Experimental Route Guidance Head-Up Display Research

R. W. BENZINGER and E. BELL, Kollsman Instrument Corporation

The head-up display is a new technique developed by the aerospace industry as a pilot landing aid. This concept provides a virtual image symbolic representation of the visual scene projected on the windshield of the aircraft and superimposed on the real world. The symbology is focused at infinity and permits the pilot to observe both the real world, the superimposed image and other visual cues without lowering his head to look at the instrument panel. The term "head-up display" was coined to describe this feature. This technique has been adapted to present directional symbols to the driver in the same manner so that he need not take his eyes off the road. The design of the vehicle display unit is derived from evaluation and tradeoff of the various optical and electronic techniques developed for an aircraft application. Design criteria were established to meet the objectives of optimum image quality, minimum package size, and most economical cost. Several alternative approaches to display design were investigated that involved various types of lenses, reflecting surfaces, and symbol production techniques. Other engineering considerations involved included temperature and vibration environment, vehicle design, and safety. A feasibility model of the selected approach was built and delivered to the Bureau of Public Roads for road testing in their experimental vehicle and subsequent incorporation in the route guidance test network.

•FUTURE urban and highway planning must consider the requirement for providing a system for coordinating urban traffic control and en route highway guidance that will enable traffic flow to be regulated in an orderly, efficient and safe manner. Many more miles are being added to the Interstate Highway System each year. New freeways are being constructed between and around urban areas. The complexity of these modern road systems, with their multi-level interchanges and multiple intersections, produces a vast amount of information via road signs and other related outside media which must be communicated to the driver to permit him to reach his destination. Since road signs must serve the whole driver population, the information presented is general in nature. The driver must know his route or consult road maps or other references to determine which exits and turns will take him to his destination. A driver traveling in unfamiliar territory is often faced with uncertainty when approaching an unknown intersection. At present turnpike speeds, with the look angle constantly changing, he may not be able to read the sign at all. Further, the time available to make his decision, move into the appropriate lane, and then execute the required maneuver is extremely short. Any hesitation or delay in decision-making may result in

---

Paper sponsored by Special Committee on Electronic Research in the Highway Field and Committee on Traffic Control Devices and presented at the 48th Annual Meeting.

missing the turn entirely or cause a driver to make an abrupt change in direction which disrupts normal traffic flow and creates a potentially hazardous situation for other drivers. When traffic is heavy or when adverse environmental conditions, such as glare, darkness, rain, snow or fog prevail, the problem is more serious.

The primary objective of the Bureau of Public Roads' experimental route guidance system is to provide the driver, automatically and within his vehicle, specific directional information that will guide him to his destination over the most efficient routes. Upon interrogation by the vehicle encoded destination signal, route guidance information is received from a roadside computer unit which is part of the integrated ERGS network. This information is decoded and converted into a directional symbol displayed within the vehicle. Previous research by the Bureau of Public Roads led to the adoption of a basic set of 16 directional symbols, 11 of which are directional arrows and 5 are simple two- or three-word instructions (Fig. 1). These symbols are concise and nonambiguous; they represent the simple format required for an efficient visual display.

A research program led to the selection of the head-up display concept as the most effective display method for presenting the directional information to the driver with a minimum of distraction. This paper explains the concept and its advantages, outlines the investigations and engineering tradeoffs involved in selecting a head-up display from various alternative display configurations, and describes the design and operation of a working model built and delivered to the Bureau of Public Roads for evaluation.

HEAD-UP DISPLAY

The term "head-up display" was coined by the aerospace industry to describe a new avionics technique that provides a virtual-image symbolic representation of the visual scene, projected on the aircraft windshield or other partially reflective surface, and superimposed on the real world. This technique has been used to provide target reticles for airborne gunsights, and recently, the aerospace industry has been exploring its tremendous potential as a low-visibility or all-weather landing aid. The displayed symbology, consisting of visual cues, such as the outline of the runway and instrument readings, is focused at infinity and permits the pilot to look at the real world through the windshield and simultaneously obtain instrumental flight control and situation information without lowering his head to look at the instrument panel. Figure 2 shows typical display symbology as seen by the pilot during a landing approach.

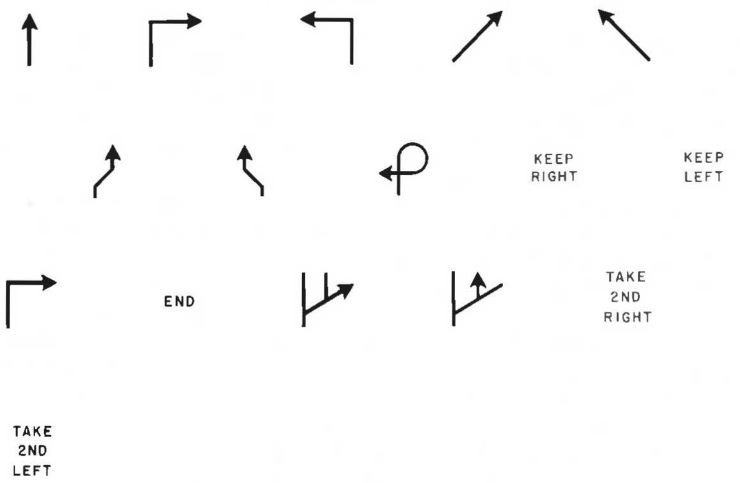
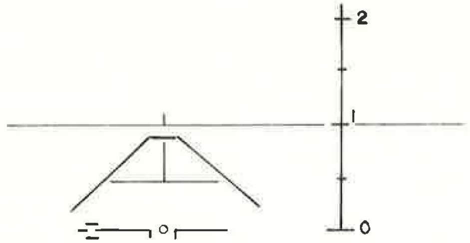
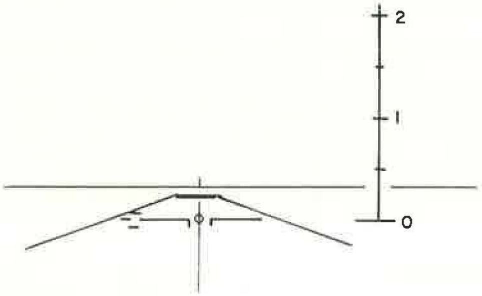


Figure 1. Directional symbols.



Aircraft aligned with runway centerline at 100-ft altitude, approaching runway.



Aircraft over the runway just before touchdown; image adjusts to proper perspective.

Figure 2. Typical head-up display symbology.

This technique is particularly suited for the ERGS application because it offers a distinct advantage over other display methods. The symbology is projected on the windshield in the driver's normal line of vision through a collimating lens system in which light rays reflected from the windshield are essentially parallel. This causes the symbol to appear to be focused at or near infinity and superimposed on the road scene. The driver can observe both the road scene and the symbol simultaneously without refocusing his eyes and with minimum distraction.

DISPLAY REQUIREMENTS

In order to display the symbols so that they could be readily observed and correctly identified by the driver, the symbol characteristics relating to size, stroke width, brightness, contrast ratio and distortion were established by human factors analyses which considered the perceptual limitations of the driver's eye. In addition, other factors influencing the projected symbol design were virtual-image distance, head movement constraints and the effects of vehicle vibration.

The investigations involved a review of published research results in the area of visual acuity and perception. These data were evaluated in terms of the specific application to the route guidance head-up display and resulted in the list of design recommendations given in Table 1. Later validation tests in the laboratory demonstrated that these parametric values will unequivocally allow 99 percent correct symbol identification by the driver in less than 200 milliseconds of display "on" time.

Size and stroke width were selected to insure identification and legibility under low contrast and/or low brightness viewing conditions. Symbol color was selected in the region of the visible spectrum most sensitive to the eye for day as well as night driving. To establish symbol brightness and background contrast ratio, consideration was given to the total driving situation where background illumination may vary from 0.001 ft-L under a moonlit sky, to approximately 10,000 ft-L for fresh snow at midday under

TABLE 1

DESIGN RECOMMENDATIONS FOR HEAD-UP DISPLAY SYSTEM

Parameter	Recommendation
Symbol size	1 in.
Symbol size/strokewidth ratio	5:1 to 6:1
Viewing distance	22 to 28 in.
System vibration tolerance	Approx. 10 min and 30 cps
Symbol luminance requirements	Variable from 1 to 1,000 ft-L
Symbol luminance-background contrast ratio	0.1 minimum
Preferred symbol color	Green region of spectrum, 500-550 mμ
Exit pupil size	8.5 in. horizontal; 4.0 in. vertical
Image location	0 to 4° below the horizontal in the forward plane
Symbol duration	Controlled by driver; could be as short as 200 millisec for recognition

a clear sky. Symbol brightness, variable to about 1,000 ft-L is required for 0.99 identification probability.

Presentation time for the symbol should be of sufficient duration to permit the driver to assimilate the information but not so long as to interfere with visual performance. The tests conducted indicated correct identification was obtained with presentation times of under 200 milliseconds. It appears reasonable to permit the driver to control presentation time.

One of the more critical parameters is the exit pupil size, which determines the amount of lateral and vertical head movement which can be allowed and still keep the driver's eyes in the optical field of view. The head-up display must allow freedom of head movement for normal driver motions and must also accommodate the various sitting heights of different drivers. The diameter of the collimating lens determines the amount of field visible for a given eye position. In the ERGS display a lateral head movement of 10 in. and a vertical head movement of 8 in. would be desirable. However, engineering constraints imposed by specific vehicle dimensions limit the maximum achievable exit pupil size.

ALTERNATIVE DISPLAY CONFIGURATIONS

Various techniques of displaying collimated images were reviewed to determine their applicability to particular requirements of vehicle route guidance. These included most of the aircraft head-up display systems currently being developed by the aerospace industry. Although the airborne systems are too complex and costly to be adapted to vehicle use, the techniques of optical design that made feasible the packaging of the optical elements in a minimum-space envelope were of special interest to the ERGS display application.

Along with space considerations, other factors were important in guiding the selection of a display configuration. Cost is of paramount importance because the route guidance display must be suitable for mass production at the lowest possible cost. Simple and rugged construction, high reliability, easy installation and service are other important factors.

With these guidelines in mind, the investigation proceeded to evaluate alternative configurations in each of the three major functional blocks or subsystems of the head-up display: the optical subsystem, the symbol generation subsystem, and the light source.

OPTICAL SUBSYSTEM

Optical elements in the head-up display include lenses and reflecting surfaces. Since the windshield is partially reflective, it can be used as the final reflecting surface on which the symbol appears. The objective was to select the optical configuration which would produce an image of acceptable quality within the space limitations of the vehicle.

Four collimating viewer designs, identified by the type of collimating lens utilized, were investigated. They are achromatic, plano-convex, lenticular and fresnel. Each was found to have particular advantages and disadvantages.

Achromatic—This design incorporates a compound lens which has the same focal length and the same magnification of light for two different wavelengths and nearly the same focal length for all intervening wavelengths. The achromatic lens exhibited the best resolution when tested, however its required focal length is too long to be compatible with packaging constraints and its exit pupil is limited. Finally, even for the small lens diameter required, the cost is prohibitive.

Plano-Convex—This lens, which is flat on one side and convex on the other, has a practical focal length and is much less costly then the achromatic. However, when tested, this lens, due to its large aperture relative to focal length, exhibited severe spherical aberration. In addition, its excessive weight eliminated it from further consideration.

Lenticular—This lens system consists of a mosaic of 16 lenses, typically in a 4 by 4 matrix molded into one piece of clear plastic. An individual symbol mask and light source would be placed behind each lens. For each symbol to be projected in the same area on the windshield, an optical wedge or prism in the optical path would be required. The drawbacks of this system are high cost, inherent low reliability because of the multiplicity of projection units, and small exit pupil that would severely constrain the driver's head movement. Adjustment of the symbol position on the windshield would be difficult.

Fresnel—This is a flat plastic lens having a number of finely spaced concentric grooves embossed on one surface. Its most desirable quality is large exit pupil size and relatively short focal length. Other advantages are light weight and extremely low cost. It is less fragile than glass and can be easily cut to the elongated rectangular shape required for the head-up display. This lens provided an acceptable image although the quality was not as good as the achromatic. The large exit pupil however provided for comfortable viewing for lateral head movements. On a comparison basis, the fresnel lens offered significant advantages in the areas of cost and packageability and was therefore selected for the head-up display.

SYMBOL GENERATION SUBSYSTEM

Ideally, a symbol generator with no moving parts would be most desirable. The lenticular system meets this objective. However, it cannot be seriously considered because of complexity, high cost, and the extremely high light intensity required for symbol recognition.

Another alternative is to provide a simple mechanical system consisting of a mask, containing the 16 symbols, which is indexed in front of a light source. The symbol mask is driven by a small dc motor. Indexing to a selected symbol is accomplished by a rotating sequence switch.

The latter alternative was selected for the feasibility model as offering low cost, ruggedness, life, reliability, and the least complexity.

LIGHT SOURCE

Use of the rotating symbol wheel permits the incorporation of a single high-intensity light source and a large projection lens to produce an image of the desired symbol compatible with the human factors design criteria (Table 1). This recommended level of maximum symbol luminance of 1,000 ft-L was based on a symbol luminance to background contrast ratio of 0.1 and a background luminance of 10,000 ft-L maximum.

Measurements made inside an automobile, under bright sunlight and high reflection conditions, indicated a maximum level of approximately 5,000 ft-L. It was concluded therefore that for most driving conditions a maximum image brightness of 500-700 ft-L would be sufficient to satisfy the purpose of demonstrating a feasibility model.

Due to the 12-volt operating requirement, it was found that the choice of high candlepower automobile bulbs was quite limited. Two types of single-filament lamps were tested. One, a type 1963 quartz iodine lamp is rated at 100 cp, 75 watts and draws 6.25 amp. The second is a commercially available Type 1195 miniature automobile lamp and is rated at 50 cp, 36 watts and draws 3 amp. Use of a diffuser to eliminate the lamp filament image from showing in the projection reduced the available brightness level by 50 percent. In tests with a diffuser, symbol mask, fresnel lens and simulated windshield, the 100-cp lamp produced a symbol brightness of approximately 1,200 ft-L. The 50-cp lamp produced a symbol brightness of about 750 ft-L which was judged adequate for feasibility model evaluation. The smaller bulb is significantly less costly.

The final results of this evaluation produced the recommended design of the feasibility model head-up display which was to consist of a single bulb light source and diffuser, a motor-driven symbol mask and selector and a fresnel lens projection system.

For the future, some refinements of this design are recommended; however, the basic design approach would be preserved.

FEASIBILITY MODEL

A feasibility model head-up display was constructed and subjected to laboratory and limited field testing to insure that the system produced a symbol image which met the design criteria established by human factors and engineering analyses. This unit was delivered to the Bureau of Public Roads in July 1968 for further evaluation of the display concept in ERGS.

Figures 3 and 4 show the external and internal views of the packaged unit which was designed to be mounted on top of the dashboard of a 1968 Oldsmobile Delmont sedan, selected by the Bureau of Public Roads as the test vehicle. The dashboard unit is entirely self-contained. To keep package size to a minimum, the optical path is folded, i.e., reflected from a mirror. The symbol image is projected through the fresnel lens, mounted vertically (to eliminate glare) on the windshield side. The collimated symbol is then reflected upward by means of an adjustable mirror that can be controlled by a push rod located in the front of the unit. This adjustment accommodates the various driver sitting heights and enables positioning of the symbol on the windshield for comfortable viewing. A dimmer control for symbol brightness is also provided.

The connector receptacle is wired to be directly compatible with the signal lines of the in-vehicle computer-decoder which is being separately developed by the Bureau.

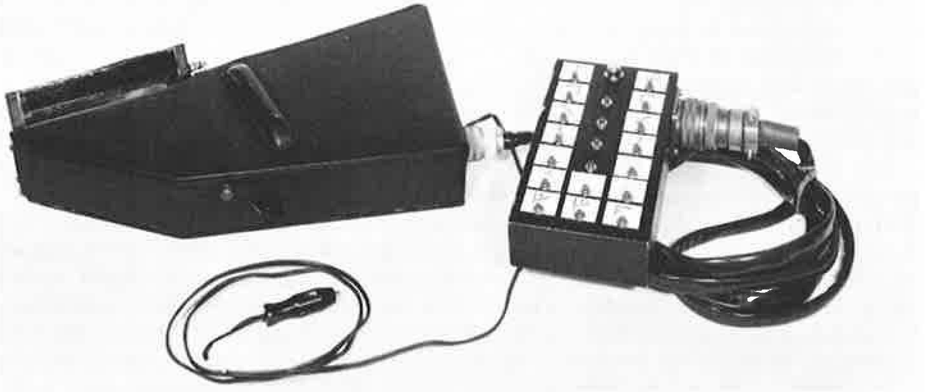


Figure 3. Head-up display, external view.

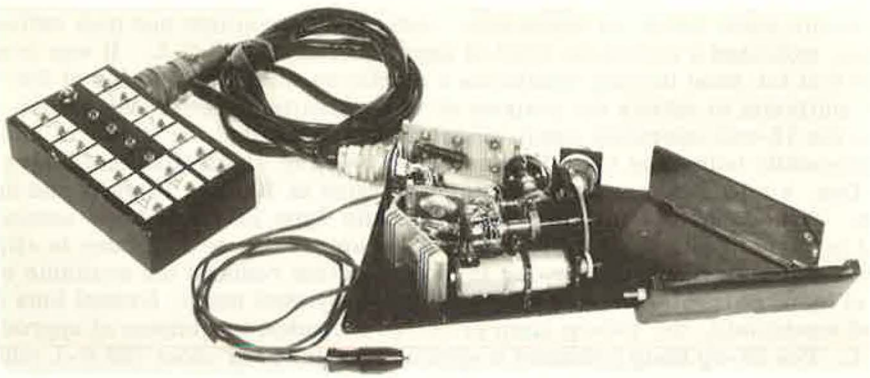


Figure 4. Head-up display, internal view.

For the purpose of feasibility testing, however, the control box was provided to simulate the inputs of the ERGS computer. Sixteen push-button switches, one for each symbol, and an indicator light, which signifies when the projector lamp filament is energized, are provided. During field testing, the evaluator would be seated in the rear seat and could select any desired symbol which would remain in view until the button was released. Testing of various symbol "on" times could thus be accomplished.

The mounted unit does not interfere with normal driving operation and does not obstruct the driver's field of view. Packaging and form factors were subject to constraints due to the specific dimensional limits of the vehicle and the need for an installation that would not require a permanent alteration of the vehicle structure. These constraints on package size limited the size of the lens. The exit pupil, which determines the amount of permissible head movement, was reduced from the recommended 8.5 in. horizontal and 4.0 in. vertical to approximately 6.5 in. horizontal and 2.5 in. vertical.

The requirement to keep the profile of the unit above the dashboard low enough so that it would not obscure any portion of the driver's view of the road restricted the vertical dimension. The acute angle formed by the slanted windshield and the need to keep the fore and aft dimensions from interfering with steering operations correspondingly affected the exit pupil dimensions.

This restriction is not viewed as a hindrance to demonstrating feasibility. However, any production design would give primary consideration to accommodating an exit pupil of approximately 10 in. horizontally by 6 to 8 in. vertically.

RECOMMENDED DESIGN IMPROVEMENTS

The design concept for production units envisions an integrally mounted unit with a larger lens recessed in the dashboard which would provide the required exit pupil size for greater freedom of head movement. Figures 5, 6 and 7 show the prototype under-the-dashboard unit manufactured and installed by Kollsman in the test vehicle.

The projection unit is mounted under the dashboard. A longer optical path than that provided in the feasibility model is incorporated, compatible with the larger lens exit pupil. The intermediate mirror is cold reflective, filtering out the heat produced by sunlight directed through the lens, and thus precluding any damage to the projection unit symbol mask. In future production units, modular packaging techniques would be used to achieve a minimum projection unit package size. The electronics associated with the projection device could be packaged separately in an encapsulated module and mounted in any convenient space. The 12-volt dc stepper motor and sequencing switch used in the feasibility model were selected because of their availability. In the production design, it would be desirable to incorporate a commutator type of symbol selector that would use a low torque drive motor with corresponding cost and weight savings. A singular advantage of the head-up display design is that all of the elec-

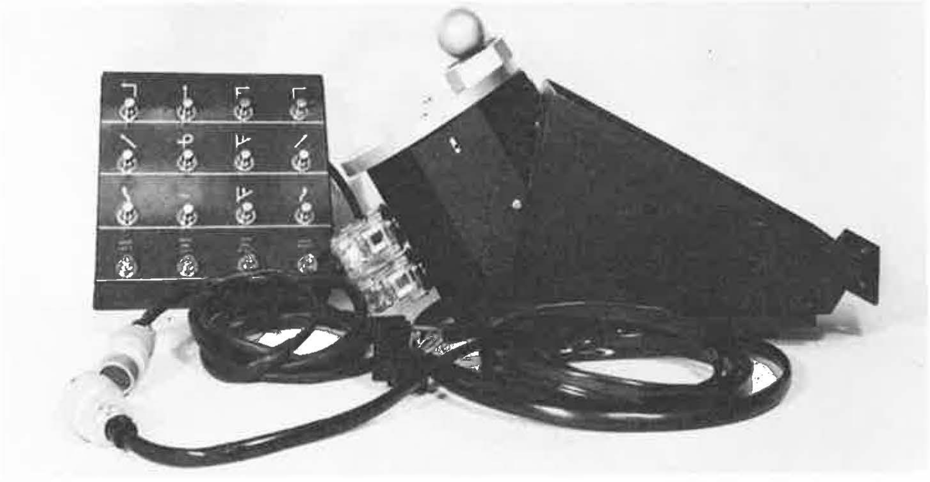


Figure 5. Integral head-up display unit with control box.

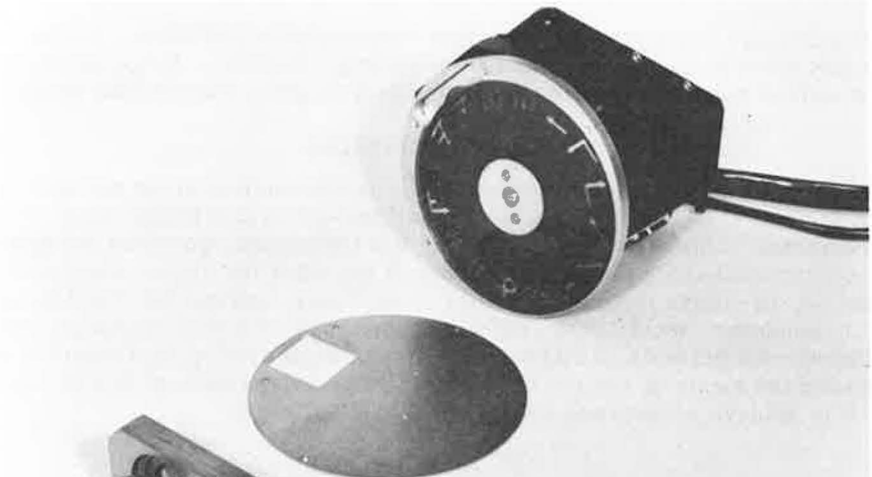


Figure 6. Integral head-up display unit projector and symbol drive assembly.

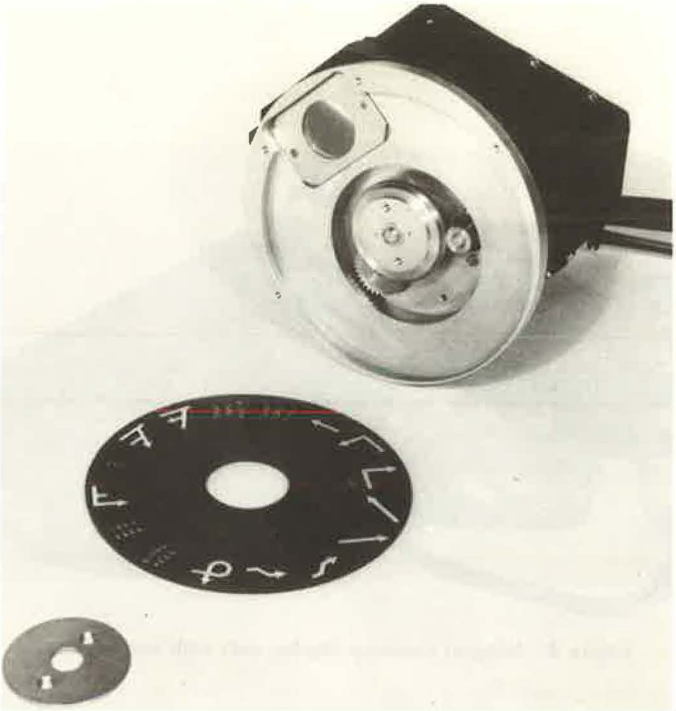


Figure 7. Integral head-up display unit symbol drive assembly.

tronic parts are representative of items commercially available. Lenses and the symbol mask drive motor would be tailored designs. However, large production quantities would reduce their cost to a level consistent with other commercial items.

CONCLUSIONS

The feasibility of projecting route guidance information on an automobile windshield, in the form of directional symbols using a head-up virtual image display technique, has been demonstrated. This type of display has tremendous potential for application to the experimental route guidance system. It provides the driver clear and concise information, in simple format, is easily assimilated, and can be timed to assure proper lead distance for executing turning maneuvers. By reducing confusion and uncertainty, it enhances the driver's ability to achieve maximum driving performance and greatly increases the safety of vehicle operations. The convenience of this device should enable it to achieve widespread acceptance among drivers.

REFERENCES

1. Graham, C. H. Visual Perception. In: Stevens, S.S., Handbook of Experimental Psychology, Wiley, 1951.
2. Graham, C. H., et al. Vision and Visual Perception. Wiley, 1966.
3. Colwell, D. Manual of Photointerpretation. Holt, 1954.
4. McCormick, E. J. Human Engineering. McGraw-Hill, 1957.
5. Baker, C. A., and Guther, W. F. Visual Presentation of Information. WADC-TR-54-160, Wright-Patterson AFB, 1954.
6. Morgan, C. T., et al. Human Engineering Guide to Equipment Design. McGraw-Hill, 1963.
7. Wulfeck, J. W. Vision in Military Aviation. WADC Technical Report 58-399, Nov. 1958.