Federal Motor Carrier Safety Administration's Advanced System Testing Utilizing a Data Acquisition System on the Highways (FAST DASH) Safety Technology Evaluation Project #3: Novel Convex Mirrors

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Federal Motor Carrier Safety Administration

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FOREWORD

The mission of the Federal Motor Carrier Safety Administration (FMCSA) is to reduce crashes, injuries, and fatalities involving large trucks and buses. According to FMCSA, the development, evaluation, and deployment of advanced safety technologies is key to realizing this objective. Currently, there are numerous safety systems in development that have the potential to reduce crashes on our Nation's roadways; however, for a variety of reasons, including lack of supporting tests and evaluations, the potential benefits that these systems may provide in reducing crashes may never be realized.

A key focus of FMCSA is to provide leadership in the testing and evaluation of promising technologies so that these technologies can be implemented more rapidly and their potential benefits realized sooner. Moving promising safety technologies from the design stage to the implementation and deployment stages is expected to lead to a reduction in large-truck crashes and their associated injuries and fatalities. The objective of FMCSA's Advanced System Testing utilizing a Data Acquisition System on the Highways (FAST DASH) program is to perform independent evaluations of promising safety technologies aimed at commercial vehicle operations (CVO).

For this study, an independent evaluation of a set of novel prototype mirrors was conducted. The objective was to determine whether the prototype mirrors were able to perform as well as traditional production mirrors across the basic functions of field of view (FOV), image distortion, and distance estimation. Driver acceptance of prototype mirrors also was evaluated.

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16. Abstract

An independent evaluation of a set of novel prototype mirrors was conducted to determine whether the mirrors perform as well as traditional production mirrors across the basic functions of field of view (FOV), image distortion, and distance estimation. Driver acceptance of prototype mirrors was evaluated, as well. The study involved a controlled test with research staff and a static evaluation with recruited participants on the Virginia Smart Road's static test area (STA). Controlled testing determined capabilities by assessing the maximum FOV presented to specific individuals. The static evaluation allowed participants to provide feedback regarding the prototype mirrors. Driver ratings indicated a preference for the way production mirrors handled image distortion and an overall preference for production mirrors on trucks. Analyses show a larger FOV with increased distortion in prototype over production mirrors, with no difference in accurately measuring distances.

Recommendations are presented for next steps of mirror development, a follow-up controlled test on the Virginia Smart Road, and field operational testing with fleets using these prototype mirrors.

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SI* (MODERN METRIC) CONVERSION FACTORS

Table of APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME	1000 L shall be shown in m^3	
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE	Temperature is in exact degrees	
°F	Fahrenheit	5 × (F-32) ÷ 9 or (F-32) ÷ 1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		Force and Pressure or Stress		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

Table of APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
Mm	millimeters	0.039	inches	in
M	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE	Temperature is in exact degrees	
°C	Celsius	1.8c + 32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		Force & Pressure Or Stress		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003, Section 508-accessible version September 2009).

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Acronym **Acronym**	**Definition**
3D	three-dimensional
CAD	computer-aided design
CDC	Centers for Disease Control and Prevention
CDL	commercial driver’s license
cm	centimeter
CMV	commercial motor vehicle
COR	Contracting Officer’s Representative
CUT	combination-unit truck
CVO	commercial vehicle operations
DAS	data acquisition system
DDC	driver door convex
DHC	driver hood convex
ECE	Economic Commission for Europe
FAST DASH	FMCSA’s Advanced System Testing utilizing a Data Acquisition System on the Highways
FMCSA	Federal Motor Carrier Safety Administration
FOV	field of view
MCS	mirror check station
NHTSA	National Highway Traffic Safety Administration
NIOSH	National Institute for Occupational Safety and Health
OEM	original equipment manufacturer
PDC	passenger door convex
PHC	passenger hood convex
POV-Ray	Persistence Vision Raytracer
PRA	Paperwork Reduction Act

Acronym Acronym	Definition
SAE	Society of Automotive Engineers
SD	standard deviation
SOW	statement of work
STA	static test area
TFU	small female manikin model
TFV	large female manikin model
TMC	Technology and Maintenance Council
TMU	small male manikin model
TMV	large male manikin model
VTTI	Virginia Tech Transportation Institute
ASTM	American Society for Testing and Materials
USDOT	United States Department of Transportation

EXECUTIVE SUMMARY

PURPOSE

A focus of the Federal Motor Carrier Safety Administration (FMCSA) is to provide leadership in the testing and evaluation of promising safety technologies developed for use in commercial motor vehicles (CMVs). One approach to evaluating such technologies is to assess their in-service benefits through naturalistic driving studies. By identifying, quantifying, and documenting safety benefits of promising technologies, FMCSA expects to positively influence motor carriers' voluntary adoption of proven technologies.

The goal of FMCSA's Advanced System Testing utilizing a Data Acquisition System on the Highways (FAST DASH) program is to conduct efficient, independent evaluations of promising safety technologies aimed at commercial vehicle operations (CVO). The FAST DASH program was tasked to complete three technology evaluations over a period of 5 years. The current report details all tasks completed during FAST DASH Safety Technology Evaluation Project #3: Novel Convex Mirrors.

For this safety technology evaluation project, a novel set of multi-radii convex mirrors (developed by Dr. R. Andrew Hicks of Drexel University under patent #US20100033854 A1) was selected for evaluation.[(1)] These mirrors are designed to increase field of view (FOV) for drivers and provide reflection similar to that found on flat mirrors (i.e., 1:1 unit magnification of images). Four prototype mirrors—door-mounted and hood-mounted, for both driver-side and passenger-side—were created through simulations and fabricated for testing purposes.

PROCESS

This report presents findings from an independent evaluation of the tested mirrors by the Virginia Tech Transportation Institute (VTTI). The study process included the following steps:

1. **Mirror Development:** Novel mirrors were developed. Manikins were created and used in simulations, supporting specification of the mirror views prior to fabrication of prototype mirrors.
2. **Preliminary Mirror Mapping:** The research team performed preliminary FOV mapping with the prototype and production mirrors in a controlled area to assess capabilities of the mirrors.
3. **Static Evaluation:** The intent of the static evaluation was to introduce the prototype mirrors to commercial driver's license, class A (CDL-A) drivers and to solicit their feedback on the utility, look, and effectiveness of the mirrors, as well as their overall preferences. This allowed researchers to understand how drivers assess the prototype mirrors, and to examine the mirrors' potential limitations and areas for improvement before production.
4. **Dynamic Evaluation:** This supplemental test drive garnered feedback from an experienced heavy-vehicle driver in a dynamic test setting featuring real-world scenarios and tasks aimed at comparing the production and prototype mirrors.

RATIONALE AND BACKGROUND

Large trucks, because of their size and design, have extensive areas around their bodies that are obscured from the driver's direct and indirect vision. These blind spot areas have the potential to hide other road users from the drivers (due to restricted FOV), contributing to safety weaknesses and crashes during maneuvers such as lane changes and merges. In fact, lane changes and merges are considered some of the riskiest maneuvers that a driver can perform on the highway, due to the high demand on the driver's attention and vision.(2) Between 2001 and 2003, 14 percent of large-truck crashes occurred due to inadequate surveillance by CMV drivers of their driving environments.(3) Furthermore, the average cost of a large-truck crash is about $91,000 per incident, with those resulting in a fatality costing $3.6 million per crash, on average.

Cameras, novel mirror designs, and object detection technologies provide viable options to enhance, supplement, or replace current standard mirror configurations on heavy vehicles. The predominant issues with these new approaches are the unknown limitations of each technology, and the subsequent work required to address recognized limitations, all while ensuring credible driver acceptance. The limitations of existing mirrors are predominantly the inability to capture all potential hazardous zones surrounding a heavy vehicle and user misconfiguration of the mirror.

Conventional convex mirrors on CMVs provide indirect visibility in areas surrounding the truck and function as a means for drivers to detect and identify objects within those areas. Additionally, conventional convex mirrors enable drivers to locate objects and estimate distances between their vehicles and these objects. Accurate distance estimation allows drivers to safely navigate their surroundings, which often include other vehicles or obstacles.

Conventional convex mirrors are shown to reduce blind spots substantially when compared with conventional planar mirrors, but with distortion to objects via indirect visibility. This distortion narrows the horizontal dimensions of the corresponding image, and is a potential problem for drivers.(4) The proposed novel prototype mirror is expected to reduce distortion when compared to a conventional convex mirror, while also increasing driver FOV.

The third FAST DASH safety technology evaluation explored the feasibility and user acceptance of a novel mirror prototype to replace existing convex mirrors on a heavy vehicle. This was accomplished by examining the interaction between driver and object placement for FOV and distance estimations as described in the National Highway Traffic Safety Administration's (NHTSA's) static testing method.(5)

STUDY FINDINGS

The research team systematically tested the novel convex mirrors under various operational scenarios to understand their abilities and limitations. Static testing was performed on the Virginia Smart Road's static test area (STA). A dynamic evaluation was conducted on a major interstate, on local roads, and in a parking lot.

Preliminary Mirror Mapping

Preliminary FOV measurements were collected first by selecting two research staff members, a male model at the 95th percentile and a female model at the 5th percentile of anthropometric sitting eye-height. This allowed for a set threshold of viewable area within the prototype and production mirrors. The viewable area was set first by having participants adjust their mirrors to view specific target areas and to minimize overlap of the mirror view. Following that, researchers maneuvered a pole of a set height to determine the models' boundaries of indirect visibility to create a set of FOV maps.

FOV mapping revealed a larger area of indirect visibility for prototype mirrors than for production mirrors in several ways. Figure 1 provides examples of the view in the passenger-side production (left) and prototype (right) mirrors. First, the prototype door-mounted mirrors provided an increased view over corresponding production mirrors with regard to the two lanes outward from the vehicle, which was the maximum distance mapped. Second, horizon was visible in both driver- and passenger-side, door-mounted prototype mirrors; however, measurements in the evaluation extended only to the 100-foot mark from the front of the cab. Although there was horizon, the models noted increased distortion toward the top of the mirror, increasing the difficulty of mapping the FOV. Third, the curvature in the prototype mirrors increased forward indirect visibility further forward than the production mirrors.

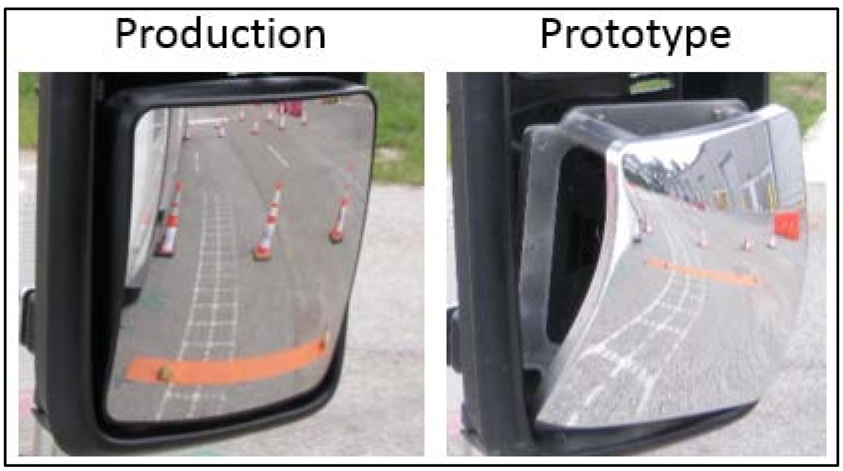

Figure 1. Photos. View of the passenger-side production (left) and prototype (right) convex mirrors.

Static Evaluation

A formal study involving prototype mirrors was conducted using participant drivers on the Virginia Smart Road's STA. Analyses were performed to investigate whether drivers would accept the implementation of a novel mirror design replacing existing convex mirrors on both the door and hood mounts of a Class A combination-unit truck (CUT) with a 53-foot trailer. It was anticipated that drivers would be able to view more of the roadway with less distortion using the novel mirror design, with the understanding that there could be limitations given the possible distortion of areas within the mirror's reflection.

Results indicated that drivers had an increased FOV using the prototype mirrors, but also had increased distortion. Estimating distance with the prototype mirrors was no worse than estimating distance with the production mirrors, and, though drivers were on average more accurate using prototype mirrors to judge distance, the results were not significant. Drivers ultimately preferred production mirrors over the prototype mirrors, but suggested that prototype mirrors could be useful with further development iterations.

The use of a mirror check station protocol for adjusting mirrors and targeting similar regions on the ground across all mirrors standardized drivers' indirect visibility.[6] Due to this, little difference was shown between FOVs of the production and prototype mirrors outside of the driver-side, door-mounted convex mirror. This effect was demonstrated in the participating drivers' description of the number of cones that were visible to them in the FOV task.

Drivers classified the image distortion of each mirror type (i.e., production, prototype) and position (i.e., door/hood, driver-side/passenger-side) by viewing a flat grid that was situated at an individually defined position covering the majority of the mirror (see Figure 2). Drivers classified the outside and lower regions as most distorted on both of the door mirrors. Drivers also classified the outside and lower regions of both of the hood mirrors as most distorted. Among the four mirror positions, drivers identified all four of the prototype mirrors as creating more image distortion than the production mirrors; however, the passenger-side hood mirror was not rated as having significantly more distortion.

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Figure 2. Photo. The location of the checkerboard used during the image distortion task for driver-side, door-mounted convex mirror. The numbers were mirrored to provide a properly oriented number sequence for driver identification while looking at mirrors.

Drivers were asked to estimate distances to a cone placed on alternating sides of the truck at one of two positions rearward from the door mirrors. The result of these estimates provides some insight into the effect of the prototype mirrors on judging objects in nearby lanes of traffic on the road. The average gap estimated by the drivers was smaller for the prototype mirrors than the production mirrors on both the driver- and passenger-side mirrors; however, the distance was not significantly lower.

User Acceptance

Drivers provided mixed feedback on the prototype mirrors; suggested other ways to improve them; and proposed follow-up tests that they would like to see. General positive comments included the following: "field of view is larger," "actual image presentation is clearer," "more definitive," "I like the design better, no sun glare." General negative comments included the following: "harder to place things in the mirror," "too distorted," and "still a bit of work to do on the mirror." Some drivers expressed interest in seeing future mirror developments and applying mirrors in a real driving scenario. The nine drivers in the study expressed acceptance of certain facets of the prototype mirrors; however, most drivers noted their preference of the production mirrors.

Dynamic Evaluation

This supplemental test drive garnered feedback from an experienced heavy-vehicle driver in a dynamic test setting featuring real-world scenarios and tasks aimed at comparing the production and prototype mirrors. This driver was a staff member of the contracted research institution with no connection to the project. The driver operated a CUT with production and prototype mirrors on a major interstate, on local roads, and in a parking lot. The driver provided feedback regarding the mirrors. The focus of this evaluation was to assess the driver's ability to change lanes, merge, conduct parking lot maneuvers, and assess the mirrors' available FOV on the road.

The driver successfully completed the dynamic on-road evaluation of the prototype mirrors. Results of the evaluation showed that, for merging and overtaking actions using the prototype mirrors, the gap-acceptance was very similar to the production mirrors for both driver-side and passenger-side. However, the driver noted that in the passenger-side prototype mirror, visual cues, such as shadows, were used to decipher the location of the remote vehicle and its relation to the CUT. The driver also noted that the remote vehicle was very difficult to see readily by glancing at the mirror, as were other vehicles on the road. This may have been a result of the location of distortion on the mirror; high distortion areas were often where vehicles in lanes beside the CUT would travel along the mirror face.

NEXT STEPS

Prototype Mirror Dynamic Testing (Phase 1)

Refining the design of the prototype mirrors is recommended for increasing utility and acceptability of the mirrors. Specifically, vertical FOV must be limited to decrease distortion of objects in the mirrors. Furthermore, the mirror surface should be adjusted to remove distortion from primary areas on the mirror face. These primary areas are the typical trajectories of vehicles in the lanes beside the CUT as they pass through the mirror.

Once redesigned, future static and dynamic testing of the prototype mirrors would involve participants performing various tasks using the prototype and production mirrors to assess usefulness and acceptance. Tasks would include merge and pass scenarios, FOV evaluation, distortion evaluation, and differing backup scenarios. If performance and driver acceptance of mirrors is satisfactory, multiple sets of mirrors could be produced for field testing.

Prototype Mirror Field Testing (Phase 2)

Field testing of the prototype mirrors would involve installing prototype mirrors on 10 participant driver vehicles and evaluating the effectiveness of the mirrors across various criteria. Objective measures would gauge safety-related benefits of the prototype mirrors, as well as unintentional consequences. Subjective measures would gauge driver acceptance of prototype mirrors.

The proposed field study would investigate the efficacy of the prototype mirror by evaluating safety benefits, unintended consequences (i.e., safety disadvantages), and user acceptance. This would be accomplished through a before-after study design comparing driver performance using the conventional convex mirror configuration with driver performance after the replacement of convex mirrors with prototype mirrors (see Figure 3).

During a 1-month baseline phase, drivers would operate their un-instrumented CMVs (i.e., no prototype mirrors installed) while baseline driving data were captured. Immediately following this 1-month baseline period, a 2-month intervention phase would begin. In this phase, the baseline convex mirrors would be removed from the drivers' CMVs and replaced with the prototype mirrors, and drivers would continue to operate the instrumented vehicles (see Figure 2). The primary safety benefit measure of interest would be the rate of merge-related and lane-change-related safety-critical events per 10,000 miles traveled involving the subject CMV and at least one other vehicle positioned in an adjacent lane. Following the 3-month period of data collection, reduction and analyses would occur.

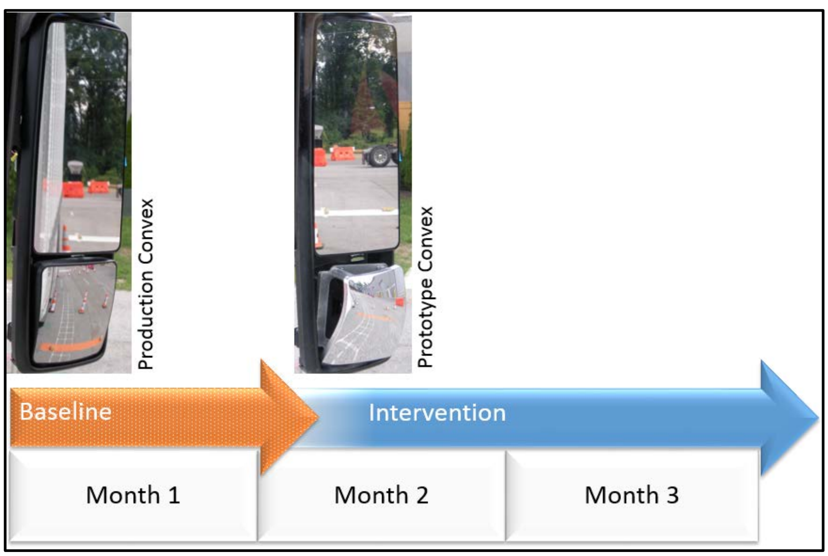

Figure 3. Diagram. The baseline and intervention phase field test plan with mirror type installation.

CONCLUSIONS

Prototype (novel convex) mirrors were provided to drivers to gauge interest, acceptance, and obtain feedback.

In summary, the prototype mirrors' FOV was greater than the production mirrors. However, this increase was demonstrated to exist at the cost of increased image distortion. While some drivers were not bothered by the increased distortion, most drivers were hesitant to accept the prototype mirrors for their personal use.

Subsequently, drivers noted preference for production mirrors over prototype mirrors for the purpose of distance estimation. Some drivers noted the distortion in prototype mirrors made it difficult to estimate distances via indirect visibility. Drivers' estimates tended to be more accurate with the prototype mirrors (note that drivers did not receive feedback on the accuracy of their estimates). Further testing could reveal driver acceptance of the prototype mirrors, provided they are able to drive while using them (i.e., in a field test).

Of the nine participating drivers, eight stated that they would prefer to use the production door mirrors on their CMV, while six stated that they would prefer to use the production hood mirrors on their CMV. Drivers were more comfortable with the hood-mounted prototype mirrors than door-mounted prototype mirrors, based on their comments. Additionally, some drivers showed interest in seeing further development and iterations of the prototype mirrors.

Supplemental dynamic evaluation by a staff member of the contracted research institution evoked reactions toward the mirrors that were similar to those demonstrated by participants in the static evaluation. Though safe driving behaviors did not diminish using the prototype mirrors versus the production mirrors, the prototype mirrors did not offer much improvement over the production mirrors. The driver in the dynamic evaluation noted that the door-mounted prototype mirror did provide a larger FOV, but that the passenger door-mounted prototype mirror also made driving safely discernably more difficult due to the distortion and reduction in size of the objects viewed in that mirror.

RECOMMENDATIONS

The evaluation of this specific novel mirror technology provides guidance for future development and testing to benefit next-generation mirror prototype designs that may support the CMV industry. The tested paradigm was based on the idea that current production convex mirrors carry FOV and image distortion properties that are tied together by nature of a simple reflective surface made up of a constant radius of curvature and maximum surface perimeter length. This paradigm was tested to determine if the FOV property could be maintained or increased while reducing the distortion perceived by drivers (compared to production convex mirrors). Future testing recommendations are as follows:

- Maintain and continue testing driver-side and passenger-side hood prototype mirror surfaces.

- Refine and develop driver-side and passenger-side door mirror surfaces to decrease vertical FOV requirements and reduce excessive image distortion identified in preliminary mirror mapping and evaluations. Concurrently, reduce image distortion along common vehicle paths in the mirror face by shifting radii to less-used areas of the mirror.
- Discover and develop a more affordable mirror replacement with short turn-around methods of producing prototype mirror surfaces that can conform to commercial test vehicles.

Following these recommendations, the novel mirrors may provide an increased FOV as described in the development process, while also minimizing the amount of distortion present, thus increasing their utility and potentially increasing user acceptance.

1. INTRODUCTION

1.1 BACKGROUND AND RESEARCH OBJECTIVES

The safety objective of the Federal Motor Carrier Safety Administration (FMCSA) is to reduce crashes, injuries, and fatalities involving large trucks and buses.[(7)] The development, evaluation, and deployment of advanced safety technologies can assist in achieving this objective.

While there are numerous safety systems in development that have the potential to reduce crashes on our Nation's roadways, the benefits that these systems might provide may never be realized. While the reasons vary, one factor is the lack of supporting tests and evaluations to understand and communicate the underlying safety systems' true in-service benefits. FMCSA envisions, through cooperation with the trucking industry, promising commercial motor vehicle (CMV) safety technologies that support the expanding role of the trucking industry to transport the Nation's goods and products safely, securely, and efficiently. Implementation of vehicle safety technologies—such as passive and active collision mitigation and active driver behavior monitoring—could reduce large-truck and bus crashes. Data to assess the effectiveness of these systems are necessary to promote their use in the trucking industry.

A key focus of FMCSA is to provide leadership in the testing and evaluation of promising technologies so that these technologies can be implemented more rapidly and their potential benefits realized in the commercial trucking industry. Moving promising safety technologies from the design stage to the implementation and deployment stages is expected to lead to a reduction in large-truck crashes and their associated injuries and fatalities. The goal of FMCSA's Advanced System Testing utilizing a Data Acquisition System on the Highways (FAST DASH) program is to perform efficient independent evaluations of promising safety technologies aimed at commercial vehicle operations (CVO). The vision of this technology transfer program is to provide technology insight to the commercial trucking industry in hopes of promoting the adoption of effective and proven safety systems validated during in-service operations. The efficacy of these safety systems is investigated using the following high-level metrics:

- Crash reduction effectiveness (i.e., safety benefits).
- Unintended consequences (i.e., safety disadvantages).
- User acceptance (e.g., driver and safety manager subjective opinions).

Under a 5-year cooperative agreement between FMCSA and the Virginia Tech Transportation Institute (VTTI), the FAST DASH program was structured to complete three technology evaluations. The body of this report focuses on the third safety technology evaluation, which has been completed.

The FAST DASH technology evaluation process commenced with a solicitation for technology candidates to submit their interest in partnering with VTTI to assess their systems. The research team developed and posted a sources-sought notice via a dedicated FAST DASH Web page for the purpose of soliciting proposals from safety technology vendors (see Appendix A). A technology vendor statement of work (SOW) providing details on the FAST DASH program and the requirements for proposal submission was made available on this Web page. In addition to posting the sources-sought notice, researchers created a list of potential technology vendors and notified them of the Web page solicitation. A press release regarding this solicitation was created and sent to CVO media outlets and was posted on the research team's Web site. Eight technology vendors submitted proposals for a total of seven safety systems/technologies. VTTI researchers conducted an initial review of these proposals and categorized the safety technologies by type, potential safety benefits, and ease of implementation. A decision matrix was used to identify, analyze, and rate the technology applicants systematically. Each technology applicant was given a rating on a scale of 1–10 for meeting 14 relevant criteria, such as FMCSA's area of authority, FMCSA's mission, expected safety effectiveness, technology maturity, fitness for research, and prior research. These criteria were assigned weights by the FAST DASH team (i.e., FMCSA and VTTI). A total score was computed for each technology applicant. These scores were used in selection discussions and helped differentiate the technologies, but were not the sole determinant for choosing a technology.

All technology proposals and the FAST DASH decision matrix were presented to the FMCSA Contracting Officer's Representative (COR) and other FMCSA personnel for consideration. After a thorough review, a final candidate was selected by FMCSA. A novel, multi-radii convex mirror (see Figure 4), developed by Dr. R. Andrew Hicks of Drexel University, was selected for evaluation. This mirror is designed to increase field of view (FOV) for drivers and provide reflection similar to that found on flat mirrors (i.e., a 1:1 unit magnification of images). More information about this mirror can be found in Section 2.1. This report details the user acceptance and feasibility of the prototype mirrors.

Figure 4. Photo. Driver-side, door-mounted prototype mirror.

1.2 PROBLEM SCOPE

Fourteen percent of large-truck crashes occur due to inadequate surveillance by CMV drivers of their driving environments.[8] Furthermore, the average cost of a large truck crash is about $91,000 per incident, with those resulting in a fatality costing an average of $3.6 million per crash. Cameras, novel mirror designs, and object detection technologies provide viable options to enhance, supplement, or replace current standard mirror configurations on heavy vehicles. The predominant issues with these new approaches are the unknown limitations of each technology, and the subsequent work required to address recognized limitations, all while ensuring credible driver acceptance. The limitations of existing mirrors are predominantly user misconfiguration and the inability of existing mirrors to capture all potential hazardous zones surrounding a heavy vehicle.

Conventional convex mirrors on CMVs provide indirect visibility in areas surrounding the truck and function as a means for drivers to detect and identify objects within those areas. Additionally, conventional convex mirrors serve as a means for drivers to locate objects and estimate distances between their vehicles and these objects. Accurate distance estimation allows drivers to safely navigate their surroundings, which often include other vehicles or obstacles. Accuracy is a crucial component of estimation, as overestimation of distance leads to actual clearances that are less than the driver perceives them to be. A study on aspheric mirrors conducted by Wierwille, W.W., et al., suggests that the use of convex mirrors leads to overestimation of distances more than mirrors with unit magnification.[9]

Conventional convex mirrors are shown to reduce blind areas substantially when compared with conventional planar mirrors, but with distortion to objects via indirect visibility. This distortion narrows the horizontal dimensions of the corresponding image, and is a potential problem for drivers.[10] The proposed novel mirror is expected to reduce distortion when compared to a conventional convex mirror, while also increasing drivers' FOV. The third FAST DASH safety technology evaluation attempted to investigate feasibility and driver acceptance of the prototype mirror. This was accomplished by examining the interaction between driver and object placement for FOV and distance estimations as described in the National Highway Traffic Safety Administration's (NHTSA's) static testing method.[11]

1.3 ORGANIZATION OF THE CURRENT REPORT

The current report details all tasks completed during the third FAST DASH technology evaluation. These tasks are briefly described in this section so that the reader can understand the logical progression of events that took place.

Section 2: Novel Convex Mirror Prototype Development

In this section, logistics of novel mirror development and production are discussed, including the development of manikins used in the simulations, which were performed to support specification of the mirror views prior to fabrication of prototype mirrors.

Section 3: Preliminary Mirror Mapping

Production and prototype mirrors were installed at separate times on a combination-unit truck (CUT) at VTTI. Two research staff members, one male and one female, served as models for performing FOV mirror mapping for both production and prototype mirrors. Efficient interchangeability of each set of mirrors was also tested. This section discusses the two-fold purpose of the preliminary performance evaluation and the results of the static evaluation testing.

Section 4: Static Evaluation

Drivers were recruited to participate in this study. Primary factors considered during the recruitment process included experience driving large trucks, current or recent employment in the trucking industry, and driver availability. A total of nine participant drivers evaluated the prototype mirrors. Evaluation methods and static evaluation results are discussed in this section.

Section 5: Dynamic Test Drive

A VTTI research staff member with a Class A CDL performed a supplemental test drive using both production and prototype mirrors over the course of 2 hours on a major interstate, on local roads, and in a parking lot with a dock. Evaluation methods and results are discussed in this section.

Section 6: Conclusions

Conclusions found across all methods of technology evaluation are detailed throughout this section. These methods include preliminary mirror mapping, objective and subjective data analysis (FOV, image distortion, and distance estimation), and qualitative assessments from drivers.

Section 7: Next Steps

Instructions for future development and evaluation approaches are detailed in this section.

Section 8: Recommendations

Based on the findings of this evaluation, the research team has provided recommendations for further development and/or testing of the mirror technology.

2. NOVEL CONVEX MIRROR PROTOTYPE DEVELOPMENT

2.1 INTRODUCTION

A three-dimensional (3D) computer-aided design (CAD) model of a current production CUT was provided by a major North American original equipment manufacturer (OEM) for the research team to apply to the vehicle and mirror modeling. Availability of CAD data for the design phase of this study played a strong role in the static evaluation property selection, and required that a similar vehicle make, model, and configuration be applied. Critical components of the CAD model for the development exercise included vehicle, mirrors, ground, and driver packaging points for human modeling packaging.

A human modeling software called RAMSIS was applied for the demonstration of driver anthropometry, driver packaging in the vehicle, and mirror visibility.(12) A cadre of manikins was developed to serve as the sample models of CUT drivers. This sample provided insight into how drivers of various minimum and maximum body size variables (e.g., stature, sitting height, abdomen depth, arm reach, leg reach/clearance) are positioned inside the production vehicle model.

The indirect visibility (i.e., mirror view) zones were developed by applying a mirror modeling tool available in the human modeling software. The software provides features for the manikin head and eye gaze to be adjusted along with the adjustment range of the mirror faces, all within the simulation modeling environment. The mirror views are demonstrated as view cones that intersect the ground within the modeling environment.

2.2 MANIKIN DEVELOPMENT

A recent measurement database, the 2010 National Institute for Occupational Safety and Health (NIOSH) U.S. Long-haul Truck Driver Survey, which has provided a human dimensional sample model of similar transportation drivers, was applied as the basis for the manikin development.(13) The NIOSH survey report provides dimensions for 30 manikin models, which were given alphabetic labels correlating with body size, and uniform for female and male manikins (e.g., "Female V" and "Male V" are the largest models in multiple body dimensions). To simplify the development process, a subset of four models (see Figure 5 and Figure 6) was applied for driver-vehicle packaging and to develop the production mirror FOV performance. The following manikin models were selected based on their "eye-height, sitting" dimensions (see Table 1 for dimensions):

- Truck Female U (TFU): small female.
- Truck Female V (TFV): large female.
- Truck Male U (TMU): small male.
- Truck Male V (TMV): large male.

Table 1. Sitting eye-height dimensions, in centimeters (cm), for U.S. truck driver manikin models and for the 5th and 95th percentiles of the U.S. truck driver population.

Driver Population/Model Type	Female	Male
Truck Driver Population: 5th Percentile*	69.1 cm	74.2 cm
Simulation Model: Small, U	68.1 cm	73.6 cm
Truck Driver Population: 95th Percentile*	81.3 cm	85.8 cm
Simulation Model: Tall, V	82.5 cm	86.6 cm

*Data Source: 2010 NIOSH U.S. Long-haul Truck Driver Survey.

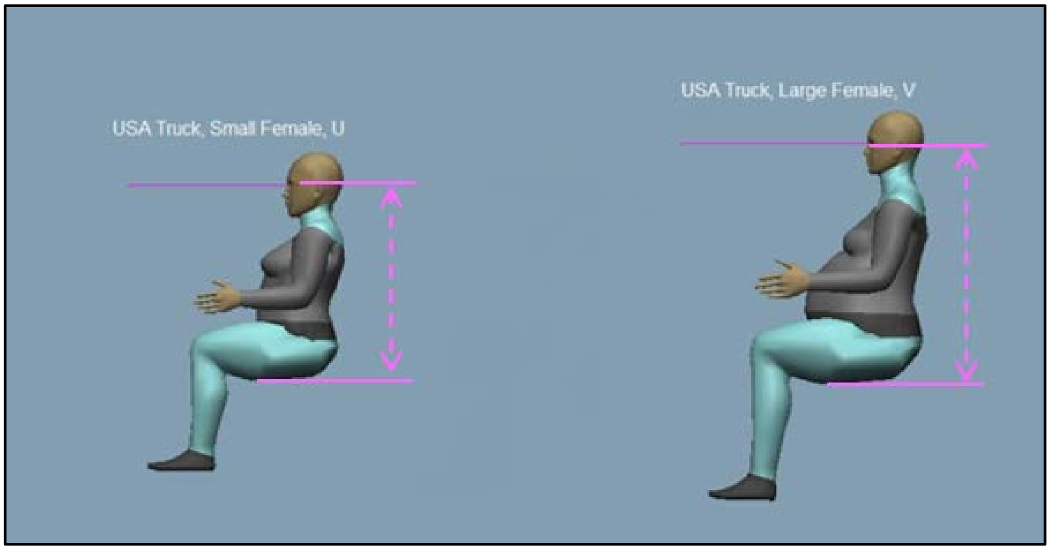

Figure 5. Screen image. Driver cadre: TFU and TFV manikins.

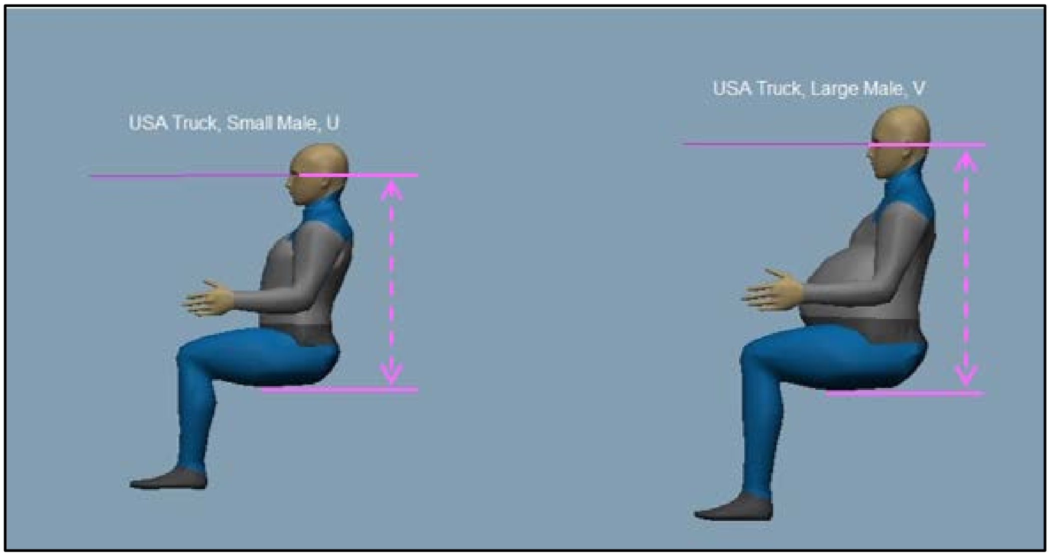

Figure 6. Screen image. Driver cadre: TMU and TMV manikins.

2.3 VEHICLE ARRANGEMENT

The applied production vehicle model was an International ProStar, 6x4, 122-inch bumper-to-back-of-cab, sleeper tractor-truck unit. The OEM provided a ground plane reference in addition to the truck model to allow for orientation of surfaces and objects in the surrounding simulation environment (e.g., the intersection of mirror view cones with the ground). A 53-foot trailer was also delivered. The rear tractor axles were modified to match a typical wheelbase configuration. The tractor fifth wheel was positioned at the center of the rear tractor axles (forward-rearward). Based on the position of the fifth wheel, the trailer's kingpin was joined at the center of the fifth wheel jaw. The trailer and vehicle ground plane was assumed to be flat (0-degree angle) across the length of the modeling environment. The vehicle arrangement in the modeling environment is shown in Figure 7 and Figure 8.

Figure 7. Screen image. Front view of the CUT 3D CAD model.

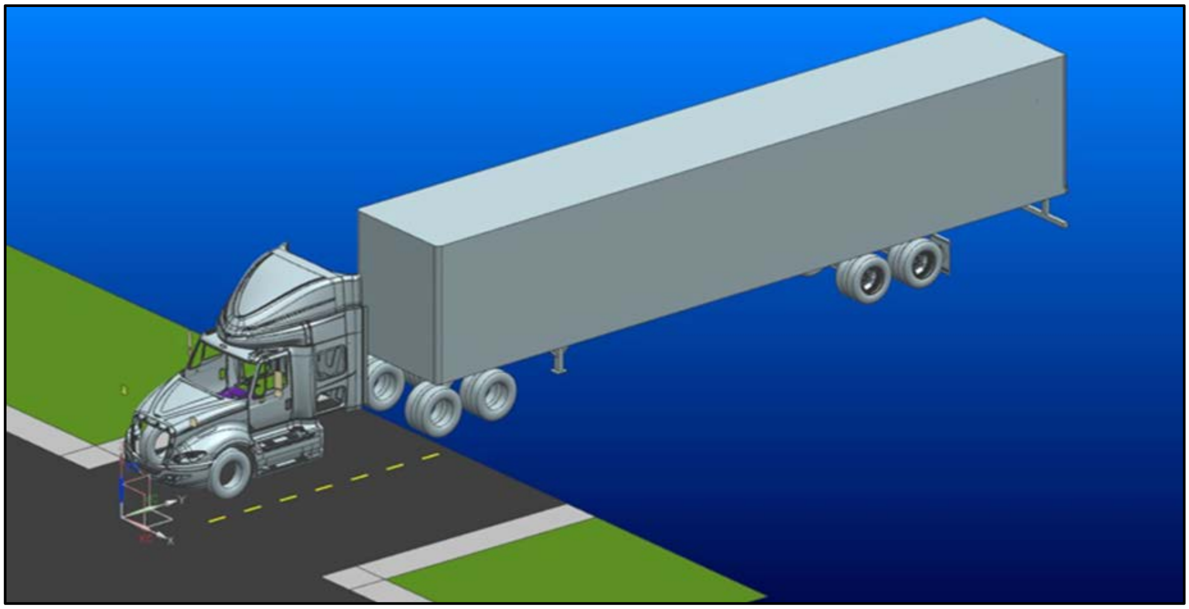

Figure 8. Screen image. Isometric view of the CUT 3D CAD model.

Current production door flat mirror and convex mirror surfaces, along with hood convex mirror surfaces, were also provided. The position of the mirrors and adjustment range of the mirror faces were provided by the OEM. The orientation of the mirror faces was specified at the middle range of adjustment. The adjustment range was as follows:

- Door flat mirror adjustment: ±12 degrees left/right; up/down.
- Door convex mirror adjustment: ±12 degrees left/right; up/down.
- Hood convex mirror adjustment: ±11 degrees left/right; ±8.5 degrees up/down.

2.4 MANIKIN POSITIONING IN VEHICLE

Prior to activating the mirror modeling tool in the human modeling software, the manikins had to be positioned into the driver seat, steering wheel, pedal, and forward-roadway gaze posture. This process is intended to prepare the manikins to represent real driving positions in a Society of Automotive Engineers (SAE) Class B driver configuration. There are multiple factors that affect the application of SAE Class A (light vehicle) versus Class B (CMV) configuration. The predominant factor is the height of the seat hip reference dimension, generally referred to as the h-point or H30 (SAE J1100), from the vehicle floor.[(14)] The Class B configuration is applied when the height of the H30 is greater than 405 millimeters.

2.4.1 Manikin Posture Modeling

The initial posture calculation involved four external constraints and two internal constraints on each manikin. The external constraints included the following manikin-to-component restrictions: right shoe to the accelerator pedal plane and left shoe to the footrest trim block, manikin h-point to the recommended seat h-point range box, left and right hands to the steering wheel outer rim at 9 o'clock and 3 o'clock positions, and eyes fixed straight forward. The constraints internal to each manikin included a soft hand grasp for left and right hands and pelvis rotation locked at 0 degrees.

For demonstration purposes, the driver-vehicle packaging of all four manikins is shown in Figure 9. The manikins are overlaid onto the model of the production interior of the truck along the driver seat, steering wheel, and pedals. The figure demonstrates the fixation of the manikin's head and eyes straight forward at the road. The most significant point of the figure is the difference between the eye positions among the four manikins, which varies slightly forward/rearward, but most significantly up/down. The figure illustrates the posture prediction for the manikins in the interior of the production sample tractor. The differences in eye positions strongly affect their view outside of the tractor cab, but also affect the reflected view of objects and the roadway for each manikin. The same result occurs for real drivers of various sizes. The same manikin posture constraint arrangement is available in a different view, shown in Figure 10, solely for the TMV manikin.

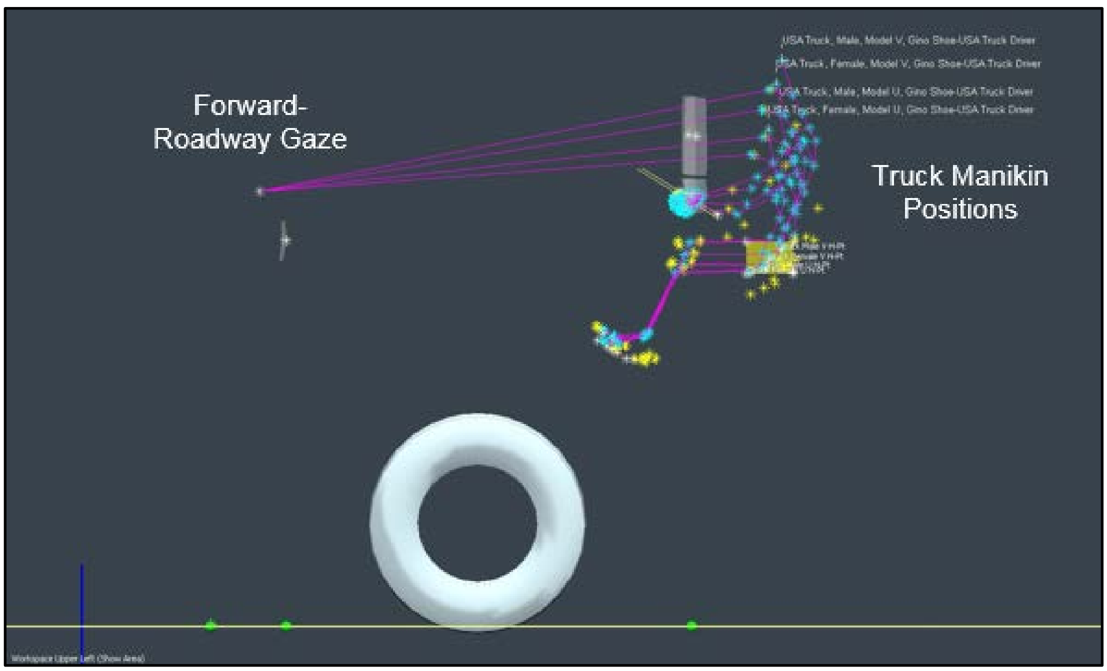

Figure 9. Screen image. U.S. truck manikins (TFU, TFV, TMU, TMV) in skeleton view mode with posture prediction in production truck interior.

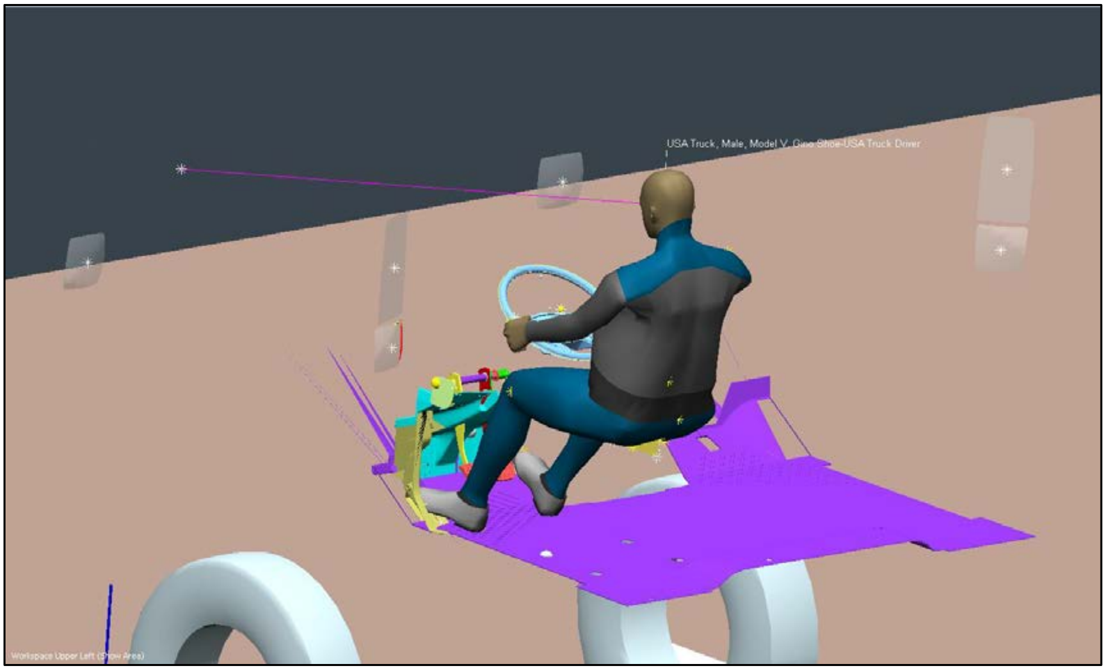

Figure 10. Screen image. Rear-isometric view. Truck manikin (TMV) in figure view mode with posture prediction in production truck interior.

2.4.2 Mirror Gaze

After each manikin's body position was established, their eyes and neck joint angles were modified, adjusting their gaze, at each individual mirror face. This process was repeated for each of the four manikins toward the center of each of the six mirrors. The purpose of this simulation was to demonstrate the complete mirror visibility among all mirrors, as they can be used in conjunction with one another. Therefore, even though the focus of the mirror development was the door and hood convex mirrors, the flat mirrors were included in the simulation of the mirror zones. As each manikin's gaze was fixed on each mirror, the mirror face could be adjusted within its design range, as described above (e.g., door flat mirror adjustment: ±12 degrees left/right; up/down), until the desired ground zone was available in each manikin's view for that mirror part (see Figure 11). The simulation used cones that extend from the manikin's eye-point to the mirror face and from the mirror face to the ground (see Figure 12). The resulting ground zone was a function of the position of the manikin relative to the mirror face and the position of the mirror face and angle relative to the ground.

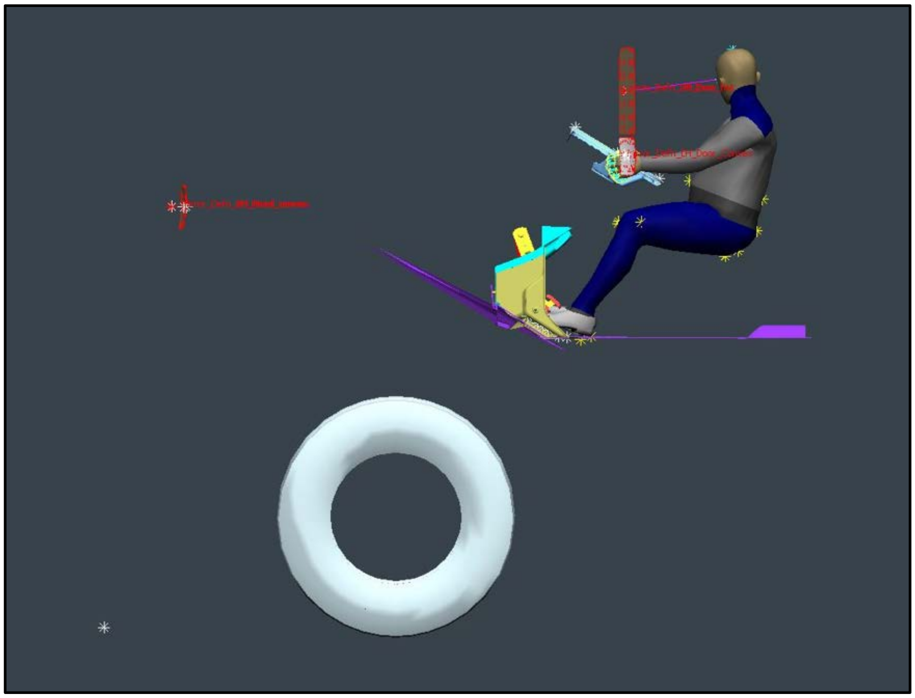

Figure 11. Screen image. Side view. Manikin positioned in the truck cab with eyes and neck gaze fixed on passenger-side door flat mirror.

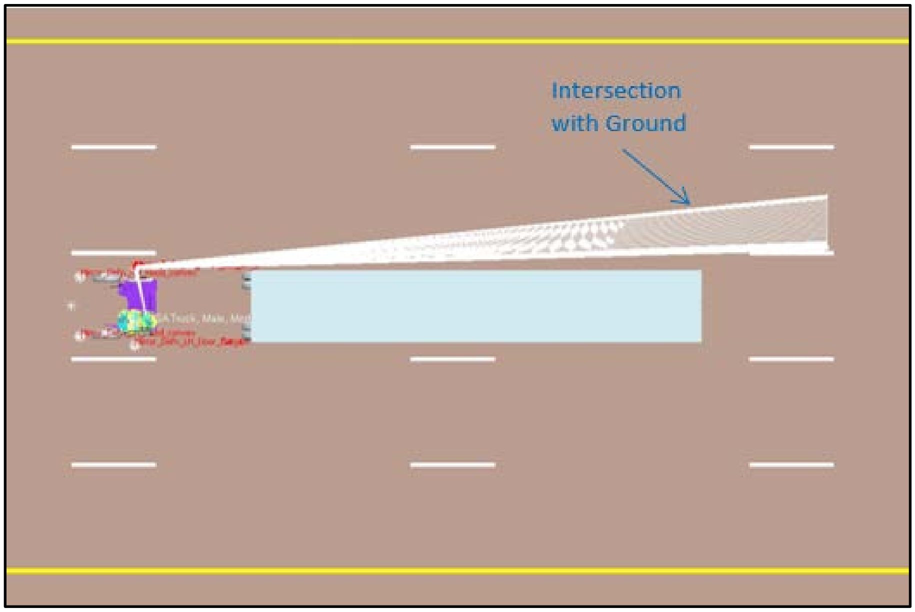

Figure 12. Screen image. Top view. Resulting driver-to-mirror and mirror-to-world view cones with manikin gaze targeting passenger-side flat mirror set to 0-degree rotation pitch and yaw.

2.5 MIRROR GROUND FIELD OF VIEW MAPS

Each production mirror was optimized within its adjustment range to maximize the FOV for each manikin. Even though the focus of this project was on replacing conventional convex mirrors with the prototype convex mirrors, the flat (unit magnification) mirrors were included in the analysis to demonstrate the complete mirror FOV available on current production CUTs.

2.5.1 Mirror Adjustment Procedure

A protocol was necessary to create a consistent process by which each of the four manikins' FOVs could be defined within the adjustment range of each of the production mirrors. An industry process—the mirror check station (MCS)—has been defined for mirror adjustment within the guideline "Mirrors for Heavy Trucks and Tractor-Trailers."[15] This guideline provides a process for drivers of revenue-production fleets to use when checking their mirror views prior to each trip. The MCS includes flat rectangular targets that can be placed on the ground of any parking lot at prescribed positions relative to the CUT, as seen in Figure 13. The mirrors can be adjusted until the specified targets are visible within a recommended position on each mirror, as seen in Figure 14.

The application of this guideline is not being suggested as a best practice, but rather provided a consistent methodology to reduce overlap in the zones viewed on the ground by any individual driver, thus maximizing the combined indirect visibility of all mirrors and minimizing the size of blind spots surrounding the CUT.

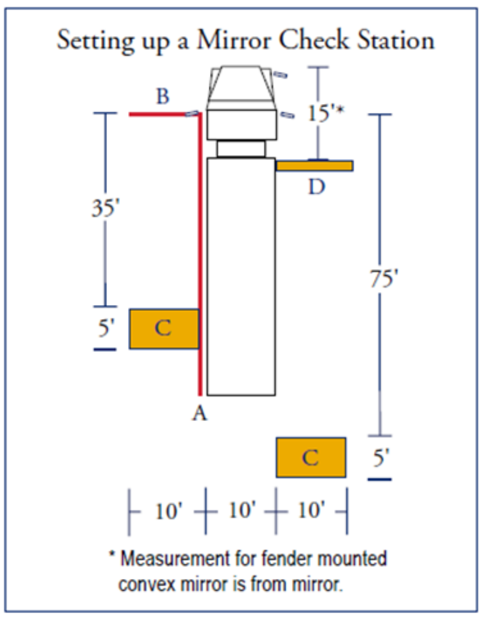

Figure 13. Diagram. Mirrors for heavy trucks and tractor-trailers, adjustment protocol: target locations.

As shown in Figure 14, the prescribed process for adjusting the flat mirror on each side suggests that the passenger-mirror target should be visible at the bottom of the flat mirror's reflective surface by 35 feet and the target of the driver mirror by 75 feet. The process for adjusting the door convex mirrors on each side calls for those same targets to be visible on the top of the convex mirror on each side. This indicates that there is overlap in the FOV for each mirror, but that overlap is minimized. It was also observed that the result of this arrangement removes the view of the horizon from the door-mounted convex mirror and instead focuses the reflective view on the area immediately next to the front of the trailer, a location where the view provided by the flat mirror is limited.

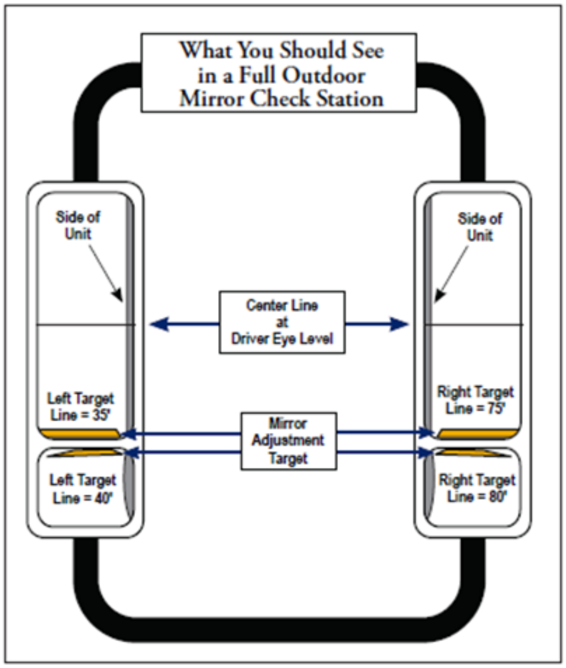

Figure 14. Diagram. Mirrors for heavy trucks and tractor-trailers, adjustment protocol: mirror target view.

Based on the MCS methodology, each mirror was adjusted in the CAD model for each manikin to maximize the combined driver-side and passenger-side mirror FOV. Each mirror view zone was developed by targeting each manikin's eye rotation and neck to the center point of each mirror (see Figure 15). The target object view was captured for each manikin eye point, as shown in Figure 16. Using a mirror zone simulation tool, each mirror was adjusted and its resulting mirror view cone was updated (see Figure 17). The focus on the front section of the trailer is highlighted in this same figure. A limitation of this mirror adjustment procedure is that the trailer tires may not be visible to some drivers in the door convex mirrors.

Figure 15. Screen image. Rear-isometric view. TMV eyes and neck rotated to driver-side door convex mirror.

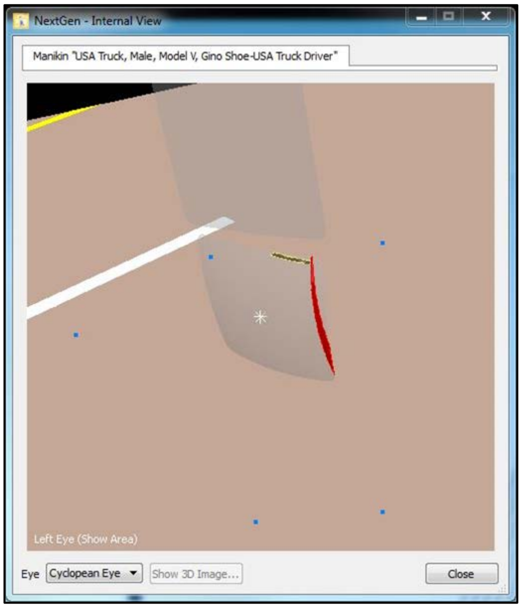

Figure 16. Screen image. Manikin eye view. TMV driver-side door convex mirror rendering view of ground targets.

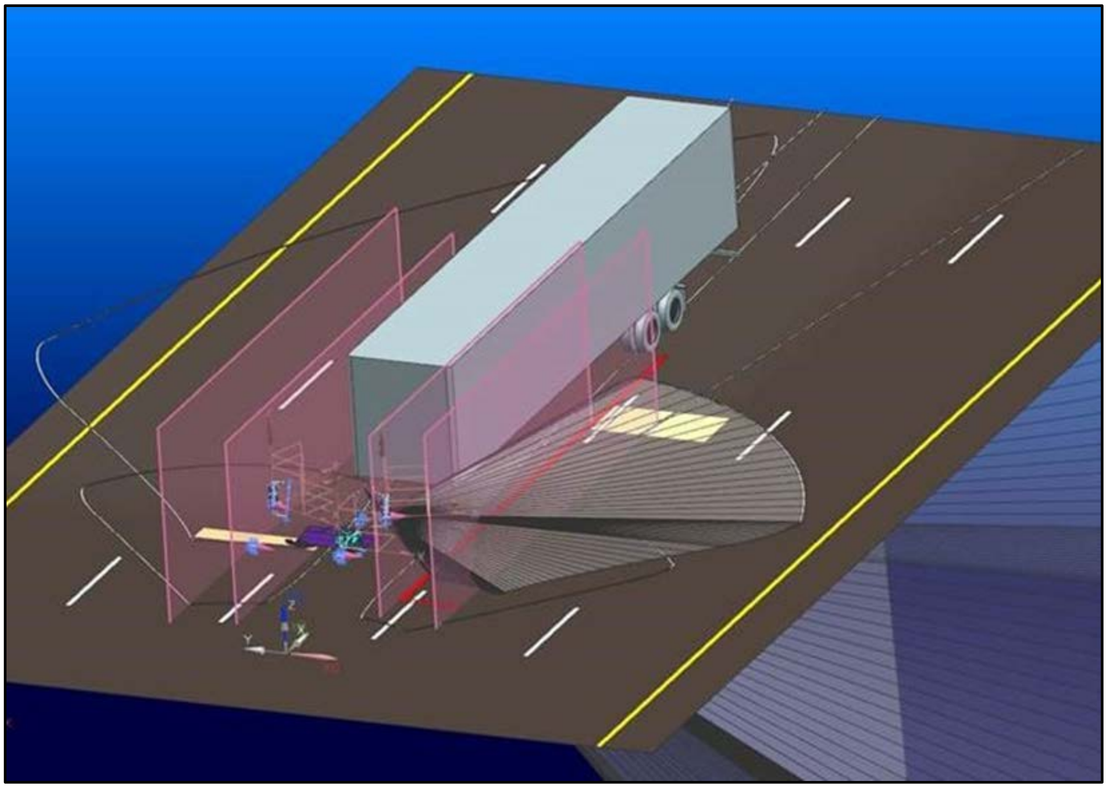

Figure 17. Screen image. Isometric view. Construction of manikin eye point–to-mirror and mirror-to-ground view cones.

While it is recognized that the methodology used in mirror adjustment among the manikins for the current production mirror simulation may vary significantly from many commercial driver's license (CDL) drivers' preferences, the procedure was chosen for multiple reasons, as discussed below.

- The mirror target procedure provided a means to handle a range of production design mirror adjustment angles combined with a range of simulated eye points without having to guess the most preferential mirror adjustment position for each manikin. Early in the simulation activity, another method—targeting the horizon at the top edge of each convex mirror—was attempted. The result was that a large portion of the convex mirror's reflective FOV was the same as that provided by the flat mirror's FOV, and another portion provided a view of nothing but higher elevations or sky.
- As discussed above, horizon targeting reduces the amount of surface applied to viewing objects that are within the CUT's view of the immediate surroundings. To stay in line with the purpose of the first phase of this study—to evaluate and compare a set of production mirrors against the prototype mirrors—a method that could bring the entire mirror surface under observation was required.
- Last, the primary purpose of this study was to determine if and how a novel method of constructing a convex mirror surface could improve upon any of the production mirrors on today's standard CUTs by improving the FOV or by reducing blind spots or image distortion. The targeting method of CUT mirror adjustment takes into account the fact

that there are at least three mirrors available on each side of the CUT that can work together to allow drivers to see objects that are not directly visible.

2.5.2 Result

This above-described mirror adjustment process was completed for all four manikins on each of the CUT's mirrors (six total) (see Figure 18, Figure 19, Figure 20, and Figure 21). The convex mirror zones were collected and provided to Dr. Hicks at Drexel University, who was subcontracted through the cooperative agreement between FMCSA and VTTI to provide the technology concept and optical expertise in development of the complex prototype mirror surfaces. Using these zones, it was determined that the large male eye point and resulting FOV zones would be selected as the design criteria for the novel convex mirrors (see Figure 21). Due to a tall male driver's height and distance seated rearward from the mirrors, his FOV and related blind zones around the CUT represent a worst-case scenario. Drivers who are shorter or sit closer to the mirrors will experience mirror views that are larger and have reduced blind zones. Furthermore, the size of the mirror zones created by the large male provided guidance for the minimum FOV—two adjacent lanes in width—for the novel convex mirrors.

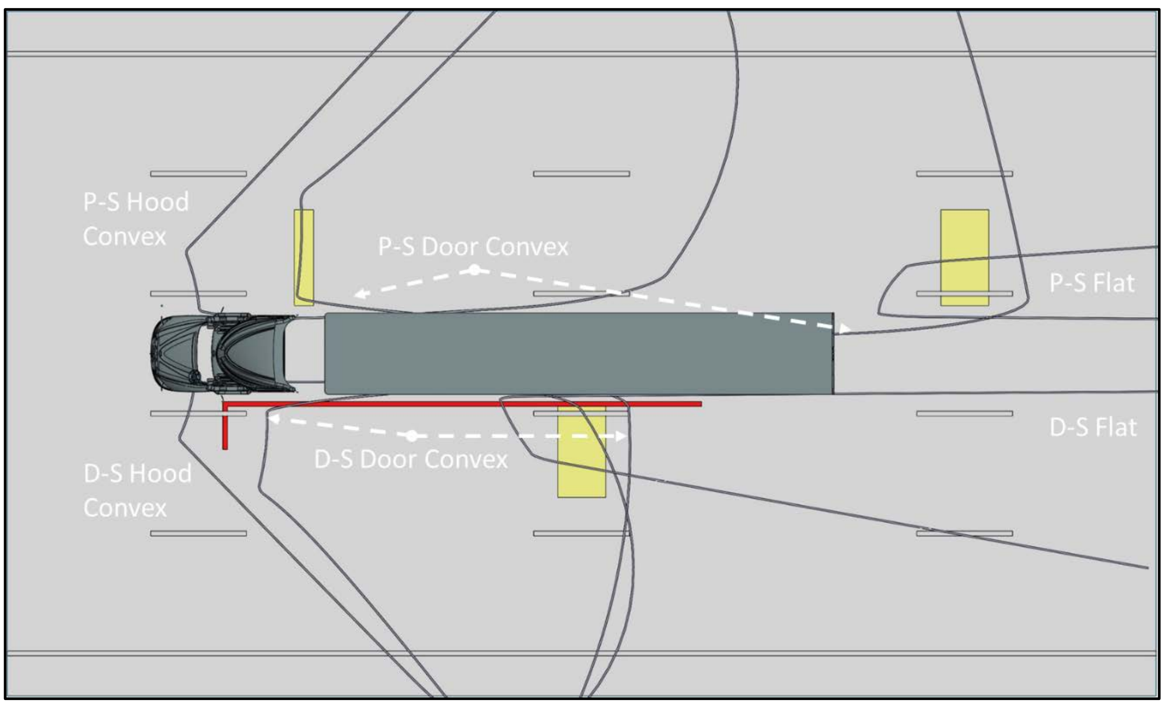

Figure 18. Screen image. Top view. Small female manikin, TFU.

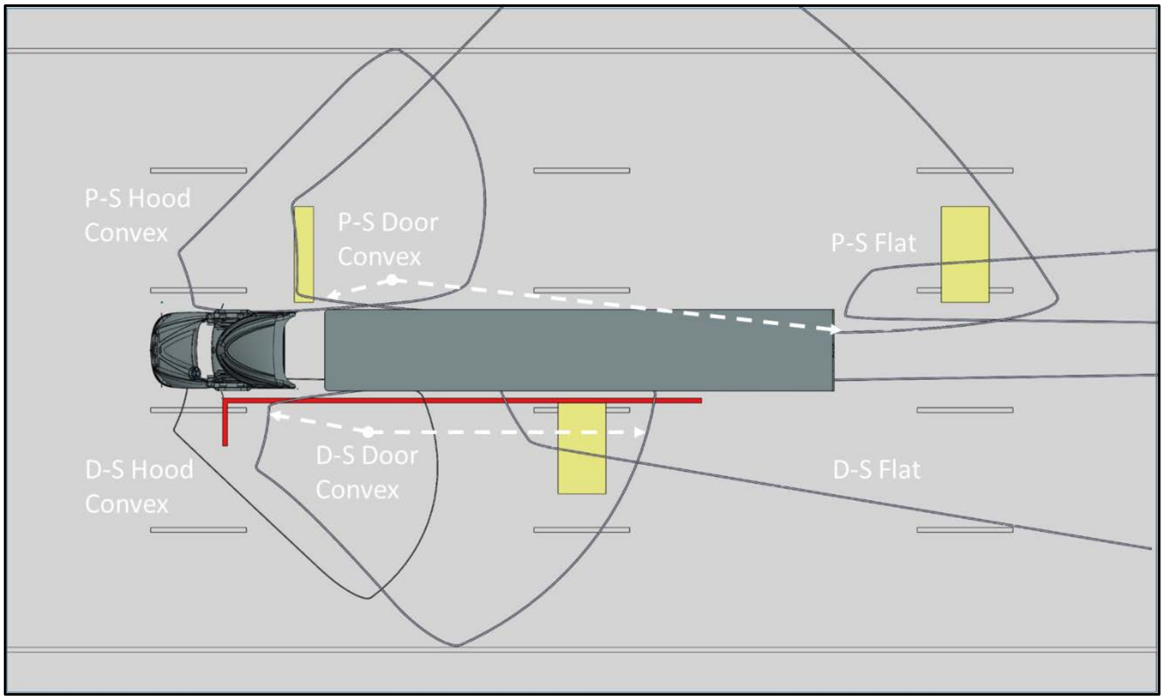

Figure 19. Screen image. Top view. Large female manikin, TFV.

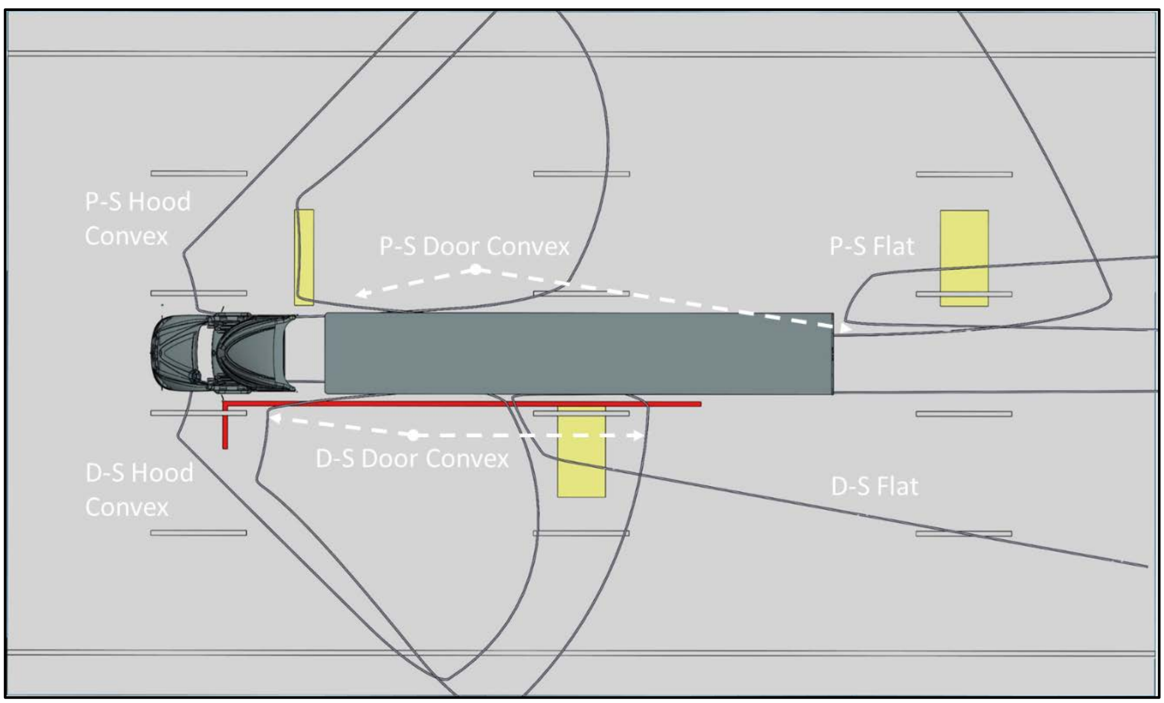

Figure 20. Screen image. Top view. Small male manikin, TMU.

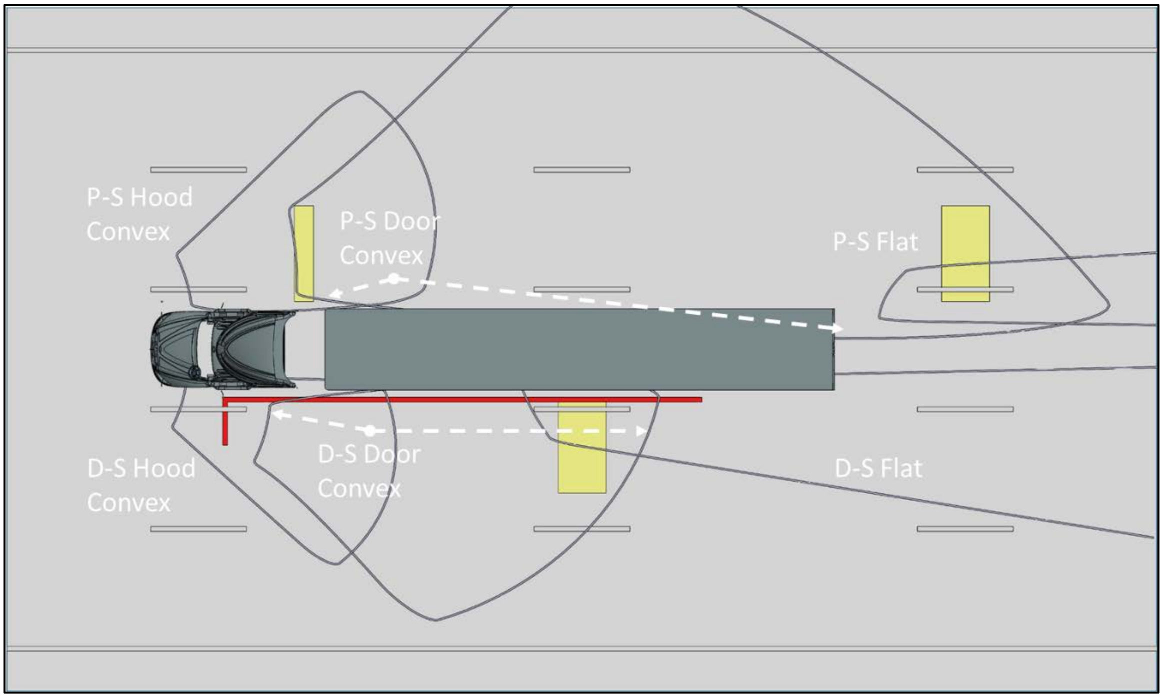

Figure 21. Screen image. Top view. Large male manikin, TMV.

2.6 PROTOTYPE MIRROR DEVELOPMENT

The eye points, mirror targets, and production mirror center and perimeter sizes were supplied to Dr. Hicks. Discussions between Dr. Hicks and the research team led to the conclusion that in order to simplify the calculations and number of resulting surfaces that could be developed, only the worst-case ground-view mirror reflective zones from the large male manikin would be applied for targeting the FOV mirror limits or perimeter, and the image distortion within the perimeter would apply average eye points. The average point for each mirror was different, as each manikin's gaze varied per mirror. Dr. Hicks calculated the averages from manikin coordinates provided by VTTI for the small female and large male manikins.

Using this guidance, Dr. Hicks applied the mirror adjustment targets and additional targets to specify the FOV of the novel convex mirrors for the hood and driver- and passenger-side doors, as shown in Figure 22.

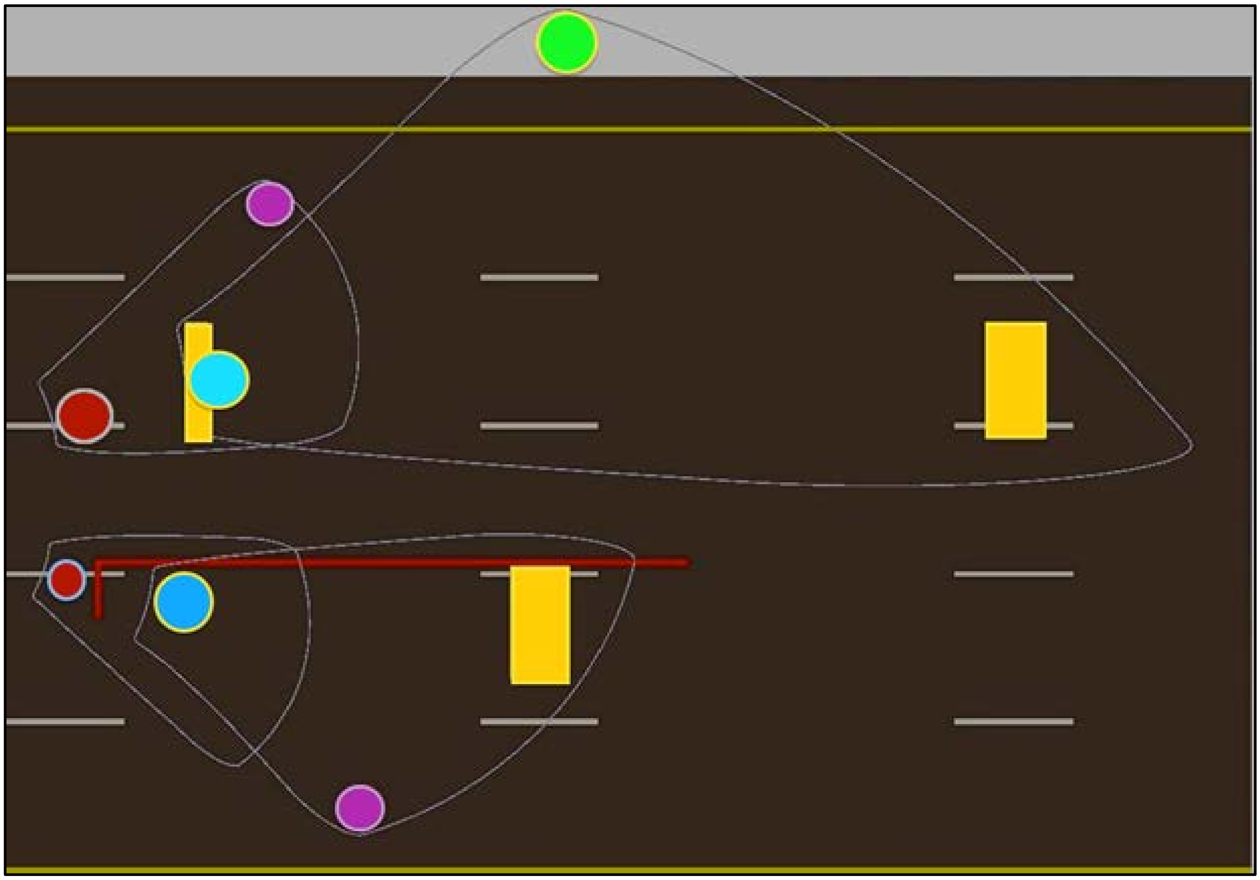

Figure 22. Screen image. Computational schematic view used for guidance of mirror surfaces.

For the two hood and two door mirrors, numerous color markers were applied using ray tracing simulations, which involve calculating iterating paths of light rays through an optical instrument to form boundary positions. The two smaller outlined triangular regions containing red disks are domains on the road that are typically shown by conventional production convex hood mirrors. The two larger outlined regions correspond to regions on the road shown by conventional production convex door mirrors.

While Dr. Hicks has applied this ray tracing simulation methodology in the past to the driver-side mirror of a light passenger vehicle, heavy CUTs require very different viewing areas. As such, this computational methodology was applied to a heavy CUT—and to passenger-side mirrors (rather than driver-side only)—for the first time during this study. Past work on light vehicles focused on targeting the horizon in the reflective image. However, the regions of interest for the CUT are more complex because the driver is essentially above those regions and needs to look down to see them. Nevertheless, the techniques developed in 2008 by Hicks are quite flexible, and while keeping the distortion down was a challenge, it was possible to image the triangular domains of interest, and regions even larger than that. As a result, the targeted regions for the prototype mirrors included the horizon.[16]

Using this approach, the surfaces of four mirrors were generated, one of which appears in Figure 23. The data provided by VTTI, along with the target visual regions, was enough to determine mirror shapes. The point plot of the driver-side hood mirror is also shown in Figure 23 (note that units are inches).

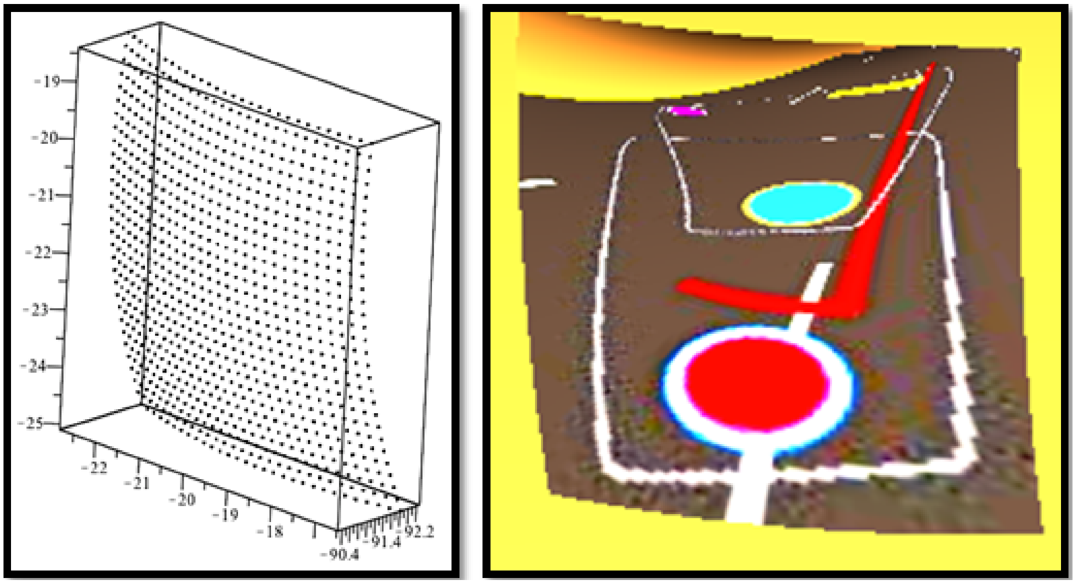

Figure 23. Screen images. Surface computational result (left) and reflective image rendering (right).

Once the data for a mirror was generated, the mirror was tested in simulation. This simulation was performed with a graphical ray tracer software called Persistence of Vision Raytracer or POV-Ray.(17) The test pattern demonstrated in Figure 22 was used as the ground, and the camera viewpoint could be selected to present a particular eye position. The results for the driver-side hood mirror appear on the right of Figure 23. Targets in this figure can be compared to positions of the test markers in Figure 22: the red circle, the aqua circle, and the red "L" shaped marker. Beyond the test pattern, the ground is set to appear yellow. The region enclosed by the closer white line, which includes the red disk, is the region imaged by a conventional production spherical mirror. The prototype mirror provides a significantly larger view. The red 'L' appears to be mostly straight, although the edge of the road in the upper left is somewhat curved. This is consistent with the work done with passenger vehicles; this method of producing mirrors minimizes distortion in the center of the image. Distortion is greatest on the edge of the image.

2.6.1 Fabrication

Point clouds of data were sent to the manufacturing contractor, B-Con Engineering Services, Inc. From these clouds, they created a 3D surface polynomial relative to the reference frame used on a diamond-turning machine. The diamond-turning machine utilized two linear axes and one rotating axis. B-Con Engineering programmed the surface in polar coordinates, allowing them to rough machine the mirror blank, stress relieve it, and then cut the optical surface on the aforementioned diamond-turning center. The final step was to polish the aluminum surface to remove the 5-nanometer-high marks from the diamond tool.

Prior to the optical expert's delivery of the mirror surface guidance to B-Con Engineering, mounting specifications were developed by the VTTI engineering team. The mountings were designed so that conventional production mirrors and the prototype convex mirrors could be quickly exchanged during the static CDL driver evaluation. The VTTI Hardware and Electronics Group also developed mounting plates to provide a transition between both the prototype and production mirrors and the production mirror mounting heads and arms to allow for quick removal and installation.

2.6.2 Result

The surfaces were fabricated by B-Con Engineering and delivered to VTTI prior to the start of the static driver evaluation. Upon receiving the prototype mirrors, the VTTI Hardware and Electronics Group attached the mirror parts to the transition plates. The transition plates and the mirror parts were then attached to the production mirror heads on the door and hood mounts. The resulting door assembly is shown in Figure 24, and the resulting hood assembly is shown in Figure 25. These combinations were applied in the driver static evaluation.

Figure 24. Photos. Driver-side (left) and passenger-side (right) flat and prototype convex door mirrors.

Figure 25. Photos. Driver-side (left) and passenger-side (right) prototype convex hood mirrors.

3. PRELIMINARY MIRROR MAPPING

3.1 INTRODUCTION

This section discusses the two-fold purpose of the preliminary mirror mapping. First, two research staff members, one male and one female, served as models for performing FOV mirror mapping for both production and prototype mirrors. Second, mirror setting and adjustment procedures were tested.

3.2 STATIC TEST AREA (VIRGINIA SMART ROAD)

The static test area (STA) is a level asphalt test pad designed to simulate five adjacent highway travel lanes. For this evaluation, each lane was 12 feet (3.7 meters) wide and marked with white lane tape.

3.2.1 Setup

Throughout testing, the CUT remained stationary and was parked in the center lane with two lanes on either side and minimal truck and trailer articulation. The CUT was equipped with standard flat production mirrors mounted on the driver and passenger sides of the truck cab along with smaller production convex mirrors mounted just below each of the flat mirrors. Additional sets of convex mirrors were mounted on the right and left front fenders of the tractor-truck. The CUT configuration dimensions are displayed in Figure 26.

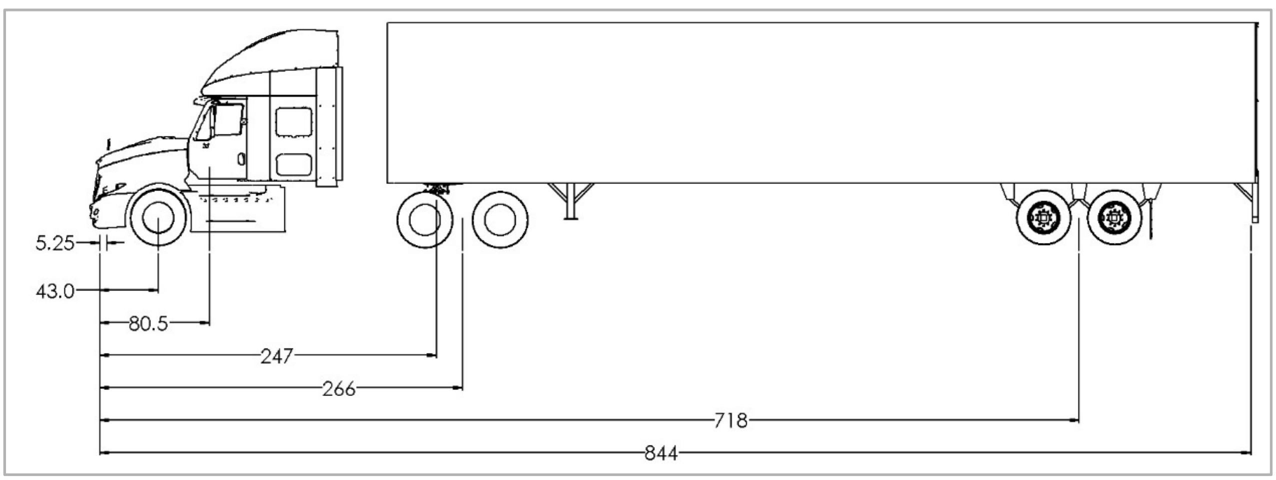

Figure 26. CAD image. A side view of the scaled model of the configuration of the CUT used for preliminary FOV and static evaluation testing. Units are in inches.

A zero line was created by dropping a plumb bob from designated points on the truck and trailer chassis, including but not limited to the front-bumper mount/front-of-truck frame and the rear trailer under-ride guard. A multi-axis laser level was used to create a 90-degree angle from the zero line of the truck out to various target distances that replicated a multi-lane highway, where approximately two 12-foot lanes were marked on either side of the truck. These measurements were also used to properly configure the MCS (see Section 2.5.1). A snap/chalk line was created using the plumb bob points. All subsequent lines were marked with chalk marking paint from 0 to 100 feet on 2-foot increments.

3.3 MIRROR APPLICATION

Standard production mirrors for an International ProStar were used as the production mirrors, and the prototype mirrors were machined out of aluminum then polished to mirror image quality. Both sets of mirrors were disassembled and a bracket system using an interlocking finger design was developed, allowing both sets to be removed quickly, while still allowing the mirror and mount to be recessed into the factory housings.

3.3.1 Mirror Check Station Protocol

The MCS, described in Section 2.5.1, was applied to reduce overlapping mirror views while maintaining views of both sides of the trailer and maximizing the viewable area for each mirror. To begin, four targets were placed around the tractor and trailer. Two of the targets were orange, 1×10 feet, and located 15 feet from the hood-mounted convex mirror on the passenger side and 9 feet from the hood-mounted driver-side mirror. It is important to note that researchers added a second 1×10-foot target in addition to the MCS protocol to aid in applying similar proportional viewing areas for targets on both sides. The results of this allowed the driver/viewer to see the target in the same position on both mirrors. The two remaining targets were 5×10 feet long. One was placed on the driver side, 35 feet rearward from the driver-door mirror. The second target was placed 75 feet rearward from the passenger-side mirror and oriented comparably to the driver-side target.

3.3.2 Changing Mirrors

The mirrors were changed out by lifting up on the mirror, releasing the interlocking finger design, and then replaced/interchanged by sliding the interlocking fingers back down into the housing as seen in Figure 27.

Figure 27. Photos. Mirror changing procedure demonstration of hood (left) without mirror installed and door (right) with mirror installed.

3.3.3 Mirror Adjustments

Mirror adjustments were made by the researcher outside of the vehicle as prompted by radio communication from the researcher inside the vehicle. A laser grid was designed that projected out of the back of the mirror housing onto a Plexiglas square with corresponding grid coordinates. The grid had an incremental change of .01 inches, which equated to a 1-degree change.[i] Each mirror was set to a zero state before the driver entered the vehicle and before the driver adjusted the mirrors, based on the MCS protocol.

3.4 RESEARCHER ACQUISITION

Drivers representing both bookends of the sitting eye-height (low and high) spectrum were used based on the manikin development referred to in Section 2.2 (see Table 1). The research team selected a 5th percentile stature female driver, measuring 69.6 cm, to represent the low-sitting eye-height position, and a 95th percentile stature male driver, measuring 85.5cm, to represent the high-sitting eye-height position.

[i] The OEM specifications that were applied to the CAD modeling were discovered to be different than the actual measured degree range of the production mirrors that were on the truck. The OEM specified: for door mirrors: ±12 degrees adjustment in the left/right and up/down positions from the nominal position; for the hood mirrors: ±11 degrees left/right, and ±8.5 degrees up/down. The actual degree range measured for this study for door mirrors was ±16 degrees left/right, and ±14 degrees up/down. The hood mirror range was ±17 degrees left/right and ±16 degrees up/down.

3.5 FIELD OF VIEW MAPPING

For FOV mapping, a measurement tool with a colored base holding a pole of a contrasting color was constructed. The contrasting color went up the pole to a height of 32 inches, and was then separated by a 1-inch horizontal bar. On top of the bar, a different contrasting color ran up the pole to a total height of 48 inches. This tool allowed for measurements and data to be taken from the subject's view in relation to ground level and approximate maximum bumper height of sedan vehicles (32 inches). Researcher 1 started with the measurement tool base placed on the ground at the zero line of the tractor's front bumper mount and walked along the CUT-side zero line in 2-foot increments until the model could see either the tool's 32-inch intersection or its base (see Figure 28).

Figure 28. Photos. FOV mapping process demonstration with 0-inch base and 32-inch above-ground features.

Once a measurement was recorded, a steel tape measure was extended 90 degrees perpendicular, along the pavement, from the CUT-side zero line to the outermost second lane marking tape. Researcher 1 slid the measurement tool away from the zero line along the tape measure until the model identified either its 0-inch (base) or until the 32-inch mark was no longer visible. Once the measurement was recorded, Researcher 1 continued to move the measurement tool along the tape measure until it was no longer visible at the last unmeasured intersection, and that measurement was then recorded. This measuring procedure continued along the entire length of the vehicle in 2-foot increments, stopping at the 100-foot mark, and was then repeated for the opposite side.

A consistent approach to establishing FOV size was published in a report entitled "Vehicle Rearview Image Field of View and Quality Measurement."[18] This approach also helped facilitate the use of contrasting areas of height for the measurement tool.

3.5.1 Field of View Mapping Results

The 5th percentile female model FOV mapping is shown in Figure 29, and the 95th percentile male model FOV mapping is shown in Figure 30. The prototype hood-mounted convex mirrors mostly provided a slight FOV rearrangement when compared to the production hood-mounted convex mirrors, though prototype mirrors generally extended the FOV slightly outward from the truck. There are a few noteworthy results concerning the door-mounted convex mirrors. Between models, the production mirrors provided similar FOVs, with the male model seeing slightly more for most mirrors. However, using the prototype mirror, the female model noted a much larger FOV on the driver side.

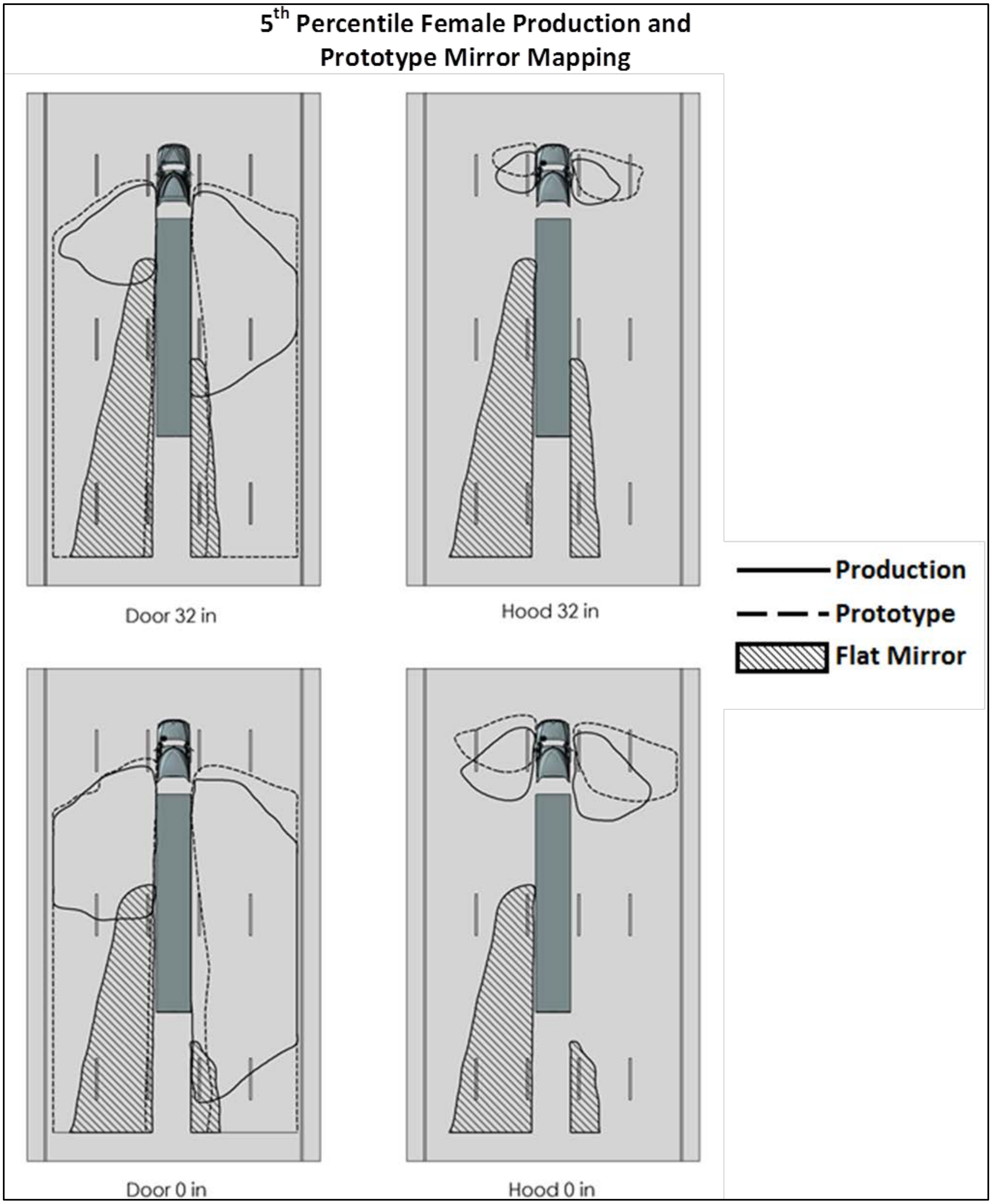

Figure 29. Diagram. 5th percentile individuals' FOV mappings of door and hood prototype mirrors at 0-inch and 32-inch measurements.

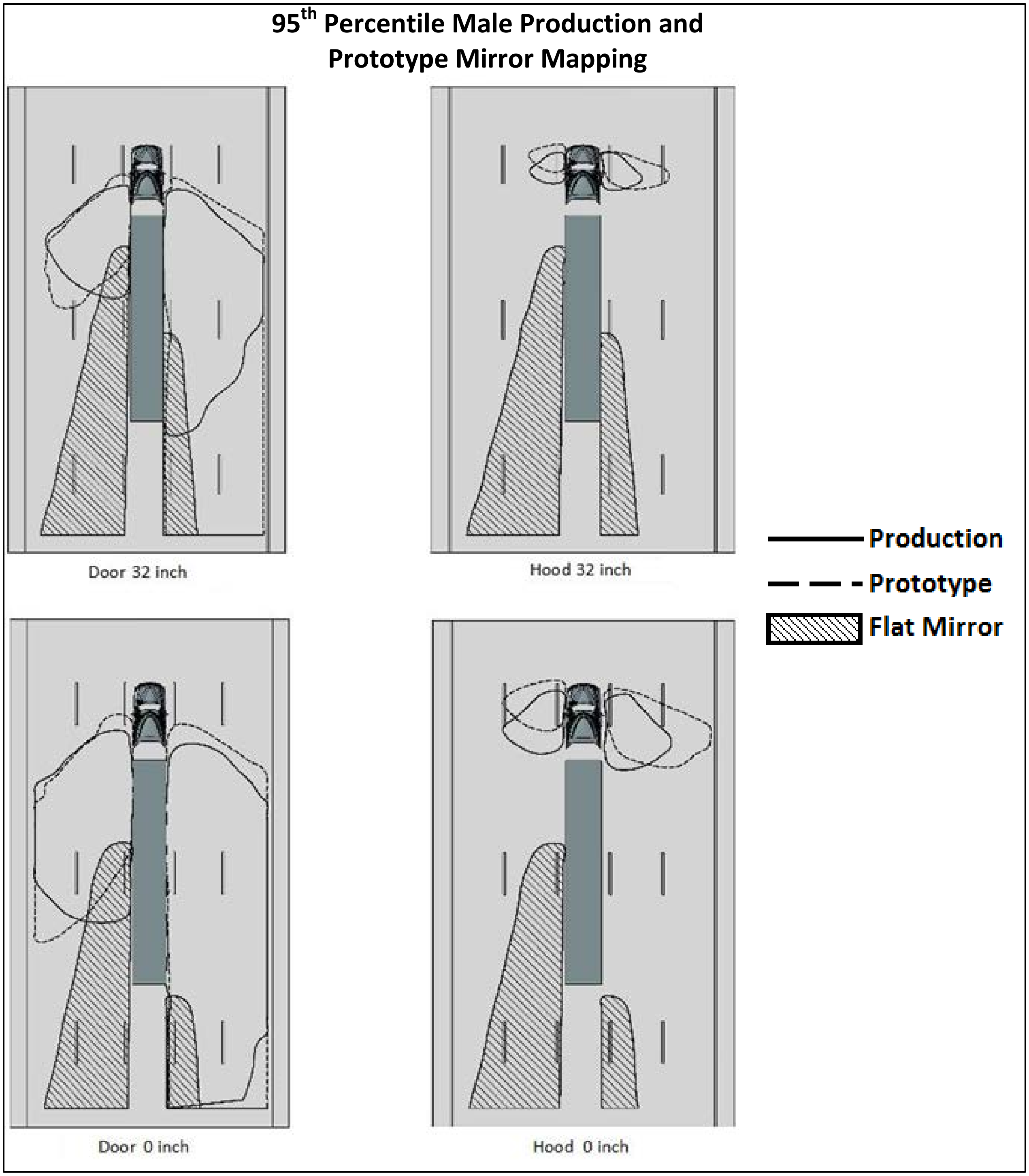

Figure 30. Diagram. 95th percentile individuals' FOV mappings of door and hood prototype mirrors at 0-inch and 32-inch measurements.

4. STATIC EVALUATION

4.1 STUDY DESIGN

This study was designed to collect quantitative and qualitative data on drivers' subjective ratings of a prototype mirror design. Subjective ratings were garnered through interview-style questions, while measurements of some aspects were taken based on driver responses during the study. This approach allowed for a well-rounded view of how CMV drivers might accept these prototype mirrors and allowed them to provide feedback regarding any potential limitations of the prototype mirror design and functional application.

4.1.1 Development of Evaluations

The three functions of the convex mirrors that were tested during the third FAST DASH safety technology evaluation were FOV, image distortion, and distance estimation.

4.1.2 Field of View

FOV is an important factor in understanding mirror-reflected views. Development of these study procedures involved demonstrating to drivers the existing FOV for production and prototype mirrors to help with a proper comparison. Near and far FOV zones were identified and marked off. A total of 30 cones were placed around the truck, crossing from one zone to another (see Figure 31 and Figure 32). FOV for each mirror was established by recording the number and location of cones surrounding the truck that were visible to the driver.

4.1.2.1 Field of View Process Development

Utilizing vision zones established in SAE J1750 and Technology and Maintenance Council (TMC) RP-428 guidance, the research team established the near and far field zones to create the overall measurement space schema.[19] This, along with the previous design of targets, led to the use of traffic cones as the vision targets. The TMC report also influenced the placement of the FOV targets through minimum target visibility in specific areas of the truck (i.e., front truck axle and rear trailer axle).

Establishing a perimeter FOV is important in determining breadth of view, and combined with the above report, influenced the MCS-based approach to mirror adjustment for maximizing indirect visibility. The reduction of overlap in mirror image was another important factor for achieving a realistic FOV for each participant. This also influenced the restriction of participant actions to focusing on direct looks and minimal head movements.[20]

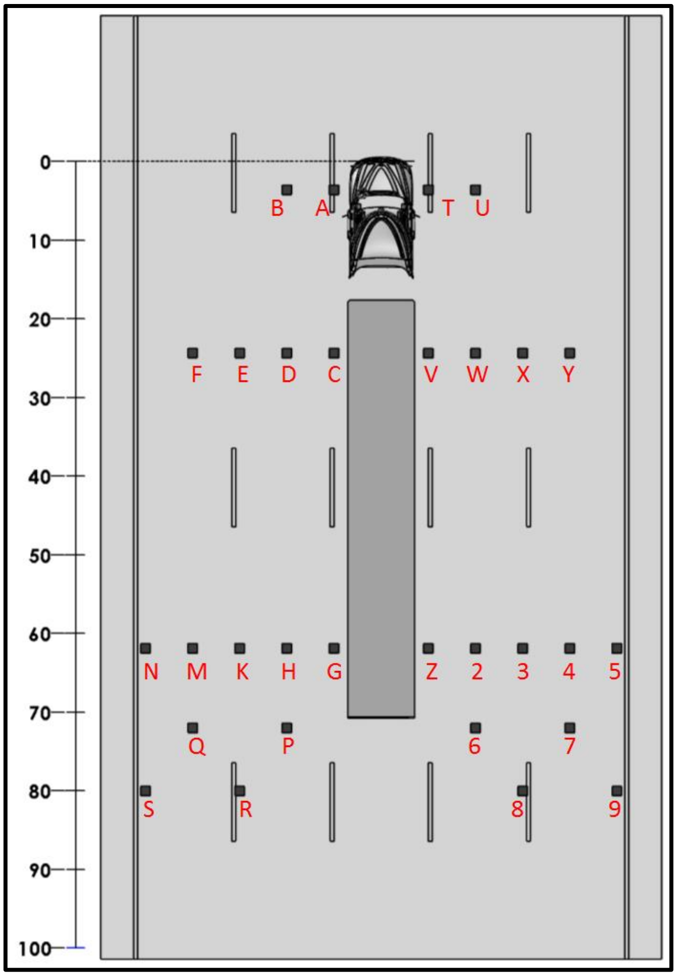

Figure 31. Diagram. A scaled overview image representing the cone labels identified by drivers in the FOV task. Measurements are labeled in feet.

Figure 32. Photos. An image of the cones that were available to drivers in the FOV task (on both sides of the CUT).

4.1.3 Image Distortion

Image distortion can be a complex issue when dealing with any non-flat mirror. To ensure accurate understanding of image distortion between the convex and prototype mirrors, a 5×5-foot grid consisting of 1×1-foot squares in a checkerboard pattern was constructed. Each grid square had the numbers 1–25 labeled in reverse so that in the reflected image the number was clearly readable (see Figure 33). This grid was used to determine distortion across the surface of the mirror. The grid was placed on a rolling platform that could be adjusted from flush (0 inches) to 28 inches in height, allowing a maximum height of 88 inches. The grid was then positioned so that it filled the mirror fully, while all grid squares were still visible (see Figure 34). Drivers identified each square that was distorted, indicating enlargement, shrinkage, and overall distortion.

Figure 33. Photo. The checkerboard used during the image distortion task. The numbers were mirrored to provide a properly oriented number sequence for driver identification while looking at mirrors.

Figure 34. Photos. The checkerboard was adjusted based on feedback from the drivers to cover the majority of the four mirror surface positions on the hood and doors during the image distortion task. The left image is the prototype driver-side door convex mirror and the right image is the production driver-side door convex mirror.

4.1.4 Distance Estimation

All cones from the FOV portion of the study were removed for this task and the flat door mirrors were covered. The driver was told to stare at the center console control cluster while the exterior researcher placed a 4-foot cylindrical cone in a designated position, to ensure that the driver got no visual reference by watching movement in the mirror. Those positions from the front of the cab were 20 and 28 feet on the driver side and 58 and 66 feet on the passenger side (see Figure 35). Researchers asked drivers to estimate distance rearward from the mirror they were using (see Figure 36). The researcher inside the vehicle would prompt the driver to look up and at the appropriate convex mirror (driver-side or passenger-side), and after 2 seconds to turn back to the researcher and estimate the distance from the respective mirror to the cylindrical cone.

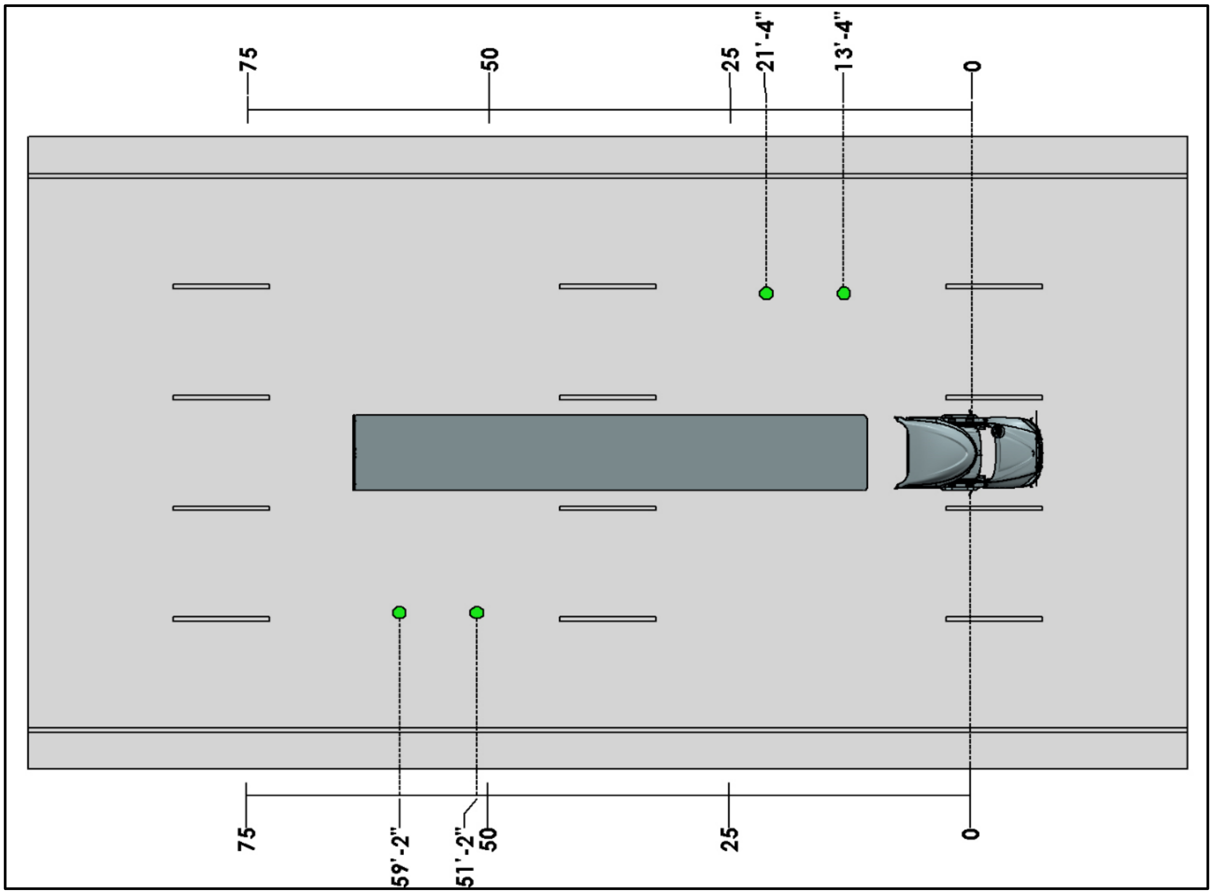

Figure 35. Diagram. Overview representation of the two cone positions on the passenger-side (lower-near trailer rear axle) and driver-side (upper-near tractor rear axle) provided for the drivers during the distance estimation task. Dimensions illustrate the true distances rearward of the driver-side and passenger-side mirrors. Measurements are labeled in feet, with cones labeled in feet and inches.

Figure 36. Photos. The images provide an example of the passenger-side (left) and driver-side (right) cones positioned at one of the two randomly assigned locations for drivers during the distance estimation task.

4.2 METHOD

The methodology used in this study is described in this section. The figure in Appendix C details a methodological flow chart of procedure.

4.2.1 Recruitment and Participants

Due to the Paperwork Reduction Act (PRA), limitations exist on the number of study participants who can fill out surveys and/or questionnaires (no more than nine participants are allowed to fill out questionnaires/surveys). During the third FAST DASH safety technology evaluation, nine individuals were evaluated. Via phone, the research team contacted potential participants from the VTTI Participant Interest Database who had indicated that they held a CDL. The research team also selected individuals to contact with preference for a close location (within 30 minutes of the research site in Blacksburg, VA). Contacted individuals were informed about study details and compensation and then asked for a confirmation of interest. At this point, individuals were screened with the following criteria:

- Must hold a current Class A CDL (with expiration after September 2015).
- Must have held a Class A CDL position within the last 6 months.
- Must be at least 26 years old.
- Must be willing to fill out a W-9 tax form.
- Minimum 5 years of CDL driving experience.
- Visual acuity of 20/40 or better.
- Regularly operates a CUT comfortably.
- Has some experience with hood mirrors.

Upon confirmation that the driver was eligible for participation, the researcher would offer dates/times available for participation and obtain an email address to provide the participant with directions, a day-before reminder, and a copy of the informed consent for early review.

4.2.2 Arrival Procedure

Upon arrival, the participant was met by a researcher and escorted to a prep room on site. At this time, paperwork—such as the informed consent, W-9, and demographics questionnaire (see Appendix A)—was completed. Next, a vision test and seated eye-height measurement were completed. The vision test was standard, and based on a Snellen Eye Chart. For seated eye height (the distance between a sitting surface and the ectocanthus landmark on the outer corner of the right eye) an anthropometer was used. Participants were instructed to sit on a table with their knees at a 90-degree angle with the head in a Frankfort plane and their hands placed according to the Centers for Disease Control and Prevention (CDC) Anthropometric Guide.(21)

Afterwards, participants were moved outside for the remainder of the study. All experimental sessions were conducted during daylight hours while the sun was at various angles overhead. Weather conditions on the day of each session were recorded and a note was made if there were issues. No experimental sessions were conducted at times when visibility was reduced by conditions such as rain or fog.

Two researchers with radios were present for communication during the study. A tractor with trailer attachment was located in the STA at VTTI in the middle of five designated lanes. The truck seat was set in the farthest rearward and down position. Production convex mirrors were attached. The MCS protocol was set up upon participant arrival.

At the beginning of the outside portion of the study, the participants were shown the experimental test vehicle in the STA and asked to walk around the vehicle, where the researcher pointed out placed cones and the checkerboard panel. The participants sat in the driver seat and adjusted to a normal driving position.

4.2.3 Mirror Adjustment

Each participating driver adjusted production and prototype mirrors according to the MCS protocol(22) and the 5×10-foot and 1×10-foot visual markers placed surrounding the CUT (see Figure 37). Precise mirror settings were recorded using a laser and grid measurement system (pictured in Figure 38). These measurements were necessary for referencing later in the study. The mirror adjustment procedures and measurements were completed at various points during the study, following the process outlined below:

- Rotate each flat mirror horizontally until the inside edge shows only the left or right edge of the truck body and trailer.
- Tilt each flat mirror vertically until the appropriate 5×10-foot target is visible in the bottom of the mirror.
- Rotate each convex mirror horizontally until the inside edge shows only the left and right sides of the truck body or trailer.
  - Tilt each door-mounted convex mirror vertically until the appropriate 5×10-foot target is visible in the top of the mirror while keeping the trailer rear axle tires in view.
  - Adjust the hood convex mirrors so that the inside edges of the mirrors shows the side of the tractor, and the 1×10-foot target is visible at the top of each hood convex mirror.

Figure 37. Photos. The mirror adjustment procedure used targets to direct drivers how to coordinate the view of the convex mirrors and upper flat mirror on each side of the CUT. An example is provided here using the white target as demonstrated on the driver-side door with prototype convex (left) and production convex (right) mirrors.

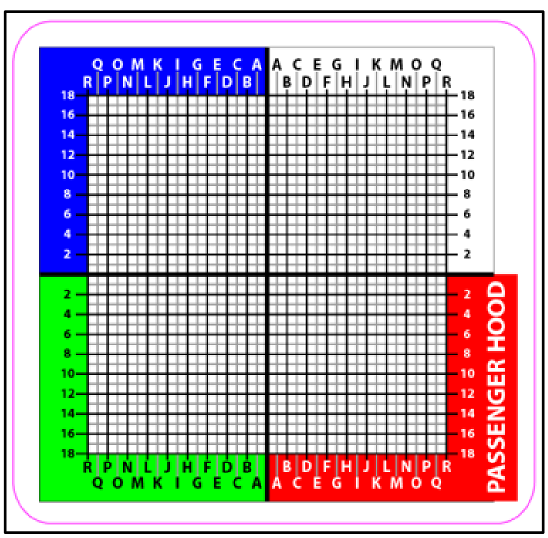

Figure 38. Grid. Mirror adjustment laser grid. Example of the grid applied on the passenger-hood mirror mount.

4.2.4 Field of View

The in-cab researcher asked the drivers to evaluate the view of the 15 labeled cones on the driver side and then to evaluate the view of 15 labeled cones on the passenger side using both sets of mirrors (independently) multiple times during the study.

4.2.5 Image Distortion

The second researcher moved the checkerboard panel (refer to Section 4.1.3) clockwise starting at the driver-side door-mounted convex mirror, and ending at the passenger-side door-mounted convex mirror. Drivers rated the distortion and their satisfaction level for each of the mirrors. This process was carried out twice with production mirrors (both before and after viewing prototype mirrors, to determine if viewing the prototype mirror had any effect on production mirror ratings) and once with prototype mirrors.

4.2.6 Distance Estimation

Each driver first estimated differences in the prototype mirrors four times (two for driver side, two for passenger side), and was then asked to repeat the process with the production mirrors. The flat mirrors were covered during the evaluation of each set of convex mirrors. The drivers then responded to follow-up questions (see Appendix B). The outside researcher had a list of randomly generated cone locations for both production and prototype mirrors for each individual driver. This allowed counter-balancing of cones in front of or behind the respective tire axle.

4.2.7 Summary Questions

After evaluating the production mirrors for a second time, the drivers verbally responded to another set of evaluative questions pertaining to their preference of each mirror for FOV image distortion, distance estimation, and then overall preference (see Appendix B).

4.2.8 Data Handling

Appendix B contains the questionnaire used for driver evaluation of mirrors. Questions regarding satisfaction or objective evaluation were asked on a per mirror basis. To create a comparison, data across mirror location (e.g., driver-side door-mounted convex mirror) was often aggregated to create one average for each of the two mirror types. This allowed for the corresponding analyses to be performed on the averages and standard deviations of these newly created aggregate variables.

For objective evaluation of distance estimation, data were handled in two ways. First, an overall aggregated value was created based on the difference between estimated distance and actual distance. Then, estimates were broken into overestimation and underestimation and examined piece by piece.

4.2.9 Analysis

The following section details the results of the static evaluation with participant drivers. Primary analyses include one-sample *t*-test and paired-sample *t*-test of means. Additionally, when data suggested a violation of the assumption of normal distribution, a Wilcoxon signed rank test of medians was used. These analyses provide *t*-statistics and *p*-values when performing *t*-tests, and a *W*-statistic when performing the Wilcoxon signed rank test.

4.3 RESULTS

4.3.1 Participant Demographics

A total of nine drivers were recruited over the 2-week data collection period. The drivers (all male) reported both personal demographics and work experience during the screening process. The average age of drivers was 44.7 years (standard deviation [SD] = 14.2). Drivers had an average self-reported height of 71.9 inches (SD = 1.9), and an average self-reported weight of 223.7 pounds (SD =30.2). Drivers reported working an average of 52.1 hours per week (SD = 18.6). They reported driving approximately 40.7 hours per week on average (SD = 17.3). All drivers reported being currently employed and operating company-owned trucks. Drivers reported an average of 18.8 years (SD = 11.4) of CDL experience, with a minimum of 8 years and a maximum of 39 years. Sitting eye-height for drivers averaged at 816.7 mm (SD = 18.1), including their measurements along with male and female models at 5th and 95th percentile sitting eye-height,[23] displayed in Figure 39.

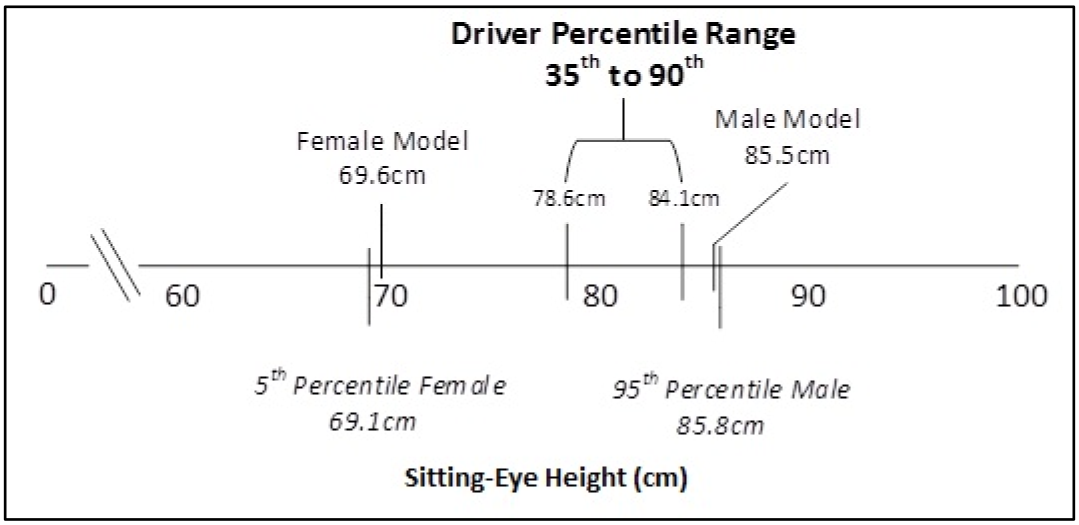

Figure 39. Diagram. Sitting eye-height of drivers, models, and 5th/95th percentile individuals.

4.3.2 Mirror Adjustment

Proper mirror positioning according to the MCS protocol allows for standardization of what objects and targets drivers can see in their indirect vision.[24] This provided researchers with the most control over what individuals were able to view in mirrors. This was previously demonstrated in Figure 38, displaying the mirror adjustment quadrant with the positions of drivers and models, detailing the angles set by individuals. Positions closer to the top represent moving the mirror down, while positions nearer the right edge represent the mirror pointed more to the driver's left. Drivers were allowed to adjust their seats according to how they would normally drive, so there is some variance expected in mirror position despite similarities in sitting eye-height.

4.3.3 Field of View

Individual differences regarding FOV are composed of both objective ratings of visual capabilities based on the seated, sitting-eye height, and mirror positions, and also subjective assessment of said FOV. Identifying what individuals see for both production and prototype mirrors and learning their corresponding attitudes towards these mirrors is imperative for evaluating the prototype mirrors with regard to FOV indirect visibility.

4.3.3.1 Objective Evaluation of Field of View

To gauge indirect visibility provided by both mirror types, drivers were instructed to view and label the cones according to what they could see (see Figure 31). This allowed researchers to understand the viewing angle each driver had, and supplied drivers with a comparison between production and prototype mirrors. This also provided each driver with time to become more comfortable and familiar with the mirrors before asking questions related to other mirror functions.

Minimal differences between mirrors with regard to cone visibility were expected due to the positioning of the mirrors in accordance with the MCS protocol.(25) However, some differences were still noted. Table 2 shows the average number of cones visible for each mirror examined by drivers. On average, drivers were able to see 26.44 cones using the production mirrors, and 36.00 cones using the prototype mirrors. As such, drivers saw a significantly larger number of cones using the prototype mirrors ($t = 11.44$, $p < 0.05$).

Table 2. Average number of cones visible by mirror location and mirror type.

Average Cones by Mirror	D. Door Flat	D. Door Convex	D. Hood Convex	P. Door Flat	P. Door Convex	P. Hood Convex	Total Cones Visible
Production mirrors	5.00	4.00	2.00	1.67	11.22	2.56	26.44
Prototype mirrors	5.00	11.33	3.11	1.78	11.44	3.33	36.00
Difference in prototype to production	0	7.33*	1.11	0.11	0.22	0.77	9.56*

Note: “D.” references driver-side; “P.” references passenger-side.

*Significant at the 0.05 level.

Of the 15 cones visible on the driver side of the vehicle, drivers saw an average of 5.00 cones using the flat mirrors, 4.00 cones in the production door mirrors, and 2.00 cones in the production hood mirrors, while reporting 11.33 cones in the prototype door mirrors and 3.11 cones in the prototype hood mirrors. Of the 15 cones visible on the passenger side of the vehicle, they saw an average of 1.72 cones using the flat mirrors, 11.22 cones in the production door mirrors and 2.56 cones in the production hood mirrors, while reporting 11.44 cones in the prototype door mirrors and 3.33 cones in the prototype hood mirrors. Drivers were able to see significantly more cones in the driver-side door mirror using the prototype mirror ($t = 6.42$, $p < 0.05$), but no other mirrors demonstrated that significance. However, drivers did not see fewer cones for any prototype mirror.

The door convex mirrors provided the most overall visibility of the static test area. This represented the largest difference between production and convex mirrors; however, these results were only for the driver side. This is likely due to the fact that the target on the passenger side was further back, allowing for greater visibility of cones than on the driver side.

Note: flat mirrors remained in relatively the same position, though mirror adjustment allowed one driver to see an extra cone during FOV evaluation after switching from production to prototype mirrors.

4.3.3.2 Subjective Evaluation of Field of View

Drivers were asked three different sets of questions about FOV each time they viewed a set of mirrors. Their satisfaction with the mirrors was evaluated on a mirror-by-mirror basis. In addition, drivers evaluated their overall preference for FOV and the degree that they believed FOV would help with driving safety. Table 3 details participant average ratings of mirrors on a 1–7 Likert-type scale. For both mirror preference and safety ratings, the average score for drivers was 3.44 (t = 1.22, p > 0.05). Though not significant, the trend was that drivers preferred production mirrors to prototype mirrors with regards to FOV.

Table 3. Response set with average and standard deviation for field of view.

Rate how much you agree or disagree with the following statements:	1	2	3	4	5	6	7	n	Avg.	SD
Prototype: I am satisfied with the field of view provided by the driver’s side door-mounted convex mirror.	1	0	2	0	3	2	1	9	4.56	1.88
Prototype: I am satisfied with the field of view provided by the driver’s side hood-mounted convex mirror.	0	0	1	0	5	1	2	9	5.33	1.22
Prototype: I am satisfied with the field of view provided by the passenger’s side door-mounted convex mirror.	1	1	1	0	2	2	2	9	4.67	2.18
Prototype: I am satisfied with the field of view provided by the passenger’s side hood-mounted convex mirror.	0	0	1	2	1	2	3	9	5.44	1.51
Production: I am satisfied with the field of view provided by the driver’s side door-mounted convex mirror.	0	0	1	0	2	4	2	9	5.67	1.22
Production: I am satisfied with the field of view provided by the driver’s hood-mounted convex mirror.	0	1	1	0	0	3	4	9	5.67	1.87
Production: I am satisfied with the field of view provided by the passenger’s side door-mounted convex mirror.	0	0	0	1	0	5	3	9	6.11	0.93
Production: I am satisfied with the field of view provided by the passenger’s hood-mounted convex mirror.	0	2	0	1	0	2	4	9	5.33	2.12

Rate how much you agree or disagree with the following statements:	1	2	3	4	5	6	7	n	Avg.	SD
I prefer the field of view provided by the prototype mirrors.	2	2	1	1	1	1	1	9	3.44	2.19
I believe driving would be safer with the field of view provided by the prototype mirrors.	2	2	1	1	1	1	1	9	3.44	2.19

Note: Response scale is as follows: 1 = "Strongly Disagree," 2 = "Disagree," 3 = "Somewhat Disagree," 4 = Neither Agree nor Disagree," 5 = "Somewhat Agree," 6 = "Agree," 7 = "Strongly Agree."

4.3.4 Image Distortion

Understanding how individuals comprehend and visualize image distortion is critical when evaluating radial or multiple-radii convex mirrors, as distortion becomes a greater issue the more the face of the mirror bends. The research team examined how image distortion affected drivers' views in the mirror, and then asked them for their subjective evaluation of the mirrors.

4.3.4.1 Objective Evaluation of Image Distortion

Due to the nature of perceptual differences, an objective evaluation of image distortion using drivers was implausible. However, because of the within-subjects design of providing both prototype and production mirrors, the research team was able to control for differences in individual perception. As such, researchers asked drivers first to allow a researcher to adjust the checkerboard so that it was filling as much mirror space as possible, then researchers asked drivers to list the numbers that looked distorted or unclear to them. More specifically, drivers were asked to comment on numbers that no longer looked like the squares they had seen during the walk-around via direct visibility.

The drivers provided feedback by identifying the individual squares that had the most distortion (by number). Note that some squares were not visible to some drivers depending on their mirror adjustment and position of the image distortion checkerboard relative to the mirror being rated. Therefore, each square represents the number of drivers who rated the square as distorted of those drivers who could see that square.

Table 4 details the average number of distorted squares as noted by drivers for each mirror location and mirror type (prototype and production). On average, the prototype mirror had 14.17 squares reported as distorted, while drivers reported an average of 8.17 distorted squares for the production mirrors. This difference is significant, in that prototype mirrors display more perceived distortion than production mirrors ($t = 3.71$, $p < 0.05$). Between production and prototype mirrors, hood mirrors showed less average distortion difference than door mirrors (3.78 versus 8.22). These results are available as percentages in each square in Figure 40 (production) and Figure 41 (prototype).

Table 4. Average number of distorted squares, by mirror location and type.

Average Distortion by Mirror	D. Door Convex	D. Hood Convex	P. Door Convex	P. Hood Convex	Average Distortion
Production mirrors	5.00	8.33	8.56	10.78	8.17
Prototype mirrors	13.78	13.56	16.22	13.11	14.17
Difference in prototype to production	8.78*	5.23*	7.66*	2.33	6.00*

Note: "D." references driver; "P." references passenger.

*Significant at the 0.05 level.

Driver Hood

6 (75%)	3 (38%)	2 (22%)	0 (0%)	0 (0%)
2 (29%)	2 (22%)	0 (0%)	0 (0%)	0 (0%)
2 (29%)	1 (13%)	2 (22%)	1 (11%)	2 (22%)
7 (78%)	6 (67%)	3 (33%)	2 (22%)	3 (33%)
9 (100%)	7 (78%)	7 (78%)	4 (44%)	4 (44%)

Passenger Hood

0 (0%)	0 (0%)	0 (0%)	1 (11%)	4 (50%)
0 (0%)	0 (0%)	0 (0%)	1 (11%)	4 (44%)
0 (0%)	0 (0%)	2 (22%)	2 (22%)	5 (56%)
3 (38%)	2 (22%)	5 (56%)	5 (56%)	8 (89%)
4 (57%)	4 (44%)	6 (67%)	6 (67%)	9 (100%)

Driver Door

4 (50%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
3 (38%)	1 (11%)	0 (0%)	0 (0%)	0 (0%)
3 (38%)	1 (11%)	0 (0%)	0 (0%)	0 (0%)
4 (50%)	3 (33%)	2 (22%)	2 (22%)	1 (11%)
5 (63%)	4 (44%)	4 (44%)	4 (44%)	4 (44%)

Passenger Door

2 (22%)	0 (0%)	1 (11%)	1 (11%)	2 (22%)
2 (22%)	1 (11%)	1 (11%)	2 (22%)	3 (33%)
2 (22%)	2 (22%)	4 (44%)	4 (44%)	5 (56%)
3 (38%)	4 (50%)	4 (50%)	5 (63%)	4 (50%)
5 (63%)	5 (63%)	4 (50%)	5 (63%)	6 (75%)

0-10%	11-20%	21-30%	31-40%	41-50%	51-60%	61-70%	71-80%	81-90%	91-100%

Figure 40. Chart. Percentages of drivers who rated each square as most distorted. Color scale is provided to summarize the region of each mirror that was most distorted. Production mirrors, in clockwise order from top left: driver hood, passenger hood, passenger door, driver door.

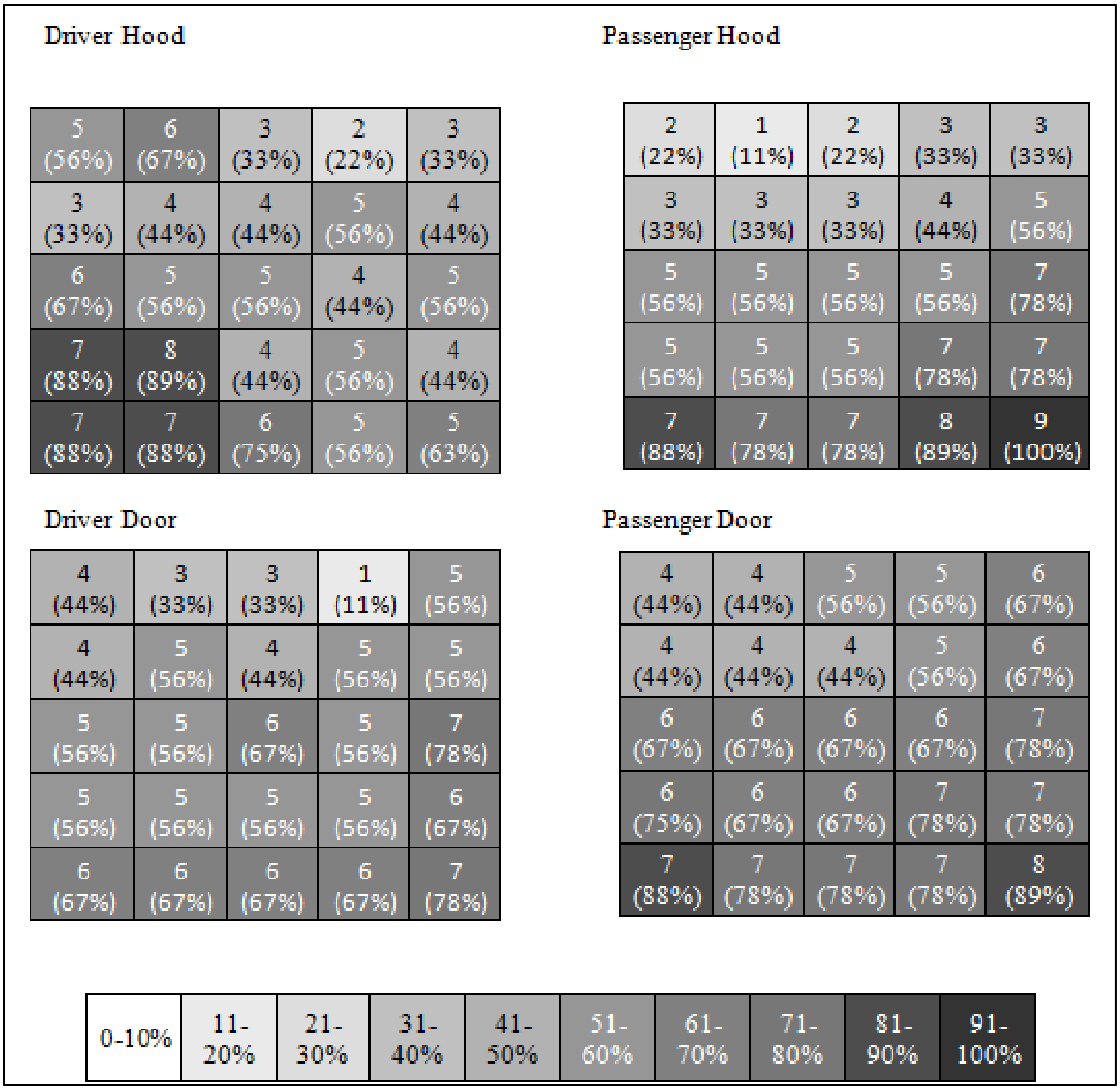

Figure 41. Chart. Percentages of drivers who rated each square as most distorted. Color scale is provided to summarize the region of each mirror that was most distorted. Prototype mirrors, in clockwise order from top left: driver hood, passenger hood, passenger door, driver door.

4.3.4.2 Subjective Evaluation of Image Distortion

Subjective evaluation of image distortion included satisfaction of image clarity (distortion) for each mirror, overall preference for prototype mirror, and belief that the prototype mirror's image clarity (distortion) would make driving safer than the production mirrors. Table 5 details driver average ratings of mirrors on a 1–7 Likert-type scale. Average rating of preference of mirror type for image distortion is 2.67. Performing a one-sample *t*-test against no difference (i.e., prototype mirror is equivalent to production mirror) produces no significance ($t = 2.22$, $p > 0.05$) in that individuals have no preference for mirror type with regard to distortion. The average belief of usefulness with regard to image distortion using these mirrors is 2.56, and a one-sample *t*-test does produce significance ($t = 2.39$, $p < 0.05$), suggesting that people do believe production mirrors are more useful than prototype mirrors in relation to the distortion of images presented.

Table 5. Response set with average and standard deviation for image distortion.

Rate how much you agree or disagree with the following statements	1	2	3	4	5	6	7	n	Avg.	SD
Prototype: I am satisfied with the degree of clarity present in the prototype convex mirrors.	1	0	1	1	2	2	2	9	4.89	1.96
Prototype: I am satisfied with the degree of clarity present in the prototype convex mirrors.	1	1	0	1	3	1	2	9	4.67	2.06
Prototype: I am satisfied with the degree of clarity present in the prototype convex mirrors.	1	1	0	2	0	3	2	9	4.78	2.17
Prototype: I am satisfied with the degree of clarity present in the prototype convex mirrors.	2	0	0	1	2	3	1	9	4.56	2.19
Production: I am satisfied with the degree of clarity present in the production convex mirrors.	0	0	0	1	2	3	3	9	5.89	1.05
Production: I am satisfied with the degree of clarity present in the production convex mirrors.	0	0	1	1	1	4	2	9	5.56	1.33
Production: I am satisfied with the degree of clarity present in the production convex mirrors.	0	0	0	2	2	3	2	9	5.56	1.13
Production: I am satisfied with the degree of clarity present in the production convex mirrors.	0	0	0	1	3	2	3	9	5.78	1.09
I prefer the degree of image distortion provided by the prototype mirrors.	2	3	3	0	0	0	1	9	2.67	1.80
I believe the degree of image distortion provided by prototype mirrors is more useful than the images provided by production mirrors.	2	4	2	0	0	0	1	9	2.56	1.81

Note: Response scale is as follows: 1 = "Strongly Disagree," 2 = "Disagree," 3 = "Somewhat Disagree," 4 = "Neither Agree nor Disagree," 5 = "Somewhat Agree," 6 = "Agree," 7 = "Strongly Agree."

4.3.5 Distance Estimation

Separate from FOV and image distortion, estimating distances using vehicle mirrors while driving highlights an important purpose and function of the mirrors. Exploring the abilities of drivers performing distance estimation is necessary in determining usefulness of the mirrors. Drivers first estimated distances of cones using mirrors for direct visibility and rated their own confidence in estimating these distances.

4.3.5.1 Objective Evaluation of Distance Estimation

Distance estimation is another important element of mirror functioning via indirect visibility, and its objective evaluation demonstrates drivers' abilities to accurately estimate the rearward distance of objects using the mirrors. On average, drivers estimated cones on the driver side to be 10.39 feet rearward from the mirror using the production mirrors, and 6.67 feet rearward using the prototype mirrors (see Table 6). Similarly, drivers estimated cones on the driver side to be 15.94 feet rearward from the mirror using the production mirrors, and 13.28 feet rearward using the prototype mirrors. Overall, there is no significant difference between production and prototype mirror estimates ($t = -1.70$, $p > 0.05$); however, drivers had lower residual estimates using the prototype mirrors than using production mirrors within the sample for both driver- and passenger-side mirrors.

Table 6. Average residual difference of distance estimated by mirror location and mirror type.

Average Residual (ft.)	D. Door Convex	P. Door Convex	Average Distance Off
Production mirrors	10.39	15.94	**13.17**
Prototype mirrors	6.67	13.28	**9.98**
Difference in prototype to production	**3.72**	**2.66**	**3.19**

Note: "D." references driver-side; "P." references passenger-side.

One key element of distance estimation using mirrors' indirect visibility is in understanding whether individuals are more likely to overestimate or underestimate distances. This element of distance estimation is critical given the consequences of overestimating distances when performing passing or merging functions. Using the driver-side convex mirrors, participants underestimated distances in 11 of 18 trials (61 percent) with production mirrors, and underestimated distances in 7 of 18 trials (39 percent) with prototype mirrors (see Table 7 below). Drivers underestimated an average of 4.3 feet and 5.3 feet on average with production and prototype mirrors, respectively.

Using the passenger- side convex mirrors, drivers underestimated distances in 14 of 18 trials (78 percent) with production mirrors, and underestimated distances in 12 of 18 trials (67 percent) with prototype mirrors (see Table 8). Drivers underestimated an average of 13 feet and 11.7 feet on average with production and prototype mirrors, respectively.

Differences between production and prototype mirrors are insignificant, though drivers in the sample had a higher tendency to overestimate distances using production mirrors: 11 of 36 distance overestimations occurred using production mirrors and 17 of 36 of overestimations occurred using prototype mirrors; however, average distance overestimated is almost equivalent between the two mirror types.

Table 7. Under- and overestimation by mirror type for the driver-side convex mirrors.

Driver Side	Production Mirrors Total (ft.)	Production Mirrors N	Production Mirrors Average (ft.)	Prototype Mirrors Total (ft.)	Prototype Mirrors N	Prototype Mirrors Average (ft.)	Mirror Difference N	Mirror Difference Average (ft.)
Under-estimation	47	11	**4.3**	37	7	**5.3**	**4**	**-1**
Over-estimation	61	7	**8.7**	51	11	**8.6**	**-4**	**0.10**

Note: "D." references driver-side; "P." references passenger-side.

Table 8. Under- and overestimation by mirror type for the passenger-side convex mirrors.

Passenger Side	Production Mirrors Total (ft.)	Production Mirrors N	Production Mirrors Average (ft.)	Prototype Mirrors Total (ft.)	Prototype Mirrors N	Prototype Mirrors Average (ft.)	Mirror Difference N	Mirror Difference Average (ft.)
Under-estimation	182	14	**13**	140	12	**11.7**	**2**	**1.3**
Over-estimation	16	4	**4**	25	6	**4.2**	**-2**	**-0.20**

Note: "D." references driver-side; "P." references passenger-side.

4.3.5.2 Subjective Evaluation of Distance Estimation

Subjective evaluation of distance estimation included satisfaction of using production and prototype mirrors to estimate distances, ratings of overall preference for the prototype mirror when estimating distances, and belief that the prototype mirror's estimation of distances would make driving safer than the production mirrors. Table 9 details participants' average ratings of mirrors on a 1–7 Likert-type scale. Average rating of preference of mirror type for distance estimation is 2.22. Performing a one-sample *t*-test against no difference (i.e., prototype mirror is equivalent to production mirror) produces significance ($t = 2.87$, $p < 0.05$), in that people prefer to use production mirrors to estimate distances. The average belief of accuracy in using these mirrors is 2.44, and a one-sample *t*-test produces significance ($t = 2.58$, $p < 0.05$), suggesting people believe distance estimation is more accurate when using production mirrors over prototype mirrors.

Table 9. Response set with average and standard deviation for distance estimation.

Rate how much you agree or disagree with the following statements:	1	2	3	4	5	6	7	n	Avg.	SD
Prototype: I am confident in my estimating abilities using these mirrors.	2	1	3	1	0	1	1	9	3.33	2.06
Prototype: I believe I could safely drive using these mirrors.	2	1	1	1	1	2	1	9	3.89	2.26
Production: I am confident in my estimating abilities using these mirrors.	0	0	0	1	6	2	0	9	5.11	0.6
Production: I believe I could safely drive using these mirrors.	0	0	0	0	2	4	3	9	6.11	0.78
I prefer using the prototype mirrors to estimate distances.	3	5	0	0	0	0	1	9	2.22	1.86

Rate how much you agree or disagree with the following statements:	1	2	3	4	5	6	7	n	Avg.	SD
I believe the estimation of distances would be more accurate with the prototype mirrors.	2	5	1	0	0	0	1	9	2.44	1.81

Note: Response scale is as follows: 1 = "Strongly Disagree," 2 = "Disagree," 3 = "Somewhat Disagree," 4 = "Neither Agree nor Disagree," 5 = "Somewhat Agree," 6 = "Agree," 7 = "Strongly Agree".

4.3.6 Preference

Overall mirror preferences were garnered from each driver. Preference results were separated into sets of mirrors: door-mounted and hood-mounted. Table 10 details drivers' responses. Overall, eight of nine drivers would prefer production door-mounted convex mirrors; however, six of nine made the same choice regarding the hood-mounted prototype mirror.

Table 10. Response set with average and standard deviation for mirror preference.

Rate how much you agree or disagree with the following statements:	1	2	3	4	5	6	7	n	Avg.	SD
If I were given a choice to use the door-mounted prototype mirrors on my truck, I would use them.	3	3	2	0	0	0	1	9	2.44	1.88
If I were given a choice to use the hood-mounted prototype mirrors on my truck, I would use them.	2	2	2	2	0	0	1	9	3.00	1.87

Note: Response scale is as follows: 1 = "Strongly Disagree," 2 = "Disagree," 3 = "Somewhat Disagree," 4 = "Neither Agree nor Disagree," 5 = "Somewhat Agree," 6 = "Agree," 7 = "Strongly Agree."

4.3.7 Qualitative Analysis

Comments regarding the prototype and production mirrors were obtained. First, individuals responded to two likes and two dislikes regarding the prototype mirrors. That was then repeated for production mirrors. Drivers were asked to give a final commentary about the effectiveness and capabilities of the mirrors. Appendix F contains the list of comments concerning the mirrors. The following list details a summary of participant driver comments:

- Eight drivers mentioned an increase in FOV using the prototype mirrors.
- Six drivers mentioned more distortion/dislike of distortion present in prototype.
- Four drivers mentioned poor mirror positioning.
- Four drivers suggested they would try the hood-mounted mirrors.
- Three drivers mentioned they would want to see improved versions of the mirrors.
- Four drivers mentioned liking the design of the mirrors.

In addition to comments related to FOV, image distortion, distance estimation, and overall "look and feel" of the mirrors, drivers made comments regarding the prototype mirror functions and capabilities, suggesting that prototype mirrors:

- May help avoid parking lot accidents.

- Would be useful if they alleviate fog build up compared to normal mirrors.
- Would help with people merging into CMVs.
- Would be useful to evaluate with regard to glare.
- Are hard to judge in a stationary vehicle.

4.3.8 Supplemental Analyses

As noted in previous research, and as expressed by a driver in this study, individuals who are older are more resistant to change. [26] A regression analysis was conducted to examine whether age had an effect on preference of mirror type. A multiple R^2 of 0.20 suggests that age explains 20 percent of the variance in preference for prototype mirrors, and, though insignificant, younger drivers tended to rate the prototype mirrors higher than older drivers.

Researchers sought to determine whether drivers felt any ill effects from looking at the prototype mirrors. This was a concern due to the odd shape and curvature of the mirrors, particularly the door-mounted mirrors. Using a 1–7 Likert-scale, drivers were asked to rate their agreement with the statement, “I feel comfortable when looking at the mirrors.” Two individuals indicated disagreement, while six individuals indicated agreement. The average rating was 4.89. It should be noted that drivers might have assumed the question was in regard to mirror positioning, rather than comfort of use.

An important consideration with regard to subjective evaluation of an object is participant rating bias. Such a bias exists when individuals’ initial impressions influence their ratings of an object without proper evaluation. This is most noticeable when examining subjective evaluations of FOV ratings for the prototype mirrors. Although eight of the nine participants mentioned a greater FOV when using the prototype mirrors, they rated lower satisfaction scores for all mirrors except the passenger-side, hood-mounted mirror. In addition to lower satisfaction scores, six of nine drivers disagreed or were neutral toward the following two statements: “I prefer the field of view provided by the prototype mirrors,” and, “I believe driving would be safer with the field of view provided by the prototype mirrors.” While the subjective evaluation questions may be construed in an unintentional manner, the ratings should generally reflect driver comments.

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5. DYNAMIC TEST DRIVE

5.1 DYNAMIC EVALUATION

Performing a static evaluation can provide only limited information about mirrors that are regularly used in a dynamic environment. This supplemental dynamic test drive was intended to garner feedback from an experienced heavy vehicle driver in a dynamic test setting featuring real-world scenarios and tasks aimed at comparing the production and prototype mirrors. The driver who performed the test was a VTTI research staff member, with no connection to the project. The driver piloted a CUT with production and prototype mirrors on a major interstate, local roads, and a parking lot. The driver then provided feedback on the mirrors.

5.1.1 Development of Evaluation

Evaluating the mirrors dynamically involved performing real-world maneuvers that utilized important aspects of both sets of mirrors. These tasks included overtaking a vehicle, merging around other vehicles, docking, curb-docking, and performing a U-turn.

One of VTTI's CUTs was outfitted with mounts that allowed for switching between production and prototype door mirrors. Hood mirrors were not tested on the vehicle due to the dynamic CUT parameters (i.e., hood) varying from the simulation and static evaluation CUT parameters. However, it is important to note that the driver seat and door mirror positioning was consistent between the dynamic CUT and the static CUT. During the evaluation, the driver was asked to adjust the door mirrors as he usually would while driving. A second vehicle, a Chevrolet Malibu, was used as a remote vehicle to ensure safety on the road and to participate in dynamic scenarios. Both vehicles are shown in Figure 42. Video recording devices were set up in both the CUT and the remote vehicle to capture the dynamic evaluation.

Figure 42. Photo. VTTI's outfitted CUT and Chevrolet Malibu used in dynamic road test.

The evaluation consisted of a 2-hour period, focusing on driving on a major interstate and local roads, as well as performing common parking lot and docking maneuvers. The test plan, along with the driving route and task list, is located in Appendix G. Appendix H contains the post-drive questionnaire for the driver's response after completing the test drive with both sets of mirrors.

5.1.2 Overtaking and Merging

Lane changes and merging are two of the most common driving activities involving convex mirror use. A gap-acceptance task was conducted to evaluate the driver's ability to use the prototype door mirrors as compared to the production mirrors during lane change and merging maneuvers. The driver of the CUT noted when he was comfortable changing lanes based on the position of the remote vehicle. This evaluation was conducted on both the driver-side and the passenger-side of the CUT. The lane change consisted of both 'last-second' and 'first-second' lane change instances. The last-second lane change involved a second vehicle in a different lane approaching the side of the CUT. The gap-acceptance was evaluated by determining when the driver of the CUT no longer felt comfortable changing lanes. The first-second lane change involved the CUT approaching a second vehicle in a different lane. The gap-acceptance was evaluated by determining when the driver of the CUT first felt comfortable changing lanes. Figure 43 displays an overtake maneuver on the passenger's side using the production mirrors. Figure 44 displays the same maneuver using the prototype mirror, with the remote vehicle in the same location relative to the CUT.

Figure 43. Photo. NextGen DAS video output of VTTI research staff member dynamic test drive using the production mirrors. In clockwise order: Driver-side view of mirror, passenger-side view of mirror, driver face view, and passenger-side rear view/driver-side (split) rear view.

Figure 44. Photo. NextGen DAS video output of VTTI research staff member dynamic test drive using the prototype mirrors. In clockwise order: Driver-side view of mirror, passenger-side view of mirror, driver face view, and passenger-side rear view/driver-side (split) rear view.

5.1.3 Field of View Measurements

The driver evaluated FOV by performing a maneuver with the remote vehicle in the lane next to the CUT. The remote vehicle started from behind the truck and moved forward past the front bumper. The driver of the CUT marked the point when the view of the remote vehicle was lost between mirrors and direct sight, if at all. This was done for both production and prototype mirrors.

5.1.4 Parking Lot Maneuvers

Common parking lot maneuvers were conducted to allow the driver to evaluate the prototype mirrors in low-speed environments. The maneuvers consisted of a curb dock, an alley dock, and a low-radius U-turn.

5.2 RESULTS

The VTTI research staff driver successfully completed the dynamic on-road evaluation of the prototype mirrors following the path and script found in Appendix G.

5.2.1 Overtaking and Merging

The driver was able to successfully perform all merging and overtaking actions using the prototype mirrors. The gap-acceptance between both production and prototype mirrors was very similar for both driver-side and passenger-side, as well as first-second and last-second merge. The driver noted that when evaluating the passenger-side prototype mirror, he had to use visual cues, such as shadows, at times, to decipher the location of the vehicle and its relation to the CUT. The driver also noted that the remote vehicle was very difficult to see readily by glancing at the mirror, as were other vehicles on the road. Specifically, the driver commented, “I had to look at the passenger-side mirror too long to digest the information.”

5.2.2 Field of View Measurements

The driver was able to see approximately the same areas with regard to the remote vehicle when using both production and prototype mirrors, but noted that the driver-side prototype mirror did provide a larger FOV. The driver also noted that the prototype mirror’s passenger-side FOV was expansive, but so much so that objects in the mirror were too difficult to readily discern due to the reduction in object size.

5.2.3 Parking Lot Maneuvers

The driver was able to successfully perform a curb dock, alley dock, and U-turn using the prototype mirrors. The driver noted that use of the convex mirror was minimal throughout these maneuvers.

5.2.4 General Comments

The driver noted difficulty in using the passenger-side prototype mirror due to the miniaturization of objects and the distortion present in the bottom left of the mirror. Figure 45 displays a solid white line lane marking on a straight road as viewed in the passenger-side mirror. The driver relied heavily on the passenger-side flat mirror during maneuvers due to the excess time required to decipher the other vehicle’s location in the prototype. The driver noted that over time, he could grow accustomed to the prototype mirrors, but did not find value in their use as of the dynamic test drive. The location of the distortion on the mirror may have been the cause of this, as areas of high distortion were often located where vehicles in lanes beside the CUT would travel along the mirror face.

Figure 45. Photo. Close-up of the passenger-side prototype mirror showing solid lane distortion.

6. CONCLUSIONS

During a static evaluation on the Virginia Smart Road's STA, a sample of nine drivers provided feedback on a novel set of multi-radii convex prototype mirrors. The following conclusions demonstrate the steps that the research team took to capture and measure characteristics of the prototype mirrors. Opportunities for mirror improvement are discussed in Section 7.

6.1 MIRROR PERFORMANCE

Both user acceptance and prototype mirror performance were assessed based on 1) a controlled performance evaluation using research staff, 2) a static evaluation (on the Virginia Smart Road's STA) using participants, and 3) a dynamic evaluation involving one driver (employed by the contracted research institution) on a highway, on local roads, and in a parking lot. The controlled performance evaluation involved interchangeability of mirrors and mapping out the FOV of both production and prototype mirrors, while the static evaluation examined user acceptance of the mirrors. The dynamic evaluation targeted components of the mirror evaluation that could not be captured in a static evaluation.

6.1.1 Controlled Performance Evaluation

The purpose of the controlled performance evaluation was to determine the capability of the prototype mirrors with regard to the available FOV. The evaluation used research staff whose sitting eye-heights closely matched the sizes of a 5th percentile female and a 95th percentile male CMV driver as representative driver models. The evaluation demonstrated some limitations of the mirrors with regard to image distortion and the MCS protocol.

FOV mapping revealed a larger area of indirect visibility for prototype mirrors than for production mirrors in a few ways. First, the prototype door-mounted mirrors provided an increased view area, especially in the rear half of the trailer, for the small female. The large male experienced an increased view area of the two far adjacent lanes in the five-lane roadway. Second, horizon was largely visible in both driver- and passenger-side, door-mounted prototype mirrors, whereas it was not visible in the production mirrors due to the MCS arrangement. Although the horizon was visible in the prototype mirrors, the research staff noted increased distortion toward the top of the mirror, increasing the difficulty of mapping the FOV even in the lanes immediately adjacent to the trailer. Third, the curvature in the hood-mounted prototype mirrors extended beyond the production hood mirrors (forward), which could help drivers check for objects in the passenger-side blind spot or check bumper clearances on both sides. The driver-side prototype hood mirror even allowed for indirect visibility further forward than the mounted mirror itself—along the 0-foot line with the front of the vehicle.

6.1.2 Static Evaluation

Drivers were asked to evaluate the prototype mirrors across the following: FOV, image distortion, and distance estimation. In the FOV task, drivers were asked to identify a limited number of cones to efficiently describe their FOV. Drivers also applied the MCS (see Section 2.5.1) protocol for adjusting mirrors. These methods standardized drivers' indirect visibility, and little difference was shown between FOVs of the production and prototype mirrors outside of the driver-side, door-mounted convex mirror. The MCS protocol created the desired control between drivers of different eye heights and among varying mirror adjustment preferences. That variability could have led to unexplained positive or negative extremes in objective and subjective measures based solely on mirror adjustment instead of the mirror surface properties under investigation.

Drivers classified the image distortion of each mirror type (production, prototype) and position (door/hood, driver-side/passenger-side) by viewing a flat grid that was situated at an individually defined position covering the majority of the mirror. Drivers classified the majority of the prototype door mirrors as distorted. Drivers classified the lower regions of both of the hood mirrors as most distorted. Among the four mirror positions, drivers identified all four of the prototype mirrors as creating more image distortion than the production mirrors; however, the passenger-side hood mirror was not rated significantly worse.

Drivers were asked to estimate distances to a cone placed on alternating sides of the truck at one of two positions rearward from the door mirrors. The results of these estimates provide some limited insight into the effect of the prototype mirrors on judging objects in nearby lanes of traffic on the road. Cones were positioned in different locations that were visible in each mirror on the driver side and passenger side. The true cone locations surrounded the tractor-truck rear axle on the driver side and the trailer rear axle on the passenger side. The distance estimates were subtracted from the true distance and those gaps were averaged across drivers. The average gap estimated by the drivers was smaller for the prototype mirrors than the production mirrors on both the driver- and passenger-side mirrors; however, the distance was not significantly lower. It is worth noting that all nine drivers were presented with the prototype mirrors before the production mirrors during the distance estimation task.

6.1.3 Dynamic Evaluation

A staff member of the contracted research institution participated in a supplemental dynamic evaluation targeting components of the mirror evaluation that could not be captured in a static evaluation. This driver had similar reactions toward the mirrors as participants in the static evaluation. Though safe driving behaviors did not diminish using the prototype mirrors versus the production mirrors, the prototype mirrors did not offer much improvement over the production mirrors. The driver performed equally in overtaking and merging tasks with both mirrors. The driver noted that the door-mounted prototype mirror did provide a larger FOV, but the passenger door-mounted prototype mirror made driving safely discernably more difficult due to the distortion and reduction in size of the objects viewed in the prototype mirror. The driver also had no difficulty in the parking lot tasks, utilizing the passenger-side prototype mirror to perform a curb dock, but relying heavily on the flat mirrors for the alley dock, as is the nature of the task.

6.2 USER ACCEPTANCE

The investigation of drivers' opinions of the prototype mirrors during evaluation revealed the following:

- Drivers, on average, did not prefer the FOV provided by prototype mirrors over the FOV provided by production mirrors, despite the fact that the number of FOV cones identified by the drivers was higher with the prototype mirrors.
- On average, drivers believed the smaller degree of image distortion on production mirrors would make them more useful than prototype mirrors. This rating was found to be significant.
- Drivers' ratings indicated that they believed they could estimate distances more accurately with production mirrors than prototype mirrors. This rating was found to be significant.

The nine drivers in the study had limited acceptance of the prototype mirrors. Drivers provided feedback regarding both positives and negatives of the prototype mirrors, as well as ways to improve them and/or follow-up tests that they would like to see. General positive comments included the following: "field of view is larger," "actual image presentation is clearer," "more definitive," "I like the design better, no sun glare." General negative comments included the following: "harder to place things in the mirror," "too distorted," and "still a bit of work to do on the mirror." Some drivers expressed interest in seeing future mirror developments and applying mirrors in a real driving scenario. A full list of comments along with questions is provided in Appendix F.

In summary, the prototype mirrors' FOV was greater than the production mirrors. However, this increase was demonstrated to exist at the cost of increased image distortion. Of the nine participating drivers, eight stated that they would prefer to use the production door mirrors on their CMVs. Additionally, six of the nine drivers stated that they would prefer to use the production hood mirrors on their CMVs. Comments and ratings regarding the prototype hood mirrors were in general more positive than those regarding the door mirrors. The extreme shape of the door mirrors requires further development to reduce the resulting areas of distortion.

6.3 STUDY LIMITATIONS

The following limitations should be considered when assessing the results of this study:

- The evaluation of the prototype mirrors was carried out on the first iteration of mirrors. Any imperfections, incorrect radial curvature, or improper calculations during mirror development were not addressed before the mirrors' evaluation phase.
- Although use of the MCS protocol allowed researchers control over the positioning of the mirrors across drivers, it created a set of mirror positions unnatural to most drivers. The MCS required drivers to point the convex mirrors at the targets in a way that was angled toward the ground more than usual. This was a point of frustration to some drivers, as they felt driving would be unreasonable using this mirror set-up, despite the maximized indirect visibility resulting from the limited amount of overlap between mirrors.
- The amount of exposure time to the prototype mirrors was very short. Furthermore, the task of sitting still and responding to mirror-related tasks did not fully represent the task of viewing objects of interest around the CUT while in motion. The study may not have

fully represented the type of interaction that takes place with mirrors during slow back-up maneuvers, which were performed only during the brief dynamic evaluation.

7. NEXT STEPS

7.1 OUTLINE OF EVENTS

The following section details general methodology for future iterations of mirror development and testing.

7.1.1 Prototype Mirror Iterative Design Testing (Phase 1)

Refining the design of the prototype mirrors is required for increasing their utility and acceptability. Specifically, vertical FOV must be limited to decrease distortion of objects in the mirrors. Further, the mirror must be adjusted to remove the distortion within primary areas on the mirror face. These primary areas are the typical trajectories of vehicles in the lanes beside the CUT as they pass through the mirror.

Once redesigned, future static and dynamic testing of the prototype mirrors would involve participants performing various tasks using the prototype and production mirrors to assess usefulness and acceptance. Tasks would include merge and pass scenarios, FOV evaluation, distortion evaluation, and differing backup scenarios. If performance and driver acceptance of mirrors is satisfactory, multiple sets of mirrors could be produced for field testing.

7.1.2 Prototype Mirror Field Testing (Phase 2)

Field testing of the prototype mirrors would involve installing prototype mirrors on participant driver vehicles and evaluating the effectiveness of the mirrors across various criteria. Objective measures would gauge safety-related benefits of the prototype mirrors, as well as unintentional consequences (i.e., safety disadvantages). Subjective measures would gauge driver acceptance of prototype mirrors.

7.2 PROTOTYPE MIRROR DYNAMIC TESTING (PHASE 1)

While complete sets of mirrors were being fabricated, a contractor would reevaluate mirror capabilities on a static area and perform minimal dynamic testing using naïve CDL drivers. In addition to FOV testing performed on a static lot, the research team would create various driving scenarios using the experimental CUT and an additional passenger vehicle. The scenarios would be designed to exercise the driver-side and passenger-side mirrors separately. The scenarios would include passing, merging, and backing maneuvers by the participant. Finally, the participant would perform a “last comfortable gap” scenario in which the driver would indicate the last point where he or she would feel comfortable changing lanes to move safely into the lane of overtaking vehicles. For safety reasons, participants would not actually make the lane change; instead, they would be instructed to press a button to indicate their estimate of last comfortable gap.

Both objective and subjective measures would be collected. The objective measures would include distances at time of pass or merge initiation, distances at button presses, backing-up behaviors, and eye-glance behaviors. Subjective measures would include driver acceptance of mirrors on-road and ratings of mirror utility.

A contractor would compile the methods, data analyses, and conclusions in a draft final report. Upon FMCSA's review, a contractor would update the report with any necessary changes and submit a final report.

7.3 PROTOTYPE MIRROR FIELD TESTING (PHASE 2)

The proposed field study would investigate the efficacy of the prototype mirror by evaluating safety benefits, unintended consequences (i.e., safety disadvantages), and user acceptance. A summary of these measures and associated analyses are provided below in Table 11. This analysis plan is similar to the one used in a previous FAST DASH safety technology evaluation that used field operational testing.[(27)]

A before-after study design would be used to compare the safety benefits of the prototype mirror with the conventional convex mirror configuration by examining driver performance after the prototype mirrors replaced the convex mirrors. This quasi-experiment constitutes an A^1B^2 design, where 'A' and 'B' refer to the baseline and intervention phases, respectively. The superscript refers to the number of months in each phase (e.g., '1' would refer to 1 month). During the 1-month baseline phase, drivers would operate their normal CMVs while baseline driving data were captured. Immediately following this 1-month baseline period, a 2-month intervention phase would begin, with the drivers continuing to operate their instrumented in-service vehicles. However, in the intervention phase, the prototype mirrors would be installed in place of the baseline door-mounted convex mirrors below the planar mirrors and in place of the baseline hood-mounted convex mirrors. The primary safety benefit measure of interest would be the rate of merge-related and lane-change-related safety-critical events per 10,000 miles involving the subject commercial vehicle and at least one other vehicle positioned in an adjacent lane.

A second aspect of assessing novel safety equipment in real-world environments is examining the occurrence of unintended consequences. These undesirable events are often observed as improper/unanticipated reactions by the drivers of the vehicle equipped with the safety system or drivers adjacent to that vehicle; however, they can also be found in other contexts, such as effects found on carrier operational characteristics. These unforeseen issues can be observed through data collection, including captured video and kinematic data, then categorized and reported as frequencies (see Table 11). Additionally, unintended consequences can be determined through open feedback from drivers and safety managers participating in the study.

Table 11. Overview of data analysis plan.

Analysis Category	Data Source	Analyses	Reported As:
Determining Safety Benefits	Frequency and severity of driver errors (i.e., safety-critical incidents) estimated from sampled data acquisition system (DAS) data.	Paired sample *t*-test	Reported as the mean rate of safety-critical incidents/ 10,000 miles during the baseline to intervention phases.
Unintended Consequences	Estimated from sampled DAS data.	Contingency table analysis	Reported as frequencies of unforeseen actions.
User Acceptance	Obtained from subjective assessment.	Within-subject analysis of variance	Reported as mean ratings of use and acceptability.

A third important aspect in the successful implementation of the prototype mirror is user (e.g., driver and manager) acceptance of the technology. Without acceptance, the adoption of an evaluated safety system may fail to take hold. Therefore, opinions from drivers and fleet managers would be gathered through post-study interviews.

At the conclusion of the 3-month data collection period, a period of data reduction and analysis performance would occur. Based on previous field study experience of similar scope, this data reduction and analysis period would take approximately 4 months to execute.[28]

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8. RECOMMENDATIONS

The evaluation of this specific novel mirror technology provides guidance for future development and testing to support next-generation mirror designs that may benefit the CMV industry. The paradigm that was tested was based on the idea that current production convex mirrors carry FOV and image distortion properties that are tied together by nature of a simple reflective surface made up of a constant radius of curvature and maximum surface perimeter length. This paradigm was tested to determine if the FOV property could be maintained or increased while reducing the distortion perceived by drivers compared to production convex mirrors. The conclusions of the preliminary evaluation, controlled static evaluation, and dynamic evaluation drive led to some key points and recommendations.

- Lesson 1: The preliminary FOV measurement suggests that allowing complex radii to be applied to a mirror surface can lead to increases in FOV and reductions in blind spots around CMVs. The objective and subjective evaluation by drivers suggests that the prototype mirrors did not improve image distortion compared to production convex mirrors.
  - RECOMMEND: Maintain and continue testing driver-side and passenger-side hood prototype mirror surfaces.
  - RECOMMEND: Refine and develop driver-side and passenger-side door mirror surfaces to decrease large vertical FOV requirements and reduce excessive image distortion identified in preliminary mirror mapping and evaluations. Concurrently, reduce image distortion along common vehicle paths in the mirror face by shifting radii to less-used areas of the mirror.
- Lesson 2: The results of the static and dynamic evaluations provided valuable real-world experience and guidance into modifying the design of the novel mirrors. The benefit of increasing FOV was not demonstrated in either user acceptance or the dynamic drive, suggesting additional modifications to the prototype mirrors are required.
  - RECOMMEND: Discover and develop a more affordable mirror replacement with short turn-around methods of producing prototype mirror surfaces that can conform to test vehicles.

This technology was originally tested on light vehicles under a different paradigm: increased driver-side FOV while maintaining unit magnification. Following this paradigm for CMVs could lead to improved FOVs in North American markets and reduced image distortion in other markets. For example, CMV regulations in North America require that mirrors that provide unit magnification exist on both sides of CMVs, while regulations in markets that apply Economic Commission for Europe (ECE) 46-01 require that CMVs apply Class II mirrors, which have a large radius of curvature for better FOV than traditional flat mirrors.

- Goal: Combine FOV required for ECE 46-01 CMV markets with unit magnification required by North American markets to provide a novel convex mirror surface that can serve global markets.

- RECOMMEND: Adjust computations in a future version of the prototype convex mirrors to match ECE 46-01, Class II mirrors. Test application of prototype convex mirrors with North American drivers on driving tasks that require high-fidelity, visual information, and complex CUT manipulations, such as lane merge and backup tasks.

The MCS protocol provided consistency among simulated models, human models (researcher FOV), and CDL drivers while they evaluated and compared two considerably different types of mirror surfaces. However, research staff and drivers observed some weaknesses in the protocol that should be improved to bring it closer to mirror positions usually experienced by drivers in their CMVs.

- RECOMMEND: Modify position of driver-side door mirror ground target rearward to ensure that driver-door convex mirror includes the view of the trailer rear axle in the lane immediately adjacent to the CUT.
- RECOMMEND: Modify position of passenger-side door mirror ground target forward to ensure that passenger-door flat glass mirror includes the view of the trailer rear axle in the lane immediately adjacent to the CUT.
- RECOMMEND: Increase both driver and passenger door mirror targets' size to increase overlap of door flat and convex mirrors.

APPENDIX A: DEMOGRAPHICS QUESTIONNAIRE

FAST DASH Evaluation 3: Novel Mirror Demographics Questionnaire

Please mark with a check or write in the answer that best fits your response to the following questions: Please note, all answers are kept confidential.

1. What is your sex? __ Male __ Female
2. What is your height? __ ft. __ in.
3. What is your weight? _______ pounds (lbs.)
4. What is your age? _______ years old
5. Is English your first language? __ Yes __ No

   A. If you marked 'No', what is your first language? _____________
6. Are you currently employed driving a tractor-trailer? __ Yes __ No

   A. If you marked 'Yes', is your truck… __ Company-owned __ Privately owned?
7. How long have you had a **driver's license (non-CDL + CDL)**? ______ years
8. How long have you had a c**ommercial driver's license (CDL)**? ______ years
9. Approximately how many total years of CDL driving experience do you have? _____ years
10. What type of CDL endorsement/restrictions do you have? **(Check all that apply)**

    - ☐ Air brakes restriction (L)
    - ☐ Passenger (P)
    - ☐ Tank (N)
    - ☐ Tank and HazMat (X)
    - ☐ Instrastate only (K)
    - ☐ Double/triple trailer (T)
    - ☐ HazMat (H)
    - ☐ Other, please specify ____________________
11. How many hours a week (7-8 days) do you work? _______ hours
12. How many hours a week (7-8 days) do you driver for work? _______ hours
13. Do you work 7 or 8 days consecutively on a regular basis? __ Yes __ No

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Snellen Vision Test Results ____________ Sitting Eye-Height __________mm

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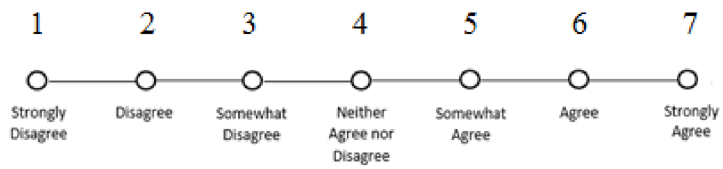
APPENDIX B: PARTICIPANT QUESTIONNAIRE

On a scale of 1 to 7, please rate the extent to which you agree with the following statements.

Note: Statements with a * use the following scale:



After first (1st) mirror adjustments of production mirrors:

1. *I feel comfortable in this truck.
2. *I feel comfortable with my mirror positioning.
3. *I am confident that I would be able to drive and maneuver in this truck.
4. *I find that the **door**-mounted production convex mirrors are useful.
5. *I find that the **hood**-mounted production convex mirrors are useful.

Field of View:

6. Please list all labeled cone letters that you can see in the driver's side **door**-mounted flat mirror.
7. Please list all labeled cone letters that you can see in the driver's side **door**-mounted convex mirror.
8. Please list all labeled cone letters that you can see in the driver's side **hood**-mounted convex mirror.
9. Please list all labeled cone letters that you can see in the passenger's side **door**-mounted flat mirror.
10. Please list all labeled cone letters that you can see in the passenger's side **door**-mounted convex mirror.
11. Please list all labeled cone letters that you can see in the passenger's side **hood**-mounted convex mirror.
12. *I am satisfied with the field of view provided by the driver's side **door**-mounted convex mirror.
13. *I am satisfied with the field of view provided by the driver's side **hood**-mounted convex mirror.
14. *I am satisfied with the field of view provided by the passenger's side **door**-mounted convex mirror.
15. *I am satisfied with the field of view provided by the passenger's **hood**-mounted convex mirror.

16. *I believe that the production convex mirrors can be improved to increase the provided field of view.

Image Distortion:

17. Can you see the entire checkerboard panel board in the driver's side **door**-mounted convex mirror?
18. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
19. If any, list square numbers that seem the largest to you?
20. *I am satisfied with the degree of clarity present in the production convex mirrors.
21. Can you see the entire checkerboard panel board in the driver's side **hood**-mounted convex mirror?
22. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
23. If any, list square numbers that seem the largest to you?
24. *I am satisfied with the degree of clarity present in the production convex mirrors.
25. Can you see the entire checkerboard panel board in the passenger's side **door**-mounted convex mirror?
26. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
27. If any, list square numbers that seem the largest to you?
28. *I am satisfied with the degree of clarity present in the production convex mirrors.
29. Can you see the entire checkerboard panel board in the passenger's side **hood**-mounted convex mirror?
30. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
31. If any, list square numbers that seem the largest to you?
32. *I am satisfied with the degree of clarity present in the production convex mirrors.

After mirror adjustments of prototype (Hicks) mirrors:

33. *I feel comfortable with my mirror positioning.
34. *I am content when looking at the mirrors.
35. *I am confident that I would be able to drive and maneuver in this truck.
36. *I find that the **door**-mounted prototype convex mirrors are useful.
37. *I find that the **hood**-mounted prototype convex mirrors are useful.

Field of View:

38. Please list all labeled cone letters that you can see in the driver’s side **door**-mounted flat mirror.
39. Please list all labeled cone letters that you can see in the driver’s side **door**-mounted convex mirror.
40. Please list all labeled cone letters that you can see in the driver’s side **hood**-mounted convex mirror.
41. Please list all labeled cone letters that you can see in the passenger’s side **door**-mounted flat mirror.
42. Please list all labeled cone letters that you can see in the passenger’s side **door**-mounted convex mirror.
43. Please list all labeled cone letters that you can see in the passenger’s side **hood**-mounted convex mirror.
44. *I am satisfied with the field of view provided by the driver’s side **door**-mounted convex mirror.
45. *I am satisfied with the field of view provided by the driver’s side **hood**-mounted convex mirror.
46. *I am satisfied with the field of view provided by the passenger’s side **door**-mounted convex mirror.
47. *I am satisfied with the field of view provided by the passenger’s side **hood**-mounted convex mirror.
48. *I believe that the prototype mirrors can be improved to increase the provided field of view.

Image Distortion:

49. Can you see the entire checkerboard panel board in the driver’s side **door**-mounted prototype convex mirror?
50. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
51. If any, list square numbers that seem the largest to you?
52. *I am satisfied with the degree of clarity present in the prototype convex mirrors.
53. Can you see the entire checkerboard panel board in the driver’s side **hood**-mounted prototype convex mirror?
54. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
55. If any, list square numbers that seem the largest to you?
56. *I am satisfied with the degree of clarity present in the prototype convex mirrors.

57. Can you see the entire checkerboard panel board in the passenger's side **door**-mounted prototype convex mirror?
58. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
59. If any, list square numbers that seem the largest to you?
60. *I am satisfied with the degree of clarity present in the prototype convex mirrors.
61. Can you see the entire checkerboard panel board in the passenger's side **hood**-mounted prototype convex mirror?
62. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
63. If any, list square numbers that seem the largest to you?
64. *I am satisfied with the degree of clarity present in the prototype convex mirrors.

Distance Estimation

Cone 1

65. Please tell me whether or not the cone you see in your driver's side **door**-mounted convex mirror is in front of or behind the trailer rear axle tire.
66. Please estimate the distance to the cone from the mirror in feet.

Cone 2

67. Please tell me whether or not the cone you see in your passenger's side **door**-mounted convex mirror is in front of or behind the trailer rear axle tire.
68. Please estimate the distance to the cone from the mirror in feet.

Cone 3

69. Please tell me whether or not the cone you see in your driver's side **door**-mounted convex mirror is in front of or behind the trailer rear axle tire.
70. Please estimate the distance to the cone from the mirror in feet.

Cone 4

71. Please tell me whether or not the cone you see in your passenger's side **door**-mounted convex mirror is in front of or behind the trailer rear axle tire.
72. Please estimate the distance to the cone from the mirror in feet.
73. *I am confident in my estimating abilities using these mirrors.
74. *I believe I could safely drive using these mirrors.
75. What are two things you like about the prototype mirrors?

1. ____

2. ____

76. What are two things you dislike about the prototype mirrors?

    1. ____

    2. ____

After second (2^{nd}) mirror adjustments of production mirrors:

**If any of these ratings change from above, follow-up with "This differs from your previous response of '___'. Is there any specific reason for the change?"

77. *I feel comfortable with the mirror positioning.
78. *I am confident that I would be able to drive and maneuver in this truck.
79. *I find that the **door**-mounted production convex mirrors are useful.**
80. *I find that the **hood**-mounted production convex mirrors are useful.**

Field of View:

81. *I am satisfied with the field of view provided by the driver's side **door**-mounted convex mirror.**
82. *I am satisfied with the field of view provided by the driver's **hood**-mounted convex mirror.**
83. *I am satisfied with the field of view provided by the passenger's side **door**-mounted convex mirror.**
84. *I am satisfied with the field of view provided by the passenger's **hood**-mounted convex mirror.**
85. *I believe that the production convex mirrors can be improved to increase the provided field of view.**

Image Distortion

86. Can you see the entire checkerboard panel board in the driver's side **door**-mounted convex mirror?
87. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
88. If any, list square numbers that seem the largest to you?
89. *I am satisfied with the degree of clarity present in the production convex mirrors.**

90. Can you see the entire checkerboard panel board in the driver's side **hood**-mounted convex mirror?
91. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
92. If any, list square numbers that seem the largest to you?
93. *I am satisfied with the degree of clarity present in the production convex mirrors.**
94. Can you see the entire checkerboard panel board in the passenger's side **door**-mounted convex mirror?
95. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
96. If any, list square numbers that seem the largest to you?
97. *I am satisfied with the degree of clarity present in the production convex mirrors.**
98. Can you see the entire checkerboard panel board in the passenger's side **hood**-mounted convex mirror?
99. Please list all labeled squares by number which you believe look distorted or unclear. This can be any squares that are larger or smaller than they would appear in person.
100. If any, list square numbers that seem the largest to you?
101. * I am satisfied with the degree of clarity present in the production convex mirrors.**

Distance Estimation

Cone 1

102. Please tell me whether or not the cone you see in your driver's side **door**-mounted convex mirror is in front of or behind the trailer rear axle tire.
103. Please estimate the distance to the cone from the mirror in feet.

Cone 2

104. Please tell me whether or not the cone you see in your passenger's side **door**-mounted convex mirror is in front of or behind the trailer rear axle tire.
105. Please estimate the distance to the cone from the mirror in feet.

Cone 3

106. Please tell me whether or not the cone you see in your driver's side **door**-mounted convex mirror is in front of or behind the trailer rear axle tire.
107. Please estimate the distance to the cone from the mirror in feet.

Cone 4

108. Please tell me whether or not the cone you see in your passenger's side **door**-mounted convex mirror is in front of or behind the trailer rear axle tire.

109. Please estimate the distance to the cone from the mirror in feet.

110. *I am confident in my estimating abilities using these mirrors.

111. *I believe I could safely drive using these mirrors.

112. What are two things you like about the production mirrors?

1. ____

2. ____

113. What are two things you dislike about the production mirrors?

1. ____

2. ____

Given enough time and practice using the prototype mirrors, please rate the extent to which you agree with the following statements:

114. *I prefer the field of view provided by the prototype mirrors.

115. *I believe driving would be safer with the field of view provided by the prototype mirrors.

116. *I prefer the degree of image distortion provided by the prototype mirrors.

117. *I believe the degree of image distortion provided by prototype mirrors is more useful than the images provided by production mirrors.

118. *I prefer using the prototype mirrors to estimate distances.

119. *I believe the estimation of distances would be more accurate with the prototype mirrors.

120. *If I were given a choice to use the **door**-mounted prototype mirrors on my truck, I would use them.

121. *If I were given a choice to use the **hood**-mounted prototype mirrors on my truck, I would use them.

122. Do you have any additional comments for us?

____

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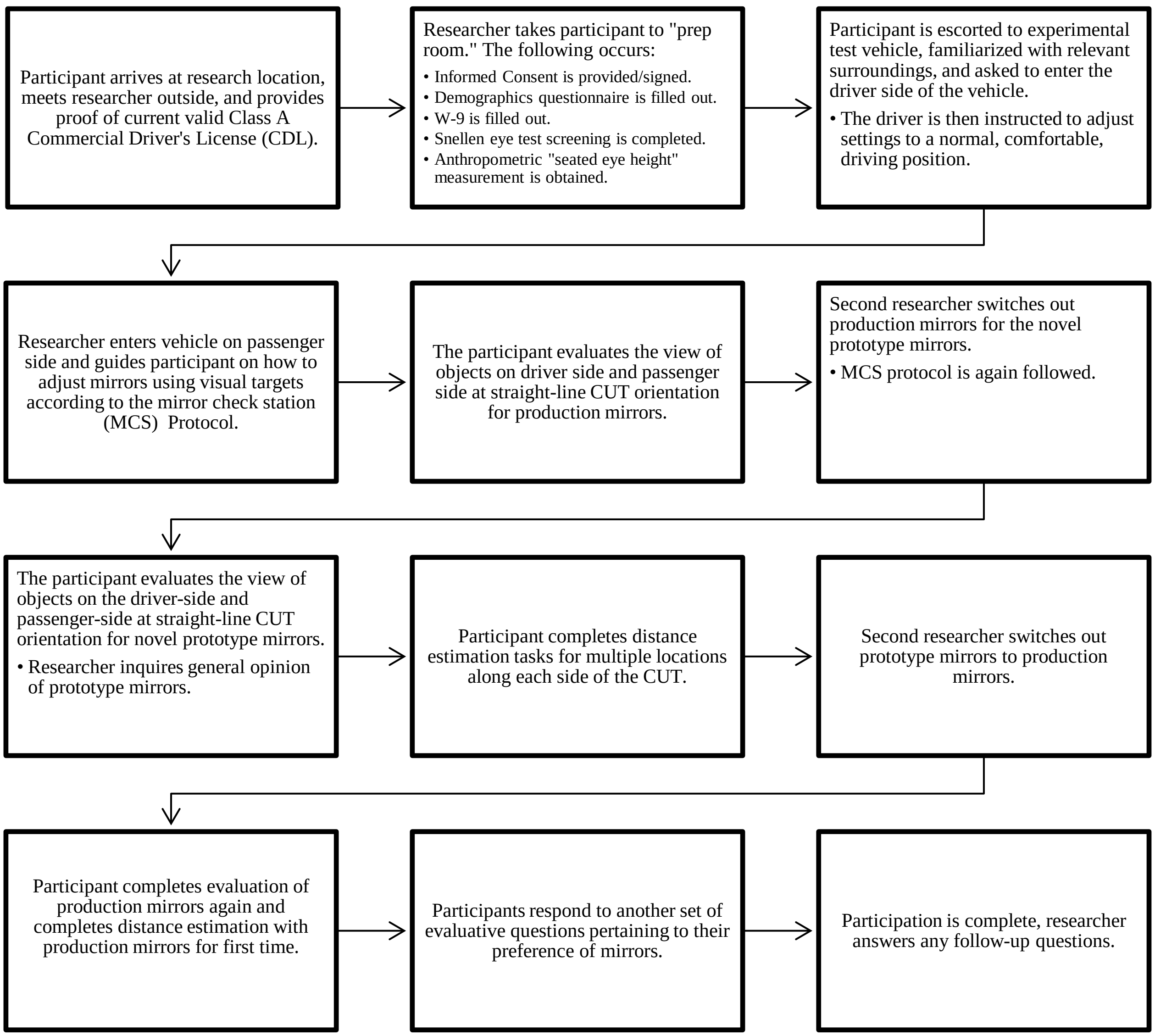
APPENDIX C: METHODOLOGICAL FLOW CHART



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APPENDIX D: FIELD-OF-VIEW MIRROR POSITIONS

The following tables provide the total cones visible across drivers by vehicle side and mirror type.

Table 12. Total cones visible for production, driver-side view.

Production; Driver Side	A	B	C	D	E	F	G	H	K	M	N	P	Q	R	S
Door flat	0	0	0	0	0	0	6	9	8	1	0	9	3	8	1
Door convex	0	0	9	9	6	5	1	1	1	1	1	1	1	0	0
Hood convex	9	5	1	1	1	1	0	0	0	0	0	0	0	0	0

Table 13. Total cones visible for production, passenger-side view.

Production; Passenger Side	T	U	V	W	X	Y	Z	2	3	4	5	6	7	8	9
Door flat	0	0	0	0	0	0	8	4	0	0	0	4	0	0	0
Door convex	0	0	9	9	9	3	6	7	7	7	7	7	7	7	6
Hood convex	9	8	1	3	3	2	0	1	1	1	1	0	1	1	1

Table 14. Total cones visible for prototype, driver-side view.

Prototype; Driver Side	A	B	C	D	E	F	G	H	K	M	N	P	Q	R	S
Door flat	0	0	0	0	0	0	6	9	8	1	0	9	2	8	1
Door convex	0	0	9	9	9	9	3	8	8	8	8	7	8	7	8
Hood convex	8	9	2	2	2	2	0	0	1	1	1	0	0	0	0

Table 15. Total cones visible for prototype, passenger-side view.

Prototype; Passenger Side	T	U	V	W	X	Y	Z	2	3	4	5	6	7	8	9
Door flat	0	0	0	0	0	0	8	2	0	0	0	6	0	0	0
Door convex	0	0	9	9	9	9	7	9	9	8	8	7	8	5	4
Hood convex	9	8	2	3	3	2	0	0	1	1	1	0	0	0	0

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APPENDIX E: MIRROR ADJUSTMENT POSITIONS

The following appendix contains positions of prototype and production convex mirrors. The mirror adjustment grid, shown in Figure 38 above, was used when models and drivers set their mirrors. The grids below are displayed on an ordinal axis.

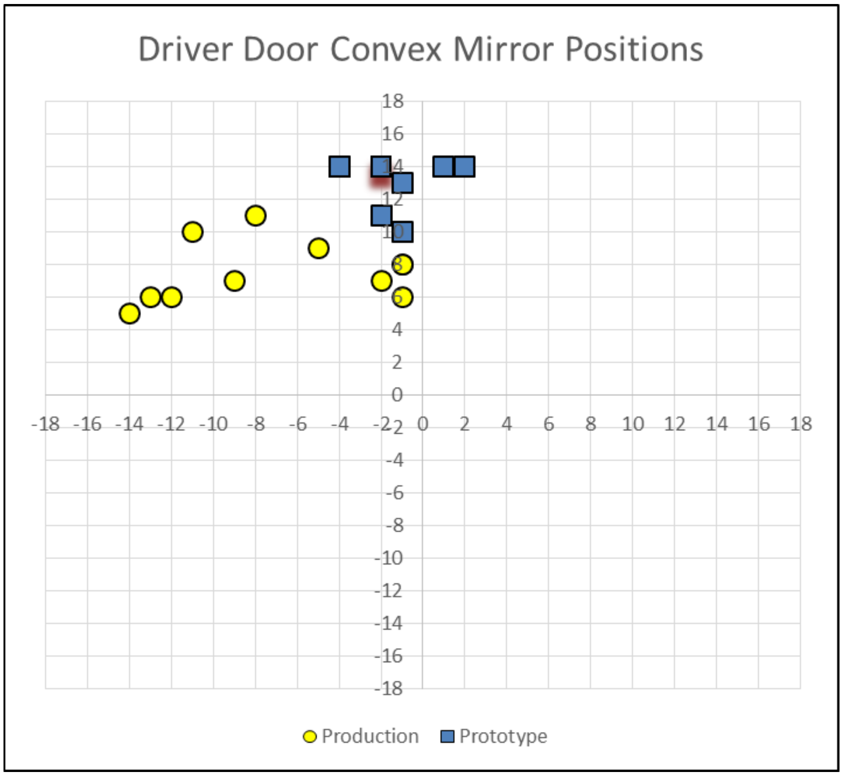

Figure 46. Graphic. Driver door convex (DDC) mirror positions on an ordinal axis.

Production DDC		Prototype DDC	
x	y	x	y
-8	11	1	14
-14	5	-2	14
-11	10	-2	14
-5	9	-1	13
-1	8	-1	10
-9	7	-2	14
-1	6	-2	11
-1	8	2	14
-12	6	-2	14
-2	7	-4	14
-13	6	-4	14

Figure 47. Graphic. Production DDC and prototype DDC ordinal values.

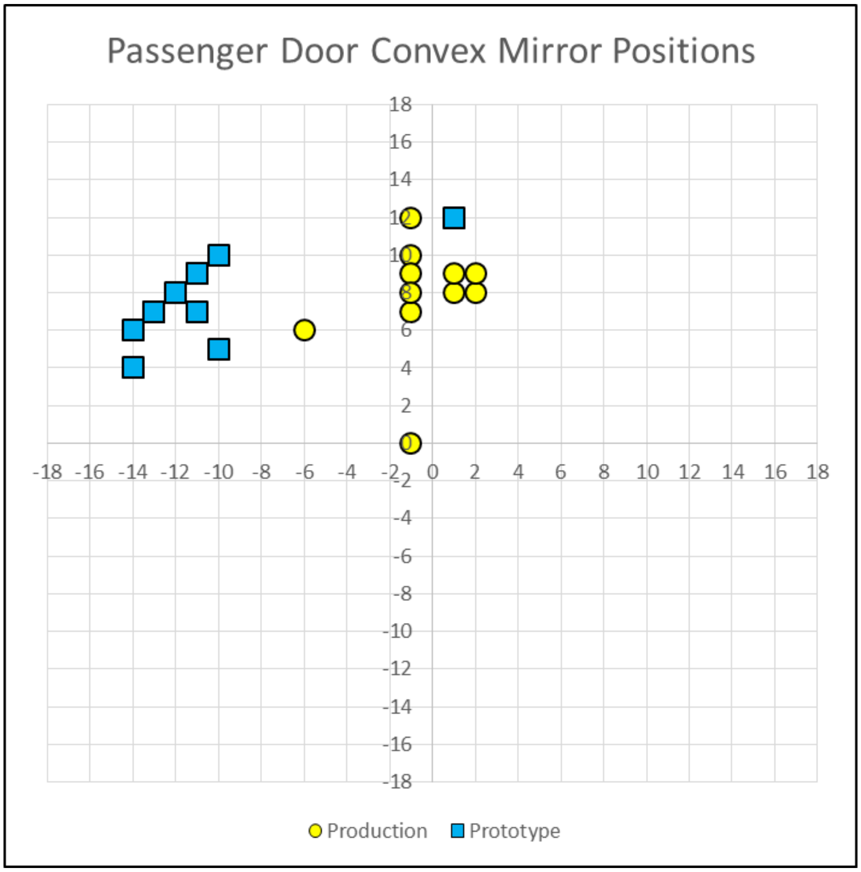

Figure 48. Graphic. Passenger door convex (PDC) mirror positions for production and prototype on an ordinal axis.

Production PDC		Prototype PDC	
x	y	x	y
-1	12	-11	9
2	8	-11	9
2	9	1	12
-6	6	-14	4
-1	7	-11	7
-1	10	-10	10
-1	0	-10	5
-1	9	-13	7
-1	8	-14	6
1	8	-13	7
1	9	-12	8

Figure 49. Graphic. Production PDC and prototype PCD ordinal values.

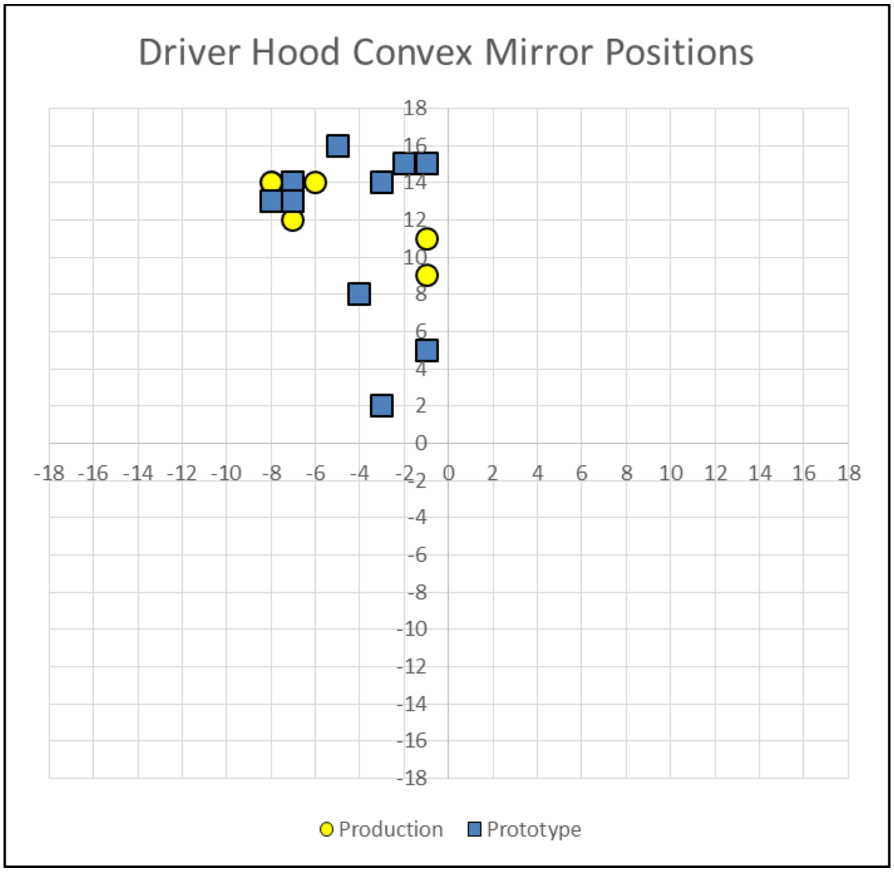

Figure 50. Graphic. Driver hood convex (DHC) mirror positions for production and prototype on an ordinal axis.

Production DHC		Prototype DHC	
x	y	x	y
-8	14	-7	14
-8	14	-7	14
-2	15	-5	16
-1	9	-3	2
-7	12	-4	8
-7	14	-1	5
-2	15	-2	15
-1	11	-1	15
-7	14	-7	13
-6	14	-3	14
-8	13	-8	13

Figure 51. Graphic. Production DHC and prototype DHC ordinal values.

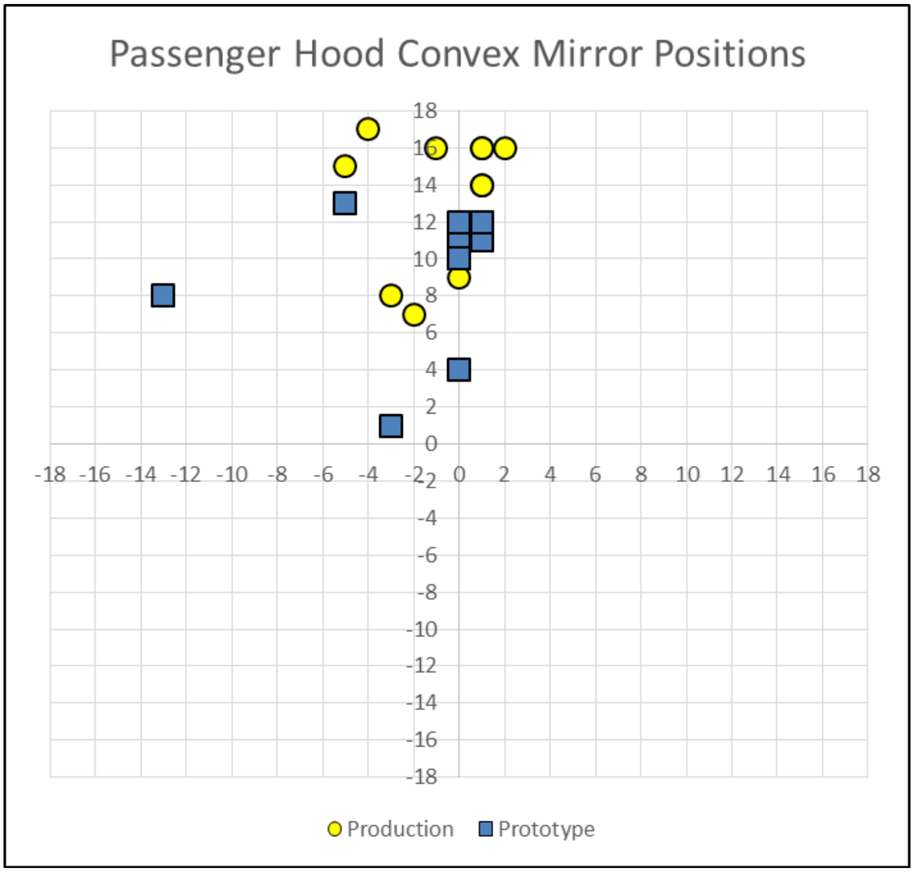

Figure 52. Graphic. Passenger hood convex (PHC) mirror positions for production and prototype on an ordinal axis.

Production PHC		Prototype PHC	
x	y	x	y
1	16	1	12
2	16	1	11
1	14	-13	8
-3	8	-3	1
0	9	0	4
1	16	1	12
1	14	0	10
-2	7	0	11
-4	17	0	10
-5	15	-5	13
-1	16	0	12

Figure 53. Graphic. Production PHC and prototype PHC ordinal values.

APPENDIX F: PARTICIPANT COMMENTS

WHAT ARE TWO THINGS YOU LIKE ABOUT THE PROTOTYPE MIRRORS?

- More, broader vision, you can see a little more.
- The wide angle.
- I can see more back, there's more of a range, they're more clear.
- I can see more area with them.
- Clearer, more definitive.
- I like that you can see more, left and right, up and down. They have way more vision.
- They look cool.
- Angle of vision passenger side hood most.
- Wider Field of View, especially passenger door convex.
- The clarity with checkerboard is good.
- Neat looking design, I like the design better. No sun glare, no brightness from them.
- The two hood mirrors weren't as bad as door mirrors (distortion).
- Cover more space, more view.
- Actual image presentation is clearer (sharper), still distorted out of focus.
- Like wider field of view on hood mounts.

WHAT ARE TWO THINGS YOU DISLIKE ABOUT THE PROTOTYPE MIRRORS?

- Distortion, how it looks like it's in a bubble, the farther back they got, they got a lot smaller than the standard.
- The distortion, other than checkerboard, lack of clarity on judging distance.
- Distance judgment was way off, I think.
- Because of the angle of the mirrors, I can estimate distance better with production.
- Need to be bigger.
- Distortion, twist and curves, convex angles.
- Harder to place things in the mirror (especially driver side door convex).
- Harder to judge the distance.
- If you could clear it up, the clarity is not real good.

- Too distorted.
- They seem like they distort a little, they're more wide angled.
- Don't like the appearance of objects in them.

WHAT ARE TWO THINGS YOU LIKE ABOUT THE PRODUCTION MIRRORS?

- Distance, you seem to adjust [judge?] distance better.
- Clarity, lack of distortion.
- Not as distorted.
- Clearer.
- It's easier to judge distance.
- About the right size.
- Wide range angle of view.
- Less distortion. Easier to place things in space.
- Large field of view.
- Wide angle.
- Feel like I could judge distance better.
- There's a lot less distortion then the other mirrors.
- Don't have distortion on the shape.
- More used to that style of mirror.

WHAT ARE TWO THINGS YOU DISLIKE ABOUT THE PRODUCTION MIRRORS?

- The angle of the mirrors on the hood, point them up more so they aren't pointed at the ground.
- If you could judge distance a little better.
- Can't see as well as the other ones, limited without moving my body around.
- Field of vision – smaller.
- Not as much field of view.
- Squarer (than normal) [circular mirrors].
- Need to know objects are closer than they appear.
- Bend down and look, full view prototype.

- You don't have as wide a span of view.
- The position.

DO YOU HAVE ANY ADDITIONAL COMMENTS FOR US?

- I didn't like the new mirrors much. I think the distortion was too bad. They were quite a bit different. The farther back things got, they were harder to see. The position on the hood mirrors I don't like, they're pointed on the ground too much.
- Still a bit of work to do on the mirrors. The closer you get physically the more distorted it became. The hood mirrors are better that the doors in terms of the distortion. The mirrors are interesting.
- Initial impressions - can see further on back. Can see more behind me than I did with the other ones. Pretty good. I like the new ones better. I could see the whole width of the truck. I like to know what's back there. DO they fog up? At night pushing snow, my mirrors fog up. How well are they with glare?
- Initial impressions: weird. I would try hood mirrors on my truck. I use spot mirrors too much to give those up, they're too good to give up. If you can get more of the distortion, that would be awesome. Field of view is more but distortion is horrible. The more you see, the better off you are. If some of the newer guys grew up with this it would probably be fine.
- Other mirrors showed more, but it was harder to make out (such as distance).
- Even though prototypes eliminate more blind spots, I have a harder time estimating distance and the distortion. The distortion messes me up. The one positive thing, they eliminate a lot of the blind spots. It would avoid parking lot accidents. People don’t know how to merge, they want to come out on you. If you have guys on your left, you can’t merge, if people want to die it’s their own doing. Judging where they are in relation to the trailer and truck I still prefer the old mirrors. I like the hood mounted mirrors. If you can work on distortion, it’s a good idea, just need to be perfected.
- Normal round mirrors are more useful.
- Like the passenger hood prototype. Reword questions to experimenter can find out the difference position rating versus mirror themselves. I have not been aware of the distortion of the production mirrors. I am a driver CDL trainer, train the trainer. I cannot use the mirrors in this position.
- Judging distance with all mirrors. A lot of times I move my head to judge distance. The time to estimate was tight. It would be interesting to drive with them. It is so different, but I wouldn't dismiss them. Driving with them would give a better feel for them.

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APPENDIX G: DYNAMIC EVALUATION TEST PLAN

FAST DASH 3 Dynamic Test Plan

Equipment:
Lonestar with trailer – DAS implemented
Remote Vehicle (Green Malibu vehicle B)
Prototype mirrors
5 Cones (as large as possible)
Questionnaire packet
Radio Pairs (4 total) - (one in each vehicle)
Go Pros (4):

1. Mirror Camera – driver
2. Mirror Camera – passenger
3. Face view of Driver
4. Remote vehicle – Sunroof/windshield

Drive Route and Tasks:
Production mirrors attached

1. 460 E to I-81 S
2. I-81 S to Exit 98
3. Immediate left into gas station
4. Back up into available spot

Change mirrors to prototype

1. Sharp turn to go out the way they came in, if possible
2. Merge onto I-81S
3. I-81S to Exit 89A
4. Navigate clover leaf x6 to return to I-81N
5. Exit 118C, left onto Roanoke St, US-11
6. Right onto 460W
7. Exit 4B
8. Right turn into back lot
9. Curb dock
10. U-turn to prepare for alley docking maneuver

11. Perform alley docking maneuver
12. Navigate to parking lot (U-turn or side street)
13. Enter parking lot, perform parking lot maneuvers
14. Parallel park
15. Exit parking lot
16. Return to VTTI

Specific Tasks:

Lane changing on interstate

Gap acceptance task using vocalization: (two times minimum each mirror)

Driver of host vehicle (HOST VEHICLE) will be asked when they feel it would be safe to pass remote vehicle (the REMOTE VEHICLE will be ahead of the truck and continually reduce speed in the left lane). Driver will say into the radio "Now" at the earliest moment they feel comfortable passing the REMOTE VEHICLE.

Overtaking / Lane Change: (two times minimum each mirror)

Driver of heavy vehicle will be asked to overtake a slow moving vehicle in the right lane (REMOTE VEHICLE). Driver will move into left lane to overtake REMOTE VEHICLE. Driver will say into the radio "Now" at the earliest moment they feel comfortable passing the REMOTE VEHICLE. REMOTE VEHICLE will confirm it is safe and the driver will reenter the right lane.

Scenario specific questions:

- "When do you feel comfortable passing the remote vehicle?"
- "When do you feel comfortable overtaking the remote vehicle?"
- "When is the last moment that you feel comfortable passing this vehicle?"
- "Please talk me through anything noteworthy between production and prototype mirrors."

Blind spot visual confirmation (one time each mirror)

REMOTE VEHICLE is instructed to pass the HOST VEHICLE slowly on the left side. Driver of HOST VEHICLE is asked if and when visual of REMOTE VEHICLE is lost, and will say "Gone" into the radio (for visual confirmation by REMOTE VEHICLE's camera). When the driver is able to see the vehicle in peripheral or direct vision, the driver will say "Back" into the radio. This process will be repeated on the right side of the HOST VEHICLE.

Scenario specific questions:

- "When do you lose sight of the remote vehicle on the driver's side mirror?"
- "When do you regain sight of the remote vehicle in peripheral or direct vision?"
- "When do you lose sight of the remote vehicle on the passenger's side mirror?"
- "When do you regain sight of the remote vehicle in peripheral or direct vision?"

- “Please talk me through anything noteworthy between production and prototype mirrors.”

Night driving (night run only, one time each mirror)

Lane changing and overtaking will be completed again, with the REMOTE VEHICLE having high-beams on. Additionally, the REMOTE VEHICLE will fall back behind the HOST VEHICLE about 300 feet, and rapidly approach with high beams on in the HOST VEHICLE lane, and overtake the HOST VEHICLE.

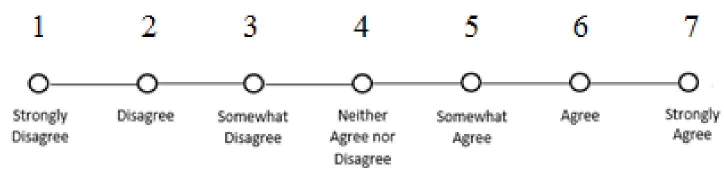
Scenario specific questions:

- “Please talk me through anything noteworthy between production and prototype mirrors.”

APPENDIX H: DYNAMIC EVALUATION QUESTIONNAIRE

Questionnaire Packet:

On a scale of 1 to 7, please rate the extent to which you agree with the following statements.



Note: Statements with a * use the above scale

Driver's Side:

1. *I prefer the field of view provided by the prototype mirror.
2. *I believe driving was safer with the field of view provided by the prototype mirror.
3. *I prefer the degree of image clarity provided by the prototype mirror.
4. *I believe the degree of image clarity provided by prototype mirror was more useful than that provided by production mirror.
5. *I prefer using the prototype mirror to estimate distances.
6. *I believe estimating distances was more accurate with the prototype mirror.
7. *If I were given a choice to use the prototype mirror regularly while driving a heavy vehicle, I would use them.

Passenger's Side:

1. *I prefer the field of view provided by the prototype mirror.
2. *I believe driving was safer with the field of view provided by the prototype mirror.
3. *I prefer the degree of image clarity provided by the prototype mirror.
4. *I believe the degree of image clarity provided by prototype mirror was more useful than that provided by production mirror.
5. *I prefer using the prototype mirror to estimate distances.
6. *I believe estimating distances was more accurate with the prototype mirror.
7. *If I were given a choice to use the prototype mirror regularly while driving a heavy vehicle, I would use them.
8. Do you have any additional comments regarding the mirrors?

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