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NightDriver™ Thermal Imaging Camera and HUD Development Program for Collision Avoidance Applications

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16. Abstract

Raytheon Company completed the Head-up Display (HUD) Development Program under a Cooperative Agreement with the National Highway Traffic Safety Administration (NHTSA) in support of NHTSA's collision avoidance research program. The focus of the effort was to investigate new methods and technologies related to the development of automotive head-up displays and to develop an improved, production-realistic prototype HUD capable of supporting night-driving applications and operating reliably in the automotive environment.

The program involved the evaluation of the NightDriver (tm) HUD and development of an advanced HUD prototype. NightDriver (tm) is the term previously adopted by Raytheon for a developmental automotive night-driving system, which consists of a thermal imaging camera mounted on the front of the automobile and a HUD mounted inside the automobile within the driver's line of sight or on top of the instrument panel.

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FINAL REPORT

NIGHTDRIVER™ THERMAL IMAGING CAMERA AND HUD DEVELOPMENT PROGRAM FOR COLLISION AVOIDANCE APPLICATIONS

1. EXECUTIVE SUMMARY

Raytheon Company completed the Head-up Display (HUD) Development Program under a Cooperative Agreement with the National Highway Traffic Safety Administration (NHTSA) in support of NHTSA Collision Avoidance Research efforts. The focus of the effort was to investigate new methods and technologies related to the development of automotive head-up displays and to develop an improved-production realistic prototype HUD capable of supporting night-driving applications and operating reliably in the automotive environment.

The program involved evaluation of the NightDriver™ HUD and development of an advanced HUD prototype. NightDriver™ is the term previously adopted by Raytheon for the developmental automotive night-driving system, which consists of the thermal imaging camera mounted on the front of the automobile and a HUD mounted inside the automobile within the driver's line of sight on or on top of the instrument panel (the "dash area"). The NHTSA research program leveraged the NightSight™ Consortium Uncooled Infrared (IR) Sensors Technology Reinvestment Project (TRP) to advance HUD concepts for application as a collision avoidance system in automobiles and trucks. Deliverables under the NHTSA program included one advanced HUD prototype, written quarterly cost/schedule/status reports, and written meeting minutes after each major NHTSA/Raytheon meeting. Raytheon successfully completed the program with delivery of the final report and one advanced HUD with a thermal imaging camera to NHTSA on 30 June 2000.

2. BACKGROUND

The Automotive Project under the Uncooled IR Systems TRP progressed somewhat ahead of schedule to provide five early developmental (engineering) prototype NightVision™ cameras (box cameras and NightDriver™ prototypes) and HUDs that Raytheon installed in five automobiles. The box camera consisted of a thermal imaging camera core inside a rectangular box-like housing. Raytheon designed the NightDriver™ prototypes to facilitate commonality with the camera core in the car-mounted NightSight™.

2.1 NightDriver™ Camera

The prototype NightDriver™ camera, pictured in **Figure 1**, weighed approximately 2 pounds with a volume of approximately 60 cubic inches. The prototypes provided clear, sharp thermal imagery that facilitated detection of a person at approximately 700 meters. Preliminary design verification testing of the engineering prototypes indicated that the cameras would be reliable and rugged. During October 1996, the NightDriver™ camera officially debuted publicly at the 1996 Convergence Conference in Detroit, further adding interest from automobile manufacturers. The original prototype cameras were used extensively in demonstrations and trials such as the Baja 1000 race. Further Raytheon NightDriver™ development, testing, and prototyping followed and a production program was consummated with General Motors for the NightVision™ system.

Figure 1. The original prototype NightDriver™ camera paved the way for an automotive thermal imaging camera and HUD (NightVision™) production program

2.2 Head-Up Display

The IR camera is of no use as a driving aid in a passenger vehicle without a suitable means for displaying the video in a manner that does not compromise safety. To continue development of the NightDriver™ HUD and to provide a means for NHTSA to evaluate safety and human factors, NHTSA and Raytheon entered into a cooperative agreement under the NHTSA Collision Avoidance Program.

Raytheon matched the NHTSA research program funding by means of our automotive program HUD development effort, which involves multiple U.S. and international vendors. The specific goal was to minimize the package size to provide non-intrusive HUD images to a person in a normal driving position. This meant that the HUD image needed to be below the driver's forward line of sight so that the driver could safely perform normal driving tasks without being distracted by the HUD image. Normal driving tasks include but are not limited to consistent observation of the forward and peripheral visible scenes and steering the vehicle to stay within the appropriate street or highway lanes—and to safely avoid people, animals, other vehicles, and objects; glancing at the rear view mirror for awareness of what is behind and to detect unsafe situations; and glancing at the instrument panel for awareness of speed and to note potential engine malfunctions. To make the automotive HUD useful as a safety enhancement system, the HUD was to display thermal images clearly and prominently within the driver's normal field of regard. Nominally, "clearly and prominently" were defined as a TV-like image bright enough to be easily detected and viewed but not so bright as to be distracting. The center of the HUD image needed to be downward from the driver's normal line of sight a minimum of 3 degrees, and no portion of the automobile hood was to appear as background to the video scene in the HUD.

3. HUD PROGRAM GOALS AND OBJECTIVES

The primary goal of the HUD Development Program for Collision Avoidance Applications was to develop a production-realistic prototype HUD with better performance than the NightDriver™ beta HUD, and with capability to operate reliably in the "dash" area of automobiles. The objective was to leverage the IR camera, HUD, and technology developments under the NightSight™ Consortium TRP to enhance development of an automotive thermal imaging collision avoidance system.

The research program consisted of one specific task as defined in the following paragraphs.

3.1 Head-Up Display Development

After measuring and evaluating the critical HUD performance parameters [listed in **Table 1** for the then-existing NightDriver™ HUD (beta) design], Raytheon engineers determined which areas could most likely benefit from further engineering development. The plan for the improved-design NightDriver™ HUD involved upgrading the image quality (specifically distortion and vertical disparity) of the existing design. Incorporating these improvements, Raytheon was to design, build, and test the improved HUD. Other candidate optical system parameters that were to be investigated for improvement included, but were not limited to:

- Day/night capability
- Field of view (FOV) (vertical and/or horizontal)
- Image projection ratio
- Aspect ratio
- Package size
- Cost
- Test set development
- Reliability.

Image quality was characterized by using a flat piece of glass in place of an actual windshield to avoid windshield-induced image quality degradation (over which we have no control). Raytheon was also to include the windshield in the characterization tests to determine the effect of the windshield on the HUD performance. Technical goals are summarized in **Table 1**.

Table 1. Goals for Collision Avoidance Program HUD

Parameter	Existing Design	Improved Design Goal
Distortion	>5%	<5%
Vertical disparity	<5 mrad max	<1 mrad average <5 mrad maximum
Image projection	1:0.86	1:1
Aspect ratio	2.5×1	3×1
Operational functionality	Night-only	Night-only
Luminance adjustment	0 to 15 fL	0 to 15 fL
Virtual image focus plane	>2 meters	>2 meters
Look-down angle	>3 degrees	>3 degrees
Location adjustment	Vertical	Vertical

3.2 Development Path

Raytheon completed a kickoff meeting with NHTSA on 6 November 1997 at the Nassif Building in Washington, DC, where we presented the HUD development plans. During the first quarter of 1998, NHTSA and Raytheon participated in a working group session to decide future efforts. As shown in **Figure 2**, the specific choices were either (1) to help the HUD vendors improve the GMX270 HUDs, or (2) to create advanced HUD designs.

During the working group session, we agreed that the path to take was the “Create Advanced HUD Designs” path. The rationale for this decision was that the HUD vendors (Delco and Japan’s Kansei Corporation) had credible paths to provide good HUDs and that the issues they were experiencing were not ones we could impact economically.

4. WIDE FIELD-OF-VIEW (WFOV) TRADE STUDY

The first step in the “Create Advanced HUD Designs” process was to conduct a wide field-of-view (WFOV) trade study. Raytheon divided the WFOV trade study into two sections. In Section 1, we investigated various optical system configurations and their performance sensitivity to FOV and other critical HUD parameters. A major output of this section of the study was the “required image size” for the six different optical configurations considered. For each of the six configurations, we used an Optical Research Associates (ORA) Code V analytical tool to compare the various parameters (listed in **Tables 1** and **2**). The field of view, for example, would affect the focal length, width of the box, distortion, etc. Part 2 of Section 1 involved further modeling of the three most promising configurations considered, this time adding the windshield model (based on a Cadillac windshield) into the trade study and analyzing the effects of more “overlap” into the designs. The conclusions of these modeled comparisons are listed in Section 4.1. Physical measurements were accomplished on an engineering breadboard unit and the measured performance is outlined in Section 5.2.

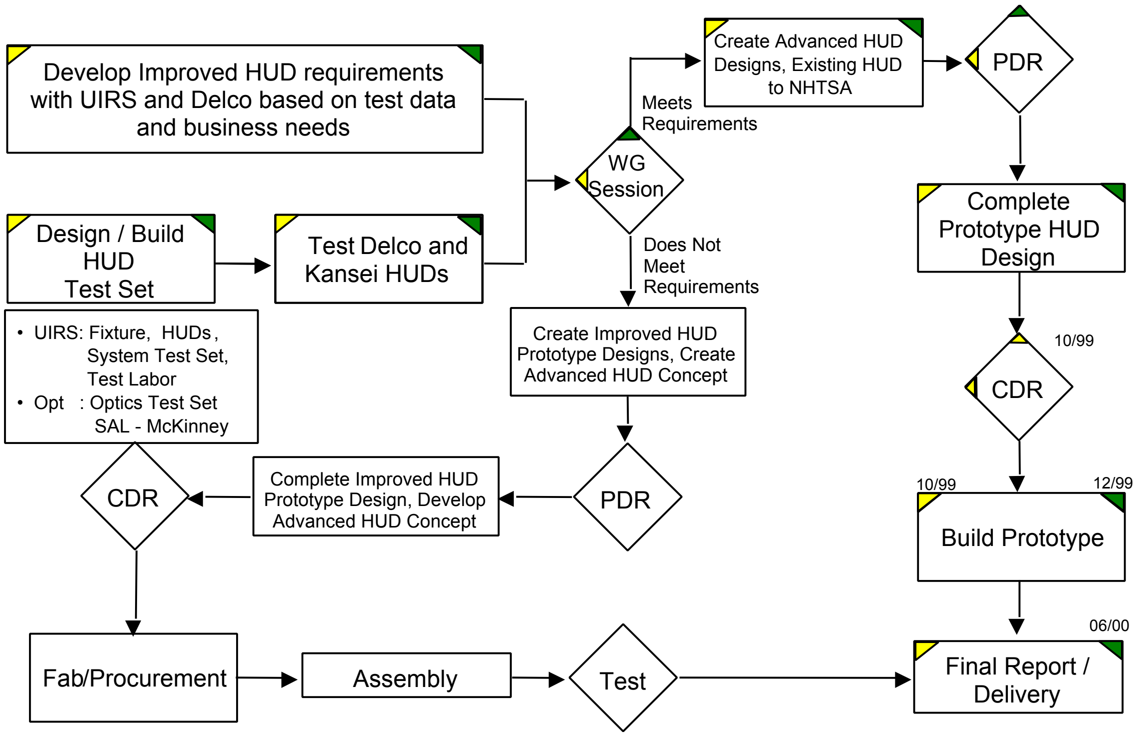

Figure 2. Top-Level Integrated Product Development Process (IPDP) Improved HUD

The three HUD configurations further studied were the Fresnel lens system (FLS), the aspheric mirror with beamsplitter system, and the asphere/Fresnel optical system.

4.1 Trade Study Results and Conclusions

The primary conclusion of the WFOV trade study was that the Fresnel lens system provides the best opportunity for a low-cost, good-performance HUD. The following factors support that conclusion:

- The FLS and the aspheric mirror with beamsplitter system require the smallest optic width; however, the FLS has fewer, and less expensive, optical components, thus yielding a lower optical components cost for the HUD system
- Performance between the FLS and the aspheric mirror with beamsplitter system are inconclusive, as the FLS has better maximum vertical disparity and the aspheric mirror with beamsplitter system has better distortion
- The FLS requires a short focal length, which requires less packaging depth in the dash
- The FLS has the smallest required image size [liquid crystal display (LCD) width] and probably requires a monochrome LCD, again yielding a lower LCD cost for the HUD system.

The overall results and conclusions are summarized as follows.

- Fresnel lens system offers best low-cost, WFOV HUD candidate
  - Lowest cost
    - Single lens element

        - Injection-moldable lens element
            - Low producibility risk process
            - High production capacity process
            - Low-cost process
        - Smallest LCD required
    - Good image quality
    - Smallest in-dash package
        - Shortest focal length
        - Smallest required optical width
    - Excellent on-dash package
- Off-the-shelf Fresnel lens system is best choice for breadboarding and characterization
- Market needs a WFOV, low-cost automotive HUD
- Our Fresnel lens HUD design can meet the requirements
    - Performance
    - Cost
- The Fresnel lens design can be used in-dash or on-dash.

The second section of the WFOV trade study identified displays that meet the HUD system requirements and the required image size determined in Section 1. These displays are listed in **Table 2**. The goal was to select the smallest available LCD with the lowest risk and cost that could be used in both an in-dash and an on-dash configuration HUD. A survey of the market located a monochrome LCD that was the appropriate size for the 18-degree FOV Fresnel lens system.

Table 2. Identification of Suitable Displays

Type	Disparity (maximum vertical) (mrad)	Distortion (maximum vertical) (percent)	Width (in.)	Image Width (in.)	Focal Length (in.)	Cost Considerations	Risk
On-dash Fresnel	5.1	3.4	11.0	2.5	6.7	Small LCD, 1 lens, injection-moldable	Low
In-dash Fresnel	4.3	4.2	17.2	3.0	6.7	Small LCD, 1 lens, injection-moldable	Low
Asphere with beamsplitter	2.2	1.2	17.4	4.6	9.8	Medium LCD, 2 elements	Medium
Asphere with Fresnel	3.5	5.3	17.6	5.0	9.0	Medium LCD, 2 elements	Medium
Zemike mirror	8.9	2.4	18.6	8.2	15.6	Large LCD, replicated mirror	Medium
Anamorphic mirror	6.0	10.1	19.0	9.3	20.2	Large LCD, complex replicated mirror	High

5. HUD DESIGN AND DEVELOPMENT

5.1 Breadboard HUD

Following the trade study, Raytheon designed and assembled a Fresnel Lens System (FLS) breadboard test set to provide an accurate method for testing Fresnel-lens-equipped HUDs. The FLS HUD breadboard was installed on this test set and demonstrated at the Preliminary Design Review (PDR) in September 1998. The FLS HUD breadboard consisted of an inexpensive, off-the-shelf Fresnel lens and a 3-inch, black and white LCD with support electronics. The demonstration of the Fresnel lens system HUD prototype was accomplished alongside the current NightDriver™ HUD a NHTSA conference room. An actual automotive windshield was set up in the conference room with the FLS HUD on the driver's side and the NightDriver™ HUD on the passenger's side. (Both HUDs are designed for driver's side application; the current NightDriver™ HUD was merely placed on the passenger's side of the windshield to avoid using a second windshield.) Thermal cameras were connected to both HUDs directed out into the conference room. A Raytheon attendee provided a human target at approximately 24 feet. The lights were turned off and the thermal cameras turned on. Both HUDs received positive reviews from the attendees.

The NHTSA HUD breadboard prototype is shown in **Figure 3**.

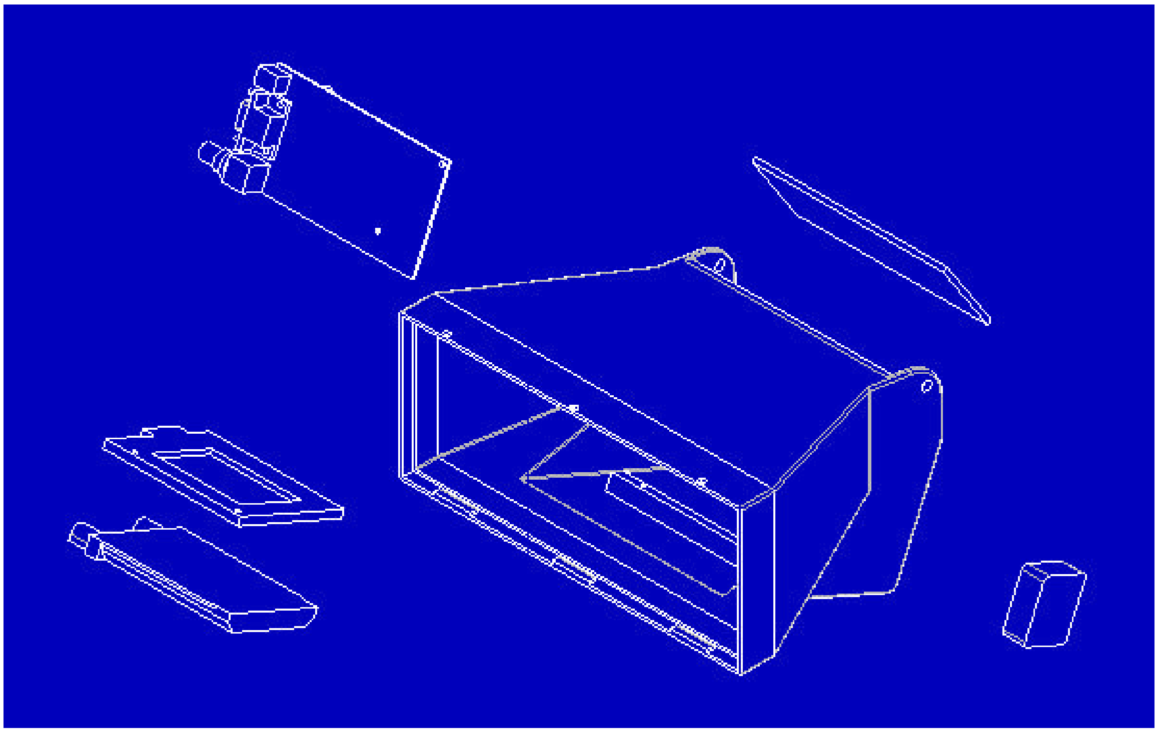

Figure 3. Breadboard Prototype HUD Demonstrated at NHTSA

5.2 Engineering Prototype HUD

The successful trade studies and breadboard efforts paved the way for progression into the engineering prototype effort during which Raytheon designed and built a prototype NHTSA HUD and installed it, along with a NightDriver™ camera, in a Raytheon-owned Suburban, as shown in **Figure 4**. Formal Human Factors testing was not a part of our NHTSA HUD program. However, to gather basic information on the suitability of the improved production realistic HUD for night driving operations, Raytheon conducted informal driving evaluations with our development team and eight or ten other individuals who had no knowledge of the project or the technology. The results indicated that the prototype HUD indeed supports night driving and enhances safety. None of the drivers reported the HUD to be a source of distraction. All of the drivers readily adapted to the HUD and quickly realized and commented on the safety benefits of being able to view the scene "far beyond" their headlights. Typical driver comments are summarized in Section 5.2.1. We reported these test results and provided the program status to NHTSA during the Critical Design Review (CDR) in October 1999. The prototype HUD design goals and measurements of performance are summarized in **Table 3**. In December 1999, we conducted a successful driving demonstration of the HUD (in the Suburban) for NHTSA and other agencies invited by NHTSA at a site near Washington, DC.

Figure 4. Engineering Prototype HUD Installed in Raytheon Suburban[2]

[2] Raytheon Company Patent Pending

Table 3. Performance for Collision Avoidance HUD

Parameter	Design Goal	Measurement
Distortion	<5%	1.5% maximum
Vertical disparity	<5 mrad (maximum)	1 mrad
Image projection—vertical	1:1	1:1
Image projection—horizontal	1:1	1:1.1
FOV (minimum)	4 × 12 degrees	5.1 × 11.4 degrees
Eyebox size	SAE 6.5	3.2 in. vertical × 13.5 in. horizontal
Operational functionality	Night-only	Night-only
Luminance adjustment	0 to 15 fL	0 to 8.4 fL
Virtual image focus plane	>2 meters	3 meters
Location adjustment	Vertical	Vertical

5.2.1 Driver Feedback

The following driver comments and suggestions were collected during our informal driving evaluations:

- Good image quality and brightness during night driving
- Intuitive interpretation of scene (didn't require extensive training)
- Easy to incorporate into normal driving routine
  - Scan rear view, side view mirrors, and thermal image display
  - Spend majority of driving time looking through windshield
- Glare (reflections) off Fresnel lens during day objectionable
- Lookdown angle incompatible with use of bifocal glasses
- A larger vertical FOV is preferred
- Vertical size of the HUD package should be reduced to limit blockage of forward road scene
- The housing size should be reduced to fit the size of the image
- Night blindness from oncoming traffic headlights is significantly reduced
- Image appears slightly closer than the object
- A folddown version would remove daytime glare off Fresnel lens and re-gain any lost forward scene visibility
- Eyebox size adequate.

5.3 Production-Intent Prototypes

The successful development efforts on the NHTSA/Raytheon HUD Development Program resulted in a lower than planned expenditure rate. Because of the success and availability of funding, Raytheon requested and NHTSA approved a no-cost extension of the program to 30 June 2000. Because General Motors had begun production and sale of the 2000 Cadillac Deville with NightVision™ as an option, it was apparent that NHTSA could conduct in-house testing with production equipment (albeit in-dash, not on-dash) rather than with prototypes. It seemed prudent, then, that Raytheon should build a second prototype for a different application, one that was also of interest to NHTSA and one that involved a near-term business interest for Raytheon. We used the remaining Raytheon funds during the first quarter of 2000 to refine the prototype design and tailor it for Class 8 truck applications. The goal was to use a small LCD (3.0-inch diagonal), a smaller housing, and an off-the-shelf Fresnel lens. Because the truck HUDs are production-intent prototypes of interest to NHTSA as well as Raytheon, we are including in this final report a detailed description of the results of the successful design and development efforts.

5.3.1 Heavy Trucking HUD Development

Raytheon designed and built two additional HUDs and installed them in a Freightliner Century Class heavy trucking application. The thermal image source for these HUDs was the camera to be used in the 2001 Cadillac DeVille. The drive electronics that were used in the previous versions of the HUDs were reused on the truck HUDs.

Raytheon designed and built one HUD model to be mounted on top of the dashboard directly in front of the driver, as shown in **Figure 5**. This HUD has two fold mirrors that bounce the light from the LCD panel up to the Fresnel lens.

We designed the second HUD to be integrated into the overhead compartment above and in front of the driver as shown in **Figure 6**, with imagery as shown in **Figure 7**. The image from the LCD panel in this HUD is reflected using a single fold mirror to the Fresnel lens. The Fresnel lens projects the image down onto a combiner. The driver can adjust the angle of the combiner to properly reflect the image toward the driver's eyes. The combiner is fabricated from acrylic material. It is coated with a 60-percent reflective coating on the side of the combiner that reflects the image to the driver. The backside of the combiner is antireflective-coated. This combiner configuration allows the driver to see the road through the combiner, as well as the IR image projected by the HUD.

The above-mentioned HUDs both use a Sharp monochrome LCD display. The resolution of the display is 320×240 pixels. The drive electronics for the LCD display panel accept standard U.S.-format [National Standard Committee (NTSC)] analog video. The backlight for the LCD panel is a cold cathode fluorescent lamp. A voltage inverter takes the automotive low-voltage direct-current power and converts it to high-voltage alternating current to power the fluorescent lamp. The performance of these two HUDs should be similar (by design) to the performance of the NHTSA HUD measured earlier, although we did not measure the performance of these HUDs.

Figure 5. Dash-Mounted Truck HUD

Figure 6. Truck HUD Mounted in Overhead Compartment

Figure 7. Imagery on Overhead Compartment-Mounted HUD

The Fresnel lens is made from molded acrylic. It is antireflective-coated to reduce glare from outside light sources such as headlights and streetlights. The image that appears in the HUD is designed to be actual size when viewed from a nominal distance of 28 inches.

The infrared camera used is the same as the one to be used in the 2001 Cadillac. We fabricated a bracket to mount to the airfoil above the windshield on the front of the cab and mounted the camera to the bracket using the same adjustable brackets as those used on the Cadillac. **Figure 8** is a photograph of the installed camera.

Figure 8. Camera Installed on Truck Airfoil

6. HUD DELIVERABLE

Based on the success of the truck HUD and the NHTSA/Raytheon mutual interest in this application, we elected to build an additional HUD for delivery to NHTSA at the end of the program in lieu of a rather fragile engineering prototype. Included with the HUD was a sturdy tabletop viewing mechanism and the necessary equipment for easy demonstrations. The HUD is rugged enough for installation in a truck if desired.

7. CONCLUSIONS

The NHTSA/Raytheon HUD Development Program for Collision Avoidance Applications successfully met the following program goals:

- Developed an improved, production-realistic prototype HUD with advanced features and performance
- Demonstrated that the HUD will be capable of operating reliably in the automobile environment
- Demonstrated that drivers adapt readily to the HUD and the concept of enhanced safety
- Demonstrated that the HUD will be capable of operating in the trucking environment.

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