more experienced drivers, with many years on the road, and less experienced drivers new to the world of heavy duty trucking are required to fully evaluate the prototype camera-based indirect vision system.

8.4 Driver Age

Both young and old drivers are required in the sample population to determine the effect of age on the usage of a camera-based indirect vision system, if any. If possible, the sample population should include young and inexperienced drivers, older and inexperienced drivers, older and experienced drivers and younger and experienced drivers.

8.5 Driver Gender

Both male and female drivers should be included in the field testing of the prototype camera-based indirect vision system. Although there is a larger number of men than women operating heavy duty vehicles, it is important to gather data for system use by both genders.

8.6 Environmental Conditions

Both closed course and road testing of the camera-based indirect vision system should be performed in a variety of weather conditions. Ideally, testing should take place in the following environmental conditions: sunny daytime, overcast daytime, nighttime, rain, snow, hail, sleet, fog and mist. Of course, it may not be possible to test in all conditions due to the inherent unpredictability of weather, but as many conditions as possible should be tested.

8.7 Closed Course Testing

Closed course testing will test the ability of the test driver to operate their vehicle in an effective manner while using the prototype camera-based indirect vision system and without the use of their mirrors. The drivers will be required to perform lane-changing manoeuvers, backing procedures as well as target identification tests. The results of the closed course testing will be used to refine the prototype camera-based indirect vision system prior to performing road testing.

8.8 Road Testing

Road testing of the prototype camera-based indirect vision system will occur on open highways. The testing of the camera-based system will require special permits to allow the vehicle to operate on public roads without the use of mirrors. It will be important that the mirrors are removed from the test vehicle to prevent the test drivers from looking at them. Even if the mirrors were to be shrouded, the shrouded mirror visible in the periphery of the drivers' vision may cause them to look at that location expecting to see a reflective surface. To fully evaluate the use of a camera-based indirect vision system it will be important that it is the only system available to the driver.

To maintain the safety of the test drivers and other vehicle operators on the road, road testing will include a number of safety measures, such as a chase vehicle. The precise nature of the safety measures will be described within the test plan for Phase II testing.

9 DISCUSSION

9.1 Travel Distance and Speed Used in Calculations

Throughout the preceding report, an assumed distance travelled and average vehicle speed of 130,000 km and 100 km/h was used to perform various calculations. These were the same values that were used by previous testing [3]. It was important to pick a specific value for both distance travelled and vehicle speed for ease of data comparison. However, the actual distances travelled and average speed of a typical tractor trailer in operation will vary based upon a number of factors. The values of fuel savings represented in this report will vary based on the actual distances travelled and the average speeds of a tractor with a camera-based indirect vision system.

9.2 Mean Times to Failure

The data presented concerning the mean time to failure of the camera-based indirect vision system arose from data collected from equipment manufacturers for each major component of the prototype system. This data may represent a best case view of the manufacturer to make their product appear more reliable than it is. Once implemented, it will be important to gather actual system failure data from systems in road-use to calculate a more accurate mean time to failure of a camera-based indirect vision system.

9.3 System Cost

The cost of the prototype system, as presented in section 5.18, is expected to be higher than the cost associated with a production version of a camera-based indirect vision system. This is because each component in the prototype system is a stand-alone unit purchased from equipment suppliers. Large scale production of the prototype camera-based indirect vision system would lower costs due to a variety of factors, the least of which is the purchasing of a larger quantity of each component and the associated price reduction per component.

The expected reduction in cost of a production model camera-based indirect vision system will decrease the payback period and increase the incentive to purchase such systems.

9.4 Implications on Cost Savings Due to Increased Driver Awareness

The use of a camera-based indirect vision system allows for the processing of the captured video data to provide the driver with information they would not normally have, as detailed in section 4. The additional information may provide a better sense of the environment surrounding the vehicle and allow for the more efficient operation of the vehicle by the driver.

When considering the costs associated with a camera-based indirect vision system, it is relevant to include the financial gains that may be realized through a decreased number of vehicle incidents. Although no data is currently available on reductions (or increases) of vehicle incidents as a result of using camera-based indirect vision systems, this data will become available as such systems become more commonplace.

9.5 Implementation of Camera-Based Systems

The full implementation of camera-based indirect vision systems to replace conventional mirror-based systems would require that CMVSS 111 be changed. It is unlikely that such camera-based indirect vision systems will be allowed as a direct replacement for mirror-based systems until it has been demonstrated that they are effective and reliable. A gradual implementation of camera-based systems alongside a gradual phase out of mirror-based systems is a more likely scenario.

As camera-based indirect vision systems are gradually introduced into the heavy duty vehicle market, the mirrors on such vehicles should decrease in size to increase aerodynamic efficiencies and reduce fuel consumption. The minimum mirror size as required by CMVSS 111 is relatively small compared to the mirrors on most tractors and, as outlined in section 6.3, significant fuel savings could be realized by using CMVSS 111 sized mirrors. It is expected, as mirror size is reduced, the driver of a vehicle equipped with a camera-based indirect vision system will rely less on the mirrors and more on the camera monitors for providing situational awareness.

10 CONCLUSIONS

The use of a camera-based indirect vision system in replacement of a conventional mirror-based indirect vision system offers the potential for a significant reduction in fuel consumption and CO_2 emissions from the heavy duty vehicle sector. By implementing camera-based indirect vision systems similar to the prototype system developed in this project on all Canadian tractors it is possible that 412 million liters of fuel be saved each year. This translates to a reduction of CO_2 emissions of roughly 1,109,600 tonnes. It is expected that these savings would increase as tractor manufacturers include camera-based indirect vision systems in their initial designs as it is likely that the camera fairings will be much more integral to the design of the tractor and pose less of an aerodynamic penalty.

Although the implementation of camera-based indirect vision systems is not expected to occur simultaneously with the removal of mirror-based systems, it is important that the use of camera-based systems become more common and that drivers become accustomed to their use. As transport vehicle manufacturers strive to reduce vehicle fuel consumption, the vehicle appearance will stray from the conventional. It is likely that the streamlined shape of the heavy duty vehicles of the future will not allow for the use of conventional mirror-based indirect vision systems and that camera-based systems will be the only option. It is important for drivers of these vehicles to gradually adjust to the sole use of camera-based systems to ensure that they maintain their capabilities of operating their vehicles in an efficient manner.

It is necessary that extensive testing be performed on the use of camera-based indirect vision systems to determine all of the human factors issues which may arise through the use of such systems. Although this report attempted to address all human factors issues, it is very likely that additional issues will arise during field testing. It is of utmost importance that the use of camera-based indirect vision systems as a replacement for conventional mirror-based systems does not result in a degradation in the driver's ability to operate their vehicle effectively.

11 RECOMMENDATIONS

In order to progress the development of camera-based indirect vision systems, NRC-AST offers the following recommendations:

1. Field testing of the prototype system should be performed to evaluate how drivers react to the use of a camera-based indirect vision system in replacement of the conventional mirror-based system.
2. Long term reliability testing of camera-based indirect vision systems should be performed to determine the likelihood of failure of such systems.
3. Extensive long term human factors testing should be performed to ensure that the use of a camera-based indirect vision system does not degrade the ability of the driver to operate their vehicle in an effective manner.

12 ACRONYMS AND ABBREVIATIONS

°C	Degrees Celsius
A	Area
A-C/VIS	Advanced Camera/Video Imaging System
AST	Automotive and Surface Transportation
C/VIS	Camera/Video Imaging System
cd	Candela
C_D	Drag Coefficient
cm	Centimeter
CMVSS	Canadian Motor Vehicle Safety Standards
CO_2	Carbon Dioxide
CUTR	Center for Urban Transportation Research
E-C/VIS	Enhanced Camera/Video Imaging System
FMVSS	Federal Motor Vehicle Safety Standards
h	Hour
HD	High Definition
Hz	Hertz
IAR	Institute for Aerospace Research
IR	Infrared
ISO	International Organization for Standardization
kg	Kilogram
km	Kilometer
km/h	Kilometers Per Hour
L	Liter
LCD	Liquid Crystal Display
LED	Light Emitting Diode
m	Meter
mm	Millimeter
MTTF	Mean Time To Failure
NHTSA	National Highway Traffic Safety Administration
nm	Nanometer
NRC	National Research Council
s	Second

SD	Standard Definition
VMHT	ViewMetrics system for Haul Trucks
VTTI	Virginia Tech Transportation Institute
W	Watt
μm	Micrometer

13 REFERENCES

[1] Transport Canada, "Motor Vehicle Safety Regulations," Minister of Justice, Ottawa, ON, 2012.

[2] J. Patten, B. McAuliffe, W. Mayda and B. Tanguay, "Review of Aerodynamic Drag Reduction Devices for Heavy Trucks and Buses," National Research Council Canada, Ottawa, ON, 2012.

[3] J. Leuschen and K. R. Cooper, "Full-Scale Wind Tunnel Tests of Production and Prototype, Second-Generation Aerodynamic Drag-Reducing Devices for Tractor-Trailers," SAE International, Warrendale, PA, 2006.

[4] K. F. Fagerström and A. Gårdlund, "Mirror Replacement in Trucks," Chalmers University of Technology, Göteborg, Sweden, 2012.

[5] J. W. Jenness, R. E. Llaneras and R. W. Huey, "Static Testing Method for Assessing Quality of Indirect Visibility on Heavy Trucks," National Highway Traffic Safety Administration, Washington, DC, 2008.

[6] W. W. Wierville, W. A. Schaudt, S. K. Gupta, J. M. Spaulding and R. J. Hanowski, "Development of a Performance Specification for Camera/Video Imaging Systems on Heavy Vehicles - Final Report: Specifications," National Highway Traffic Safety Administration, Washington, DC, 2008.

[7] W. W. Wierville, W. A. Schaudt, J. M. Spaulding, S. K. Gupta, G. M. Fitch, D. M. Wiegand and R. J. Hanowski, "Development of a Performance Specification for Camera/Video Imaging Systems on Heavy Vehicles - Final Report: Supporting Research," National Highway Traffic Safety Administration, Washington, DC, 2008.

[8] W. W. Wierwille, W. A. Schaudt, M. Blanco, A. S. Alden and R. J. Hanowski, "Enhanced Camera/Video Imaging Systems (E-C/VISs) For Heavy Vehicles: Final Report," National Highway Traffic Safety Administration, Washington, DC, 2011.

[9] G. M. Fitch, M. Blanco, M. C. Camden, R. L. Olson, J. McClafferty, J. F. Morgan, A. E. Wharton, H. E. Howard, T. Trimble and R. J. Hanowski, "Field Demonstration of Heavy Vehicle Camera/Video Imaging Systems: Final Report," National Highway Traffic Safety Administration, Washington D.C., 2011.

[10] P.-S. Lin, C. Lee, A. Kourtellis and M. Saxena, "Evaluation of Camera-Based Systems to Reduce Transit Bus Side Collisions," Florida Department of Transportation, Tallahassee, FL, 2010.

[11] U.S. Department of Transportation, "Federal Motor Vehicle Safety Standards and Regulations," National Highway Traffic Safety Administration, Washington D.C., 1998.

[12] International Organization for Standardization, "ISO/CD 16505 - Road vehicles - Ergonomics and performance aspects of Camera-Monitor Systems - Requirements and test procedures," International Organization for Standardization, 6 September 2012. [Online]. Available: http://www.iso.org/iso/catalogue_detail.htm?csnumber=56896. [Accessed 11 February 2013].

[13] Motion Metrics International Corp., "VMHT - Motion Metrics International Corp.," 20 July 2007. [Online]. Available: http://www.motionmetrics.com/files/brochures/English/MMI_Brochure_VMHT.pdf. [Accessed 11 February 2013].

[14] Zone Defense LLC, "Zone Defense LLC," Blink Tech, 2005. [Online]. Available: http://www.zonedefensetruck.com/. [Accessed 11 February 2013].

[15] Jensen Heavy Duty, "Wireless Camera Systems for Outdoor Surveillance and Security," ASA Electronics, [Online]. Available: http://www.jensenheavyduty.com/products/camera-systems.html. [Accessed 11 February 2013].

[16] MAN, "Rolling Revolution - The MAN Concept S | MAN Truck and Bus," The MAN Group, [Online]. Available: http://www.mantruckandbus.com/com/en/innovation___competence/research_and_innovation_projects/man_concept_s/MAN_Concept_S.html. [Accessed 11 February 2013].

[17] Krone, "Concept S Aero Liner," Fahrzeugwerk Bernard KRONE GmbH , 2012. [Online]. Available: http://www.krone-trailer.com/english/iaa-special/news/concept-s-aero-liner/. [Accessed 11 February 2013].

[18] Freightliner, "Innovation Truck - Freightliner Trucks," Daimler Trucks North America, [Online]. Available: http://www.freightlinertrucks.com/innovation/. [Accessed 11 February 2013].

[19] V. D. Bhise, Ergonomics in the Automotive Design Process, Boca Raton, FL: Taylor & Francis Group, LLC, 2012.

[20] C. Wickens, S. Gordon and Y. Liu, An Introduction to Human Factors Engineering, New York, NY: Addison-Wesley Educational Publishers Inc., 1998.

[21] G. Salvendy, Handbook of Human Factors and Ergonomics, Hoboken, NJ: John Wiley & Sons, Inc, 2012.

[22] R. Hicks, K. Schofield, P. Tarnow and M. Veiseh, "Panoramic Electronic Rear Vision for Automotive Applications," Society of Automotive Engineers, Inc., Detroit, Michigan, 1999.

[23] B. H. Walker, Optical Design for Visual Systems, Bellingham, WA: SPIE Optical Engineering Press, 2000.

[24] Ministry of Transportation, "Medical Review - Commercial Drivers," Government of Ontario, 9 July 2012. [Online]. Available: http://www.mto.gov.on.ca/english/dandv/driver/medical-review/process.shtml. [Accessed 11 February 2013].

[25] N. Daw, How Vision Works: The physiological mechanisms behind what we see, New York, NY: Oxford University Press, 2012.

[26] A. Tözeren, Human Body Dynamics: Classical mechanics and human movement, New York, NY: Springer, 200.

[27] Society of Automotive Engineers, "J985: Vision Factors Considerations in Rearview Mirror Design," SAE International, Warrendale, PA, 2009.

[28] R. Blackwell, "Brightness Discrimination Data for the Specification of Quantity of Illumination," *Illuminating Engineering,* pp. 602-609, November 1952.

[29] R. E. Eberts and A. G. MacMillan, "Misperception of Small Cars," *Trends in Ergonomics/Human Factors,* pp. 33-39, 15 June 1985.

[30] M. J. Flannagan and M. L. Mefford, "Distance Perception with a Camera-Based Rear Vision System in Actual Driving," Society of Automotive Engineers, Inc., Ann Arbor, Michigan, 2005.

[31] M. J. Flannagan and M. Sivak, "Distance Cues and Fields of View in Rear Vision Systems," Society of Automotive Engineers, Inc., Detroit, Michigan, 2006.

[32] S. N. Roscoe, "Judgments of Size and Distance with Imaging Displays," *Human Factors,* vol. 26, no. 6, pp. 617-629, 1984.

[33] A. Richards, Alien Vision - Exploring the Electromagnetic Spectrum with Imaging Technology, Bellingham, Washington: SPIE Press, 2011.

[34] S. B. Muttana, A. Sardar and S. Mubashir, "Lightweighting of Public Transport Buses in India: An Impact Analysis," SAE International, Warrendale, PA, 2011.

[35] A. Casadei and R. Broda, "Impact of Vehicle Weight Reduction on Fuel Economy for Various Vehicle Architectures," Ricardo Inc., Van Buren Township, MI, 2007.

[36] NATO Standardisation Agency, "Allied Environmental Conditions and Test Publications - AECTP 200: Environmental Conditions," North Atlantic Treaty Organization, Mons, Belgium, 2006.

[37] B.D.S., "B.D.S Dead Angle Mirror System," B.D.S, [Online]. Available: http://www.bdsmirror.nl/. [Accessed 8 February 2013].

[38] E. Lueder, Liquid Crystal Displays, West Sussex, United Kingdom: John Wiley & Sons, Ltd., 2010.

[39] Ministry of Transportation, Vehicle Weight and Dimension Limits in Ontario, St. Catherines, Ontario: Ministry of Transportation, 2001.

[40] J. D. E. Beynon and D. R. Lamb, Charge-Coupled Devices and Their Applications, London, England: McGraw-Hill Book Company (UK) Limited, 1980.

[41] M. J. Howes and D. V. Morgan, Charge-Coupled Devices and Systems, Surry, England: John Wiley & Sons Ltd., 1979.

[42] J. Soe Nyun, "Lost in the Landscape," WordPress, March 2011. [Online]. Available: http://www.soenyun.com/Blog/2011/03/. [Accessed 19 March 2013].

[43] New Zealand Government, "Radio Spectrum," [Online]. Available: http://www.rsm.govt.nz/cms/image-library/interference-images/big-versions/ghostinglight.jpg/view. [Accessed 19 March 2013].

[44] Today's Trucking, "2013 Ranking of Top 100 Carriers," Newcom Business Media, 2013. [Online]. Available: http://www.todaystrucking.com/top100.cfm. [Accessed 25 March 2013].

[45] Society of Automotive Engineers, J941: Motor Vehicle Drivers' Eye Locations, Warrendale, PA: SAE International, 2008.

[46] Bosch, Automotive Handbook 8th Edition, Plochingen, Germany: Robert Bosch GmbH,

2011.

[47] Department of Defense, "MIL-HDBK-217F: Reliability Prediction of Electronic Equipment," Department of Defense, Washington, D.C., 1991.

[48] G. Yang, Life Cycle Reliability Engineering, Hoboken, NJ: John Wiley & Sons, Inc., 2007.

[49] U.S. Energy Information Administration, "Carbon Dioxide Emissions Coefficients," U.S. Department of Energy, 14 2 2013. [Online]. Available: http://www.eia.gov/environment/emissions/co2_vol_mass.cfm. [Accessed 22 03 2013].

14 ACKNOWLEDGEMENTS

The following NRC-AST personnel contributed to this project:

- David Poisson, project management
- Jeff Patten, project engineering support and management
- Patrick Kehoe, engineering design
- Guy Charboneau, system installation
- Mark Croken, system installation

The following NRC-IAR personnel contributed to this project:

- Brian McAuliffe, project management
- Alain Bilodeau, test piece creation
- Mario Carrière, test piece creation
- Harold Rook, wind tunnel operator
- Jessica Beaubien, wind tunnel operator
- Eric Perron, wind tunnel operator
- Jeff Farnaud, wind tunnel operator
- Brian Jahraus, instrumentation
- Todd Cumming, data acquisition

Appendix A: FULL RESULTS OF AERODYNAMIC TESTING

Table A1: Results of testing west coast mirror mounted at 90° (with lookdown mirror)

Corrected Wind Speed (m/s)	C_D·A	ΔC_D Truck
22.79	0.1708	-0.0157
25.67	0.1701	-0.0156
28.66	0.1694	-0.0155
31.39	0.1681	-0.0154
34.23	0.1657	-0.0152
36.74	0.1649	-0.0151
39.76	0.1646	-0.0151
Average over speed range:	**0.1677**	**-0.0154**

Table A2: Results of testing west coast mirror mounted at 45° (with lookdown mirror)

Corrected Wind Speed (m/s)	C_D·A	ΔC_D Truck
22.52	0.0981	-0.0090
25.50	0.0974	-0.0089
28.48	0.0966	-0.0089
31.38	0.0967	-0.0089
34.28	0.0964	-0.0088
37.01	0.0963	-0.0088
39.85	0.0962	-0.0088
Average over speed range:	**0.0968**	**-0.0089**

Table A3: Results of testing west coast mirror mounted at 68° (with lookdown mirror)

Corrected Wind Speed (m/s)	C_D·A	ΔC_D Truck
22.78	0.1324	-0.0121
25.72	0.1308	-0.0120
28.52	0.1298	-0.0119
31.32	0.1291	-0.0118
34.28	0.1287	-0.0118
37.00	0.1282	-0.0118
39.73	0.1282	-0.0118
Average over speed range:	**0.1296**	**-0.0119**

Table A4: Results of testing west coast mirror mounted at 68° (without lookdown mirror)

Corrected Wind Speed (m/s)	C_D·A	ΔC_D Truck
22.75	0.1309	-0.0120
25.73	0.1288	-0.0118
28.55	0.1275	-0.0117
31.26	0.1276	-0.0117
34.29	0.1270	-0.0117
37.02	0.1271	-0.0117
39.75	0.1267	-0.0116
Average over speed range:	**0.1279**	**-0.0117**

Table A5: Results of testing fender mounted convex mirror

Corrected Wind Speed (m/s)	$C_D \cdot A$	ΔC_D Truck
22.65	0.0624	-0.0057
25.69	0.0623	-0.0057
28.41	0.0623	-0.0057
31.34	0.0624	-0.0057
34.20	0.0624	-0.0057
36.89	0.0625	-0.0057
39.74	0.0624	-0.0057
Average over speed range:	**0.0624**	**-0.0057**

Table A6: Results of testing large fender mounted dual-camera fairing

Corrected Wind Speed (m/s)	$C_D \cdot A$	ΔC_D Truck
22.59	0.0081	-0.0007
25.46	0.0079	-0.0007
28.24	0.0079	-0.0007
31.37	0.0078	-0.0007
33.98	0.0078	-0.0007
36.68	0.0078	-0.0007
39.61	0.0077	-0.0007
Average over speed range:	**0.0079**	**-0.0007**

Table A7: Results of testing small fender mounted single-camera fairing

Corrected Wind Speed (m/s)	$C_D \cdot A$	ΔC_D Truck
22.41	0.0018	-0.0002
25.53	0.0017	-0.0002
28.10	0.0017	-0.0002
31.15	0.0017	-0.0002
33.86	0.0017	-0.0002
36.69	0.0017	-0.0002
39.32	0.0017	-0.0002
Average over speed range:	**0.0017**	**-0.0002**

Table A8: Results of testing mirror-location mounted dual-camera fairing

Corrected Wind Speed (m/s)	$C_D \cdot A$	ΔC_D Truck
22.61	0.0044	-0.0004
25.53	0.0043	-0.0004
28.22	0.0042	-0.0004
31.10	0.0041	-0.0004
33.82	0.0039	-0.0004
36.72	0.0036	-0.0003
39.69	0.0030	-0.0003
Average over speed range:	**0.0039**	**-0.0004**

Table A9: Results of testing IR illuminator fairing (leading component only)

Corrected Wind Speed (m/s)	$C_D \cdot A$	ΔC_D Truck
22.46	0.0112	-0.0010
25.44	0.0110	-0.0010
28.30	0.0108	-0.0010
31.00	0.0106	-0.0010
33.88	0.0105	-0.0010
36.60	0.0103	-0.0009
39.51	0.0102	-0.0009
Average over speed range:	**0.0107**	**-0.0010**

Table A10: Results of testing IR illuminator fairing (leading and trailing components)

Corrected Wind Speed (m/s)	$C_D \cdot A$	ΔC_D Truck
22.58	0.007	-0.0006
25.51	0.0069	-0.0006
28.19	0.0068	-0.0006
31.40	0.0067	-0.0006
34.04	0.0067	-0.0006
36.67	0.0067	-0.0006
39.60	0.0067	-0.0006
Average over speed range:	**0.0068**	**-0.0006**