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Clarity of View: An Analytic Hierarchy Process (AHP)-Based Multi-Factor Evaluation Framework for Driver Awareness Systems in Heavy Vehicles

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CLARITY OF VIEW: AN ANALYTIC HIERARCHY PROCESS (AHP)-BASED
MULTI-FACTOR EVALUATION FRAMEWORK FOR DRIVER
AWARENESS SYSTEMS IN HEAVY VEHICLES

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Automotive Engineering

by
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August 2016

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ABSTRACT

Several emerging technologies hold great promise to improve the situational awareness of the heavy vehicle driver. However, current industry-standard evaluation methods do not measure all the comprehensive factors contributing to the overall effectiveness of such systems. The average commercial vehicle driver in the USA is 54 years old with many drivers continuing past retirement age. Current methods for evaluating visibility systems only consider field of view and do not incorporate measures of the cognitive elements critical to drivers, especially the older demographic. As a result, industry is challenged to evaluate new technologies in a way that provides enough information to make informed selection and purchase decisions.

To address this problem, we introduce a new multi-factor evaluation framework, “Clarity of View,” that incorporates several important factors for visibility systems including: field of view, image detection time, distortion, glare discomfort, cost, reliability, and gap acceptance accuracy. It employs a unique application of the Analytic Hierarchy Process (AHP) that involves both expert participants acting in a Supra-Decision Maker role alongside driver-level participants giving both actual performance data as well as subjective preference feedback. Both subjective and objective measures have been incorporated into this multi-factor decision-making model that will help industry make better technology selections involving complex variables.

A series of experiments have been performed to illustrate the usefulness of this framework that can be expanded to many types of automotive user-interface technology

selection challenges. A unique commercial-vehicle driving simulator apparatus was developed that provides a dynamic, 360-degree, naturalistic driving environment for the evaluation of rearview visibility systems. Evaluations were performed both in the simulator and on the track. Test participants included trucking industry leadership and commercially licensed drivers with experience ranging from 1 to 40 years.

Conclusions indicated that aspheric style mirrors have significant viability in the commercial vehicle market. Prior research on aspheric mirrors left questions regarding potential user adaptation, and the Clarity of View framework provides the necessary tools to reconcile that gap. Results obtained using the new Clarity of View framework were significantly different than that which would have previously been available using current industry status-quo published test methods. Additional conclusions indicated that middle-aged drivers performed better in terms of image detection time than young and elderly age categories. Experienced drivers performed better than inexperienced drivers, regardless of age. This is an important conclusion given the demographic challenges faced by the commercial vehicle industry today that is suffering a shortage of new drivers and may be seeking ways to retain its aging driver workforce.

The Clarity of View evaluation framework aggregates multiple factors critical to driver visibility system effectiveness into a single selection framework that is useful for industry. It is unique both in its multi-factor approach and custom-developed apparatus, but also in its novel approach to the application of the AHP methodology. It has shown significance in ability to discern more well-informed technology selections and is flexible to expand its application toward many different types of driver interface evaluations.

DEDICATION

I dedicate this dissertation to my Mom and Dad for their constant encouragement and support. Each of them demonstrated through the example of their own lives that you are never too old to pursue your goals. Their lives of service to others have inspired me to think beyond myself in all aspects of life and to pursue work that will make the world a better place.

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I am grateful to God for giving me the good health and energy to pursue this research while simultaneously raising a family and working full time. With His blessing, may this work be valuable to improve the lives and safety of truck and automobile drivers and passengers everywhere.

I am thankful for my supportive husband, Walter, and my children, Kyle, Kelli, Sarah, and Conley, for their ongoing encouragement and patience while I pursued this research.

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CHAPTER ONE

INTRODUCTION

The objective of this research is to improve current measurement methods for driver awareness systems in heavy vehicles. A new multi-factor evaluation model is developed, that is more comprehensive than previous approaches since it encompasses multiple factors relevant to driver safety. This model is a new and useful procedure for industry to enable more effective evaluation and selection of driver-to-vehicle interface technology.

Driver inattention is the cause of 78% of all crashes [Brostrom, 11]. The automotive industry has responded by developing new technologies intended to provide the driver with 360-degree awareness of his surroundings. These safety awareness systems intend to make the driver aware of critical safety information by grabbing their attention sufficiently and giving them enough time to safely react. However, there is risk of distracting the driver from the main critical driving task by overwhelming them with irrelevant, inaccurate, excessive, or confusing information. One study has even determined an equation correlating the increased glance frequency due to in-vehicle distractions, including that of in-vehicle technology, to accidents resulting in fatalities [Green, 32].

It is important to remember that simply conveying information to the driver is not enough to ensure they will give it sufficient attention and actually register it [Rakotonirainy, 72]. This concept is the foundational theory behind the proposed evaluation framework we call “Clarity of View.”

Industry is challenged to make decisions on which technology to implement in their fleets due to the lack of objective data regarding the relative value of the many options available [Davidse, 17]. Therefore, we will be focusing on overall system effectiveness measurement within the concept of Clarity of View that can offer objective evaluation of systems that may involve a combination of multiple technologies used simultaneously.

Motivation for the Heavy Vehicle Segment

While this research is ultimately useful for all categories and sizes of automobiles, it is focused specifically on the heavy-vehicle segment for several reasons. “The trucking industry is the lifeblood of the U.S. economy. Nearly 70% of all the freight tonnage moved in the U.S. goes on trucks. Without the industry and our truck drivers, the economy would come to a standstill. To move 9.2 billion tons of freight annually requires nearly 3 million heavy-duty Class 8 trucks and over 3 million truck drivers. It also takes over 37 billion gallons of diesel fuel to move all of that freight. Simply – without trucks, America stops [ATA, 5].” The significance and volume of highway traffic involving commercial vehicles warrants specific attention to those factors that impact the safety of both the commercial vehicle truck driver and those in passenger cars who surround them. The Technology Maintenance Council (TMC) of the American Trucking Association has identified 360-degree driver awareness as a key objective for safety improvement and industry focus of its Future Truck Task Force [TMC, 93].

Each year, NHTSA reports over 826,000 lane change accidents, with more than 160,000 resulting in injuries to the occupants [(Ghosh, 31), (Pyle, 71)]. Additional

statistics support the urgency of attention to driver visibility awareness as it relates to lane-change maneuvers:

- Over 25% of all heavy truck accidents are related to lane-change events. [Starnes, 90]
- Over 33% of all truck to car accidents occur in blind zones [Hanowski, 36], however:
- Over 78% of accidents between heavy trucks and passenger cars are initiated by the aggressive driving habits of the lighter vehicle [Hanowski, 35] or the passenger car driver simply encroaching on the truck's path of travel [ATA, 5].

Prior work analyzed accidents to provide a prioritization guideline for those areas around the vehicle most significantly in need of visibility improvement [Reed, 74].



Figure 1.1 – Prioritized zones for driver vision improvement. The highest priority zone is indicated with numeral 1 [Reed, 74]

Vehicle-to-vehicle collisions are not the only element of concern, with pedestrian accidents resulting in injuries increasing by 10% between 2011 and 2012 [NHTSA, 1]. “In more than half of all accidents involving pedestrians, the pedestrian was in the right-

hand blind spot prior to the driver beginning the turn [Reed, 74]. This scenario is illustrated in Figure 2.

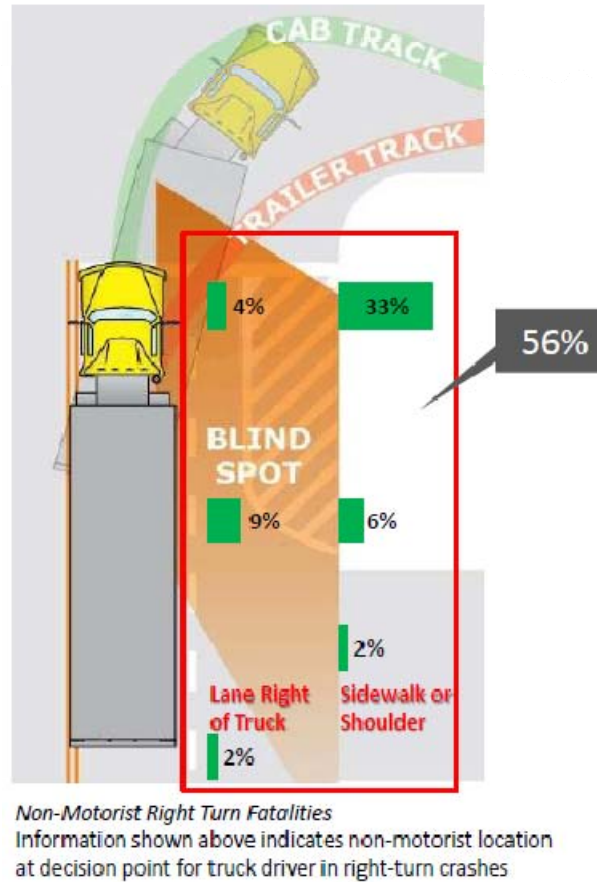


Figure 1.2 – Non-Motorist Right Turn Fatalities [Velvac, 2]

Increased highway congestion and increase of in-vehicle technology presents more distractions and higher mental workload. With increased information overload to the driver, there has been a 50% increase in the number of lane-change accidents in recent years [Millward, 59]. While there has not been a direct correlation confirmed between the increase of IVT and accidents resulting in fatalities, the trend is concerning. There has been a 3.7% increase in the number of people killed due to traffic accidents involving large trucks between 2011 and 2012 [NHTSA, 1]. The increase of IVT presents

a challenge for designers to balance the right level of information to improve driver awareness without adding so much that the increased mental workload presents a distraction beyond what most drivers can safely process.

Research Questions

This work presents a new evaluation method for driver situational awareness systems that are designed to improve driver visibility in large vehicles. Existing industry-standard evaluation methods focus on field-of-view only, defined by the angular measure of area made visible by the system. Several other factors are relevant, including: image detection time, gap acceptance accuracy, glare discomfort, and distortion. Some of these are subjective based on individual driver preference, skills, or experience. We introduce a new measurement model, “Clarity of View,” that encompasses a much wider set of metrics and provides a more robust evaluation framework. The model combines both subjective and direct measures into one multi-factor decision-making method.

The primary research question is established as: **“Will a multi-factor measurement framework enable more effective evaluation and comparison of driver awareness systems than the current state-of-the-art approach based solely on field-of-view?”** This document outlines the theoretical basis for the evaluation framework and the experiments performed to confirm its usefulness for current industry technology selection decisions. The results confirm the value of this expanded model and its potential for application toward automotive user-interface technology selection problems.

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CHAPTER TWO

BACKGROUND LITERATURE

CLARITY OF VIEW

The term “Clarity” is chosen specifically for its significance to the problem of driver visibility. It is defined by Dictionary.com as, “clearness or lucidity as to perception or understanding; freedom from indistinctness or ambiguity.” The objective of all the driver awareness or visibility systems is the same: to improve the driver understanding of his environment in order to provide clear indication of actions required to operate the vehicle in a safe manner. The lucidity of this information is dependent on many factors, and may vary as perceived by people of different physical, visual, and cognitive limitations or situations. Situational awareness may be degraded by an overload of information presented by too many sources and/or display interfaces.

Clarity of View framework fills this void in existing procedures and proposes a multi-factor approach to the measurement of overall system effectiveness. Fleet owners are currently challenged to select systems for their vehicles because none of the existing methods available provide this comprehensive, human-factors approach. This challenge often results in the selection of no new systems at all, for reluctance that results may not be worth the investment. With the new comprehensive measurement system, the trucking industry can evaluate technologies appropriate for specific vehicles in a way that gives confidence in the claims offered by the manufacturers of individual sub-systems independently.

Existing methods for determining the effectiveness of visibility systems today focus primarily on Field of View. **The SAE J1750 procedure mentions the need for additional work toward measures of Clarity:** “The Target Evaluation Method may be utilized for alternative vision systems as well (i.e., cameras & monitors), but additional work is necessary to specify system requirements that appropriately consider valid image representation (clarity, acuity, distortion, size, etc....) [SAE J1750, 86].” This procedure offers the recommendation that images in mirrors of radius < 300mm are considered “too small to be useful to the driver in making decisions in typical driving conditions [SAE J1750, 86].” While this direction is a good step toward the necessary level of acceptability guidance for industry, it does not capture all relevant elements of concern when designing driver visibility systems.

In order to fully understand the significance of capturing the human-factors elements so critical to the concept of Clarity, the interactions among all the systems contributing to driver awareness can be explained.

OVERALL SYSTEM EFFECTIVENESS

System effectiveness is comprised of two primary segments: technology response time and accuracy and human response time and accuracy, as illustrated in Figure 2.1. Whether the system is complex or simply a singular mirror display, the ultimate goal is the same: to ensure the driver reacts correctly to the information presented. The concept named Clarity of View provides a framework for quantitative evaluation that includes the important human factors that influence driver behavior. Driver reaction time and

accuracy are comprised of distinct cognitive stages, each measurable in different ways. These steps are a primary focal point of the investigations, and they comprise factors included in the model for the Clarity of View metric.

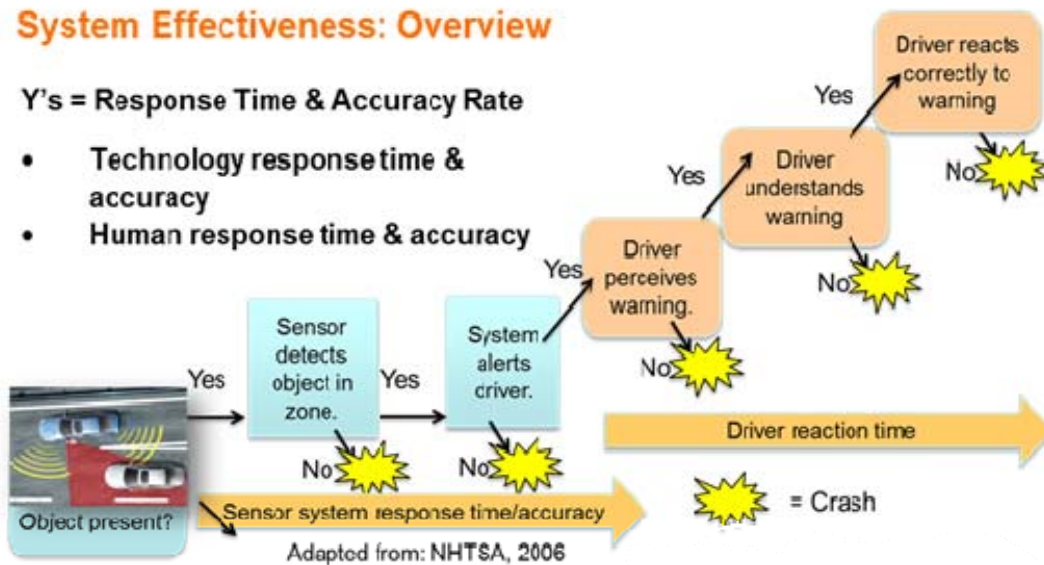


Figure 2.1 - System Effectiveness Overview

The sub-systems will be expanded in two primary sections: the technology, including sensors or displays, and the driver, including the many relevant human factors elements. The intersection between the two is the primary scope of the research.

DRIVER AWARENESS TECHNOLOGY

The Technology Maintenance Council Recommended Practice RP 428A – Guidelines for Vision Devices classifies terms relative to vision in vehicles into three categories: “Direct Vision – Objects visible with the unaided human eye; Indirect Vision

– Objects visible with a vision device (usually, but not limited to, mirrors); and Supplemental – Objects whose presence is communicated to the driver through a non-traditional vision device (e.g., camera and monitor) or audible warning [RP428A, 95].” This work seeks only to address those systems falling into the categories of Indirect Vision or Supplemental.

Multiple Systems Influence the Goal



Figure 2.2 - Detection Sensor Technology Overview

Driver awareness in commercial vehicles is augmented by traditional equipment such as rearview mirrors and new technologies such as blind spot or collision avoidance warning systems, backup video cameras, and even active assist systems. Each has been the subject of extensive research to evaluate individual system effectiveness, but there is no comprehensive test procedure that allows a subjective comparison between different

technologies toward the ultimate goal of actuating appropriate driver behavior through use of these systems.

Mirrors

United States Federal Motor Vehicle Safety Standard (FMVSS) 571.111 requires, for Truck Mirrors: “S8.1 Each multipurpose passenger vehicle and truck with a GVWR of 11,340 kg or more shall have outside mirrors of unit magnification each with not less than 323 cm² of reflective surface, installed with stable supports on both sides of the vehicle. The mirrors shall be located so as to provide the driver a view to the rear, along both sides of the vehicle, and shall be adjustable both in the horizontal and vertical directions to view the rearward scene [FMVSS111, 20].” This mirror is typically defined as a “planar” mirror. The use of alternate types of mirrors is not specifically prohibited by this regulation, but they cannot be used as a replacement for this required style. Convex auxiliary mirrors are frequently used in conjunction with a planar mirror to provide additional visibility and reduce the blind zones. Convex mirrors are defined as those having a spherical surface of continuous radius. These are allowed on the passenger side of US vehicles provided they are marked with a warning message, “Objects in mirror are closer than they appear.” Aspherical mirrors are allowed and are becoming more prevalent in Europe. These mirrors are defined as those having a complex contour that is neither entirely flat nor spherical. Both convex and aspheric mirrors offer a significantly wider field of view than that of a planar style but with the disadvantage of distortion and/or minification of the image. This presents the possibility for drivers to mis-judge the gap available to them for overtaking cars in adjacent lanes. Global

regulations vary among countries. The Indirect Vision Devices Regulation 46-02 ECE-United Nations allows, “6.1.2.2.1: The reflecting surface of a mirror must be either flat or spherically convex. Exterior mirrors may be equipped with an additional aspherical part provided that the main mirror fulfills the requirements of the indirect field of vision [UN, 4].” (Note: minimum number of mirrors and their required locations varies by vehicle class in this regulation.)

Other work examines driver performance/acceptance using aspheric mirrors in light vehicle applications. The results concluded that while “aspheric mirrors do not cause substantive detrimental performance effects, drivers found the distortion, uneasiness, and discomfort to be somewhat worse than for competing mirrors [Rau, 73].” However, there were no measurable “performance disadvantages based on driving tasks of passing, merging and gap acceptance and they provided a substantially larger field of view than a corresponding flat mirror [Rau, 74].’ With disadvantages also pointing to older drivers exhibiting reluctance to accept the mirrors due to their subjective rating of distortion, uneasiness and discomfort [Rau, 73], it is clear that further research is warranted to determine whether the advantages offered by aspheric mirrors with increased field of view and blind-spot elimination are greater than the disadvantages of general uneasiness caused by image distortion. Studies by Flannagan at University of Michigan Transportation Research Institute have shown that acceptance of aspheric or non-planar mirrors increases with use over time, with 93% of subjects reporting they had gotten used to the mirror within four weeks of driving [Flannagan, 23]. Toward our Clarity of View framework, this study aims to develop measurement techniques to quantify these human

factors surrounding usability of the driver-interface technologies, combining both direct-measurement performance evaluation with subjective user opinion data in a manner that has not been addressed in prior work.

There are several human factors issues relevant to the measure of effectiveness of mirror systems:

- Field of View
- Distortion
- Vibration
- Glare discomfort
- Image detection time

These factors each impact the drivers' ability to accurately discern objects in their surroundings and make decisions such as timing of lane change maneuvers.

Additionally, fleet owners are concerned with economic factors as well, such as cost and reliability of such systems. These factors are directly measurable for any system, and ultimately play a significant role in final technology selection processes. Prior models have not incorporated these factors.

Camera / Video Information Systems

Camera and Video Information Systems (C/VIS) have the potential to offer the driver awareness in those areas of the vehicle not currently viewable by mirror systems, such as those regions directly behind the trailer and forward of the cab. C/VIS offer the added potential to someday replace mirrors, thereby eliminating the aerodynamic drag presented

by mirrors and improving fuel economy. However, there are also several human factors issues relevant to these video systems. Many were identified through a NHTSA study done in conjunction with Virginia Tech specifically for the application of such systems on heavy vehicles [Wierwille, 101]. While all of the issues identified for traditional mirror systems remain, additional considerations for evaluating C/VIS include:

- Environmental Reliability (Poor weather, contamination, ambient light effects, operating temperature range)
- Vibration and stability of images
- System failure backup and communication protocol
- Camera placement location
- Monitor placement location
- Disorientation from image reversal
- Display brightness, color, contrast and low-light visibility
- Technical issues including: flicker, signal delay, minimum frame rate and resolution, and monitor refresh rate [Wierwille, 101].

There are still no FMVSS standards that provide guidelines for C/VIS systems, even though fleet owners are beginning to install them in vehicles with the aim of improving their drivers' awareness of surroundings. While their intent may be based on the theory that "more information is better," it could be possible that the presentation of too many displays could result in drivers taking too long to identify the relevant information required to respond quickly and accurately to potentially safety-critical information. This

work aims to develop useful measures of response time and accuracy as related not only to the image quality but to the speed and accuracy to which drivers respond.

Blind Spot Alert and Collision Warning

Blind Spot Detection and Collision Warning Systems are similarly configured in that they generally consist of a combined package of cameras and either radar or ultrasonic sensors to feed information to the warning system interface that alerts the driver. When an object is detected by the sensors in the defined potential hazard zone surrounding the vehicle, an algorithm is used to determine if the object meets the definition parameters established to qualify it as a “hazard” and whether it is within the area established as a hazard zone. For blind spot detection, an alert is then made via a signal light that is activated in the cockpit to alert the driver of the potential hazard. If the hazard is ignored and the driver initiates a lane change, (as detected via steering angle inputs and/or application of turn signal), some systems add an audible warning that may be activated to announce the increased danger to the driver or the alert light may begin to flash. In some higher-end models, a haptic vibration is activated in the seat or steering wheel. Recently, some OEM’s have implemented active assist technology to further prevent accidents. In those systems, if a lane change maneuver is attempted with a hazard present, the brakes on the side of the vehicle opposite of the hazard are applied, slowing the vehicle down and causing it to veer back into its original lane away from the oncoming traffic. Similarly, for collision warning systems, alert signals are provided to drivers when objects are detected in the forward zone of the vehicle that may be considered a crash

hazard, and active-assist technology provides proactive braking application if the driver does not react quickly enough to the alert signal to do so on his own.

There are a variety of driver-to-vehicle interface alert styles used in industry today. Variation exists between the shapes, colors, placement locations, brightness, and methods that range from simple alert lights to a combination of lights, audible warnings, and haptic vibrations in the steering wheels and/or seats. Overall, research has concluded that these systems can be useful to increase driver awareness of potential hazards. However, gaps still remain regarding the understanding of the elements affecting the effectiveness of the interface used to communicate detection sensor data to the driver. These include such factors as:

- Alert light location (Periphery is primary used for Blind Spot Alerts today and center of instrument cluster is primary used for Collision Avoidance).
- Color, brightness, and flash frequency of alerts
- Loudness and modality of audible alerts
- Frequency, duration, and location of use of haptic alerts
- Level and degree of interaction of active assist.

A primary reason why there has been little progress toward optimization of these alert systems is the lack of a measurement framework that can capture the subjective, yet important, human factors elements critical for their performance success.

DRIVER AWARENESS HUMAN FACTORS

Cognition and Mental Workload

Mental workload is the amount of mental resource which is dedicated to a particular cognitive activity. The effectiveness of working memory is limited by situational awareness, complexity and number of tasks, and the level of divided attention required in processing the tasks [Wickens, 100]. Visual perception is strongly linked to abilities of working memory [Wickens, 100]. Therefore, it could be presumed that declining vision in the elderly is linked to their cognitive ability. However, deficits in perceptual processing (such as working memory) due to aging do not indicate a loss due to lower visual acuity, but rather become evident due to task load reaching a larger level of complexity, even when tasks are simple [Faubert, 19]. This is relevant to Clarity of View in the trucking industry because the US truck driver population is also aging rapidly. The average age of truck drivers reported in 2011 as 54 years old [Crissey, 16].

Overall, the rate of accidents in the elderly group tends to be lower than others [Rakotonirainy, 72], potentially due to their lower-risk driving behavior. The CDC reports that those 65 and older have: higher incidence of seat belt use, lower incidence of impaired driving, and tend to drive when conditions are safer [CDC, 15]. However, fatalities as a percentage of total accidents tend to be greater among those age 75 and older due to their increased susceptibility to injury and physical frailty [Rakotonirainy, 72].

Data suggests that older drivers are more likely to experience a crash in “complex traffic situations” [Rakotonirainy, 72]. Presumably, this is due to age-related decline in

vision, physical ability, and cognitive functioning [CDC, 15]. One such example of a complex driving scenario is that of lane-changes.

In order to address this potential accident scenario, auto manufacturers have implemented lane-change alert and blind-spot hazard avoidance technology. With the increase of in-vehicle technology (IVT) in today's automobiles, there is much information presented to the driver. "Older drivers may be prone to confusion and distraction caused by the need to attend to multiple sources of information," making information overload a potential problem, especially for older adults [Perel, 67].

Studies have shown that while older drivers exhibit a similar level of vehicle control to younger drivers in lane-change scenarios, they actually inspect their rearview mirrors and blind-spots less frequently before changing lanes. This indicates an at-risk situation for elderly drivers [Lavalliere, 49] or anyone with physical, visual, or cognitive limitations.

Visual and Physical Abilities

The visual and physical health of the driver impacts their ability to use many forms of driver vision systems. As the truck driver population has been aging, these factors become more relevant to designers of vision systems and their interfaces. Many studies have shown a link between loss of visual acuity and physical mobility with age [Faubert, 19].

Visual Acuity

The ability to see details in stationary objections decreases with age and is worse in low light conditions [Pineiro, 69].

Color and Night Vision

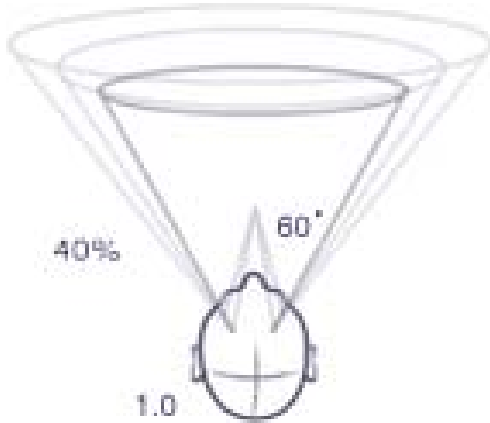
Older people do not see as well at night and have more trouble distinguishing between blue/green colors than red/yellow colors [Pinheiro, 69]. The color red is significantly more effective than other colors in enlisting a sense of urgency or potential danger among drivers [Campbell, 14].

Contrast and Glare Sensitivity

Older adults need sharper contrasts and edges (such as for a blind-spot alert icon) in order to discriminate an object, and they are more likely to be bothered by the glare of on-coming headlights [Pinheiro, 69].

Peripheral Vision

Research indicates that older drivers who have a poor “useful field of view” are more at risk for crashes. Further, restrictions of head and neck mobility hinder compensation for a reduced peripheral vision field of view [Owsley, 66].



Useful Field of View:

The area from which one can extract visual information in a brief glance without head or eye movement. The limits of this area are reduced by poor vision, difficulty dividing attention and/or ignoring distraction, and slower processing ability.

Figure 2.3 - Useful Field of View [Owsley, 66]

The useful field of view is a quantified method developed by Dr. Katherine Ball that has been proven effective as a predictor of driving performance [Ball, 8]. UFOV incorporates measures of both visual acuity and cognitive ability. It has not, however, been used specifically as an independent variable measure relative to blind spot monitoring alert effectiveness research.

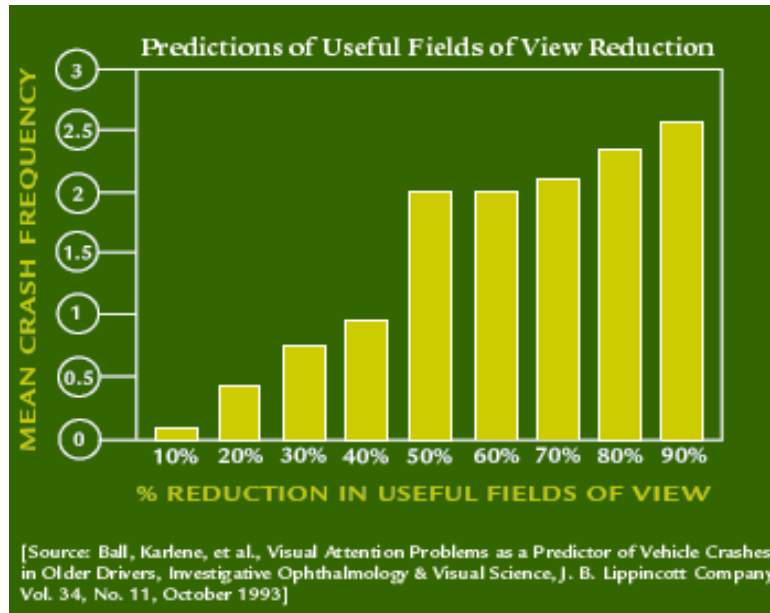


Figure 2.4 - UFOV reduction correlates to increased crash frequency [Ball, 8].

Simply using “age” as a category of comparison in research may mask real true correlating factors and limit opportunities for improved designs. Experience and risk perception levels can also be confounded variables hidden in the category of “age” and may serve to increase performance. UFOV could be a useful category for evaluation of effectiveness of blind spot interface as it removes any effect of stereotype of age from the research. This research does not address segmentation on the basis of UFOV levels, but does provide comparison on the basis of experience level as a separate factor from age.

Slower Reaction Times & Decreased Mobility

Elderly drivers have more restricted head and neck movement and slower reaction times. This has the potential to contribute to poor merging behavior and car-following patterns [Perel, 67].

The significance of the changing demographics of the US truck driving population cannot be underestimated, especially relative to the human factors issues facing the aging driver and his or her physical, visual, and cognitive limitations. The concept of Clarity of View seeks to add a measure that will allow those seeking to evaluate vision systems to do so in a manner that quantifies performance areas critical to overall effectiveness of the systems but not presently addressed within SAE J1750, RP428 or related procedures.

Human Factors for all age groups

Fitts' Law

Fitts' Law states that the time required to move to a target is a function of the target size and distance to the target [Wickens, 100].

$$\mathbf{Fitts' Law: } T = a + b \log_2 (1 + D / W)$$

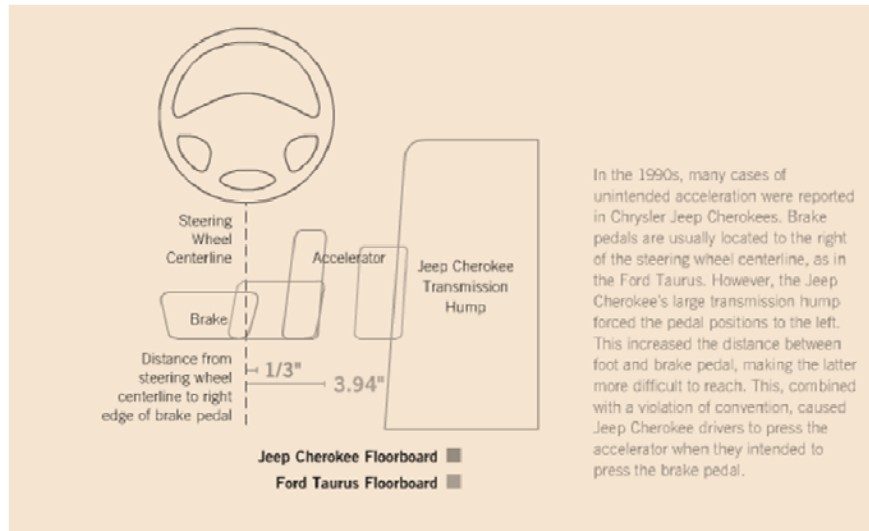


Figure 2.5 – Fitts' Law Illustration [Lidwell, 53]

In the equation presented, time (T) is a function of distance (D) and width (W) and that the relationship is logarithmic. The logarithmic relationship means that after some point Fitts' Law will have diminishing returns. This research hypothesizes that the wider field of view presented by a multi-radius aspheric style mirror will result in faster image detection time than that experienced using traditional planar mirrors.

Hick's Law

Hick's law which states that the time it takes to make a decision increases as the number of alternatives increases [Wickens, 100].

Hick's Law: $T = b \log_2 (n + 1)$

Basically, more options you offer the less likely any one of those options will be taken.

More choices = more errors or lower sales or (...) depending on your scenario.

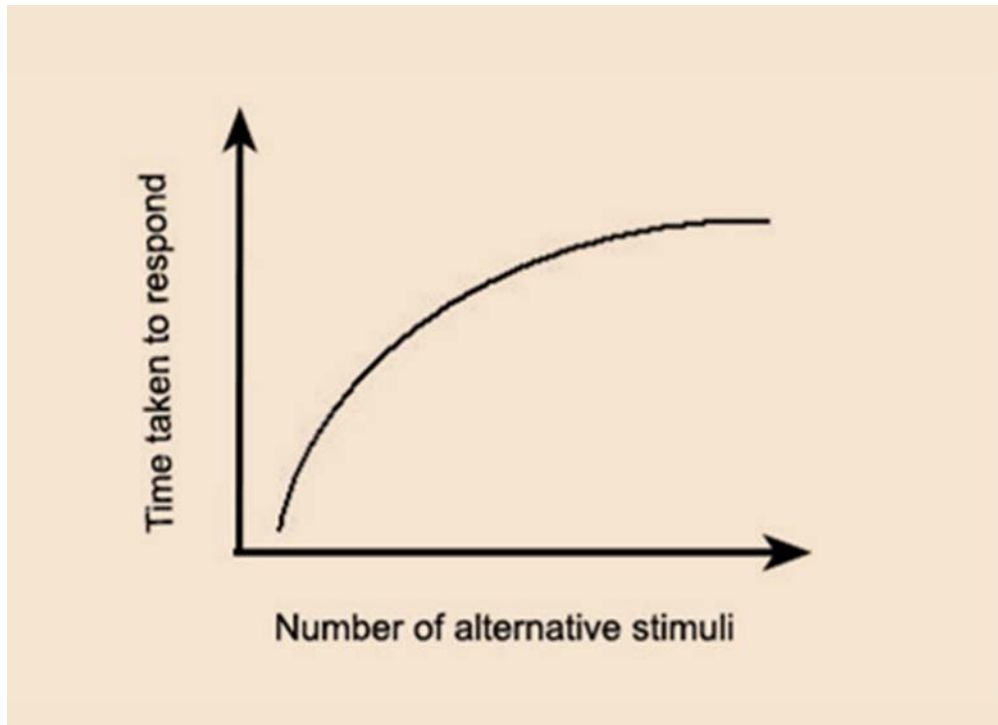


Figure 2.6 - Illustration of Hick's Law [Lidwell, 53]

As with Fitts' law we have diminishing returns after a point. The more complex the decision, the less Hick's law will apply. It does work well for simple things like navigating a website. This research hypothesizes that traditional mirror systems that make use of a combination of both a planar mirror and a convex auxiliary mirror present more focal points for the driver to discern and may delay image detection and recognition time.

Signal Detection Theory

Trust and Complacency are both significant considerations in the design of mirror or vision system image recognition, blind spot detection and alert interface systems [(Piccinini, 68), (Meester, 58)]. The detection of the stimulus depends on both the intensity of the stimulus (i.e. how big the image is or bright the signal is) and the physical and psychological state of the driver (i.e. how tired or distracted he is) [(Green & Swets, 32), (Tanner & Swets, 91), (Bliss, 10), (Lee, 50), (Wickens, 100)].

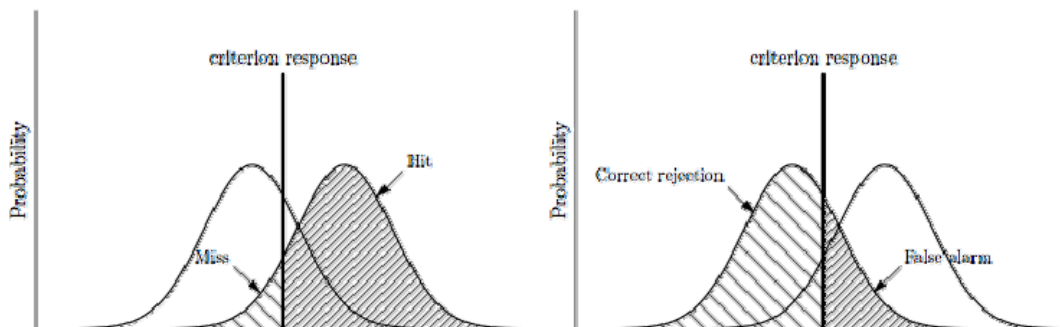


Figure 2.7 - Illustration of Signal Detection Theory [Lees, 51]

Poorly designed technology can increase mental workload and distraction and undermine performance. It can cause greater harm if it startles the driver. If it is annoying, drivers will ignore it. They may also become complacent and too dependent on the technology, ignoring safe driving habits. The overall goal is to minimize “missing” a real hazard but also to avoid “false alerts” of generating a stimulus if the hazard is not indeed a threat.

There have been no academic studies done to measure the overall long term effects of these systems for accident prevention. System detection accuracy is one thing,

but are the systems effective in a.) communicating information to drivers in a manner that allows them to react quickly enough, and b.) generating sufficient communication of information for the driver to know what appropriate action needs to be taken. This research proposes improved methodologies for assessment of a driver's image recognition speed through its inclusion of the factor of image detection time in the model.

EVALUATION METHODS FOR VISIBILITY SYSTEMS

There are limited published guidelines for industry that specify methodologies and acceptance criteria.

SAE J1050 and SAE J941

SAE J1050: Describing and Measuring the Driver's Field of View (Rev. 2009) presents three methods for measuring direct and indirect fields of view and the extend of obstructions within those fields. It references eye points defined by SAE J941: Motor Vehicle Drivers' Eye Locations [SAEJ941, 88].

SAE J1750

SAE J1750: Describing and Evaluating the Truck Driver's Viewing Environment is intended to complement procedures J1050 and J941 by adding a visual format that can describe the driver's entire viewing environment. The most recent revision expands from the original issue that only presented two methods of evaluation: polar plots and horizontal planar projection. The third method of target evaluation is useful for alternate vision systems as well as mirrors, but still has limitations that are highlighted in the following section. The target evaluation method can be simulated in a CAD environment

or performed manually, making it accessible to a wider population for practical application.

Within the January 2010, Revision 5 edition, Section 1 “Rationale,” SAE specifically calls for the need for additional work, “The Target Evaluation Method may be utilized for alternative vision systems as well (i.e., cameras & monitors), but additional work is necessary to specify system requirements that appropriately consider valid image representation (clarity, acuity, distortion, size, etc.)” [SAE J1750, 86].

RP428A and RP425

The Technology Maintenance Council of the American Trucking Association (TMC) published additional guidance to supplement these SAE procedures. The Recommended Practice RP425: Mirror Positioning and Aiming Guidelines is a generalized summary of best practice to ensure appropriate mirror position to minimize blind spots. It does not, however, give quantified measurement guidance or establish acceptance criteria [RP425, 94]. RP 428a: Guidelines for Vision Devices specifically augments the target evaluation method offered by SAE J7150 by extending reporting guidelines for consistency and direct comparisons [RP428A, 95]. The experimental comparison scenario described in the following section illustrates the application of these procedures and defines shortcomings observed.

Shortcomings of Existing Tests

Both the SAE J1750 and RP428a procedures lack guidance necessary for a direct and comprehensive comparison between systems. One issue is that of the weighting system. Figure 2.8 illustrates the differences that can exist between targets that all would qualify

under the “partially visible” score as defined by procedures as currently documented. A more granular scoring may offer a representative quantification of the true target visibility.

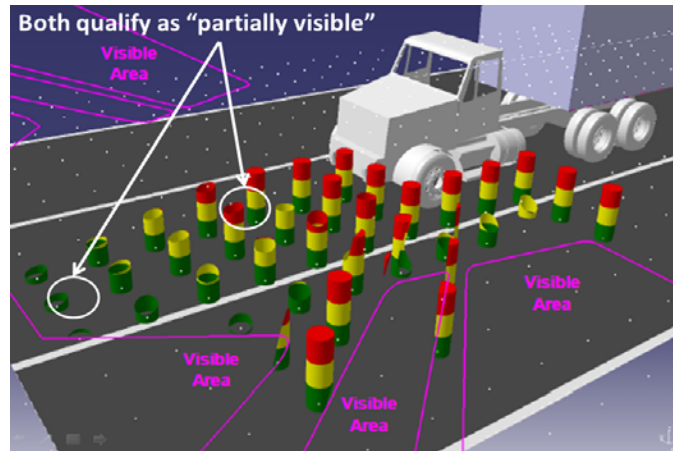


Figure 2.8 - Lack of quantified acceptability guidelines to measure partial visibility of targets in SAE J1750 Procedure [SAE J1750, 86]

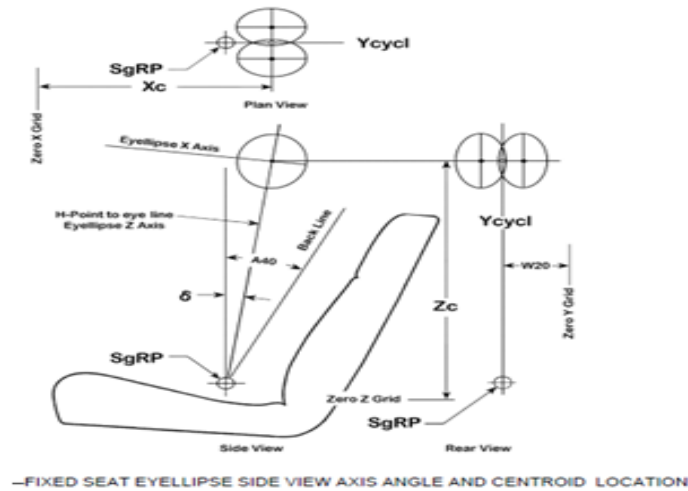


Figure 2.9 - Anthropometry guidelines are not specified in SAE J1750. This illustration is taken from *SAE J941: Motor Vehicle Drivers' Eye Locations* (2002) as an outline of the method prescribed for measurement of key dimensions [SAE J941, 88].

While SAE J941 and J1050 offer some guidance for anthropometry ranges for evaluation, neither addresses the unique demographic of the US truck driver today. Some studies illustrate the use of a 50th percentile male as defined by the study conducted by Kinghorn and Bitner in 1995 [Klinghorn & Bitner, 47]. A newer study has been performed that expands this data to include a wider range of drivers, including 5th percentile females up to 95th percentile males. The data highlighted a statistically significant increase in both weight and girth of both males and females with overall different physique from the general US population and that of truck driver counterparts from prior decades [Klinghorn & Bitner, 47]. Guidelines for the anthropometry ranges of drivers to be evaluated within this procedure would improve consistency of results reported. However, none of the published SAE guidelines highlight even the need to record, control, and report this factor as relevant to test results.

The preceding section has highlighted the complexity of the technology and human factors affecting overall driver awareness and the gaps in existing measurement protocols. What follows is a theoretical background of the AHP-based decision making methodology proposed for application to this gap.

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CHAPTER THREE

CLARITY OF VIEW USING THE ANALYTIC HIERARCHY PROCESS (AHP)

Overview

Engineering managers responsible for selecting technology solutions to improve driver safety in the automotive industry are challenged to make decisions that frequently involve consideration of multiple criteria and the inputs of a diverse set of stakeholders. In the case presented, the goal of the commercial vehicle fleet owner is to maximize safety through the selection of the most effective visibility system. The challenge includes that of balancing technical performance, driver usability, and feasibility in terms of cost.

In order to adequately address this dilemma, the underlying framework of the decision-making methodology has been given careful consideration. Within this section, I will (i.) describe the concept of the decision-making process and its basic steps; (ii.) define the decision-maker in the context of this example; (iii.) present an overview of several scientifically proven methods for decision-analysis; and (iv.) present the rationale for application of the Analytic Hierarchy Process approach to this specific case. Sections that follow will outline the specific model details, tools and methods applied toward measurement of the selected factors, and the evaluation of competing alternatives within a case study to validate the application of the methodology to a current industry-proposed set of technologies.

DECISION-MAKING PROCESS

“Decision making is the study of identifying and choosing alternatives based on the values and preferences of the decision maker. Making a decision implies that there are alternative choices to be considered, and in such a case we want not only to identify as many of those alternatives as possible but to choose the one that best fits with our goals, objectives, desires, values, and so on [Harris, 38].”

The notion of decision theory encompasses the rigor of mathematical analysis necessary for engineering decision making. The definition of the decision-maker is one that requires clarification in order to avoid common misconceptions regarding several commonly used approaches. “A decision is defined as a choice taken by an individual. A decision is not a group action [Hazelrigg, 39].” This assumption is one that will be carried throughout the context of the segments to follow. It is rational, however, to consider the significant influence of the inputs of multiple stake-holder groups, regarding some engineering decisions, and the need to capture such feedback in a systematic and mathematically sound manner is considered within the selection of methodologies given within this case. This concept is also fundamental to the selection of the AHP-based methodology that has been determined as the most appropriate for the specific nature of the problem defined by Clarity of View. The decision among potential driver awareness systems is dependent upon both quantitative data, measured scientifically and directly, as well as subjective, perception-based inputs. Some are best collected from multiple stakeholders and others can only be decided by the expert “decision maker.” Keeney and

Raiffia define this entity as the “Supra Decision-Maker [Keeney & Raiffia, 45].” This concept of the decision maker is reminded as one who may be an “individual or group that cooperates to act according to the same rational decision-making process as that would be followed by an individual [Wallenius, et al, 98].” Sections that follow, outline the process by which the AHP tool was chosen, identify its strengths and weaknesses, and explain how its potential weaknesses have been mitigated for this model.

Ultimately, the goal of this work is to produce a sound methodology, tailored for the problem statement presented, that will aid this “decision-maker” toward the reconciliation of the most well-informed choice. The gap that exists in today’s industry accepted methods for evaluation of visibility systems is a sound methodology that encompasses all factors that influence system effectiveness. One consequence of this gap is typically one of indecision altogether, thereby leaving many potentially viable, safety-enhancing technologies to remain on the shelf. Another primary gap is the failure of existing methods to identify potentially un-safe technologies. This work identifies such an example through a case-study, wherein a technology that scores highly using existing status-quo methods is determined to be both undesirable and potentially unsafe using the proposed new model.

A Disciplined Decision-Making Process

In the Guidebook to Decision-Making Methods developed for the Department of Energy, a simple eight-step process is outlined:

1. Define the problem
2. Determine requirements that the solution to the problem must meet

3. Establish goals that solving the problem should accomplish
4. Identify alternatives that will solve the problem
5. Develop evaluation criteria based on the goals
6. Select a decision-making tool
7. Apply the tool to select a preferred alternative
8. Validate the answer to make sure it solves the problem

[DOE, 18]

The theoretical foundations of the proposed Clarity of View model are presented here within this 8-step outline.

Step 1: Define the problem

The Introduction and Background Literature sections have given research and statistics that support the significance of the concept of improved visibility for heavy vehicles. The over-arching concept of the need for the decision model to make better decisions is now narrowed down to the specifics of how such a model will address this problem. The objective problem statement for the model must be clear and unambiguous in order for scientifically-based methodology to perform properly. In this case, the decision problem addressed by the case-study model is defined simply as: *Select the best visibility system.*

Step 2: Determine requirements

Existing methods for determining the effectiveness of visibility systems today focus primarily on Field of View. The SAE J1750 procedure mentions the need for additional work toward measures of Clarity [J1750, 86]. The Clarity of View Framework

fills this void in existing procedures and proposes a multi-factor approach to the measurement of overall system effectiveness.

These factors include that of image detection time, image distortion level, glare discomfort, accuracy of gap acceptance decision by the driver, and the traditional field of view (FOV) measure presented by existing procedures. Each measure illustrated in the Clarity of View model correlates to the total system effectiveness segments described in Figure 2.1 – System Effectiveness Overview.

- ***Driver perception*** is influenced by image detection time and field of view
- ***Driver understanding*** is influenced by image distortion and glare discomfort;
- ***Driver reaction accuracy*** is measurable by accuracy of gap acceptance.

In addition to these engineering and performance-oriented factors, the economic feasibility factors of both cost and reliability are added. The reality of most engineering decisions is that the theoretically best-performing technology may simply not be feasible for cost reasons alone. Failure to include this fundamentally important decision factor would yield a model that may give idealistic value only and not one of industry-applicable usefulness.

Recalling the concept of Overall Sensor System Effectiveness presented in Chapter Two, we clarify the scope of the research performed. The elements relating to the sensor-detection technology will not be part of this model. As illustrated below in Figure 3.1, this section of the driver awareness system is not part of this research.

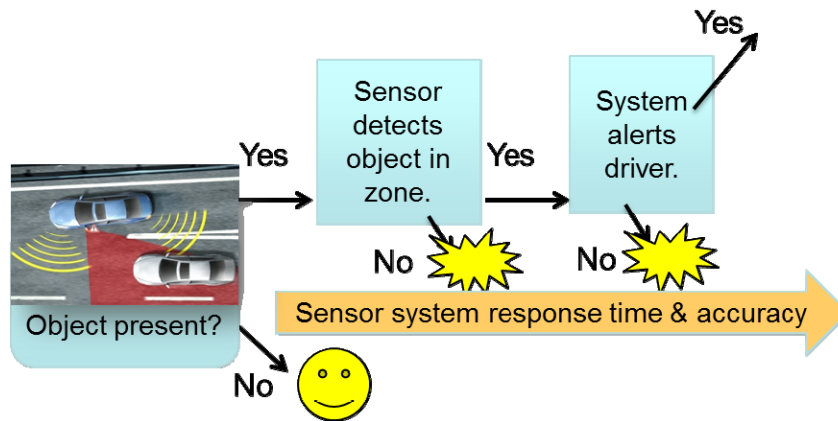


Figure 3.1 – Sensor system response time & accuracy

What will be the focus of this research is the secondary section of this overall system and those elements that affect driver reaction time and accuracy illustrated in Figure 3.2.

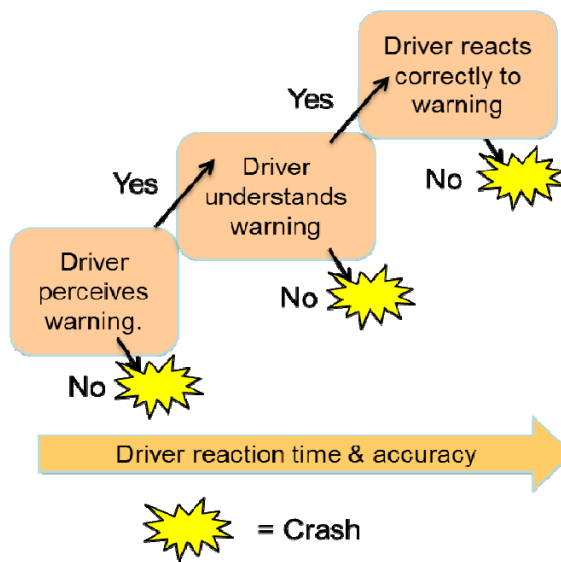


Figure 3.2 – Driver reaction time & accuracy

Step 3: Establish goals that solving the problem should accomplish

From the literature review, the factors affecting each of these sub-sections of the overall system are defined and goals are established for each.

- ***Driver perception*** is influenced by image detection time and field of view
 - Field of View is defined as the angular measure of the driver's surrounding environment that be seen in the mirror. Goal: Optimize field of view with larger values being preferred.
 - Image detection time is defined as the time required for the driver to recognize the image of the oncoming vehicle approaching them as seen in the mirror. Goal: Minimize image detection time with faster times being preferred.
- ***Driver understanding*** is influenced by image distortion and glare discomfort;
 - Image distortion occurs with mirrors of a non-planar ratio (in convex mirrors objects are closer than they appear), and will be measured subjectively based on driver perception. Goal: Minimize image distortion and the perception thereof.
 - Glare discomfort is experienced when lights of oncoming traffic or lights presented by in-vehicle displays or alert lights. This is also measured subjectively in this model. Goal: Minimize glare discomfort and the perception thereof.
- ***Driver reaction accuracy*** is measurable by accuracy of gap acceptance.
 - Gap acceptance accuracy is the measure of how accurately the driver discerns their ability to move into another lane based on visibility of surrounding environment. Goal: Optimize the percentage of correct overtaking decisions made by the driver so as to minimize the number of potential collisions.

- ***Economic feasibility*** is measurable by cost and reliability.
 - Cost is the basic cost to implement the technology. It is assumed that status-quo options are judged on the basis of zero-incremental cost to select. Goal: Minimize cost.
 - Reliability considers the expected lifecycle of the proposed technology and impact of it being unavailable for use if it should fail. Goal: Maximize reliability.

The key objective of this research is to build a useful model for the evaluation of overall driver awareness system effectiveness. The effectiveness of the model can only be as useful as the relevance of its inputs, so the process begins with the establishment of the criteria to be considered. Figure 3.3 summarizes those presently being considered for the Clarity of View measure of Overall System Effectiveness of driver awareness systems for heavy vehicles. These elements were concluded from the literature review that spanned an inquiry into both the technology and human factors elements affecting driver awareness, as well as a review of the existing evaluation methods published today.

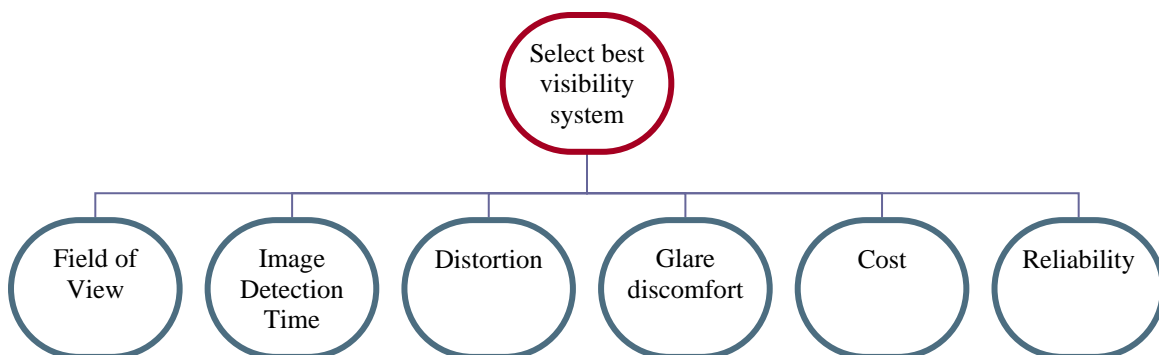


Figure 3.3 –Hierarchy structure for Clarity of View Factors

Step 4: Identify alternatives

The American Trucking Association Technology and Maintenance Council has established driver visibility improvement as a key objective [ATA/TMC, 93]. Through that initiative, they had narrowed several potentially viable visibility technology alternatives for use in the experimental testing of this study. Each is a form of direct-visibility mirror-system. Those systems are outlined in detail within the experimental methods section that follows. The model is presented in such a way that many other alternatives could be considered beyond these four specific examples. Specifically, it could equally be applied to visibility systems that rely on video-camera displays in lieu of mirrors. Such technology examples were simply not available for use at the time this study was completed.

The alternatives included within this study included:

- A. Status-quo mirror / factory installed planar
- B. Single-surface large aspheric mirror
- C. Small stick-on aspheric mirror used on factory-installed planar
- D. Combo mirror of aspheric and small planar

Photographs and detailed explanations of each are included in the experimental methods section in the following chapter.

Step 5: Develop evaluation criteria based on the goals.

Each of the factors illustrated thus far vary dramatically in the manner by which they are measured and evaluated. The best decision making methodology applied in any

model is fundamentally a factor of the nature of the data being collected and the evaluation being made. How each of these selected factors may be measured is explained in theory in this section, but will be given more detail within the methods and tools section to follow. A primary contribution of this work is the combination of all of these factors (and ability to add or change more if needed) into a single evaluation model. This approach has not been undertaken by any prior attempts to evaluate visibility systems.

- Field of View (FOV) is measurable by application of the SAE J1750 and ATA/TMC RP 4298a test procedures outlined in the background literature of Chapter 2. It is obtained as a percentage score and is interpreted with the goal of a higher number being preferred. This evaluation is done on a full-sized tractor and trailer vehicle on a test track using the barrel-target method. Field of View data is collected by only one sample on the track and is presented within the model as a fixed measurement that does not vary on the basis of driver or opinion. Other approaches to the existing FOV measurement method of SAE J1750 included: an occluded-view technique [Jennes, 44]; a horizontal FOV technique [Olson, 64]; and a portable CMM method [Way & Reed, 99]. None of these approaches offered superior ease of use to the current SAE J1750 used with the ATA/TMC RP 429a. Hence, the decision is made to retain the existing published protocols for inclusion in this evaluation.
- Image Detection Time is measurable as the time required for the driver to recognize an image in the mirror system when given a command for a lane change maneuver in the driving simulator. A verbal cue is given as confirmation of

acknowledgement and data is collected by both eye-tracking video capture and manual time-capture methods. The evaluation is performed within the safety of a driving simulator with the goal of minimizing the reaction time as theoretically being the best indicator of the driver's best usability of the system. A low time is preferred. Image detection time is collected for all test subjects in the study as it is expected to vary between users on the basis of their experience level, age, physical and visual abilities.

Prior work has included different approaches toward the quantification of image detection time. The majority include measurement of glance behavior (frequency and duration of glances) combined with verbal survey cues. One study relied simply on attribute based confirmation of images (yes/no, but no time data) [Jenness, 44]. Another study sought to quantify accidents or safety-critical incidents through predictive models [Olson, 64]. Response time of drivers was also quantified in other areas of driver performance involving driving tasks, such as reaction to stop-lights [Caird, 12]. This work differs in its proposal that while glance behavior may be useful, in the case of the visibility system scenario, simply measuring the time to fixation of a glance cannot be interpreted as a cognitive recognition of the item of interest. This theory is supported by studies of driver performance [Martens, 55] and the eye tracking technology industry [iMotions, 43]. For this reason, the Clarity of View approach targets quantification of the time between which an item of interest is made present within the driver's environment and the time elapsed for them to accurately

identify it as the item of interest (in this case, an oncoming vehicle in the lane of traffic they are attempting to enter) as an accurate indicator of time to mental recognition. An attempt was made to improve upon the verbal cue indicator for a more naturalistic approach, but the biometric sensor technology available at the time of this study proved insufficient to give accurate feedback.

- Distortion is measurable as a subjective opinion given by the driver. Because there is no widely accepted direct-measurement methodology available to quantify distortion, it is evaluated by pairwise comparison amongst alternatives. Drivers have do not have the ability to give distortion a “score” out of a theoretical best, but instead are able to compare their perception of one alternative to another in a pairwise method.

Prior work had used methods such as distance estimation and image size measurements as indicators toward acceptability of distortion levels [(Flannagan, 24, 25), (Hecht, 41), (Fitch, 22), (Mazzae, 57), and (Rau, 73)]. Several of these also included subjective ratings of mirrors based on user opinions regarding their desirability. The study by VTTI highlights the shortcomings in prior approaches with its call for dynamic studies as current work had all been statically measured [Rau, 73]. These studies all point back to the conclusion that regardless of their findings, what mattered most was driver adaptation to new mirror systems. Their shared approach to subjective survey reviews of different mirror systems left room for improvement toward better quantification of the subjective opinion of the potential alternative technologies in that none provided a clear preference

ranking that could be aggregated with other factors. The Clarity of View framework reconciles this gap.

- Glare discomfort is also measurable as a subjective opinion given by the driver. While a direct measurement of light collected is available, it does not translate to what is considered objectionable vs. comfortable to a driver. Like distortion, glare is measured via pairwise comparison amongst alternatives, with lower scores being preferred for each.

Glare measurement has been the subject of much evaluation well beyond the automotive industry. The International Commission of Illumination has recommended the “Unified Glare Rating (UGR)” as a quantitative measure of glare. The UGR describes the combined effect of luminance, size and location of glare sources [Osterhaus, 65]. Past work involving automotive mirror systems has included one study that used a simple DeBoer’s rating score (1-9 Rating) of glare discomfort [Ayres, 7]. Another used illuminance readings as indicators of glare, but were focused solely on technology comparison and did not attempt to correlate the measurements to actual driver perception as would otherwise be possible using the UGR method [Sivak, 83]. Additional work has expanded this method of using the basic illuminance measure in combination with the DeBoer’s rating scale in an effort to correlate actual illuminance (as measured in lux) to driver satisfaction levels [Flannagan, 26]. Future work toward the Clarity of View framework would benefit from the incorporation of the quantified approach

toward measurement of glare in terms of the UGR, but equipment was not funded at the time of this project.

- Cost is measured simply on a dollar range basis and is captured in a rank-categorized method of: low, medium, or high with low being preferred.
- Reliability is measured on a rank-categorized method of low, medium, high, with high being preferred and correlating to lifetime of the vehicle.

Neither cost nor reliability have been considered by any of the engineering studies published. However, industry still must consider these critical economic factors in any decision making process.

- Gap acceptance is measured within the Clarity of View framework as the percentage of correct overtaking decisions the driver makes. This factor is measured by the test administrator based on visual observation only. Any score less than 100% is considered unacceptable for the system. (Note: Later discussion will illustrate why this factor was measured, but not included in the final Clarity of View model.)

Prior work has included quantitative analysis of gap acceptance in a similar scenario using a driving simulator apparatus [Levulis, 52]. Software controls were used to measure actual gap acceptance distances and compare them to prescribed safety thresholds. While the accuracy level of this method was not clearly illustrated, it appears to be a viable opportunity for improvement and future inclusion within the Clarity of View framework methods.

Additionally, segmentation categories are simply those elements of data to be collected within the experimental studies that, if compared and contrasted, may yield useful information from the experimental results. Based on those areas of focus determined relevant from the literature review, those categories are defined as:

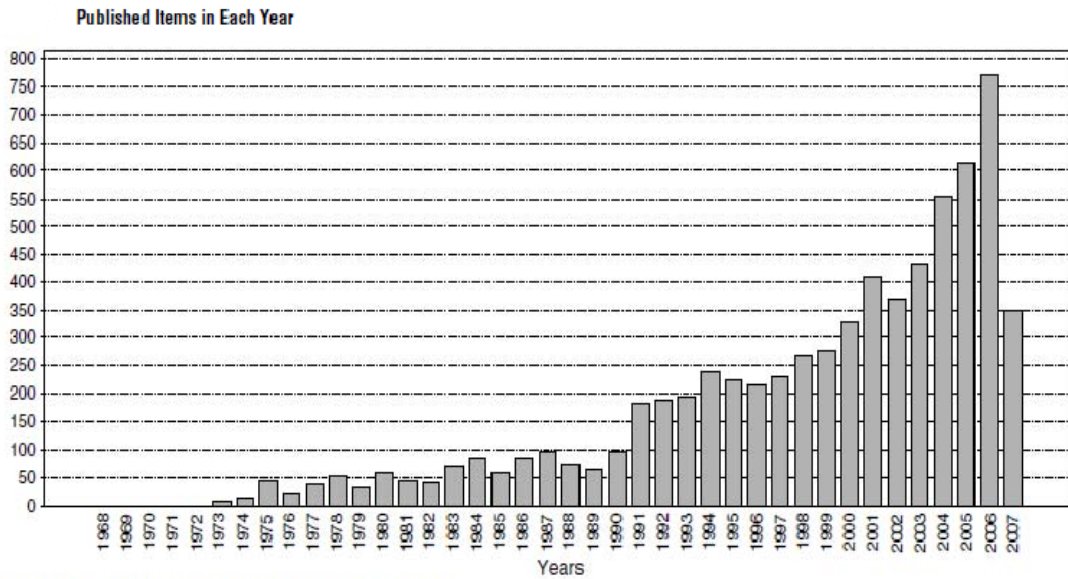
- Age
- Gender
- CDL / Truck driver years of experience
- Experience using driver alert systems
- Visual capabilities (glasses, peripheral vision ability)

Users are also categorized either as: drivers (who simply participate in the measurements collected in the driving simulator and provide feedback on subjective factors) or experts (who serve as the theoretical engineering manager / decision-maker who have the knowledge and experience to provide weightings for the importance of various objectives within the study).

Further detail on each is given with the tools and methods section to follow with the explanation of the experimental approach. The structure of these factors influences the selection of the decision modeling methodology.

Step 6: Select a decision-making tool

There has been a significant increase in the use and application of scientifically based multi-criteria decision modeling methodologies in recent decades. A recent bibliometric study produced data citing the increase in published items focused on the topic since the 1970's:



Note. Year 2007 includes published items until the end of June 2007.

Figure 3.4 – Published Items in Each Year (on topics of Multi-Criteria Decision Making)

[Wallenius, et al, 98]

This increase was concluded for several reasons, but one of the most relevant was determined to be the improved availability of computational software designed to facilitate the ease-of-use of many of the more popular methodologies available. While various authors argue their points toward the validity of one methodology over the other, most share far more in common than some authors care to acknowledge. One advocate promotes this agreement, ‘I agree with Keeney that decision making is concerned with helping people make informed, and hopefully better, decision.’ This is the aim of both a MAUT (multi-attribute utility theory) and an AHP (analytic hierarchy process) analysis” [Gass, 29].

The increased application of research utilizing multi-criteria decision modeling methodologies has been strengthened with the increase in use of the AHP method. The

same bibliometric study performed by Wallenius, et al shows the spike in research publications citing use of the AHP process:

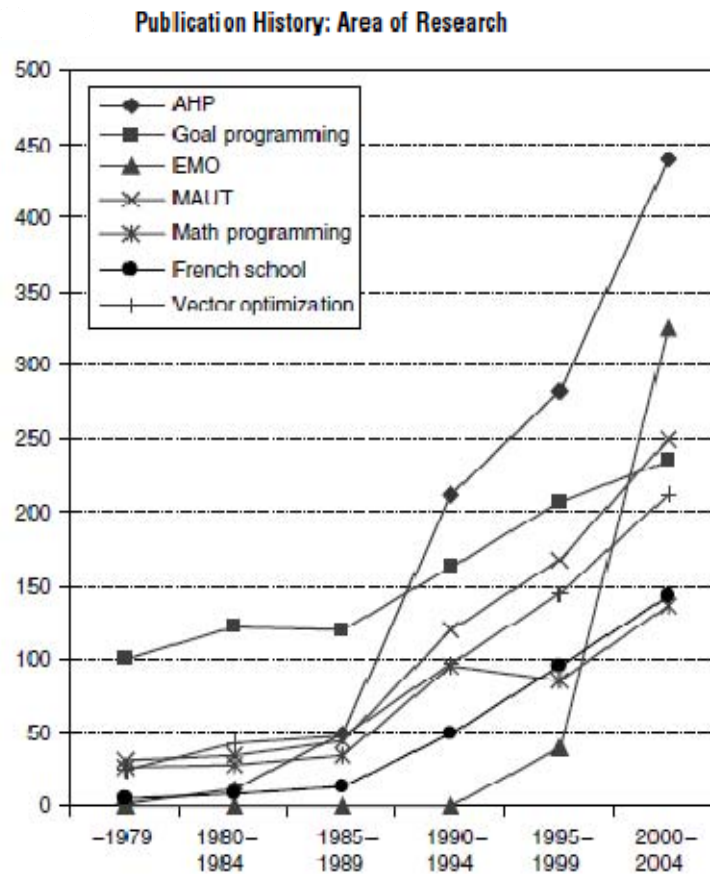


Figure 3.5 – Publication History: Areas of Research [Wallenius, 98]

Several methodologies were highlighted within that study that included: AHP, Goal Programming, EMO (evolutionary multi-objective optimization), MAUT (multi-attribute utility theory), Math Programming, French School (ELECTRE and PROMETHEE methods), and Vector optimization. Additional work highlights even more to be considered, including: Kepner-Tregoe Decision Analysis (K-T), SMART, Quality Function Deployment, PUGH, Cost-Benefit Analysis (CBA), Conjunctive Analysis, and simple Pros & Cons elementary methods.

Analytic Hierarchy Process (AHP) Concept

The Analytic Hierarchy Process (AHP) was developed by Thomas L. Saaty in the 1970's. It is rooted in both mathematics and the psychology of human decision-making and makes use of pairwise comparisons to measure intangible criteria [Saaty, 77]. Its strength lies in its ability to aggregate both this intangible data alongside that generated by quantitative, direct measures. Because AHP attempts to mirror the human decision making process, it is intuitively more easy to use than popular methods such as quality-function-deployment (QFD) and multi-attribute utility theory (MAUT). It offers a structured approach to decision problems and has the capacity to compare both quantitative and qualitative information using informed judgements to derive weights and priorities. It can accommodate inputs from multiple stakeholders and combine those inputs into a final decision model.

Three fundamental principles are essential in the use of the AHP Process: decomposition, comparative judgements, and synthesis of priorities [Saaty, 76]. The process can be described within four basic steps, the foremost Step 1 being to clearly define the problem or goal of the decision problem.

Step 2 follows by breaking down the problem into a hierarchy of criteria and sub-criteria so as to enable easier comprehension by decision makers as illustrated in the model established by Saaty in Figure 3.6.

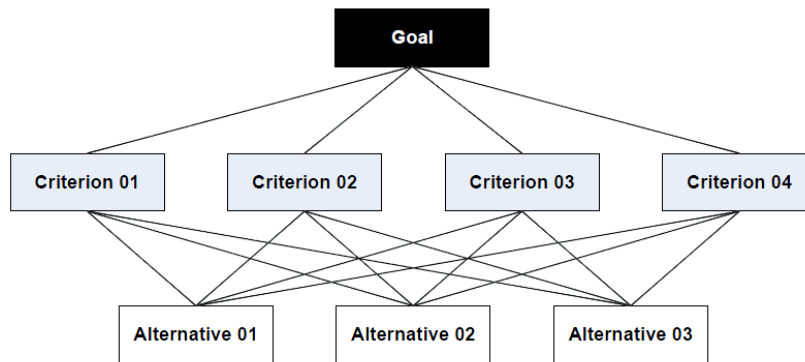


Figure 3.6 – Example of decision hierarchy and alternatives [Saaty, 77]

Criteria are selected in such a way that they are independent of one another. Related factors may easily be represented as sub-criteria if more than one criterion can contribute to a higher level one. Both direct measurement data and human judgment may be used as inputs. The ability of the AHP methodology to aggregate measurements that are each of different scales is accomplished through the application of a ratio-scale expression of preferences between alternatives. This is a departure from more traditional methods such as MUAT that employ interval-scale measures. The ability to discern the intensity between preferences yields data that is more comprehensive for use in the decision-making process.

Once defined, Step 3 follows with the assembly of the pairwise comparison matrices with each element in the upper level (criterion) compared in the level immediately below it (alternatives) as illustrated in Figure 2.10. In Step 4, decision makers prioritize the elements and determine the relative importance weights of the decision criteria and the relative rankings (priority) of the alternatives. Figure 3.7, that follows, illustrates the ranking scale proposed by Saaty.

The fundamental scale of absolute numbers

<i>Intensity of Importance</i>	<i>Definition</i>	<i>Explanation</i>
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Table 3.7 – The fundamental scale of absolute numbers [Saaty, 77]

The ranking system is based on a 1-9 system. The weighting is assigned to each category thereby enabling the logical comparison of alternatives. Rather than simply assigning each criteria a 1-9 score, each is presented to the decision maker as an alternative pairwise comparison to other criteria. For example, “Which is more important to you? Criteria A or Criteria B?” Each criteria is evaluated against all the others in this pairwise format. The alternatives being evaluated are then compared in a similar manner. Commonly used software programs for AHP introduce the 1-9 rating scale in an easy to understand format. Instead of asking the user to rate an element as a score of 7 more than another alternative, it is given with the verbal terms: moderately, strongly, very strongly, etc. as illustrated in the preceding table. This is psychologically easier for users to

process than methodologies that require them to assign arbitrary values of utility to an element where a theoretical “ideal” state is neither defined nor possible to be measured.

When direct measurement is available, then raw data may be input. For example, in the decision making process of selecting which automobile to buy, fuel economy may be a criteria for consideration. In this case, Alternative A may rate 25 mpg vs. Alternative B at 30 mpg. These are simply input as their direct values. There is no opinion associated with these values. The AHP methodology facilitates their normalization for aggregation with the other criterion.

Once all inputs are collected, a consistency index (C.I.) score provides assurance that illogical inputs are not entered into the model. For example, if $A > B$ and $B > C$, then $A > C$. This is a valuable safeguard to users that error-proofs the model from illogical ratings resulting from human error. The basic algorithm illustrated in Figure 3.8 may be utilized for any AHP process:

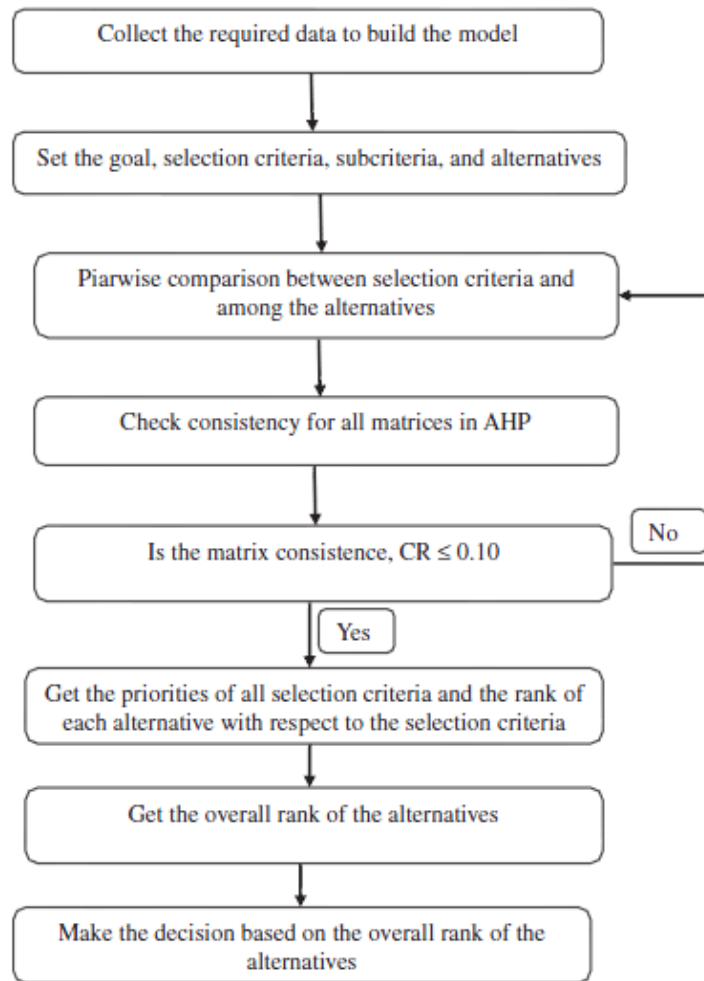


Figure 3.8 – Basic AHP Algorithm [Saaty, 76]

The ability to discern potential errors or inconsistencies in any decision model by use of this consistency index is a strength of the AHP process not found in other methodologies that provides additional credibility to the interpretation of judgement data obtained from multiple users. No decision modeling technique is free of any opportunity for human error, but the consistency index renders confidence using the AHP methodology that is not found elsewhere.

AXIOMS OF AHP

The following axioms were hypothesized by Saaty and govern the AHP process [Saaty, 78]:

Axiom 1: Reciprocal Comparison

The concept of consistency is fundamental to the AHP methodology. This insists that there is no judgmental inconsistency. As the comparison matrices are formed, if object A is judged to be 3 times bigger than object B, then it can be concluded that object B is one-third as big as object A. The Expert Choice AHP analysis software used in this case study calculates the consistency index as a measure of conformity within this axiom.

Axiom 2: Homogeneity

“The human mind cannot process comparison of widely different elements. For example, we cannot compare a grain of sand with an orange according to size. When the disparity is great, elements should be placed in separate clusters of comparable size, or in different levels altogether [Saaty, 76].” In the Clarity of View case, mirror-system alternatives being compared are all relatively similar in size, shape, and performance criteria in keeping with the principles of this axiom.

Axiom 3: Independence

Criteria being evaluated are assumed to be independent of one another. Where situations exist that there may be interdependence, then the option to combine such examples as sub-criteria under a higher order classification is one solution. Within the Clarity of View model, care was taken to select a simple set of evaluation criteria that were each distinctly different from one another, as directed within this axiom.

Axiom 4: Expectations

This axiom states that rational individuals make every effort to clearly and completely express their preferences and that all relevant expectations are represented in the model. Within the Clarity of View case, test subjects were given additional time outside the evaluations to express additional feedback, concerns, or other observations they felt were relevant to the study as a means of assuring all expectations were captured.

Criticisms of the AHP methodology:

Despite its widespread adoption in both industry and academia, there have been criticisms of the AHP methodology primarily on the basis of the concept of rank reversal. This scenario results when a “new” alternative is added to a decision-model that may in some cases be irrelevant, it is possible for the original priority rankings of previously issued judgements to become reversed. Other decision theories propose this scenario must not occur and that original rank priorities should be preserved regardless of the addition of new alternatives. In fact, the real conclusion is... it depends on the problem. Saaty’s early AHP formulation allowed such rank reversals in the original, “distributive” mode. With the addition of the “ideal” mode presented by Forman in 1993, the introduction of a new alternative can be made without worry of re-ordering of alternatives. Current industry-leading AHP software, Expert Choice, allows both scenarios: distributive (which allows ranks to change) or ideal (which preserves ranks) [Forman, 27]. By defining systems as open or closed on the basis of scarcity or abundance of resources, Forman and Gass help the lay-user understand the scenarios

where either synthesis mode may be more desirable. A closed system example would be like that of a country attempting to distribute a finite amount of resources amongst communities. A new community is discovered with considerable need. Resources would have to be taken back from those to whom they were already distributed to in order to provide help to this newly discovered population. This redistribution scenario could result in reversal of ranks of those previously ranked groups. The scenario of the US Presidential election is similar. When a third party candidate enters the race, he or she may end up influencing the current ranking of the existing Republican and Democratic candidates as people shift votes away from one or the other to the new candidate [Forman, 27]. This is a very rational scenario and should be accommodated. Open systems can be described like that of the selection of a new computer or camera, for example. You are considering 5 alternatives and a new, irrelevant alternative is introduced. In such a case it may make sense that one would not want to allow this irrelevant alternative to skew the previously issued judgements. This is the case where the ideal synthesis mode is presented as a means to preserve the original priorities. In the Clarity of View case, the Ideal Synthesis Mode is utilized, even though new alternatives have not been proposed into the model at the present time. It is quite feasible that this work will be continued and additional new alternatives may be entered into consideration.

Group vs. Individual Preferences

Reflecting back to the proposal by Hazelrigg that “a decision is not a group action” [Hazelrigg, 39], I will expand on the concept of the “supra-decision maker” and how it has been applied within the Clarity of View model [Keeney & Raiffa, 45].

In virtually every organization, whether it be an industrial institution or a societal community, there are decisions to be made that affect multiple individuals within the organization. Decision-modeling techniques have evolved over time with the shared goal of optimizing value for all stakeholders affected by the decision. The multi-criteria decision making problem frequently presents itself in the context of “social choice” questions in society. An example of such a scenario is that of selecting a candidate in a multi-party election. In such a case, there is obviously no single decision-maker, or dictator, in a free society, and “the goal is to arrive at rational decisions that respect the sovereignty of the individual citizens involved in the decision” [Scott & Antonsson, 81]. One prominent objection theory to that ideal is known as “Kenneth J. Arrow’s General Possibility Theorem” [Arrow, 6]. It is also referred to as “Arrow’s Impossibility Theorem.” In this theorem, there is the proposal that group decisions have the following properties:

1. “Unanimity – if everyone in a group prefers option X to options Y, Z, etc. then the vote of the group should be for X.
2. Transitivity – If the group prefers X to Y and Y to Z, then the vote of the group should show that the group prefers X to Z.

3. Independence of Irrelevant Outcomes – if the vote indicates a group preference for X over Y in the absence of other alternatives, then the addition of alternative Z, or any other set of alternatives, should not alter the vote between X and Y.
4. No Dictator – there is no single person who decides the outcome of the vote unilaterally”

To summarize, it postulates that any group decision outcome that respects all conditions of unanimity, transitivity, and independence of irrelevant outcomes is simply a dictatorship [Hazelrigg, 39]. Hazelrigg proposes that because of this theorem, there can be no group decisions in engineering design selections. This notion is overly idealistic in its consideration of the reality of how engineering decisions are made in industry. No engineering organization functions as a dictatorship in reality, and all organizations employ some level of group interaction and aggregation of preferences when it comes to subjective factors that affect the outcome of the decision. While this theorem may hold true in cases of social choice, I make the argument that engineering decisions are distinctly different by nature and that this theorem does not apply in the engineering technology selection problem. In social choice, the sovereignty of the individual is idealized and they have the freedom to order their alternatives in any way they choose, *including irrational choices*. In the reality of most engineering decisions, comparison of alternatives is governed by the applicable engineering laws and directly measurable. The example of comparison of automobiles for purchase can illustrate this decision-scenario. While an individual may be free to weigh their preference of the desirability of the exterior styling of the automobile, the comparison of their performance of fuel economy

is not a matter of choice. “In the social choice problem, all orderings are accorded equal worth. In the multiple criteria problem, it is desirable to be able to assign importance weightings to criteria. While it is natural to accord all human voters (in a social choice election problem for example) equal worth, there is no obvious reason to require equal weighting of the different engineering criteria that describe a device or system [Scott & Antonsson, 81].” Arrow’s theorem does not include consideration of the relevance of weighting of priorities nor comparison of alternatives in degrees of preference and therefore has no place in the discussion of engineering decision making. In the Clarity of View problem, a set of four expert decision makers were chosen and established as the “supra-decision maker” sharing an aggregated priority weighting for the criteria being considered in the study. These experts were selected based on their cross-functional experience that spans experience in engineering design, selection, and application, especially as concerned with driver and fleet safety as well as overall fleet profitability and reliability. Each expert considered in the study has over 25 years of experience in the role of the decision maker of the Clarity of View problem and the aggregate of their priority weightings of each criteria being considered. To reconcile the different schools of thought regarding groups vs. individuals in this process, all authors would agree with this concept when thinking in terms of the “supra-decision maker” group as the theoretical dictator.

Summary of the decision-making methodology of AHP

The AHP method has been used widely in business for the prioritization of projects and selection within key decision making frameworks [Vargas, 97]. It has been utilized within engineering and manufacturing design processes as well. However, there is no documented example of the application of the AHP methodology to the evaluation of human user to machine interface designs. It is a logical application through its ability to combine quantified and subjective measures into one model. The AHP technique is the foundation upon which the Clarity of View framework is proposed.

Step 7: Apply the tool to select a preferred alternative

This section describes the application of this model within the AHP-based Expert Choice software. The objective criteria hierarchy described in the earlier sections of the chapter were structured first.

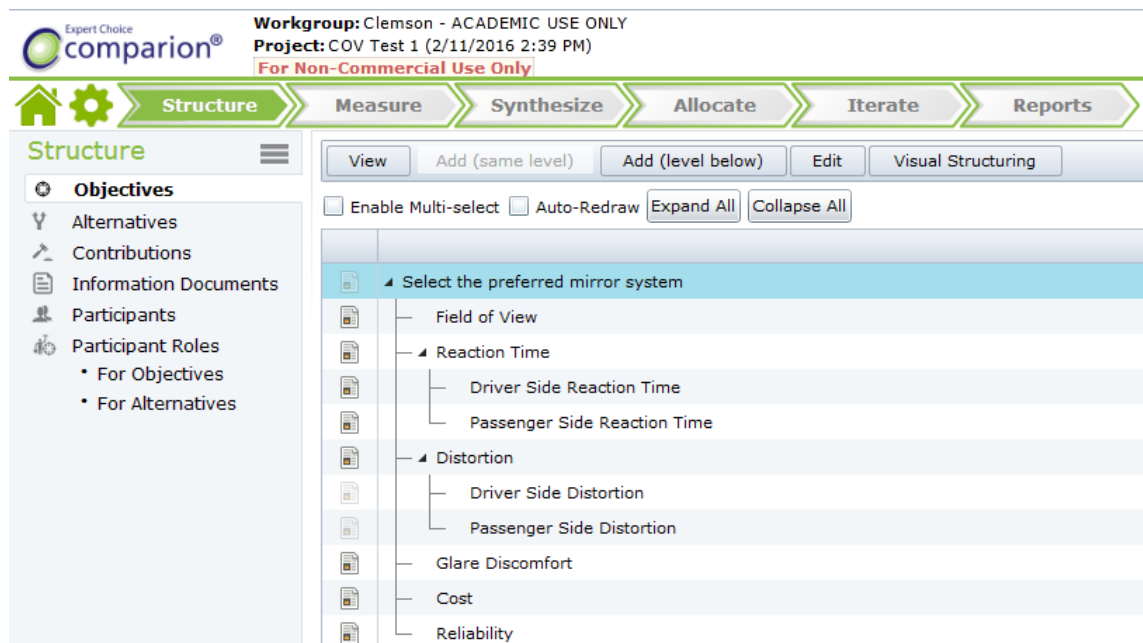


Figure 3.9 – Structure of Goal and Objectives

The primary goal was setup first: “Select the preferred mirror system.” Relevant criteria were then established in the hierarchal format as illustrated in Figure 3.9 – Structure of Goal and Objectives.

Next, the alternatives were structured.

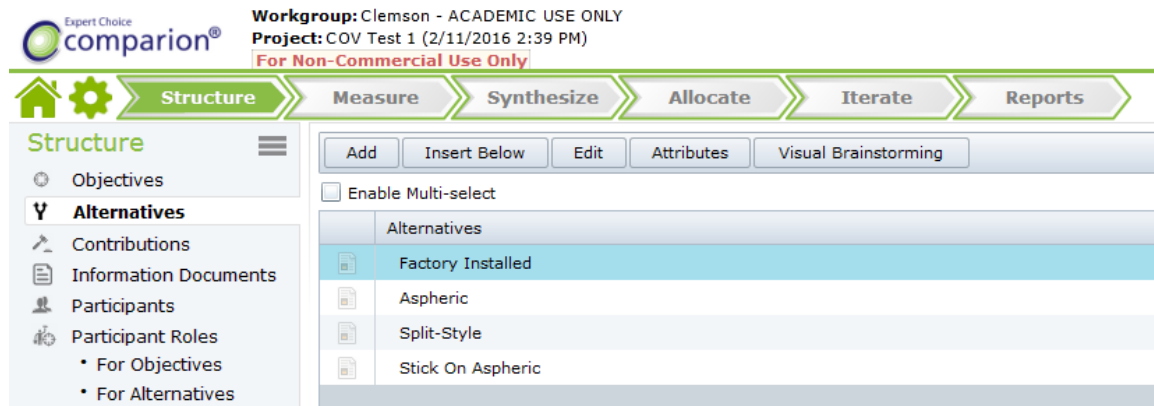


Figure 3.10 – Structure of Alternatives

Four technology alternatives were included in the study. Each was relatively similar in keeping with the axioms of applicability within the AHP theory. Illustrations of each alternative are provided in the following chapter.

The roles of participants were defined next. Two primary categories of test participant roles are established: drivers and experts. Drivers provided feedback on distortion perception and reaction time only. Their reaction time was measured quantitatively within the driving simulator experiment. Their perception and preferences relative to distortion was measured subjectively using the pairwise comparison method. Experts were also included in the driver-role and participated in the study in that capacity, but non-experts were not included in the expert-evaluations and priority weightings.

Figure 3.11 – Driver Group Role Structure illustrates this segmentation.

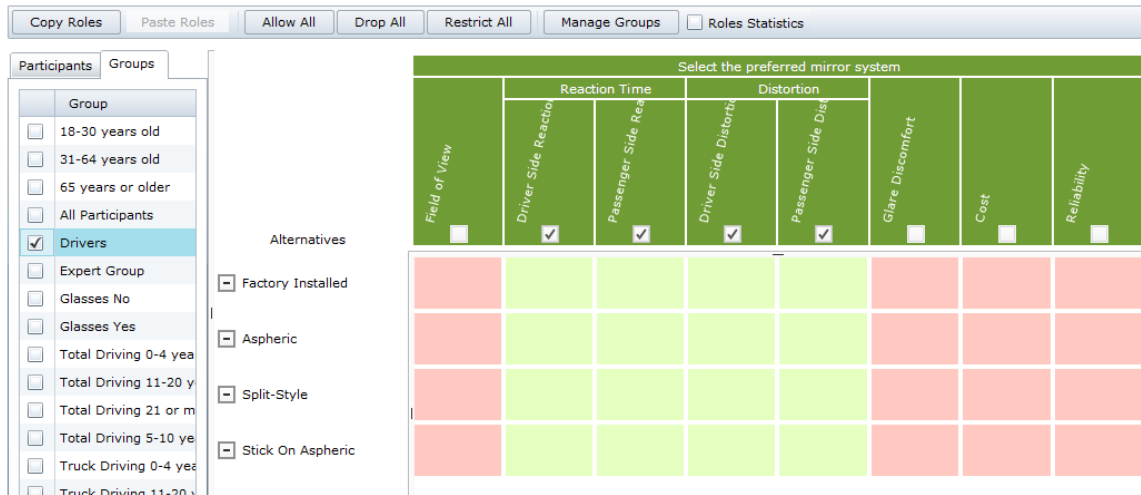


Figure 3.11 – Driver group roles structure

The expert group had ability to provide feedback on the full range of criteria within the model. The data collection mode for each criteria was structured as well in accordance with the formats presented in the earlier part of the chapter and is illustrated in Figure 3.12 below.

Measure Alternatives With Respect To	Measurement Type Default: Pairwise Co	Measurement Scale	Action	# of Elements in Cluster	# of Judgments in Cluster
Select the preferred mirror system					
Field of View	Direct		Copy	4	4
Reaction Time					
Driver Side Reaction Time	Simple Utility	Utility Curve for R	Copy Edit	4	4
Passenger Side Reaction Time	Simple Utility	Utility Curve for R	Copy Edit	4	4
Distortion					
Driver Side Distortion	Pairwise Comparis		Copy	4	$4*(4-1)/2 = 6$
Passenger Side Distortion	Pairwise Comparis		Copy	4	$4*(4-1)/2 = 6$
Glare Discomfort	Pairwise Comparis		Copy	4	$4*(4-1)/2 = 6$
Cost	Rating Scale	Scale for Cost	Copy Edit	4	4
Reliability	Rating Scale	Scale for Reliabilit	Copy Edit	4	4

Figure 3.12 – Data collection format structure for alternatives

The following chapter will illustrate the tools and apparatus used to collect this information and expand on the data-collection process.

Step 8: Validate the answer to make sure that it solves the problem

Ultimately, the synthesis of the data collected is summarized in an easy-to-understand pareto of alternatives, as illustrated in Figure 3.13 below – Summary of Alternatives.

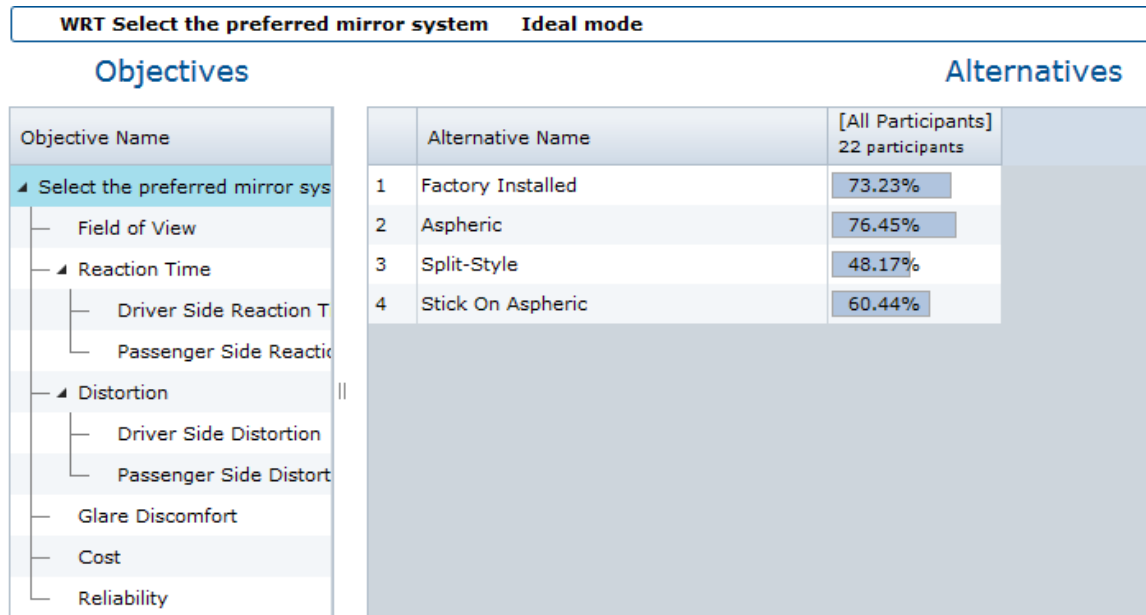


Figure 3.13 – Summary of Alternatives

Within the context of the chapters to follow, the experimental approach and results are described. The results indicate the validation of this methodology in providing a better, more informed decision toward the technology selection problem presented. The AHP-based Clarity of View model provided an insightful and more comprehensive evaluation of four competing technologies and provided the decision maker with better information than was previously available using the industry-standard, status-quo published procedure.

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CHAPTER FOUR

TOOLS, METHODS, AND PRELIMINARY EXPERIMENTS

The Clarity of View decision model theory and framework has been developed and explained within Chapter Three. This chapter provides the description of tools, methods, and preliminary experimental testing that was performed within the application of this model to the current industry problem of selecting the best visibility system for a heavy vehicle. I begin with the discussion of the preliminary experiments performed to confirm methods used for the measurement of those factors evaluated quantitatively. The remainder of the chapter is dedicated to describing the Clarity of View driving simulator test apparatus and the experimental methods used to capture data on all factors within the model framework.

PRELIMINARY EXPERIMENTS

Two rounds of preliminary experiments were performed as part of the research plan. Each was established in order to provide early data on key factors that are proposed as part of the overall model. Those elements that presented the most difficulty in measurement were selected, so that the overall method could be practiced first on a smaller scale before developing additional test equipment. Those preliminary studies were instrumental in developing the later studies and are summarized as:

1. Image Detection Time: Blind Spot Awareness for Elderly Drivers

Objective – To demonstrate how image detection time can be used as a critical indicator of situational awareness, by confirming the viability of measurement of image detection time as a measure of effectiveness of a driver alert system. The

resulting conclusions indicated that image detection time is in fact a useful factor for the overall Clarity of View framework model.

2. Field of View: 360 Degree Visibility of Heavy Trucks

Objective – To demonstrate how Clarity of View improves upon existing practices by confirming the viability of use of the J1750 and RP428a standards already proposed by industry. Results will be used to feed the Clarity of View framework model “Field of View” factor.

Both studies were conducted under approval of Clemson University IRB.

IMAGE DETECTION TIME: Blind-Spot Avoidance Awareness Study

One of the factors determined to be significant to the driver’s situational awareness is that of “Image Detection Time.” None of the published test procedures for evaluation of visibility systems provide any method for its evaluation [(SAE J1050, 19), (SAE J985, 89), (SAE J1750, 86), (SAE J182, 87), (SAE J941, 88), (TMC/ATA RP425, 94), (TMC/ATA RP428A, 95)]. To demonstrate how image detection time can be used as a critical indicator of situational awareness, I have performed a study designed to use this factor for comparison between two styles of blind-spot awareness indicators. This study also included some basic subjective surveys of driver perception of the systems being compared. It was useful in that it provided sufficient data to conclude with statistical confidence that one system was superior to the other, including the differences observed between various age categories.

Detection System

Most blind-spot avoidance systems make use of a combination of radar and ultrasonic sensors placed in lateral front and rear positions that detect the presence of another automobile in the blind-spot region. “The rear sensors observe the primary blind-spot region and the front sensors discriminate irrelevant warnings [Thiel, 92].” Figure 4.1 illustrates this concept.

Alert System

In most automobiles today, driver alert is accomplished using a small yellow/amber icon located in the outer edge of the outside rearview mirror (OSRV). This location is in the outermost edge of the peripheral vision region. Some manufacturers have recently begun placement of this alert on the lower A-pillar region. The symbols vary by manufacturer and studies regarding the “best” type of symbol or color for this purpose have been inconclusive, although results indicate that simpler images are perceived more easily [Campbell, 14]. Figures 4.2 and 4.3 illustrate this concept.

The primary mode of these alerts is for the light to come on if a driver attempts to move into the adjacent lane while detection sensors indicate a vehicle is present. In most vehicles, the light remains solid until the lane change is completed or the hazard moves out of the blind spot.

Multiple Alerts

Newer technology includes dual modality of alerts, such as the icons like those indicated in the figure above used in conjunction with other methods: in-seat vibration

and audible warnings. These systems are only available in luxury models at the present time. Data could not be found to suggest whether having more types of alerts in-use simultaneously was better or worse than singular modes used individually.

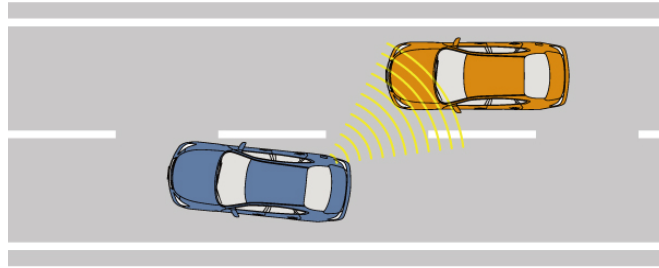


Figure 4.1 – Blind-spot Detection System [Nissan, 63]



Figure 4.2 – General Motors Blind-spot Alert System [GM, 30]



Figure 4.3 – Acura Blind-spot Alert System [Edmunds, 3]



Figure 4.4 - Image detection time through blind spot alert system comparison

Method

Participants

Participants in this study ranged in age from 16-82. There were 11 male and 5 female, and only 5 participants had experience driving a vehicle with blind spot alert before. Visual acuity was not measured prior to testing and could potentially skew interpretations about age if not considered.

Equipment

The experimental design involved the use of a 225 degree, 5-screen projection imaging driving simulator. The interior cockpit was configured to replicate a Ford Focus. DriveSafety Simulation Software was utilized to create the driving scenarios. Figures 4.4 and 4.5 illustrate the driving simulator scenario and cockpit.

Effort was made to offer maximum flexibility of experimentation with the blind-spot alert icon shape, size and color. To replicate the OSRV mirrors, 7 inch LCD monitors were used as they are of a comparable size and shape to original hardware but can be modified to easily change the style, shape or location of the icon.

New alert modality was accomplished using luminescence via an LED lighting strip that could be moved to various locations within the driving simulator to test optimal positioning. A design that requires no “labels” and is intuitively easy to use is one that affords a superior level of use. Studies have shown “red” to be a universally understood indicator of hazard alert that is successful to convey sense of urgency [Campbell, 14]. Red is also more easily discerned by older drivers [Pinheiro, 69]. Therefore, red LED lighting was selected as an alert modality that would afford ease of recognition by the driver. Figure 4.6 illustrates the old-style alert mode on the left and the new-style alert mode on the right.

Because of the high cost and time required to properly configure an eye-tracking system, a lower cost alternative was developed for this feasibility study. Response time was recorded manually with test subjects providing audible cues to indicate their recognition of the alert. While there is an expected “delay” between when the driver actually saw the alert and subsequently acknowledged it, this lag would be equal across all modalities tested and therefore would not hinder the usefulness of this data in comparing the effectiveness of different types of alert systems.



Figure 4.5 – Driving simulator cockpit with LCD monitors simulating outside rearview mirrors



Figure 4.6 – Simulated display of current alert mode (left) and Concept red-light alert mode (right)

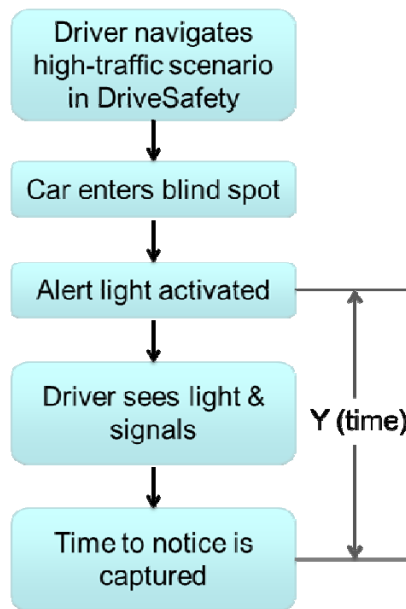


Figure 4.7 – Task sequence of events

Experimental Method

Test participants were given time to become familiar with the driving simulator before beginning the experiment. The flow diagram in Figure 4.7 outlines the process used. Each subject was allowed to drive as long as needed for the Simulator scenario to present at least 30 vehicles into a passing scenario on both sides of the vehicle. Data was captured regarding the type of alert mode used, the time required between onset of the alert and the driver taking notice of it. Data was also captured if the driver did not notice the alert. A brief survey was given regarding overall preferences between the two systems.

Using the conventional alert system, the disparity among age groups was observed, with the elderly drivers requiring longer time to recognize the alerts as shown in Figure 4.8. Elderly classification included ages 65 and above; Middle age group included ages 35-64. Young age group included ages 18-34.

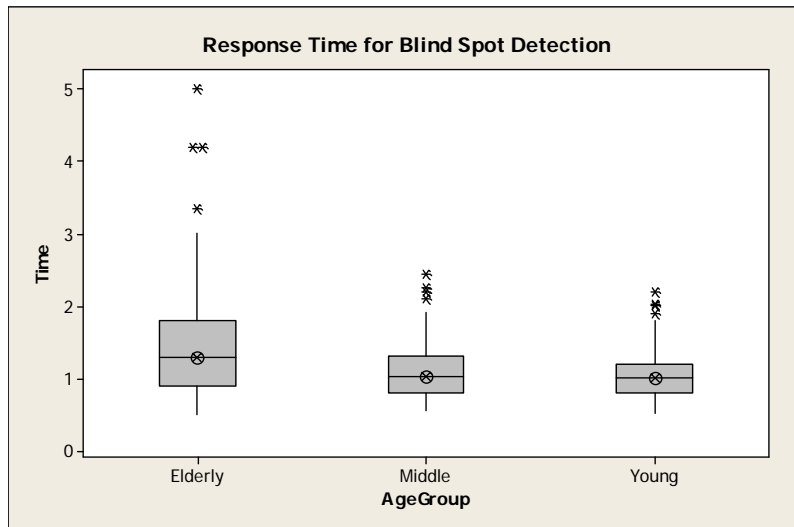


Figure 4.8 – Comparison between Age Groups

The comparison between the conventional design and the new alert system showed significant improvement with lower response times across the entire population as shown in Figure 4.9.

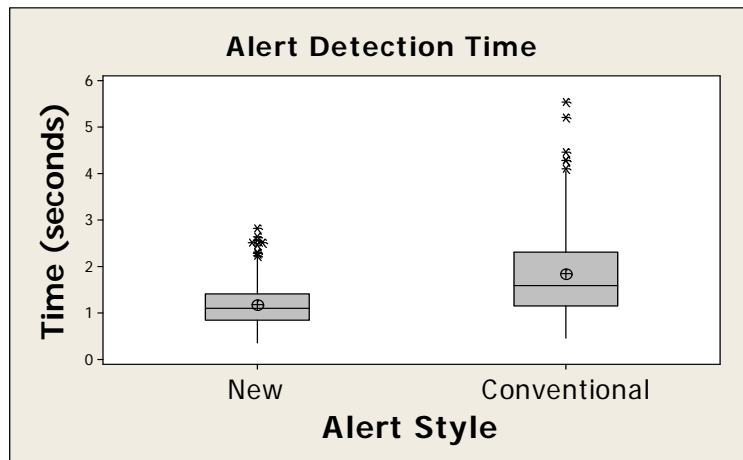


Figure 4.9 – Box plot of image detection time in quartiles with outliers for the conventional and new blind-spot alerts. Mean response times are shown as dots. A Mood’s Median Test reveals the proposed new style requires significantly less response time than a conventional alert ($p < 0.01$).

Results

Analysis of response times indicates that the new alert style was more easily recognized by all participants. The time required to detect the alert presented a non-normal data distribution; therefore, a Mood’s Median test was used to compare the groups. Significance was concluded with p -value < 0.01 (Figures 4.8 & 4.9). Over 50% of participants missed at least one alert presentation in the conventional method during the study, with some participants missing over 75% of the alerts presented in the conventional method. All participants (100%) indicated a strong preference for the new alert over the conventional one based on their ability to easily identify it while driving.

The long term effect of potential annoyance due to the brightness over time was not evaluated as part of this study.

Conclusions and future application within the research plan

This experiment offered insight into the opportunity for future work that would help in-vehicle information systems designers optimize hazard alert displays for people of all age groups and experience levels. These results were accomplished without the use of eye-tracking technology. Visual acuity testing of participants prior to testing may also provide insight into significance of this factor that may not correlate with age. In the later experiments, eye-tracking technology was utilized, as will be expanded in the chapters to follow, but ultimately it was determined to offer no better insight than that of the stopwatch method developed in this early experiment. Confirmation of the effectiveness of this manual measurement method in comparison to the eye tracking method is expanded in Chapter Four. Of primary relevance to its place in the broader research plan of this work, this preliminary experiment concluded the usefulness of driver reaction time as a relevant measurement for use in the comparison of competing visibility technology systems.

FIELD OF VIEW (FOV): 360 Degree Driver Awareness Study

To demonstrate how Clarity of View improves on published practices, I began by preparing an evaluation of Field of View as specified by the J1750 Procedure and as augmented by the ATA/TMC RP428a Procedure. In this example a new driver

awareness technology of an aspherical (multi-radius) style mirror is compared to a traditional planar + convex mirror combination as illustrated in Figure 4.10.



Figure 4.10 – Traditional Planar + Convex mirror as-installed (lower) & Prototype Aspherical mirror (upper)

The rationale for evaluation of the prototype aspherical mirror is based on success of similar designs in Europe. Currently, an aspheric (multi-radius surface) mirror is allowed in Europe, whereas it is not allowed in USA without the addition of the required 1:1 ratio “planar” style mirror currently mandated by the FMVSS 111 [FMVSS, 20].

Method for FOV Test

A Model 8100 International truck was utilized for this evaluation. Two alternate styles of rearview mirror systems were evaluated. Configuration A: The factory-installed planar mirror with a convex auxiliary mirror installed beneath it. Configuration B: A prototype aspherical mirror proposed for potential adoption on heavy vehicles. Aspherical mirrors present both a planar and convex radius on a single mirror surface, theoretically minimizing visual focus time while expanding field of view.

SAE J1750 Target Evaluation Method was employed to establish a grid of both near and far-zone targets constructed to the size and color guideline specification of 1.312 ft. diameter and 3.937 ft. height. The grid pattern was set with each cylinder point located in a 1.5 ft. x 1.5 ft. pattern, extending two truck widths beyond the vehicle on each side and one truck length fore and aft of the vehicle. An illustration of this method is provided in Figure 4.11.



Figure 4.11 – Experimental test site, truck and targets used for performance of SAE J1750 target evaluation method.

Figure 4.12 below is excerpted from RP428a and provides a more detailed illustration of the barrels used as targets for this test. Barrels used for this experiment were constructed according to the specified dimensions.

4.2 Standard Target Description

The standard target is described as a cylinder with three stacked sections, each 0.4m (1.312 ft) in diameter and in height. Each section is color-coded from top to bottom as red, yellow and green, resulting in a total cylinder height of 1.2 m (3.937 ft). See Figure 1.

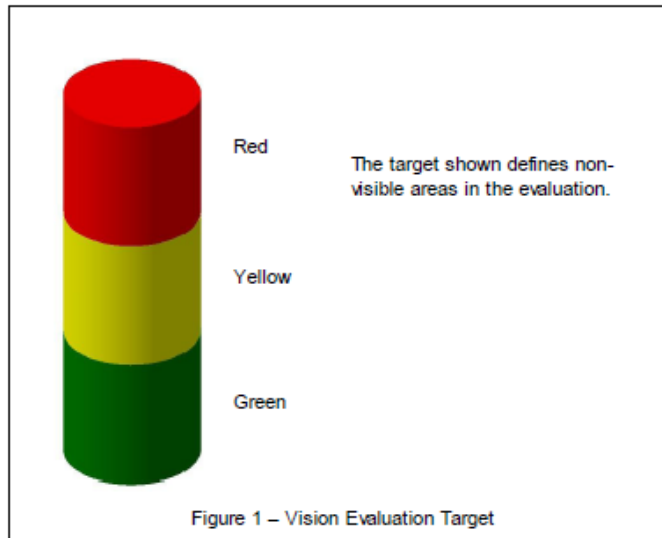


Figure 4.12 – Standard Target Barrel Construction Dimensions [SAEJ1750, 86]

Because fabrication of the barrels was both time consuming and expensive, a small batch of targets were constructed and then simply moved around to accomplish a full evaluation of all zones and locations specified by the J1750 test. Figure 4.13 provides perspective of the barrel orientation in relation to the truck's position.

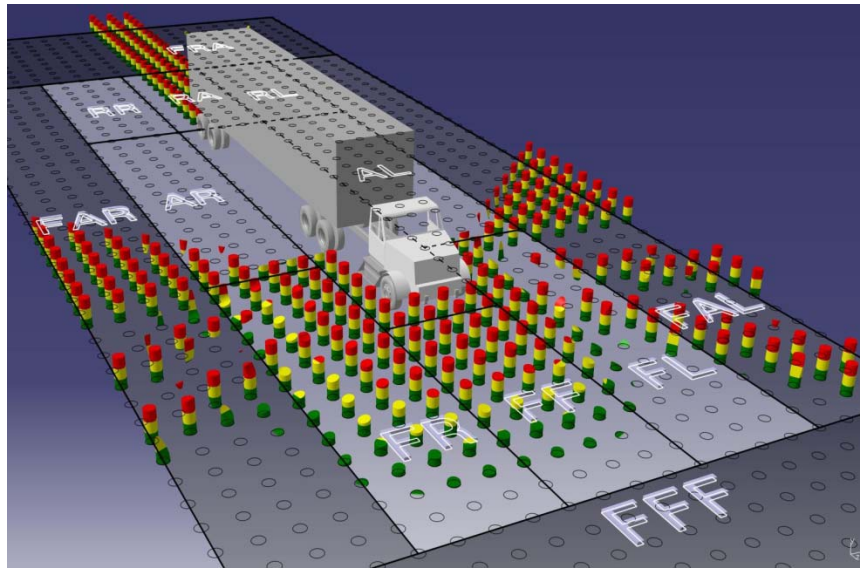


Figure 4.13 – Target layout illustration for J1750 test [SAEJ1750, 86]

Neither the J1750 or RP428a methods specify a requirement for anthropometric guidelines, so one was selected for consistency of the test results. A positioning device was used to control the driver's eye position at a consistent height to mirror that of the 50th percentile male truck driver, as defined by Klinghorn & Bittner [47].

Results for FOV Test

A graphical representation of the visibility is illustrated in Figures 4.14 – Planar + Convex auxiliary mirrors and 4.15 - the Aspherical Prototype Mirror. The large squares in red represent size of a small passenger car and smaller red squares represent the size of a motorcycle, as represented occupying the blind zone observed in each. The prototype aspherical mirror had no blind spot large enough to hide a vehicle or motorcycle.

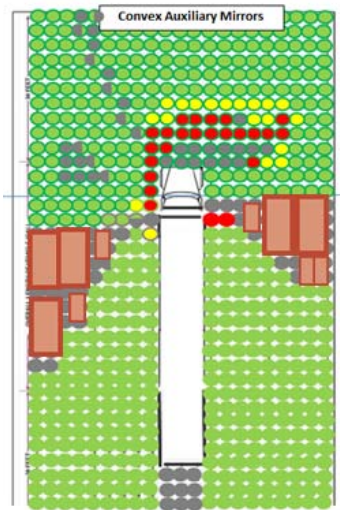


Figure 4.14 – Convex Auxiliary
Mirror test results



Figure 4.15 – Aspherical
Mirror test results

One of the primary goals of the TMC RP428a procedure [RP428a, 39] is to establish a reporting guideline for presentation of results. Using this method, the systems evaluated gave weighted scoring of: Aspheric Mirror: 96%; Planar + Convex Auxiliary Mirror: 85.4% and Planar Mirror alone: 32.1%. The weighted scoring is based on targets scored as: 0=Not Visible; 5=Partially Visible; and 10=Completely Visible. Figure 4.16 illustrates the scoring system.

		Aspheric Mirror			
Zone	Description	% Not Visible	% Partially Visible	% Visible	Weighted Score
AL	Adjacent Left	0	2	98	99
AR	Adjacent Right	2	13	85	91.5
RL	Rear Left	0	0	100	100
RR	Rear Right	0	0	100	100
FAL	Far Adjacent Left	0	0	100	100
FAR	Far Adjacent Right	9	9	82	86.5
					96.2
		Convex Auxiliary Mirror			
Zone	Description	% Not Visible	% Partially Visible	% Visible	Weighted Score
AL	Adjacent Left	9	3	88	89.5
AR	Adjacent Right	11	2	87	88
RL	Rear Left	0	0	100	100
RR	Rear Right	0	0	100	100
FAL	Far Adjacent Left	38	0	62	62
FAR	Far Adjacent Right	27	0	73	73
					85.4
		Planar Mirror			
Zone	Description	% Not Visible	% Partially Visible	% Visible	Weighted Score
AL	Adjacent Left	56	3	41	42.5
AR	Adjacent Right	85	10	5	10
RL	Rear Left	20	0	80	80
RR	Rear Right	40	0	60	60
FAL	Far Adjacent Left	100	0	0	0
FAR	Far Adjacent Right	100	0	0	0
					32.1

Result Scores based on TMC RP428a

**Aspheric Score:
96.2%**

**Convex Score:
85.4%**

**Planar Score:
32.1%**

Figure 4.16 – Result scores based on TMC RP 428a

The results of this test indicate a strong advantage of one system over the other as measured by field of view only, but it fails to capture the driver’s image detection time, gap acceptance accuracy, discomfort level due to glare or image distortion. The Clarity of View model adds these factors to the evaluation in a way that may be used not only to compare one system to another, but also to compare the effects of using multiple systems simultaneously wherein information overload may adversely affect driver response time and accuracy.

Each of these experiments were instrumental to establish the test methods for key objective criteria within the Clarity of View model.

CLARITY OF VIEW – TESTING EQUIPMENT AND METHODS

The expanded Clarity of View evaluation framework is an aggregate of multiple experiments and evaluations. The sections that follow describe the various testing apparatus and facilities, the driving simulator software and driving environment, the measurement technique employed for each category considered within the Clarity of View model, and the experimental scenario design.

Field of View

The J1750 target evaluation grid test layout has been established and described in the preceding section within the preliminary experiments. This procedure, along with the ATA/TMC RP 428 procedure were used. The truck and test-track grid used for that evaluation continues use in the same manner for the evaluation of additional test alternatives. The evaluation is simply an expansion of that preliminary experiment to add two additional alternatives to the preliminary field of view experiment already completed. Results are shared in the following chapter.

Glare Discomfort

The J1750 target evaluation grid test track is also used for the evaluation of glare discomfort. A direct measurement value was captured for the amount of light gathered from the reflection of each, using a hand-held light meter, but there was not sufficient correlation to the actual discomfort experienced by the driver using this method due to the impact of the angle of the light as it reached the driver being the primary influence on whether the light was considered acceptable or uncomfortable to the driver. Anthropometric positioning of the driver was maintained using the same fixture

methodology employed in the preliminary experiments for the field of view testing for consistency. This factor was measured by subjective pairwise comparison as a result. To gather data, the driver sat in position in the truck cockpit while the observer recorded their feedback. A passenger vehicle was positioned in the adjacent lane at the rear of the truck as though to simulate a vehicle approaching in the passing lane. The test was conducted during evening (dark) hours and lights of the oncoming vehicle were set to normal position (not high-beam). Results of this testing are presented in the following chapter. The illustration in Figure 4.17 below is an example of the pairwise comparison question presented to the evaluator for each alternative.

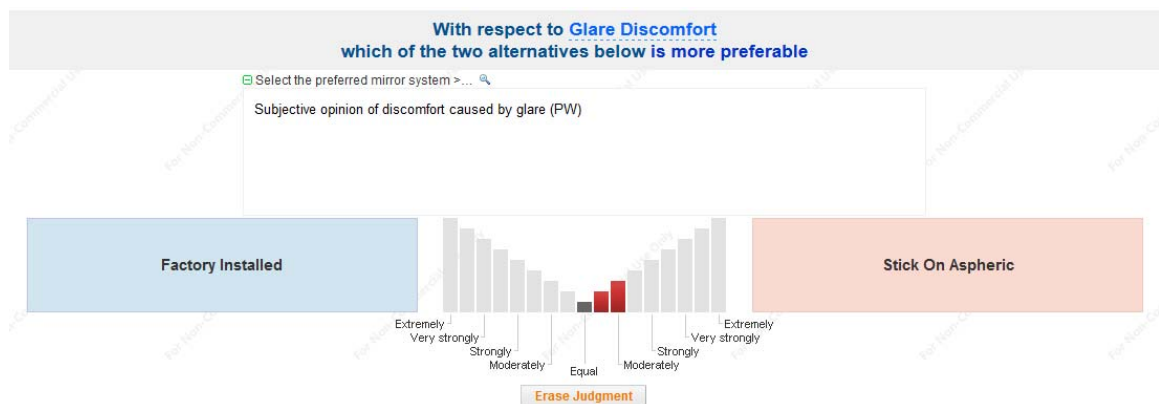


Figure 4.17 – Glare Discomfort Pairwise Comparison Evaluation Question Example

Cost & Reliability

Cost and reliability data were provided by that ATA/TMC organization and S.E.E. Technologies for each test alternative provided. The factory installed option was considered to have zero incremental cost. It was also assumed to have reliability equal to life-of-the-vehicle as it includes no parts that could fall off (such as stick on) or electronic components that could fail during use. Each of these factors was given a simple scoring

based on categorical measure since all were prototypes without exact final pricing known. Figures 4.18 & 4.19 below illustrate the rank categorization of each factor.

Intensity Name
<input checked="" type="radio"/> No incremental cost · zero cost (factory installed as-is)
<input type="radio"/> Mid-range cost · approx 0-\$500 per vehicle
<input type="radio"/> High cost · over \$500 per vehicle

Figure 4.18 – Categorical rating of COST

Intensity Name
<input checked="" type="radio"/> Lasts forever · factory installed assumption
<input type="radio"/> Mid-range reliability · limited moving parts
<input type="radio"/> Lowest reliability · electronic based systems

Figure 4.19 – Categorical rating of RELIABILITY

Reaction Time & Image Distortion

Both image distortion perception and driver reaction time were values anticipated to vary between drivers of varying ages and experience levels. For cost and safety assurance, performing these evaluations in the controlled environment of a driving simulator was the best option. Testing unknown technologies on the open highway is a potentially risky and un-safe endeavor and is one of the primary motivations for creating this driving simulator test apparatus. In order to provide a realistic driving scenario, I have developed a test apparatus designed in such a way to replicate the heavy truck driver's environment as closely as possible in a controlled setting.

Driving Simulator

A driving simulator cockpit was constructed that replicates the driving environment of a typical heavy truck, the 8100 Model International. The cockpit was constructed from a donated truck cab. Its fabrication was accomplished through an exchange partnership with Greenville Technical College Automotive Technology program. They provided the body work in exchange for donation of the truck's engine and chassis for use in their education program. A photo of the cockpit both before and after is provided below in Figures 4.20 and 4.21.



Figure 4.20 – Donated Truck Cab – Before



Figure 4.21 – Truck Cab - After

I instrumented the cockpit with Logitech Version G2 driving controls to operate within the DriveSafety software environment. A custom-designed mounting bracket was required to position the steering controls at the same height and angle as the factory configuration. Factory-original pedals were removed from the cockpit and the Logitech pedal assembly installed was into the floor. This configuration is illustrated in Figure 4.22.



Figure 4.22 – Truck Cockpit Steering Controls

Prior to this study, the CU-ICAR Creative Car Laboratory was already configured with a 225-degree set of 5-display screens for use with the DriveSafety Driving Simulator Software. An illustration of the completed heavy truck cockpit within this configuration is shown below in figure 4.23 – Heavy Truck Cockpit in Creative Car Laboratory.



Figure 4.23 – Heavy Truck Cockpit in Driving Simulator

In order to facilitate the evaluation of rearview mirrors with images coming from behind, it was necessary to expand the Creative Car Laboratory (CCL) Driving Simulator to provide a full 360-degree driving environment. This required the addition of three new DriveSafety computers, projectors, and monitors along with the configuration of each. The original five (5) projectors installed in the CCL were Projection Designs Model F22-GP2 1920 x 1080p resolution with up to 190 Hz scan frequency donated from Toyota Racing Development's driving simulator and illustrated in Figure 4.24.



Figure 4.24 – Creative Car Laboratory Simulator existing five projectors

For the slow speeds anticipated for this study and the image quality provided by DriveSafety software, this level of scan frequency was not necessary for the 45 mph scenario of the heavy truck mirror evaluation. To accomplish the best image quality at an affordable cost, BENQ Brand Model W with a 1920 x 1080 resolution and 60Hz scan frequency was selected for the 3 projector expansion.



Figure 4.25 – Three new BENQ projectors added

Projection screens were chosen to match those already in place and installed for easy retraction and ease of access into the simulator environment both by test subjects and any future cockpit apparatus that may be desired for use in the future. Three (3) new DriveSafety software computers were purchased and configured to mirror the existing environment rendered by the five screens already in place to accomplish a full 360-degree wrap around view of the truck driver's environment. The Z-height of the driver was raised to give the driver the same view that a truck driver would experience in relationship to other cars on the highway. The DriveSafety computers are illustrated in Figure 4.26.

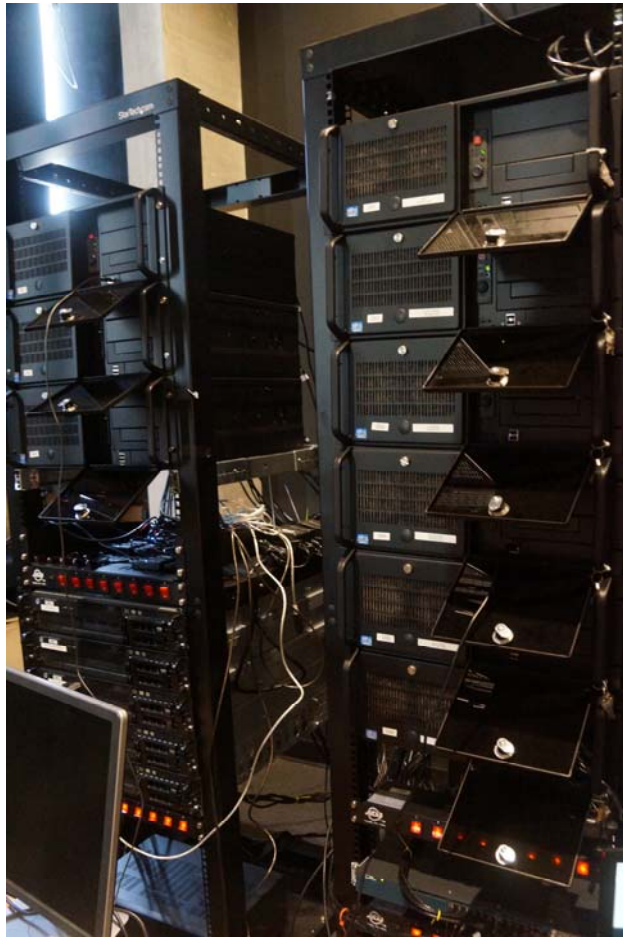


Figure 4.26 – DriveSafety Computers

The simulated driving world was configured in the HyperDrive application and gave the driver an “open-road” environment of 3-lane highway and moderate traffic levels consisting of a variety of other vehicles, including cars, other heavy trucks, service vehicles, motorcycles, and even the occasional bicycle. The driving scenario looped over approximately one hour time frame and was randomly generated to avoid any potential for the driver to “learn” the environment and anticipate oncoming traffic patterns. Figures 4.27 - 4.30 illustrate the typical driving scenes.



Figure 4.27 – Scene from drivers windows – forward left of the driver position



Figure 4.28 - Scene of approaching traffic – rear left of the driver position



Figure 4.29 - Scene showing image in full 360 degree view of the driver



Figure 4.30 – Scene from driver's view of rearview mirror with oncoming traffic approaching in passing lane

Visibility Technology Alternatives

Four different visibility systems were evaluated as part of this study. They were loaned by S.E.E. Technologies, a privately-held company that focuses on development of technologies specifically aimed at the heavy vehicle industry. Each was a mirror-style assembly. These systems were:

A. Factory – Installed

The factory-installed mirror is the one originally installed by the OEM manufacturer of the truck. It consists of a planar (flat) surface of dimension 15 inches x 6.5 inches mounted above a 7.5 inch diameter convex mirror.



Figure 4.31 – Factory-Installed Mirror

B. Aspheric

An aspheric surface is one that unlike a traditional convex mirror that has a single, consistent radius of curvature, has a curvature radius that is “flatter” across the primary surface of the mirror and more steeply curving around the outer edges. This renders an image in the central part of the mirror that offers minimal distortion, but gains the added visibility from the perimeter locations that yields an overall larger field of view. FMVSS Regulation 111 requires a planar mirror of minimum reflective surface dimension 323 cm² be used on vehicles traversing federal highways. This mirror, as tested, does not meet this requirement without some modification. Technically, it could not be utilized as-is, but evaluation of its actual performance under this model will give further confidence to industry decision makers as to whether it is suitably viable for further development.



Figure 4.32 – Aspheric Mirror

C. Split-Style

This split style mirror is actually an evolution of the aspheric mirror presented as alternative B. By combining a fully aspheric mirror with a FMVSS Regulation 111 legal sized planar mirror in a two-part combination assembly, an effort was made to accomplish the benefits of the aspheric style mirror while still meeting the legal requirements. Further explanation in the results section will expand on the results, but errors in the manufacturing execution of this concept led to lower than expected performance results.



Figure 4.33 – Split-Style Aspheric Planar Combo Mirror

D. Stick-On Aspheric

This design presents the aspheric style mirror surface in a small, attachable version mounted below the factory-standard planar in a similar configuration to that of the factory-installed convex combination assembly. Because of concerns regarding the potential impact of distortion on driver perception and usability, this particular mirror has not been used by commercial fleets even though it actually considered a legal option.



Figure 4.34 – Stick-On Aspheric Mirror

Eye Tracking

An SMI-brand, 30 Hz, binocular eye tracking device was used for this study. It was loaned by Intel for use in this driver-interface evaluation study. The eye tracking device is worn as goggles, thus enabling the driver to move naturally inside the vehicle as they would in a normal driving scenario. This equipment configuration provides a flexible apparatus for evaluating various user-interface systems in a dynamic driving scenario.



Figure 4.35 – SMI Wearable Eye Tracking Device

This device, like most modern eye-trackers, utilizes near-infrared technology along with high-resolution cameras to track gaze behavior. The near-infrared light is

directed toward the center of the eyes (pupil) causing visible reactions in the cornea (the out-most optical element of the eye), which are tracked by a camera [iMotions, 43].

BeGaze software was used to analyze the resulting video output data collected by the eye tracking device. An auxiliary time capture device was used in conjunction with this apparatus for time capture during the experiments. Together, these methods provided data of the driver's reaction time required to detect images in the mirrors.



Figure 4.36 – BeGaze Software used for video-capture analysis of eye tracking data

The auxiliary time capture apparatus was required as augmentation of the eye-tracking technology to compensate for weaknesses of simply using eye-tracking alone. The eye-tracking is capable to measuring various elements that are indicators of visual attention, such as time-to-fixation, number of glances, number of blinks, etc. However, where it falls short in a scenario such as this one is its inability to measure cognitive perception. For example, the “area-of-interest” in this activity can be defined and marked

using the BeGaze software as that of the outside rearview mirror. Two problems arise. Due to the dynamic nature of the simulated event, the area of interest moves in and out of the actual field of view of the video capture. As shown in the photo above, the video capture is only that of the driver's immediate forward-view. As the area of interest is defined around the mirror, it will "move" with the driver's head as it appears on the screen, and consequently must be manually modified in a frame-by-frame method in order to function properly relative to the data-statistics calculations of time-to-fixation in those areas of interest as well as toward number of glances in the area of interest. This an expensive and time consuming option to perform on the video captures of multiple test subjects, each recording video for 2 or 3 hours each. Analysis of even five minutes of video in this manner can take up to a half-hour. Additionally, the measurement of a "fixation" toward the area of interest does not necessarily indicate perception of a vehicle in that area of interest. The driver could fixate a gaze within the area of interest of the outside rearview mirror, but could be looking at the image of a tree or road sign without acknowledgement of the image as that of an oncoming vehicle. For this reason, the drivers were asked to give verbal indication of their perception of an oncoming vehicle, regardless of whether they felt they were clear to overtake the vehicle.

An attempt was made to measure driver perception using additional biometric sensor technology that may indicate heightened levels of cognitive arousal indicative of perception. The eMotiv EPOC EEG brainware monitor was employed in an attempt to capture data that could be correlated to image perception, but it was ultimately not

capable of offering a signal strong enough to be reliable in this dynamic scenario. Additional work would be necessary in order to incorporate such methods.

SIMULATOR-BASED TESTS

Before participation, each test subject was asked to read and sign informed consent authorization acknowledging their understanding of potential risks of participation that include primarily the sensation of motion-sickness. Drivers were encouraged to immediately alert the test administrator if they felt uncomfortable at any time. Both distortion and reaction time were measured through the driving simulator activities.

Distortion Perception

Distortion perception was captured via pairwise comparison evaluation. Figure 4.37 illustrates the evaluation question format presented to each driver.

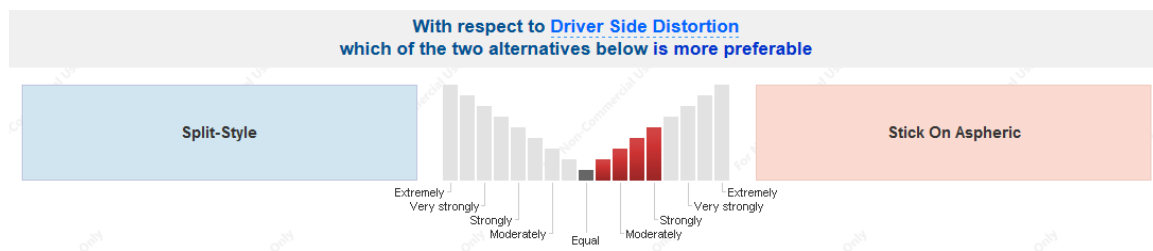


Figure 4.37 – Distortion Perception Evaluation Pairwise Comparison

Driver Reaction Time

In preliminary experiments, it was concluded that driver reaction time was a useful measurement for the comparison of user interface systems in the vehicle. Faster reaction times to identify images in a mirror system are hypothesized to be an indicator of

a better-performing system. The more quickly the image is correctly identified, the more quickly the driver can correctly react to that image and make the correct lane-change decision. Quantitative data was collected for the measurement of this reaction time. Qualitative observations were also recorded regarding any potential near-miss accidents made in the lane-change process. For the comparison of the four test mirror alternatives, the following sequence was followed and repeated for each mirror system.

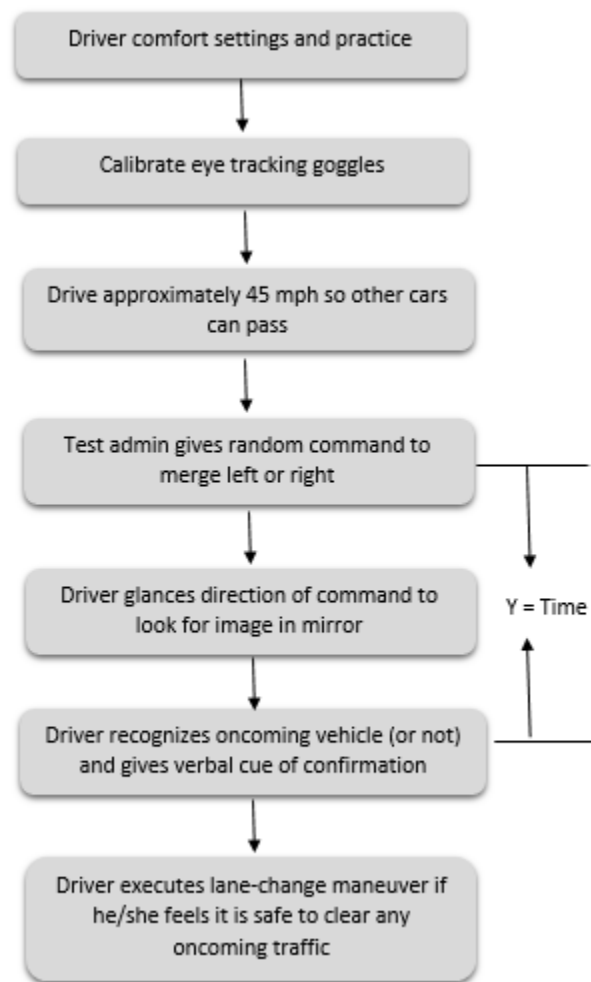


Figure 4.38 – Driver Reaction Time measurement sequence

Given the limitations of the eye tracker, the primary data capture tool employed for this testing was the auxiliary time capture device. Using the frame-by-frame video analysis method was very time consuming and ultimately gave no better data than that of the simple method. A correlation study was performed on a small sample of data as confirmation. This is an acceptable method of measurement system analysis where data is of a destructive nature (i.e. it cannot be replicated for repetition). It can be seen here by the p-value = 0.000 (≤ 0.05), that the data can be concluded as having correlation:

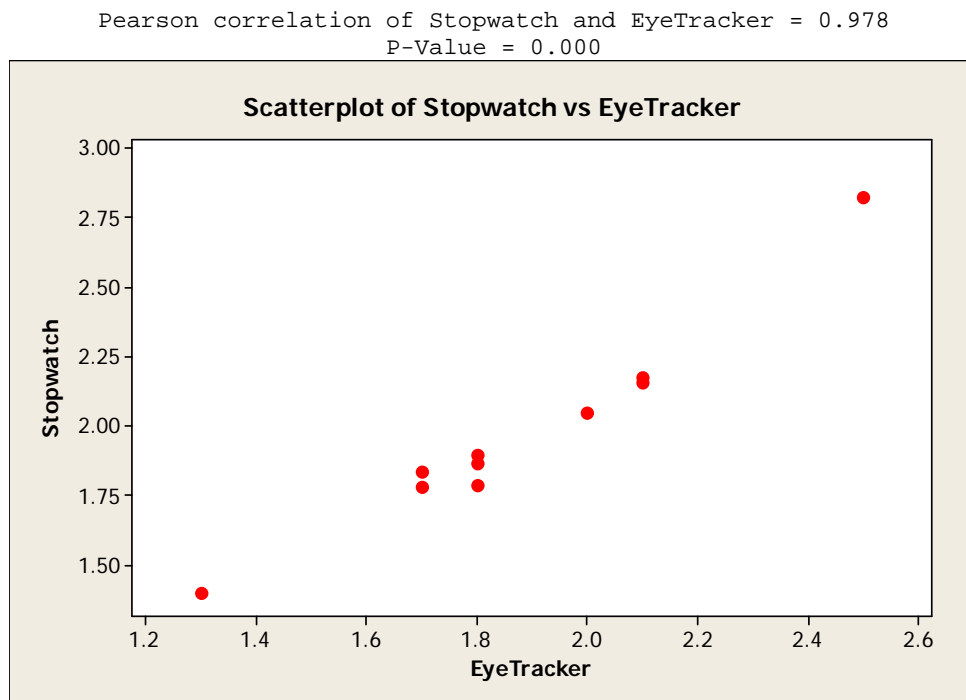


Figure 4.39 - Measurement system analysis of stopwatch method

Gap Acceptance Accuracy

Initially, I had intended to include Gap Acceptance Accuracy as a measure within the model. This factor was removed from the model for two primary reasons. It is difficult to judge the impact of a near miss using only visual observation alone. Specific

programming of the Drive Safety software is feasible to record data if/when there is “contact” made between the vehicles in the driving scenario, but such programming was not budgeted for this project. Future work would benefit from incorporating this feature. To measure it by visual observation alone was unreliable. Further, it is also assumed that any rational test participant, whether expert or simply driver category, would rate any system completely unacceptable if it was observed to allow a potential accident to occur. There was not a good way to quantify or rate possible near-miss events. For this reason, observation data was gathered for qualitative assessment of gap acceptance only, and it was not included in the Clarity of View final evaluation framework.

The dynamic driving simulator apparatus that has been developed for the Clarity of View framework is superior to methods attempted in the past for similar evaluations, as is supported by the call to action made by NHTSA in a 2008 study performed on the evaluation of driver performance and acceptance of aspheric mirrors in light vehicle applications. This study called for on-road study as an improvement to their static-only evaluations and those similar evaluations performed by others [(Mazzae, 57), (Flannagan, 23), (Jennes, 44), (Way & Reed, 99)]. This apparatus is a safer alternative to on-road testing of unproven new technologies by providing the dynamic driving simulation evaluation of images approaching from behind without the risk of real-time on-road driving.

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CHAPTER FIVE

EVALUATION AND RESULTS

The Clarity of View evaluation framework depends on data collection from several tests that have been described in preceding chapters. This chapter is dedicated to describing the test participants themselves and the process used for the sample sizes for the experimental design. I also present the results from each category evaluation, the priority weightings established by the supra-decision maker, and the aggregation of these inputs into the Clarity of View model for a final ranking of the test alternatives.

TEST PARTICIPANTS

Test subjects were recruited to include both inexperienced drivers with no truck driving experience along with trained commercial vehicle licensed (CDL) drivers. A total of 17 participants were included. Of those, nine (9) were licensed CDL drivers with driving experience ranging from 3 years to over 40 years. Of the remaining inexperienced drivers, 2 were not able to complete the full experiment due to motion sickness. Their results were not included in the evaluation. Of those who completed the full experiment, 13 were male and 2 were female. Southeastern Freight Lines operates a fleet services depot within two miles of the driving simulator laboratory and generously offered their CDL drivers for participation in the study. The drivers were not paid by Clemson as part of this study, but each of the Southeastern drivers was being compensated for his time by being allowed to participate in the study while still on the clock. Other inexperienced drivers all participated free of charge, with each test subject spending approximately three hours in the lab to complete the testing.

Data was collected on age, gender, years of driving experience, and vision. An attempt was made to quantify peripheral-vision capability of drivers using a software packaged called “Vision Builder.” Because of the extended practice time required for a user to become proficient using the test software, it was determined not to be feasible for use in this particular study. Older users had a more difficult time executing the video-gaming style controls than did younger users. This was perceived to be more due to lack of experience with the computer-keyboard based controls than a factor of their actual visual capabilities.

SAMPLE SIZE

The sample size of test participants was given careful consideration. The driver reaction time measurement testing performed in the simulator requires a three hour time commitment from each participant, so finding willing volunteers for the study can be a challenge. A survey of literature indicated that while there is a wide array of opinion on the topic of sample size in usability studies, the general consensus was 10 +/- 2 as a general range, with variations depending on the actual nature of the study [(Macefield, 54), (Schmettow, 80), (Nielson, 62), (NASA, 61), (Hwang & Salvendy, 42), and (Blink, 9)]. Because of the risk that drivers may not be able to complete the full study due to motion sickness, a slightly higher number was targeted as a safeguard to ensure a minimum of 12 was obtained with full evaluation results. The literature cites multiple cases confirming this number toward evaluations where users are seeking to identify or discover usability issues, such as for this evaluation of distortion perception. However, not all of the measurements undertaken within the Clarity of View evaluation model were

presented to multiple users for consideration. Those involving direct measurement values such as cost or reliability are scored via a tiered category approach and do not vary by participant. Field of View and Glare Discomfort were measured by expert-evaluator only and not presented to multiple participants. Distortion perception and driver reaction time was measured on all test participants. The factor of driver reaction time is one of considerable interest for further discussion due to the continuous nature of the measurement data

In an effort to conclude whether there are significant differences between the performance of the different alternatives, this data must be first concluded to be significant before it is entered into the decision modeling framework. Based on the nature of this data, a singular measurement of driver reaction time with a particular test alternative from even a large population of test subjects would not yield sufficient confidence level to simply take that singular value and enter it into the AHP framework as the value for that is representative for that alternative. Several measurements should be taken to gain confidence. The greater the sample size, the greater the confidence in the data, but with increased samples comes higher costs due to increased time commitment. At some point, there are diminishing returns where additional samples do not add additional value. An effort was made to optimize the sample size of measurements taken for driver reaction time for each test participant.

With four different test alternatives, the end goal is to conclude if there is any significant difference between the driver's reaction times observed for each. This conclusion will yield confidence that the data being entered into the Clarity of View

decision framework is sound. Such a comparative analysis is essentially a hypothesis test, with the hypothesis that Alternative A will perform better than Alternative B and/or that at least one of the test alternatives is significantly different from the others. For the case of these reaction times, the earlier studies indicated that typical reaction times may range from 0.5 seconds up to 5 seconds and present non-normal distributions. For this expectation, a non-parametric evaluation of differences of median values using the Mood's Median Test becomes a more relevant comparison tool than that of the more commonly known 2-sample t-test comparing differences in mean values that is suited only for normally distributed data. The Mood's Median test also facilitates comparison among more than 2 dataset categories. With this, the hypothesis tests are established to determine if the median time of alternative A is different than the median time of alternative B. The null hypothesis (H_0) is then established as there being no difference between the alternatives. The alternate hypothesis (H_1) is that there is a difference between them. If there were no difference between the alternatives, then the data would not likely be relevant for inclusion in the Clarity of View decision modeling framework. Rejecting the null hypothesis is a conclusion that there is no difference between the alternatives and that any differences observed are based on random chance.

It is not feasible to consider absolute 100% certainty in virtually any test. The results can be evaluated in terms of probability level that it is safe to reject the null hypothesis, with that probability being expressed as a p-value that the observed results are due to chance. A p-value of 0.1 is sometimes used, but a preferable level for most studies is 0.05 or a $\leq 5\%$ probability that the results are due to chance. This is also

referred to as the alpha (α) level. The Mood's Median test provides two statistics that may be used to test the equality of medians: the chi-square statistic and the p-value. The chi-square statistic alone is not particularly informative, but is used to calculate the p-value. If the p-value is less than the pre-determined alpha level value, then it can be concluded that two or more of the medians are significantly different. If the p-value is larger than this alpha level, then the medians are not significantly different. The lower the p-value the stronger the confidence in the significance. Hypothesis tests can fail due to two types of errors:

- Type 1 error: rejecting the null hypothesis when it is actually true (a false positive)
- Type 2 error: failure to reject the null hypothesis when it should be rejected (a true effect existed, but was not detected by the test).

The probability of making a type I error is called alpha (α) and is sometimes referred to as the level of significance. A commonly used example for explanation of hypothesis test errors is that of the courtroom case. With the type 1 error, the guilty go free, with the type 2 error, an innocent person is convicted. It is common to make every effort to avoid the type 2 error.

Relating this back to the topic of sample size: the larger the sample size, the stronger the significance level. It is desirable to test only as many samples as will be needed to conclude significance of the data. In this test scenario, I had the benefit of the preliminary evaluations showing significance of the data with a similar sample of test subjects. One simplistic option would simply be to "keep testing more subjects until test

significance is obtained,” but this is a potentially costly and time consuming proposition. To avoid this, a power analysis was performed on the basis of those earlier test results as a way to predict the minimum sample size needed to produce statistical findings. This should not be confused with a final post-hoc power analysis, but is simple a useful way to ensure that excessive time is not used in testing more samples than necessary and also to avoid running multiple test subjects through the study only to realize that more measurements were needed to establish significance.

In the preliminary testing illustrated in the earlier section of this chapter, a similar scenario of data collection of driver reaction times was used. That data indicated a standard deviation of 0.77 seconds. With this, using Minitab16 software, a *priori* (before testing) power analysis are obtained:

Power and Sample Size

One-way ANOVA

Alpha = 0.05 Assumed standard deviation = 0.77

Factors: 1 and Number of levels: 4

Maximum Difference	Sample Size	Target Power	Actual Power
1	18	0.9	0.903419

The sample size is for each level.

Figure 5.1 – Pre-Test Power analysis summary

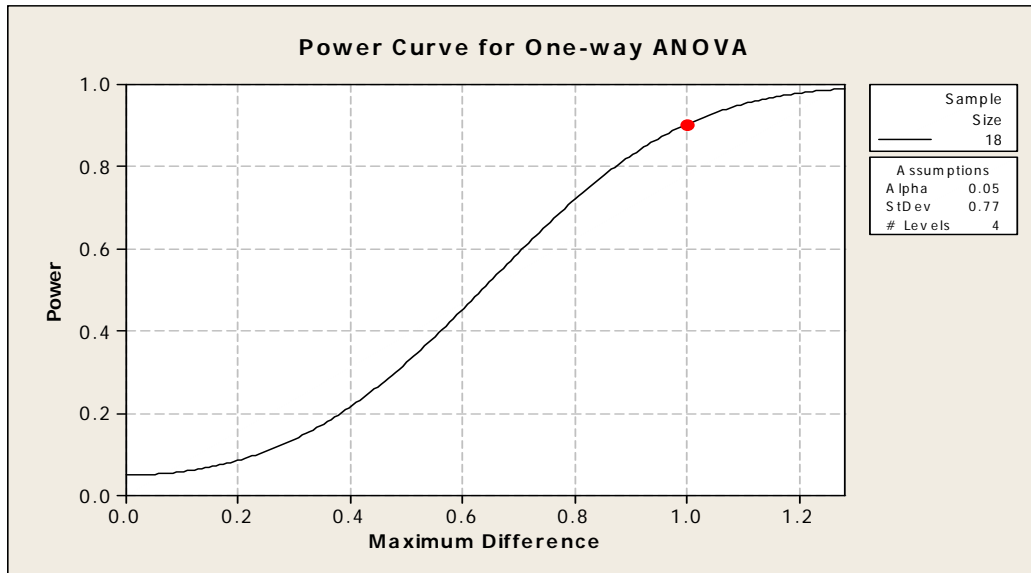


Figure 5.2 – Pre-Test Power Curve illustration

Based on this analysis it could be determined that at least 18 samples per factor would be sufficient to yield a test power of over .90. This analysis can also be performed post-testing for added confidence.

EVALUATION RESULTS FOR EACH CLARITY OF VIEW FACTOR

Field of View

Field of view results as measured by the J1750 target evaluation method and scored using the ATA/TMC RP429a test protocol. Chapter four description of the test methodology performed for the first two test alternatives, the planar and convex auxiliary combo mirror and the aspherical mirror, are both represented in Figures 5.3 and 5.4 below.

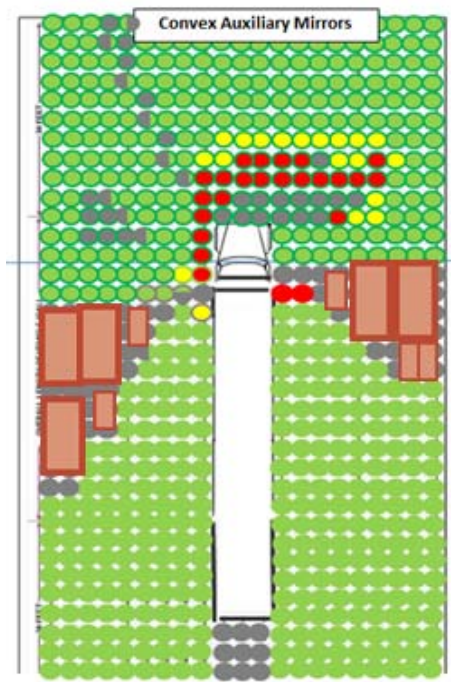


Figure 5.3 –Planar with Convex Auxiliary Mirror

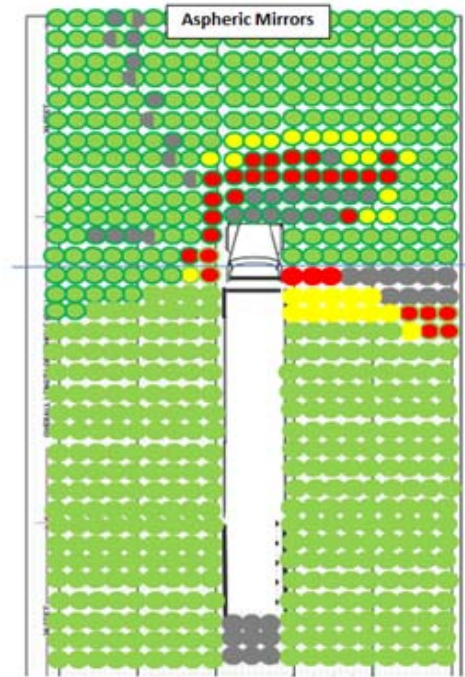


Figure 5.4 – Aspheric Mirror

(Also referred to as: Factory-Installed)

The next two test alternatives were evaluated in the same manner and results illustrated below in Figures 5.5 and 5.6.

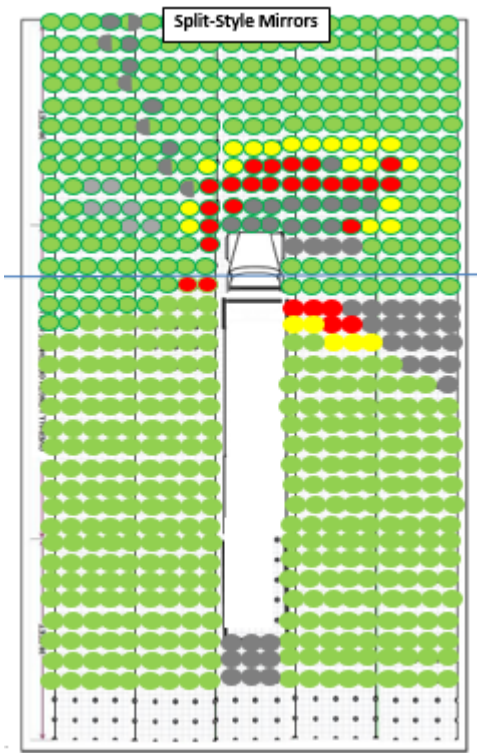


Figure 5.5 – Split Style Mirror

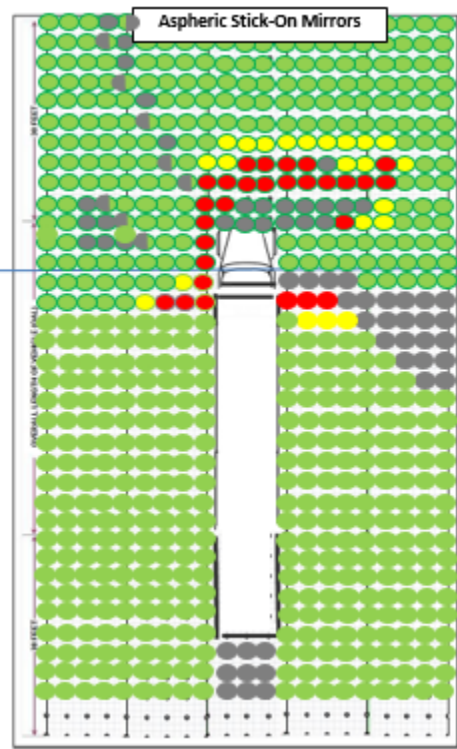


Figure 5.6 – Aspheric Stick On Mirror

The RP428a procedure provides the scoring protocol and results for each alternative are illustrated in Figure 5.7. This is the current industry status-quo methodology available for evaluating potential new mirror technologies today.

Aspheric Mirror					
Zone	Description	% Not Visible	% Partially Visible	% Visible	Weighted Score
AL	Adjacent Left	0	2	98	99
AR	Adjacent Right	2	13	85	91.5
RL	Rear Left	0	0	100	100
RR	Rear Right	0	0	100	100
FAL	Far Adjacent Left	0	0	100	100
FAR	Far Adjacent Right	9	9	82	86.5
				RP428a Score	96.2

Planar + Convex Auxiliary Mirror					
Zone	Description	% Not Visible	% Partially Visible	% Visible	Weighted Score
AL	Adjacent Left	9	3	88	89.5
AR	Adjacent Right	11	2	87	88
RL	Rear Left	0	0	100	100
RR	Rear Right	0	0	100	100
FAL	Far Adjacent Left	38	0	62	62
FAR	Far Adjacent Right	27	0	73	73
				RP428a Score	85.4

Planar Mirror					
Zone	Description	% Not Visible	% Partially Visible	% Visible	Weighted Score
AL	Adjacent Left	56	3	41	42.5
AR	Adjacent Right	85	10	5	10
RL	Rear Left	20	0	80	80
RR	Rear Right	40	0	60	60
FAL	Far Adjacent Left	100	0	0	0
FAR	Far Adjacent Right	100	0	0	0
				RP428a Score	32.1

Split-Style Mirror					
Zone	Description	% Not Visible	% Partially Visible	% Visible	Weighted Score
AL	Adjacent Left	0	5	95	97.5
AR	Adjacent Right	0	3	94	95.5
RL	Rear Left	0	0	100	100
RR	Rear Right	0	0	100	100
FAL	Far Adjacent Left	0	0	100	100
FAR	Far Adjacent Right	17	6	77	80
				RP428a Score	95.5

Aspheric Stick-On Mirror					
Zone	Description	% Not Visible	% Partially Visible	% Visible	Weighted Score
AL	Adjacent Left	0	9	91	95.5
AR	Adjacent Right	10	9	81	85.5
RL	Rear Left	0	0	100	100
RR	Rear Right	0	0	100	100
FAL	Far Adjacent Left	0	0	100	100
FAR	Far Adjacent Right	30	0	70	70
				RP428a Score	91.8

Figure 5.7 – Results of Field of View Test

Every proposed new alternative registers superior results over that of the current factory-installed standard planar mirrors. It is easy to see how industry may quickly jump to adopt any one of these potential new alternatives based on these results. These scores were entered into the Clarity of View model as direct-value measures with summary given as follows in Figure 5.8.

	Alternative Name	[All Participants] 22 participants
1	Factory Installed	85.40%
2	Aspheric	96.20%
3	Split-Style	95.50%
4	Stick On Aspheric	91.80%

Figure 5.8 – Field of View Ratings
(Shown in un-normalized format.)

On the basis of Field of View (the current industry standard evaluation methodology), the Factory-Installed mirror scores the lowest and the Aspheric style mirror is preferred over all other models.

Glare Discomfort

Using the Expert Choice software and the Clarity of View evaluation framework model, Glare Discomfort was measured via pairwise comparison method. Using the scoring method indicated in the preceding chapter, results for this category singularly were summarized in Figure 5.9.

	Alternative Name	[All Participants] 22 participants
1	Factory Installed	13.64%
2	Aspheric	55.58%
3	Split-Style	4.89%
4	Stick On Aspheric	25.89%

Figure 5.9 - Glare Discomfort Ratings

(Shown in normalized format. All values add up to 100%.)

On the basis of glare discomfort, the Aspheric style is preferred over other models.

Cost and Reliability

The analytic hierarchy method is founded on ratio-based measurements. Here, the Expert Choice software accommodated the tiered-categorical rating system I established and converted those ratings into a ratio-based format for consistency with the other factors. The cost of the factory installed mirror was considered as zero, and its reliability assumed to be the lifetime of the vehicle, so naturally it is preferred over other options. The split-style mirror system incorporated an electronic component of perimeter lighting, making it the least preferred option both from a cost and reliability standpoint.

	Alternative Name	[All Participants] 22 participants
1	Factory Installed	100.00%
2	Aspheric	34.53%
3	Split-Style	14.72%
4	Stick On Aspheric	34.53%

Figure 5.10 – Cost Ratings

(Shown in un-normalized / percent of maximum format.)

	Alternative Name	[All Participants] 22 participants
1	Factory Installed	100.00%
2	Aspheric	100.00%
3	Split-Style	34.53%
4	Stick On Aspheric	34.53%

Figure 5.11 – Reliability Ratings

(Shown in un-normalized / percent of maximum format.)

Distortion Perception

All test participants had an opportunity to provide feedback on their perception of distortion in each test mirror alternative. After nearly three hours of driving with the four options, each had ample time to observe these mirrors in a realistic driving scenario. The feedback on distortion was collected in a pairwise comparison subjective format as described in Chapter Four. The results are summarized below in Figure 5.12.

	Alternative Name	[All Participants] 22 participants
1	Factory Installed	42.79%
2	Aspheric	23.47%
3	Split-Style	7.06%
4	Stick On Aspheric	26.68%

Figure 5.12 – Distortion Perception Ratings

(Shown in normalized format. All values add up to 100%.)

These results are not surprising, as the primary reason why the new aspheric-style mirrors have not been adopted by industry is the perception that drivers would object to the distortion. While initially this may be true, as can be concluded from these ratings, studies performed at the University of Michigan (UMTRI) indicate that on passenger

cars, drivers eventually came to prefer aspheric styles over time, with most drivers scoring them favorably after approximately four weeks of use [Flannagan, 23]. In this research, I am seeking to determine whether driver perception of distortion has any effect on the driver's reaction time or if the driver(s) perform just as well, regardless of their perception of distortion.

Reaction Time

In accordance with the sequence flow diagram illustrated in the preceding chapter, data for driver reaction time was collected on both the driver and passenger sides of the vehicle, ten samples each side for a total of 20 samples per test alternative. Four alternatives were evaluated. The results were analyzed for differences between sub-groups or categories. Significant differences between the test alternatives were confirmed, giving credibility to the data for entry into the Clarity of View model framework. Because of the granular nature of this data in comparison to other objective factors, confirmation of differences between the categories helps the user of the Clarity of View model to feel confident that this data element will provide enough distinction between alternatives to add value to the model. For example, if all test alternatives measured a mean value of equal reaction time of 2 seconds, then there would not be added value to include it in the model. The descriptive statistics below illustrate this analysis and the conclusions of significance of this data.

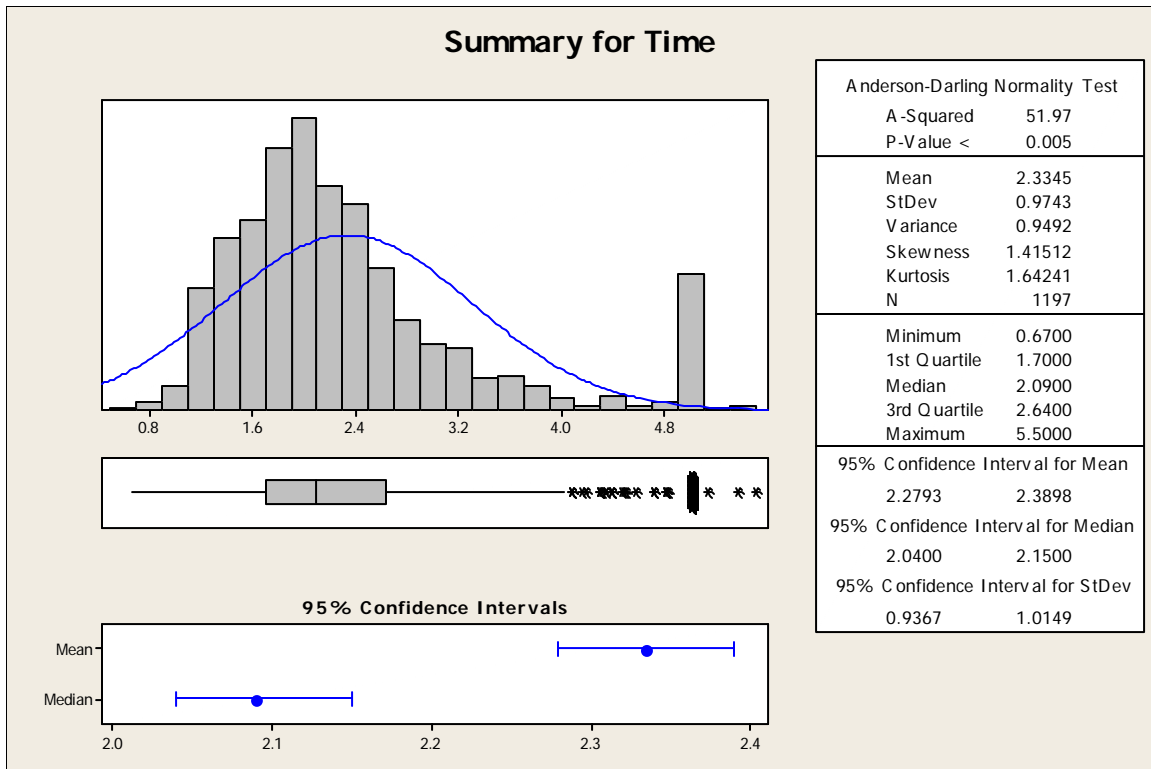


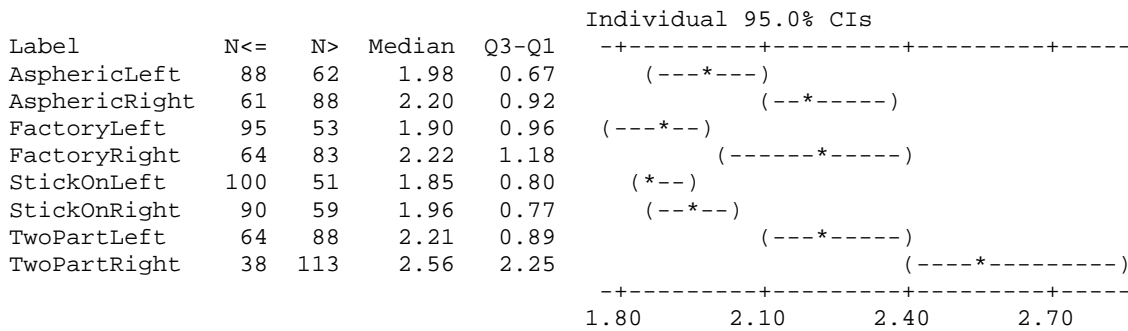
Figure 5.13 – Graphical Summary for all time data combined

This graphical summary illustrates the shape of the distributions seen among all test alternatives. Each test alternative demonstrated a similar non-normal distribution as is confirmed by the p-value ≤ 0.05 . This same confirmation was observed for every test alternative individual distribution and aids in the selection of analysis tools that are applied for the further segmentation analysis. When data is not normally distributed, the median can be a more useful point of reference than the mean for the comparison of sub-groups. This leads to the application of non-parametric testing for comparisons, as discussed in the section on sample size selection.

Application of the Mood’s Median Test confirms that there is a significant difference between the various mirrors being evaluated. This significance is confirmed with high confidence with P-value = 0.000. This can be interpreted that there is virtually zero probability that those differences are due to random chance and in fact they indicate true differences between the sub-group populations. This confirmation gives confidence to these values that are now taken and entered into the Clarity of View model framework.

Mood Median Test: Time versus Label

Mood median test for Time
 Chi-Square = 87.16 DF = 7 P = 0.000



Overall median = 2.09

Figure 5.14 – Mood’s Median Test – comparison of mirror styles

Box-plot illustrations are another useful way to better visualize the differences between the subgroups. In figure 5.15 the box-plot diagrams of this data are shown. The box represents the middle 50% of the data. The line through the box represents the median. The lines (whiskers) extending from the box represent the upper and lower 25% of the data, excluding outliers represented by asterisks. Means are illustrated by the symbol shown as an x and circle [Minitab, 60].

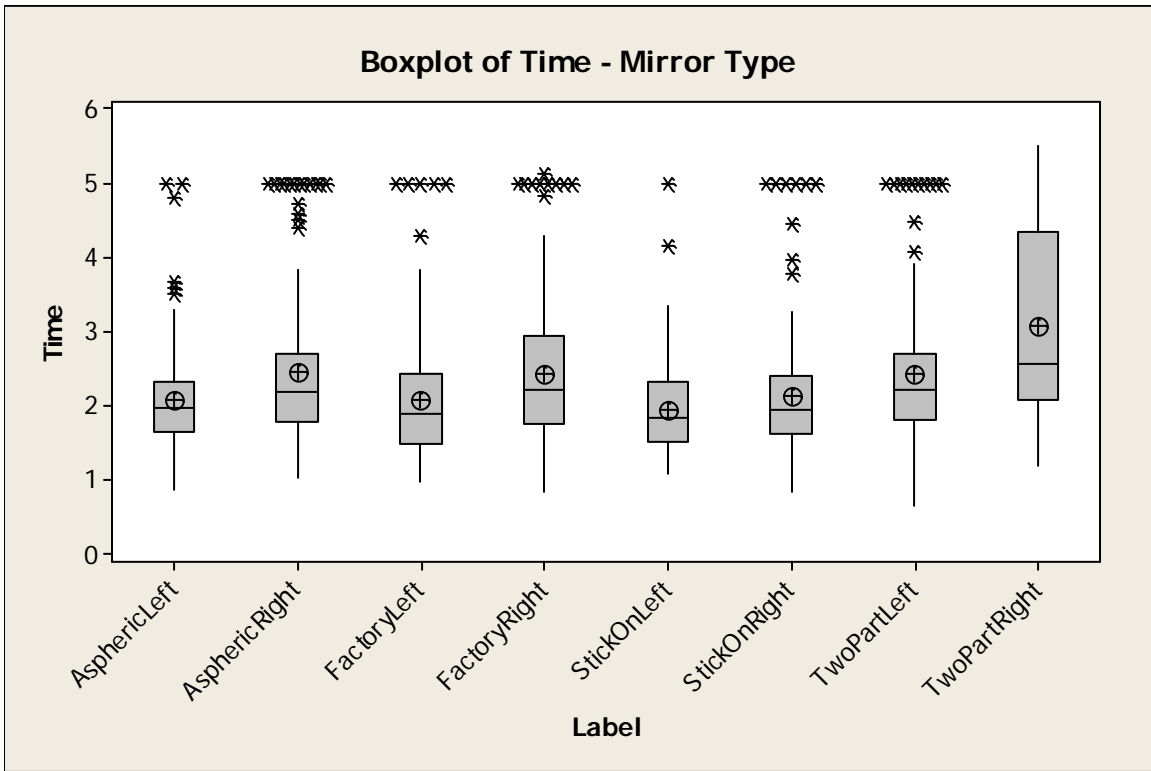


Figure 5.15 – Box Plot of Driver Reaction Times by Mirror Type

These median values are applied within the Clarity of View model in a utility-curve format as shown in Figure 5.16 below. The utility curve was established from 0 to 5 seconds with 0 being set as the theoretical ideal and 5 as the highest possible reaction time beyond which recognition would be deemed irrelevant as the oncoming vehicle would have already passed the test driver. This process was repeated for every driver, every mirror style, for both driver and passenger sides.

Asterisks (*) in the boxplot illustrate those data points considered outliers of each subgroup population dataset. In this case study, these represent those scenarios where the vehicle passed without detection by the driver.

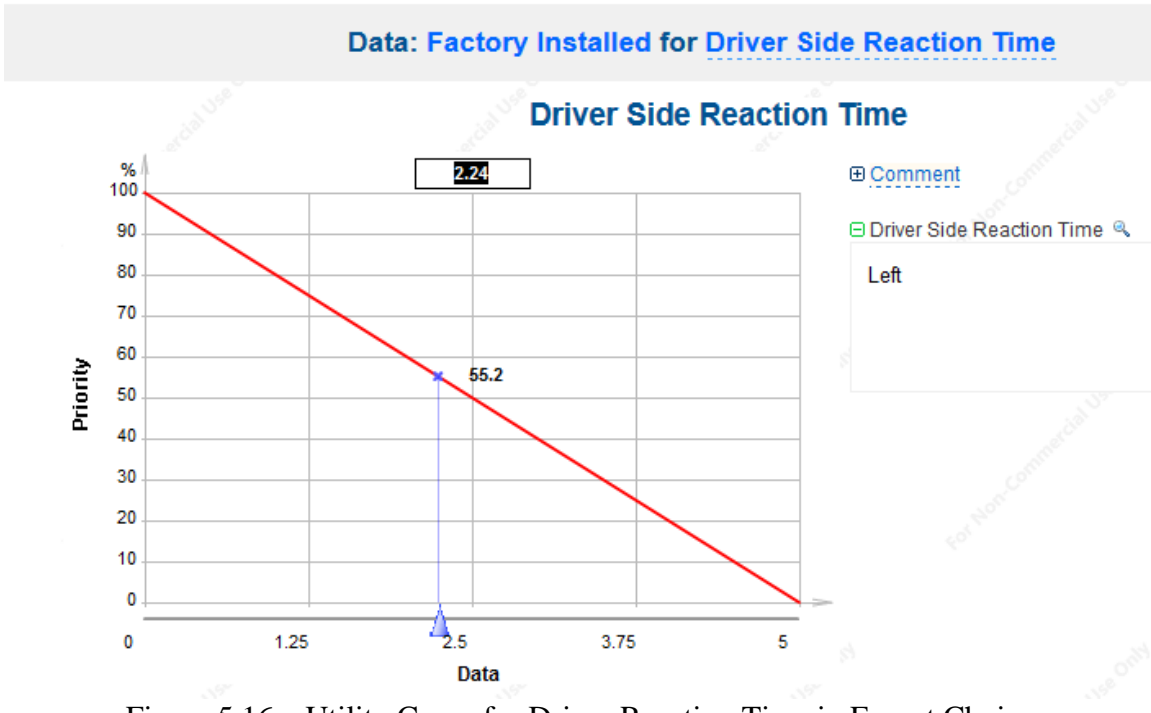


Figure 5.16 – Utility Curve for Driver Reaction Time in Expert Choice

The ranking summary resulting from this analysis indicated that the Stick-On Aspheric mirror performed the best in terms of driver reaction time and the Split-style mirror performed the worst. Of interest is the high performance of the factory installed mirror. Despite its lower field of view, drivers performed well using this style.

	Alternative Name	[All Participants] 22 participants
1	Factory Installed	57.53%
2	Aspheric	56.90%
3	Split-Style	48.87%
4	Stick On Aspheric	60.89%

Figure 5.17 – Driver Reaction Time Ratings

(Shown in un-normalized format)

Additional analysis was performed on the reaction time data to discern potential difference among additional sub-group categories. Here, it can be determined that experience is a significant factor with respect to reaction time. The higher the level of CDL driving experience, the quicker the drivers' reaction times. For a profession that is declining in numbers, this data can be useful to increase awareness of the importance of driver experience toward safety.

Mood Median Test: Time versus Driver

Mood median test for Time

Chi-Square = 40.62 DF = 2 P = 0.000

Driver	N<=	N>	Median	Q3-Q1	Individual 95.0% CIs
High-CDL	243	158	1.900	0.875	(---*---)
Low-CDL	132	108	2.030	0.857	(---*-----)
Non-CDL	225	331	2.220	0.927	(---*-----)

-----+-----+-----+-----
 1.95 2.10 2.25

Overall median = 2.090

Figure 5.18 – Mood's Median Test – Driver reaction times compared on basis of years of driver experience

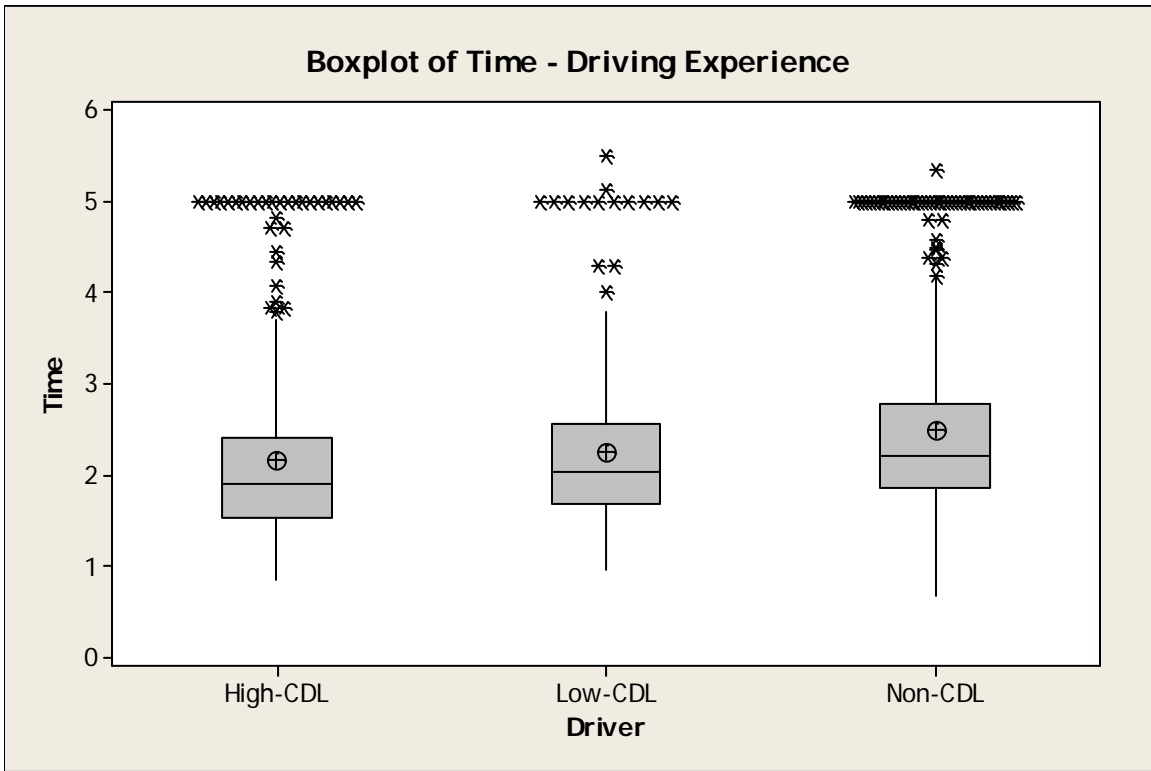


Figure 5.19 – Box Plot of Driver Reaction Times by Driver Experience Level

Age was also concluded to be a significant factor, as anticipated, and in agreement with data seen in preliminary evaluations also. Elderly drivers experienced longer reaction times as was hypothesized on the basis of overall physical and visual capability decline. Younger people experienced slower reaction times than middle aged drivers as well. This is presumed also to be related to driving inexperience as the contributing reason.

Mood Median Test: Time versus Age

Mood median test for Time
 Chi-Square = 131.91 DF = 2 P = 0.000

Age	N<=	N>	Median	Q3-Q1	Individual 95.0% CIs
Elderly	94	226	2.485	1.315	(---*---)
Middle	333	148	1.840	0.750	(--*--)
Young	173	223	2.180	0.817	(--*--)

2.00 2.25 2.50

Overall median = 2.090

Figure 5.20 – Mood’s Median Test – Driver reaction times compared on basis of age

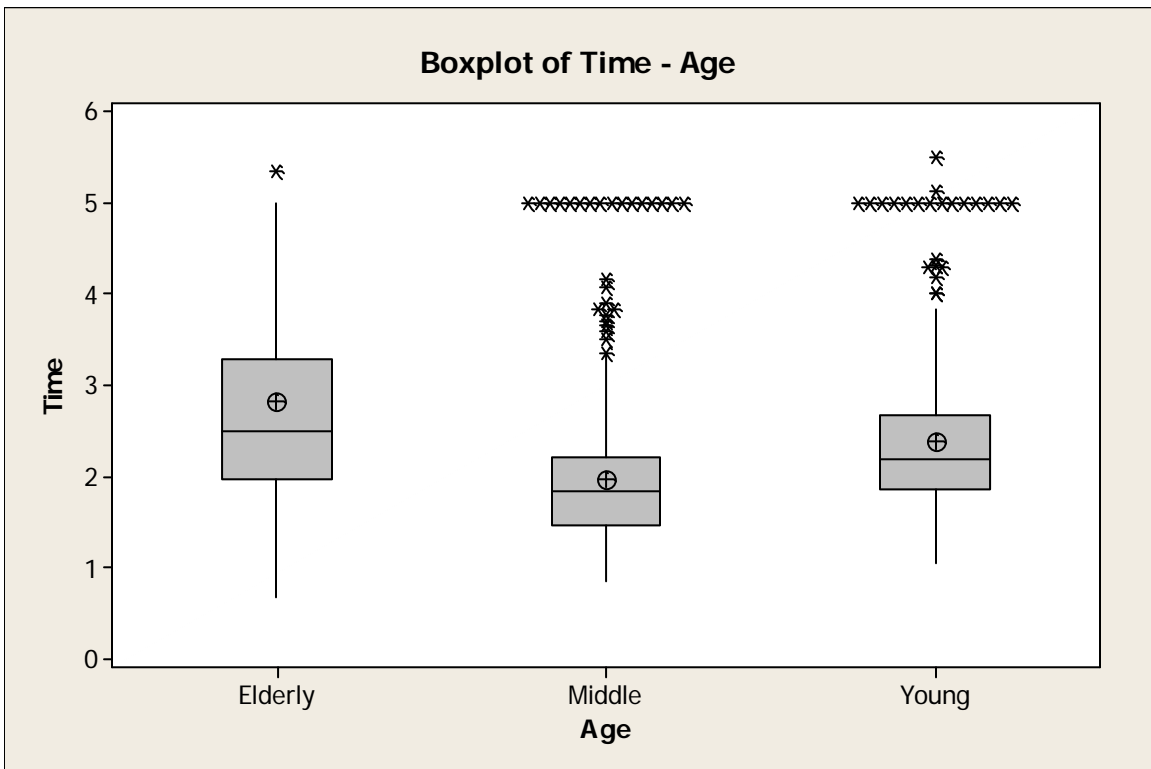


Figure 5.21 – Box Plot of Driver Reaction Times by Age Group

Priority Weighting of Factors

The role of the expert panel of evaluators as the “supra-decision maker” within this evaluation framework has been defined. Factors were presented in pairwise comparison format to each evaluator, independently, so the feedback of one was not seen by the others. The aggregation of preferences produced the priority weighting scores illustrated in Figure 5.22 below.

Objectives	[All Participants] 22 participants
Field of View	22.25%
Reaction Time	36.58%
Distortion	8.09%
Glare Discomfort	10.58%
Cost	5.02%
Reliability	17.49%

Figure 5.22– Summary of Priority Weights for Objectives

An example from a single expert evaluator inputs for objective weights is illustrated below in Figure 5.23

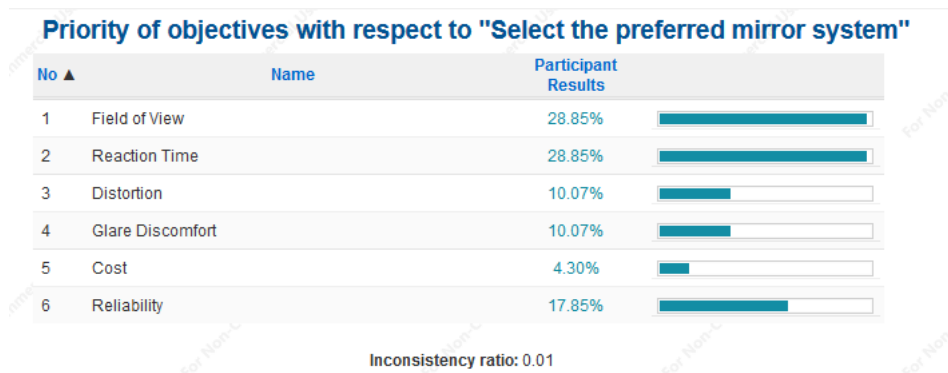


Figure 5.23 – Objective priority weights as input by one expert evaluator

(Consistency Index Ratio = 0.01)

The inconsistency ratio illustrates that this reviewer was very consistent with his evaluations. This is indication that the transitivity principle has been preserved and that there is credibility in his evaluation feedback. Each expert evaluator feedback data was screened and confirmed to have a consistency index ratio of less than 0.10, the guideline for acceptability [Saaty, 79].

The full results of the model were also evaluated for consistency between reviewers both for priorities and for measured values. This consensus is analyzed in Figure 5.x below. All in green to low-yellow scoring level indicating strong agreement. There was no overall consistency index ratio score for the full model, but each individual's ratings all had values less than 0.10 indicating all participants preserved transitivity of feedback for all measures.

Consensus View

Highest level of standard deviation implies the least amount of agreement, but does not imply judgments are incorrect

- Judgments about Alternatives
- Judgments about Objectives
- Judgments about both Alternatives and Objectives

Rank	Objective / Alternative	With respect to: Objective/Covering Objective	Standard Deviation
1	Factory Installed	Driver Side Distortion	15.18%
2	Factory Installed	Passenger Side Distortion	14.75%
3	Aspheric	Passenger Side Reaction Time	14.14%
4	Split-Style	Passenger Side Reaction Time	13.52%
5	Aspheric	Driver Side Distortion	11.93%
6	Aspheric	Passenger Side Distortion	11.39%
7	Factory Installed	Passenger Side Reaction Time	10.70%
8	Stick On Aspheric	Passenger Side Distortion	10.56%
9	Split-Style	Driver Side Reaction Time	10.41%
10	Stick On Aspheric	Driver Side Distortion	9.62%
11	Factory Installed	Driver Side Reaction Time	9.31%
12	Stick On Aspheric	Passenger Side Reaction Time	9.11%
13	Stick On Aspheric	Driver Side Reaction Time	8.02%
14	Aspheric	Driver Side Reaction Time	7.67%
15	Field of View	Select the preferred mirror system	4.36%
16	Reliability	Select the preferred mirror system	3.24%
17	Split-Style	Passenger Side Distortion	2.45%
18	Reaction Time	Select the preferred mirror system	2.36%
19	Driver Side Distortion	Distortion	2.03%
20	Passenger Side Distortion	Distortion	2.03%
21	Split-Style	Driver Side Distortion	1.74%
22	Driver Side Reaction Time	Reaction Time	1.38%
23	Passenger Side Reaction Time	Reaction Time	1.38%
24	Glare Discomfort	Select the preferred mirror system	1.14%
25	Distortion	Select the preferred mirror system	0.85%
26	Cost	Select the preferred mirror system	0.57%
27	Stick On Aspheric	Glare Discomfort	0.000003%
28	Split-Style	Glare Discomfort	0.000001%
29	Aspheric	Glare Discomfort	0.00%
30	Factory Installed	Glare Discomfort	0.00%

Figure 5.24 – Consensus View of both Objectives and Alternatives
(Variance between participants’ ratings)

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CHAPTER SIX

SUMMARY AND DISCUSSION

The Clarity of View evaluation framework has provided useful and expanded insight into the decision making process for a heavy-truck visibility awareness technology. Through the application of this model, systems that previously would have scored well using the existing industry standards for evaluation now are identified to have significant shortcomings to a degree that they may be unsafe for consideration for any on-road testing.

Figure 6.1 illustrates the final scoring of alternatives when using the Clarity of View evaluation framework.

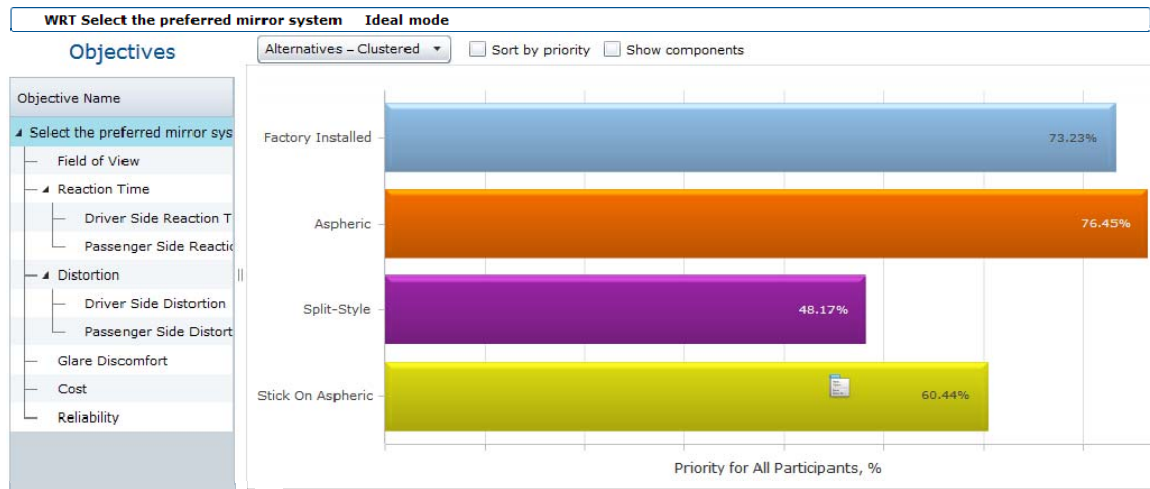


Figure 6.1 – Overall Final Ranking of Alternatives

(1 = Aspheric; 2 = Factory Installed; 3 = Stick-On Aspheric; 4 = Split-Style)

Comparison of this ranking to that which would have been given by the Field of View Test alone indicates a different conclusion:

	Alternative Name	[All Participants] 22 participants
1	Factory Installed	85.40%
2	Aspheric	96.20%
3	Split-Style	95.50%
4	Stick On Aspheric	91.80%

Figure 6.2. – Field of View Ratings

(Rankings: 1 = Aspheric; 2 = Split Style; 3 = Stick On Aspheric; 4 = Factory Installed)

In the Field of View test alone, the current industry standard method, the Split Style mirror, while not the top scoring system, was very highly rated and could likely be selected for further consideration by a freight line seeking to implement improved visibility technology in their fleets. Similarly, the Factory Installed mirror scored very poorly on the Field of View test, yet overall, it was a very close second place to the Aspheric mirror.

Using the Clarity of View method, the Aspheric mirror is concluded to the first choice, followed closely by the Factory-Installed status quo technology. The Split-Style Aspheric mirror that scored highly on the industry-standard Field of View test, is ranked last. Based on additional observations of this mirror also being the only one seeing near-miss incidents and one collision, it is deemed unsafe for any potential on-road analysis. This insight would not have been available using existing status-quo industry standard methods available today

These final summary results can be represented also in a radar chart that gives additional visibility to those factors contributing most toward the final scores.

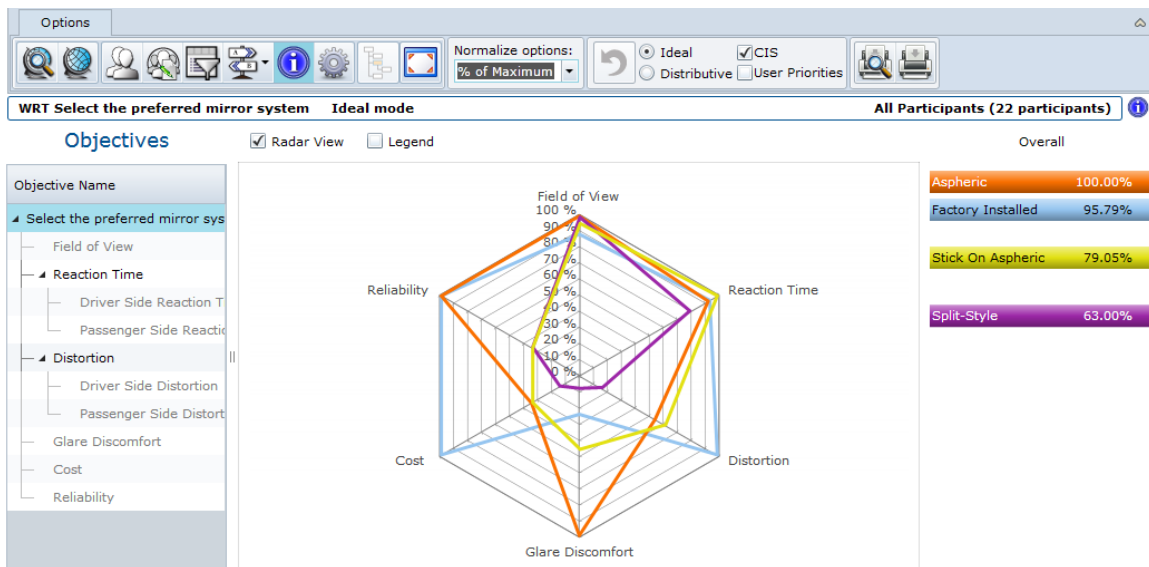


Figure 6.3 – Preferred Mirror System Performance to Objectives (% of Maximum View)

This representation offers an easy to understand visual graphic of the full model on a single chart. Even the lay-reader can see that the system illustrated by the orange outline (the Aspheric) exhibits a wider coverage of all the relevant factors that comprise the model. The more experienced user can evaluate these contributions using the dynamic sensitivity analysis feature of Expert Choice.

Sensitivity Analysis

The dynamic sensitivity analysis feature of Expert Choice allows one to consider the impact of a shift in priority weighting of any of the hierarchal factors. In doing so, those using the evaluation framework can discern opportunities for improvement for any of the proposed alternatives. For example, the current industry-accepted evaluation method is that of Field of View only.

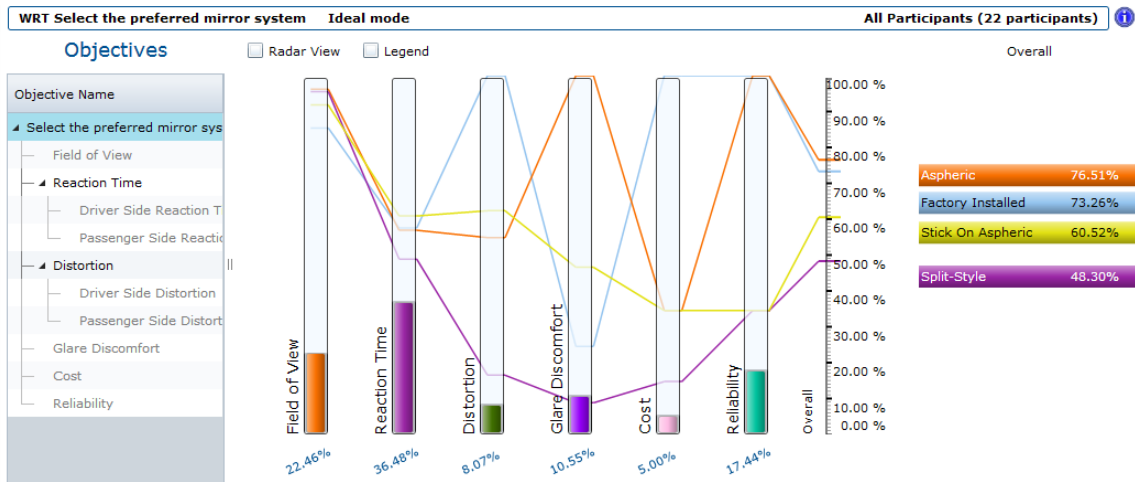


Figure 6.4 – Performance to objectives sensitivity analysis

Using the sensitivity analysis feature, Field of View can be set with 100% priority (compared to the current industry-expert priority weighting established by the model and illustrated above in Figure 6.4). Notice how this 100% emphasis on Field of View alone shifts the alternative ranking back to that which was seen by the Field of View Test individually.

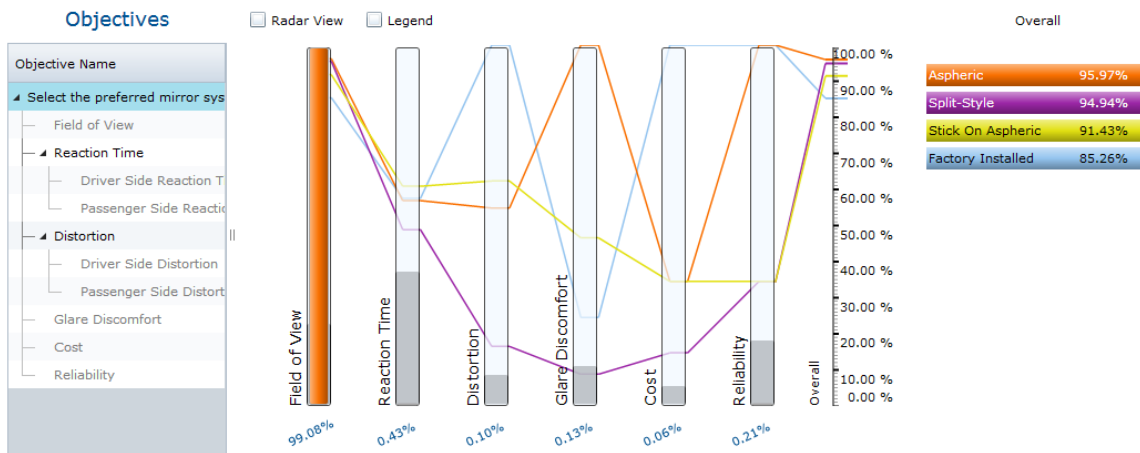


Figure 6.5 – Sensitivity Analysis illustrating the ranking impact of a 100% priority on Field of View factor alone

Similarly, any of the factors can be analyzed in a dynamic manner. Below is an illustration of the impact of a 100% priority on the factor of Distortion alone.

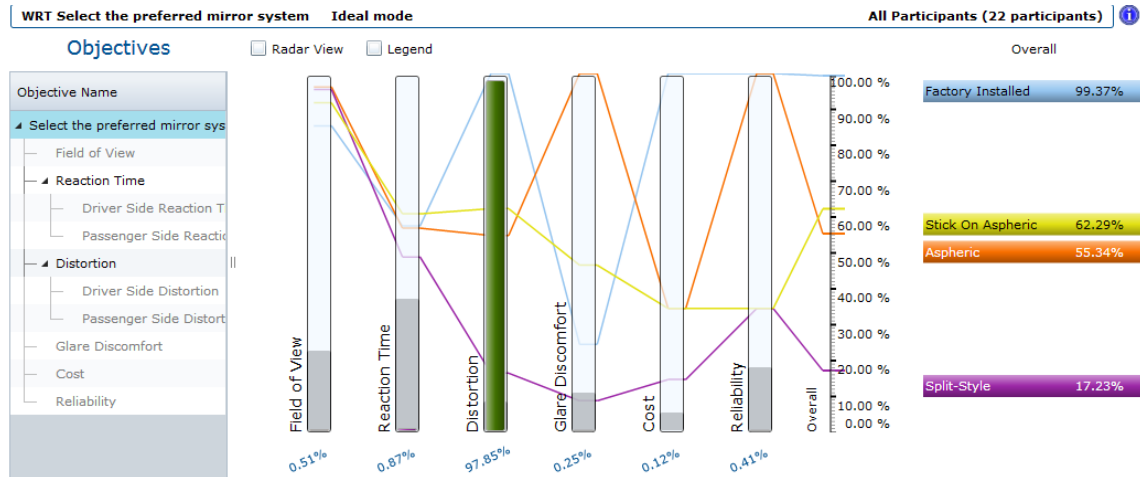


Figure 6.6 - Sensitivity Analysis illustrating the ranking impact of a 100% priority on
Distortion factor alone

Notice the spread of the rankings is also visually distributed to match the new priorities of alternatives. The significance of that spread and being able to visualize the relative differences in rank between alternatives is a strength of the AHP methodology. Some multi-criteria decision making methodologies simply score items by pure rank level alone. Figure 6.6 above, illustrating the impact of a priority on Distortion alone, illustrates how a decision maker may feel when presented with an argument about the effect of distortion. Here, it could be concluded that if distortion were the only factor for consideration, the factory installed mirror option is the clear preference. However, the comprehensive Clarity of View model brings in all relevant factors that help the decision maker understand the total system performance. Distortion does not correlate to total final performance. The Aspheric style mirror ranks 3rd in terms of distortion, but scores

first in terms of Field of View and Glare Discomfort. In lay terms, its advantages outweigh its disadvantages, and ultimately it scores first in the overall final rankings.

Additional observations

One sub-hypothesis of this specific application of the Clarity of View model was that the aspheric mirror, because it was the only one to present a singular plane for viewing, would also experience faster reaction times. The other three alternatives each had more than one mirror surface to be viewed. In those three systems, the driver would have to focus on more than one plane, deciding first which to look at first, and then managing the cognitive switching time to move from one mirror to the other and back and forth. This hypothesis was not proven, however, as the mirror exhibiting the quickest reaction times was determined as the “stick on aspheric” style.

Sub-factor categorization of data within the measurement of driver reaction time confirmed additional relevant information. Based on the results of early preliminary studies, it was hypothesized that older drivers would experience longer reaction times. This hypothesis was also confirmed in this evaluation. Additionally, I confirmed that “experience matters” as those drivers with longer commercial vehicle driving experience also exhibited quicker reaction times, regardless of age.

In summary, the application of the AHP-based Clarity of View model has provided a more insightful measurement framework than existing industry methods.

CHAPTER SEVEN

CONCLUSIONS AND INTELLECTUAL MERIT

The heavy truck industry desires technologies that improve safety. Until now, Field of View has been the primary documented evaluation method available for use by industry. This factor alone is not sufficient to evaluate all the factors that are relevant to the overall system effectiveness of a vision system. With the new multi-factor Clarity of View method, the trucking industry will be able to make better judgments before making substantial investments in new vision system technologies.

Based on extensive literature review, this is the first multi-criteria decision making model utilizing the Analytic Hierarchy Process (AHP) methodology, applied to a technology selection problem involving automotive user-interface design. Industry has called for such a multi-factor approach through its documentation of this gap directly in the Society of Automotive Engineering (SAE) Test Procedure J1750 - Describing and Evaluating the Truck Driver's Viewing Environment [SAEJ1750, 86].

The Analytic Hierarchy Process methodology is uniquely suited to the aggregation of both quantitative and qualitative information. Other Multi-Criteria Decision Modeling methods frequently employ the utility concept, but fail to accommodate the human perception reality that not all factors can be evaluated in an absolute "best utility" manner. Especially for factors that are subject to user opinion, it may not be possible for the user to conceive the "absolute best" that is typically associated with measures of utility. Instead, users are more readily able to offer a comparative, pairwise comparison and quickly conclude an A vs. B comparison. In these

situations, the AHP methodology is superior because it can accommodate simple pairwise comparisons alongside direct measurement data in varying structures. Thanks to the advancements made in processing software, AHP provides a way to normalize measures of widely different scales for a summarized order of preferences of alternatives. Compared to other decision modeling methodologies, AHP is more flexible, more robust, easier to use and provides outputs in an easy to understand manner. It even allows evaluation of what-if scenarios after feedback is summarized.

Traditionally, AHP methodology has been applied to the “group decision making” problem where multiple objectives and alternatives are considered. Some have criticized AHP citing Arrow’s Impossibility Theorem that claims optimal decisions for groups are impossible without a dictator. This research has presented the alternative concept of the “Supra Decision Maker” that was introduced by Keeney & Raiffa in their early work on Multi-Criteria Decision Modeling, as a more appropriate concept within the AHP methodology for this specific type of decision making problem that includes the aggregation of both objective and subjective measures. The Supra Decision Maker is a theoretical name for the concept of a group of decision makers all working and acting with a shared set of objectives and priorities. The Clarity of View framework offers a unique approach that combines a set of expert evaluations (as the Supra Decision Maker) with driver/user-level performance indicators and preferences in a manner that retains both the sovereignty of the Supra Decision Maker (SDM) but also engages all users in a consensus-building manner that preserves fairness and gives confidence to all parties that neither level (expert vs. driver) will neglect the critical inputs of the other. This case

study illustrates a scenario that is common in industry, especially in the technology selection problem. The SDM entities have the ultimate final authority, but must consider both real engineering performance data along-side the subjective opinions and preferences of their users when making their decision. This scenario has not previously been illustrated in published work regarding the evaluation of driver visibility systems or automotive user interface systems overall. The Clarity of View framework offers a new approach with its unique application of the AHP methodology.

Until now, there had been no prior research on the effectiveness of aspheric style mirrors in a practical, dynamic, driving-scenario setting [Mazzae, 57]. This study fills that gap by producing data that provides a comprehensive evaluation of the performance of aspheric mirrors as compared to planar mirrors through both quantitative and qualitative means. The creation of the 360-degree heavy truck driving simulator apparatus offers an affordable and safe alternative to on-road testing.

In this case study, four alternative visibility systems were considered. Each was a variation of the traditional planar + convex outside rearview mirror concept that conforms to FMVSS Regulation 111. The three prototype solutions were: A.) a fully aspheric single surface mirror, B.) a planar mirror with a small stick-on aspheric auxiliary mirror oriented in a similar fashion to the factory status-quo convex auxiliary mirror, and C.) a configuration that employed a large aspheric surface mirror mounted below a small sized planar mirror. Each mirror was evaluated by a group of expert and driver-level test participants who considered key factors identified as:

- Field of View
- Image Detection Time
- Distortion
- Cost
- Reliability
- Glare Discomfort

These factors were compiled through extensive literature review and a series of preliminary experiments performed to validate their significance. The aggregation of multiple factors into a single decision framework has not been attempted in prior work on the evaluation of driver visibility systems. The lack of such a multi-factor approach has left prior work without the ability to adequately summarize any conclusion regarding the comparison of multiple alternatives at an aggregate level. This multi-factor / single-model approach is one that could not only be modified or expanded on this specific case, but adapted toward a number of driver interface system evaluations.

Another key contribution of this research has been the development of the unique commercial-vehicle driving simulator that provides a dynamic, 360-degree, naturalistic driving environment for the evaluation of rearview mirror systems. This apparatus provides a safe, flexible evaluation environment that is superior to static methods used in prior work and safer than on-road evaluations on the highway. Eye-tracking and biometric data was gathered toward the evaluation of image detection time, but ultimately the simple stop-watch approach proved to be equally useful in providing an accuracy level sufficient to conclude statistical confidence of the validity of results.

The conclusion drawn from this case study was that aspheric mirrors offer significant viability for the commercial vehicle market. This screening experiment concluded that among the alternatives studied, the stick-on auxiliary mirror used in combination with the traditional planar surface mirror was the superior option. This was dramatically different than the conclusion that would have been drawn using simply the current industry-standard Field of View evaluation alone. Subset data within the model offered additional conclusions that elderly and younger age-group drivers do not perform as well as middle-aged drivers in terms of image detection times, but also that the more experienced commercial vehicle drivers perform better than less experienced drivers, regardless of age. This is an important conclusion given the demographic challenges faced by the commercial vehicle industry today that is suffering a shortage of new drivers and is seeking to retain its aging driver workforce.

The Clarity of View evaluation framework will provide a useful method for industry to evaluate new technologies using a mathematically-based process that incorporates a complex variety of decision-making factors. This new protocol, developed on the basis of the AHP theory, can be expanded in the future and applied toward the evaluation of many types of user-interface systems in the automotive industry.

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