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NIGHT VISION ENHANCEMENT SYSTEMS: WHAT SHOULD THEY DO AND WHAT MORE DO WE NEED TO KNOW?

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16. Abstract

Night vision enhancement systems (NVES, which use infrared (IR) cameras, are designed to supplement the visibility provided by standard headlamps. There are two main NVES systems: active, near infrared (NIR) systems, which require an IR source but give a complete picture of the scene in front of the driver, and passive, far infrared (FIR) systems, which do not need an IR source but only enhance relatively warm objects (such as people and animals). There are three main display alternatives: a contact analog display with the camera view superimposed on the direct view of the road by means of a head-up display (HUD), a separate HUD on the top of the dashboard, and a head-down display (HDD) in the dashboard.

This report analyses what a NVES should do to improve night visibility based on night crash statistics, driver vision and visibility conditions in night driving, driver tasks and behavior, technological approaches, costs, and regulations. Potential problems with using NVES are also discussed. Finally, issues requiring future research are presented. The six main questions that need to be answered concerning NVES are: What kind of information should be presented? To whom should the information be presented? Which technological approach should be used? When should the information be presented? How should the information be presented? Where should the information be presented?

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Contents

1. BACKGROUND

Since the development of automobile headlights, the limited visibility offered to drivers in night traffic has been a problem. Initially, the problem was to create headlights with enough intensity to illuminate the road scene at distances far enough in front of the vehicles. From a safety point of view, the light sources available did not match the speeds of the cars. Later, when more efficient light sources were available, other problems such as glare showed up. The present headlighting system suffers from one major drawback–the low-beam system. The low-beam system is a compromise between good illumination and limited glare. The result is that neither visibility nor glare is acceptable.

Many efforts have been made to achieve good illumination without causing glare. Intelligent (adaptive) headlights improve the situation, but do not solve it. Other technologies, such as ultraviolet headlights and polarized headlights, have given results that are more promising. Both are capable of creating illumination without causing glare, and make use of direct driver vision. But both also have drawbacks, which so far have prevented their introduction.

Consequently, researchers and manufacturers have turned to systems using radiation outside the range of the human visual system. Such systems require decoding and processing of the signals. This is not a new idea. The first products were made for military purposes–to see the enemy in dark conditions. However, the purpose and applications are different for military and civilian night vision systems. Traffic researchers have been studying systems based on infrared, radar, and ultrasound radiation for many years. Advancements in technology have now made these concepts more attractive and more realistic for wider implementation.

Present Night-Vision Enhancement Systems (NVES) are based on non-visible radiation, which directly or in reflected form is sensed by special sensors (cameras), processed, and presented to the driver on a display. The display might be contact analogue with the real scene in front of the driver or it might be a separate display. The screen might be the windshield itself, a separate screen on top of the dashboard, or a screen integrated into the dashboard. NVES can no doubt increase driver vision in night driving considerably. But there are also potentially negative effects of NVES. This report discusses weighting of the positive and negative aspects of NVES, remaining problems for research, and suggested criteria for evaluation.

2. PROBLEMS AND LIMITATIONS

In order to be acceptable as a safety improving technology, the NVES has to offer advantages in visibility during night driving without introducing increased risks. Studies of NVES already carried out seem to show convincingly that NVES has the potential to offer considerable improvements of visibility during night driving. Therefore, it is probably not necessary to establish whether NVES can offer improved visibility. However, the optimal design of such systems has not yet been established. Furthermore, it is not clear which particular visibility problem NVES should try to reduce or solve. Therefore, it may be more useful to distinguish between studies of optimal designs and studies of potential risks. As a result of trying to answer these two main questions, the direction of future studies (the critical gaps) emerge and candidates for suitable evaluation procedures appear.

The four problem areas that this report addresses are:

- What should be the purpose of NVES? Which visibility problems should NVES try to reduce? How should the image be presented to the driver?
- What could be the potential risks in using NVES and how serious are these risks?
- What kind of studies should be carried out to guide further development of NVES?
- What should be the variables and criteria (testing procedure) for evaluating NVES?

This report deals with vision enhancement systems for normal drivers in night traffic. Fog and other reduced visibility conditions are not considered, nor are military applications including night vision goggles. Separate displays as well as contact analogue displays will be treated. Separate displays are already in production, while contact analogue displays are technically more complicated to design and build. Furthermore, according to the requirements of the European Union (EU, 1977) it seems questionable to place a transmission reducing screen in the direct line of vision. Consequently, if that is a correct interpretation, contact analogue displays might not be allowed presently in Europe. This has to our knowledge not been tested. Only the law courts can decide this. Furthermore even if a vehicle is approved with regard to Directive 77/649/EEC a member state may refuse the vehicle to enter into service if it considers the vehicle to be a serious risk to road safety.

There are a number of human factors design issues associated with NVES displays and controls (e.g., brightness, contrasts, scale, position, and control function). This report only superficially discusses these issues, unless the factor is critically important for the functioning of the system. Guidelines concerning many of these issues can be found in handbooks (e.g., Weintraub and Ensing, 1992; Gish et al., 1995) or NVES reviews (e.g., Tsimhoni and Green, 2002; Hahn, 1994; Kiefer, 1995; Parkes et al., 1995).

3. METHODOLOGY

This report will analyze existing knowledge concerning night traffic characteristics, crashes and risks in night driving, visual performance and models in night driving, and driver tasks and models in general so that the suitable role of NVES in night driving becomes clearer. The existing limitations of visual, behavioral, technological, legislative, and economic factors will also be analyzed.

Much of the analysis will be based on published literature, concerning both general human factors, and NVES specifically. Tsimhoni and Green (2002) reviewed primarily the military literature on night vision systems and reference is made to this source. But to a large extent, the analysis is based on general knowledge of relevance to NVES.

4. PURPOSE OF NVES

There are a number of background variables relevant to the analysis and development of NVES. The variables, which will be mentioned here, concern information on:

- Night traffic crash types, exposure, and crash risks
- Visibility conditions in night driving
- Vision models in night driving
- Driver tasks and driver models for night traffic
- Technological approaches and performance of NVES
- Legislation and guidelines

The starting point is that the NVES of interest here are systems that would complement existing headlights and street lighting. The assumption is that NVES will not replace direct driver vision, but will supplement the direct vision that the driver has through the windshield with additional information. Consequently, the task of future NVES is probably to enhance specific parts of the night scene in front of the driver. The goal is to find support for the specific use of NVES that will give the most needed and least harmful additional information.

4.1. Characteristics of night traffic

In this report, night traffic conditions include both dark and street lighted areas, both urban and rural areas.

The proportion of the traffic volume that occurs during the dark periods of the day varies from country to country. In very densely populated and highly developed regions such as Japan, night traffic constitutes about 40% of the total traffic volume. Typical figures for industrialized countries, including the U.S., are 20 to 25% (NSC, 2000). In developing countries, on the other hand, this percentage is much lower.

However, because the crash rate is higher at night (in general two to three times higher) and crash severity is higher at night (Weber et al., 2001), the number of people killed and injured in night traffic is disproportionately high. The proportion of traffic fatalities at night does not vary as much as could be expected. A typical figure for highly industrialized countries (e.g., the U.S.) as well as for less industrialized countries (e.g., Senegal) is one third of all fatalities. However, in some countries it is much higher, e.g., Ukraine 44%, Italy 49%, Taiwan 77%, Cambodia 80% (UN, 2000).

NVES can only reduce crashes that are due to poor visibility. According to Sullivan and Flannagan (2002), such crashes primarily involve collisions between vehicles and pedestrians (being about four times higher in darkness). The proportion of pedestrians killed in night traffic is much higher in highly industrialized countries (about 50%) than in developing countries (about 30%). On the other hand, the vast majority (about 90%) of all pedestrian fatalities in night traffic occur in developing countries (Rumar, 2001). Other crash types typical of night traffic are single vehicle crashes, collisions between vehicles and bicycles, collisions between vehicles and animals, and rear-end collisions between vehicles (Moore and Rumar, 1999). However, factors other than the darkness itself seem to play a larger role in these non-pedestrian crashes. The main factors that co-vary with darkness are drunk and/or fatigued drivers and greater presence of wild animals. Alcohol and fatigue especially influence single vehicle crashes.

The volume of night traffic is limited in most countries, varying from about 20% to about 25% of the total volume. However, it is large enough to motivate a special enhancement system for visual performance in night traffic, and especially so for professional drivers who drive proportionally more in darkness, and for older drivers who have special night driving problems. The arguments in favor of NVES become even stronger considering the proportion of traffic fatalities at night, which is larger than the proportion of traffic. In most countries, the night proportion of the total number of traffic fatalities is about one third, with some countries exhibiting even higher proportions.

Based on the characteristics of night traffic and night crashes, the NVES should primarily enhance the visibility of pedestrians, cyclists, and animals. Rear-end crashes should be solved by other means, and single vehicle crashes appear to be more dependent on alcohol and fatigue.

4.2. Visibility conditions in night driving

At illumination levels typical for night traffic, visual performance is considerably decreased. The two major causes of this reduction are lowered contrast sensitivity and increased glare sensitivity. The result is that the visibility distances drivers have in normal night driving situations on two-lane rural roads are often unsafe considering the speed at with which they drive.

In the urban, lighted areas visibility conditions at night are better than in rural areas. On the other hand, there are more unprotected road users in urban areas and their movements on and across the road are much more difficult to predict. Therefore, driver night visibility conditions are often inadequate even in urban areas. This is especially the case in wet road conditions when street lighting does not work very well.

Efforts to improve night driving visibility by increasing target contrast by means of retroreflective materials have been comparatively successful. The problem in getting people to wear retroreflective materials when walking or cycling in darkness. Most efforts to improve night driving visibility by improved headlights have run into the conflict between more illumination and less glare.

Older drivers constitute a special problem group in night traffic (Rumar, 1998a). They rate night driving as one of the most difficult driving situations, and try to avoid it as much as possible. Studies show that drivers over 65 have considerably shorter visibility distances in night traffic than do younger drivers. In studies by Blanco et al. (2001) and Flannagan et al. (2000), young drivers had about 20% longer visibility distances. However, the main impairment for the older drivers seems to be target detection, not visual guidance. Table 1 summarizes realistic seeing distances for younger and older drivers based on a large number of experiments around the world.

Table 1
Detection distances to dark vertical objects, typical for present night driving in realistic conditions.

Condition	**Low beams with oncoming low beams**		**High beams with no oncoming headlights**	
	Young drivers	**Older drivers**	**Young drivers**	**Older drivers**
Dark objects	40 – 60 m	30 – 50 m	150 – 300 m	120 – 250 m
Bright objects	60 – 100 m	50 – 80 m	250 – 500 m	200 – 400 m
Dark objects with retroreflectors	100 – 200 m	80 – 160 m	350 – 700 m	300 – 600 m

A rule of thumb based on reaction distances and braking distances at normal speeds on rural roads is that the minimum visibility distance that gives the driver an opportunity to detect and identify the object and to choose an appropriate action is about 150 m. As shown in Table 1, most low-beam conditions and even a few high beam conditions do not meet this criterion.

Ideal conditions, which hardly ever occur, offer visibility distances that are approximately twice as long. However, this increase does not apply to longer distances because of the reduced angular size of the objects at those distances. With very small objects, the sensitivity of the eye depends on the product of the luminance and the area rather than the luminance itself (Ricco's Law).

Visibility of horizontal targets, such as the road surface and road markings, is considerably shorter (Rumar and Marsh, 1998). The reasons are that the reflection of light at such small angles is substantially impaired, and the angular size of the targets at those small angles is so limited that Ricco's Law is again applicable. Furthermore, the visibility of horizontal targets is seriously impaired by rain and wet road surfaces. The visibility of the road surface varies with the diffuse reflectivity of the road (from wet asphalt to snow covered road). It is up to 100 m on low beams and up to 300 m on high beams. For painted retroreflective road markings, visibility distances up to 100 m can be reached on low beams and up to 200 m on high beams.

Leibowitz and Owens (1997) suggest that driver's visual performance in night driving is based on two rather separate functions: visual guidance (mainly peripheral vision) and target recognition (mainly central vision). Target recognition (detection) is seriously impaired in night driving, while visual guidance is less impaired. This difference in degradation is the major explanation for why drivers tend to overdrive their visibility distances in night driving. They choose speed according to their always-sufficient visual guidance and do not take into consideration the very rarely experienced poor object detection distances.

Night driving is sometimes compared with fog driving in terms of reduced visibility. However, one of the main differences is that in fog drivers are well aware of the fact that both the road visibility (guidance) and visibility of other vehicles is seriously reduced. The effect of this difference in awareness is that, while driving in fog speed is reduced while in night driving speed is not reduced. Hogema and van der Horst (1994) report that when visibility in fog exceeds 300 m, only marginal speed reduction is observed (5%). This marginal speed reduction is then constant down to a fog visibility of about 150 m when speed is being reduced markedly. With fog visibility of 100 m and lower, speed is dramatically reduced. Visibility less than 100 m is what the low beams normally offer in night driving (see Table 1). But in night driving with corresponding visibility distances, speed is normally not reduced.

Raised pavement markers and side post delineators offer visibility distances corresponding to vertical targets (see Table 1). Studies indicate that drivers use two different functions for visual guidance in night driving. In daytime and in normal visibility night driving conditions, visual guidance is mainly carried out by peripheral vision. However, in more difficult night driving conditions (e.g., with wet roads and oncoming headlights, or in fog), visual guidance has to be carried out by central vision, which considerably increases the effort and the mental load (Rumar and Marsh, 1998).

Many persons, even experts in the area, believe that street lighting eliminates the visibility problems that are so obvious in dark rural areas. This is probably due to confusion between visibility of the road and visibility of objects. Introducing street lighting normally solves the poor visibility of the road itself. But visibility of objects is only partly solved by street lighting. Studies show that street lighting, especially of lower standards, usually improves the visibility of the road but does not reliably improve object visibility.

When pedestrians and bicyclists approach the street in order to cross it, they are often outside the area illuminated by the street lighting until they reach the street. Then detection might very well be too late to avoid a collision.

Based on the present visibility conditions in night driving, the NVES should enhance both vertical objects that are not retroreflectorized (such as pedestrians and other road users), and the road with its horizontal road markings. Enhancement of both objects and the road is important on dark rural roads, while on urban roads equipped with street lighting, enhancement of pedestrians and cyclists suffices. Older drivers would benefit more than young drivers from enhancement of vertical objects on and along the road.

4.3. Vision in night driving

What kind of visibility is needed in night traffic? The first question is whether the road or the objects on the road are more important. Judging from the reactions of drivers, they consider the road to be more important. That is the answer we get when we ask them what they consider most difficult in night driving (Walraven, 1980). If we expose them to gradually more difficult driving conditions, they successively leave out information sources. The source they try to keep to the very last is visual guidance, which makes it possible to stay on the road. However, as discussed in Section 4.1, crash statistics indicate that hitting pedestrians is a much larger safety problem at night than is staying on the road. Choice of speed seems to be self-regulating in relation to visual guidance, but not in relation to object detection.

Another visibility question is whether detection distance, recognition distance, target position, or any other target visibility variable is more important than any other. There is no definite answer. In military applications, identification is certainly very important. You do not want to shoot at your own units. But in civilian applications, detection of targets/objects should be the first priority, followed by positioning the target in the scene (including estimating the distance to the target), and recognizing the target. Detection is primarily dependent on object contrast, size, and motion. Positioning depends largely on the background of the target, and frame of reference. Recognition depends on resolution and motion.

Detection does not pose major demands on resolution in the display picture (Gish et al., 2002). It suffices to see the target as a spot. Recognition, on the other hand, depends on picture resolution. Gish et al. (2002) found that target motion made recognition possible, even at lower levels of resolution.

A third visibility question concerns the relative importance of central detection and peripheral detection. Experience points to central detection as being more important, partly with reference to the selective degradation model (see above), and partly because drivers continuously move their eyes to scan the traffic scene. However, the fact that peripheral detection seems to play such a limited role in night driving may be explained by present narrow headlight characteristics. With traditional headlights, there is very little peripheral information available.

Based on knowledge of vision characteristics, NVES should primarily enhance visibility by improving detection of objects in the central field of view. It would also help drivers see the position of objects on and along the road, and enhance road visibility and object recognition.

4.4. Driver tasks and driver behavior in night driving

It would be preferable to be able to base future development of NVES on knowledge concerning the tasks of drivers in night driving. There are a number of different driver models. However, none of them has reached general acceptance. The validity of existing models is contingent upon the purpose for which they were developed. Furthermore, there are no specific models for driver behavior in night traffic, with the possible exception of the model of selective visual degradation of Leibowitz and Owens (1997) discussed above. Although the model is purely visual, it offers an explanation regarding certain aspects of driver behavior (e.g., why drivers normally overdrive the visibility offered by their headlights).

The oldest still relevant driver-performance model is a perceptual model of Gibson and Crooks (1938). It has the appealing simplicity of integrating a vast number of driver subtasks into two major tasks:

- To estimate an area of safe driving in front of the vehicle
- To decide upon a minimum stopping distance within this area of safe driving

The problem in night driving is that the minimum stopping distance is often longer than the length of the area of safe driving. According to Gibson’s theory, drivers should lower their speed until the minimum stopping distance is shorter than the area of safe driving. This does not normally seem to be the case. The visual model presented by Leibowitz and Owens might explain this lack of adaptive behavior.

Two other general driver models include those developed by Michon (1971) and Rumar (1986). The Michon model divides tasks into three levels:

- Strategic tasks (planning, conscious, minutes)
- Tactical tasks (maneuvering, conscious/unconscious, seconds)
- Operational tasks (vehicle handling, unconscious, milliseconds)

The main night driving problems fall into the tactical and, to some extent, operational tasks.

The Rumar model is similar to the Michon model, but divides the tasks into eight subtasks.

1. Planning the trip
2. Finding the route
3. Keeping on the road and avoiding stationary obstacles
4. Interacting with other road users
5. Following rules, signs, and markings
6. Managing non-driving tasks (radio, climate, telephone, etc.)
7. Operating the vehicle (steering, braking, accelerating, etc.)
8. Choosing speed as a consequence of the demands from the other tasks

The main night driving tasks belong to the third, fourth, and fifth subtasks.

Rumar stresses that the choice of speed is a consequence of the demands placed on the driver from the other tasks. Driving is a self-paced task.

A central theme in both models is that driving is a self-paced task where choice of speed is the only means by which drivers can regulate the demands placed on them. At nighttime, however, drivers are incapable of regulating their speed in a safe way. According to Leibowitz and Owens (1977), and Rumar (1998b), the main reason for this seemingly irrational behavior is that drivers do not receive enough feedback about the very short visibility distances of dark objects. They match their speed to the visual guidance, which is not as impaired as obstacle visibility. This behavior is understandable considering that keeping the car on the road (which is a continuous task) is of highest priority. Obstacle detection (which occurs only rarely) is secondary. However, the drivers themselves do not complain about lack of obstacle visibility (because they are not aware of this, except on rare occasions). Instead, they complain about the lack of road visibility (which they notice continuously).

What we are particularly interested in here is driving with short visibility distances. Most models simply state that driving is a self-paced task with speed as the only dependent variable. However, drivers do not normally reduce their speed until road visibility is very much reduced (e.g., Hogema and Horst, 1994). So, from that aspect, the models just do not work. We know that drivers do reduce their speed in fog, but the reduction is not large enough to match the reduced visibility.

It is well known that drivers use various improvements in the traffic situation to solve their own problems, which are not necessarily the same as those of the authorities. The primary problem for most drivers is to reach the destination as soon as possible. Safety is a secondary target. For example, if street lighting is introduced to improve traffic safety at night, drivers increase their speed. As a consequence of this compensatory behavior, safety is not improved as much as originally estimated on the basis of improved visibility alone.

This compensatory driver behavior is relevant for the development of NVES because if already good visibility visual guidance is improved further without improving the inferior visibility of obstacles, the risk is that drivers will overdrive their visibility even more. Studies carried out by Kallberg (1993) support this argument. He found that when visual guidance along a road was improved by the installation of side post delineators, drivers increased their speed to such an extent that safety was in fact impaired instead of improved.

The conclusion from this discussion is not simple. On the one hand, drivers in night driving overdrive their visibility in relation to obstacles on the road. It follows that NVES should enhance obstacle visibility. On the other hand, the highest priority visibility from the driver's point of view is the visual guidance. From that it should follow that NVES should primarily enhance visibility of the road, offering better visual guidance. However, speed is currently regulated in relation to the existing visual guidance. Therefore, the focus of NVES should be on object visibility.

Based on this analysis of driver tasks and driver behavior, NVES should primarily enhance visibility of objects on the road, not visibility of the road itself.

4.5. NVES technological possibilities and system performance

Early designs of NVES were often based on short-wave radar. More recent designs have been dominated by infrared technologies. The infrared spectrum starts near the upper end of the visual sensitivity range at 780 nm and ends at about 16000 nm. The longer wavelengths represent heat radiation. The spectrum most relevant for NVES can be divided into three parts:

- Near infrared (NIR), approximately 780 to 3000 nm, requiring both infrared sources and infrared sensors (active systems)
- Middle infrared (MIR), approximately 3000 to 6000 nm, requiring only infrared sensors, sensing the heat wavelengths from the targets (passive systems)
- Far infrared (FIR), approximately 6000 to 16000 nm, requiring only infrared sensors, sensing the heat wave lengths from the targets (passive systems)

The NIR and FIR have attracted the most attention and interest. However, all three have been (or currently are) used for development of NVES.

In the military world, which is less price sensitive, the development of night vision systems has a long history (Tsimhoni and Green, 2002). Night vision systems were used as early as the Vietnam War. Since then, they have been successively improved. However, military applications are in many ways different from civil night driving purposes. The main difference is that the military often uses these systems instead of visible light such as headlights. In civil applications, NVES are used as an additional information source, which is either fused with the real scene or only used from time to time.

4.5.1. The different IR systems

In the automobile world, electronic and lighting companies often work together with automobile manufacturers to develop NVES. At present, the development of NVES is in a competitive phase, and it is therefore difficult to get more information on these developments.

The only vehicle in current production with a NVES is the Cadillac, which is equipped with an FIR system. That system is based on a Raytheon IR-camera and a Delphi-developed HUD. The camera has its maximum sensitivity at 35° C, which makes it very suitable to pick up thermal radiation from people and animals. Its field of view is horizontally 11.25° and vertically 4°, and it covers the adjacent lanes at a distance of about 70 m. The camera is focused at 125 m and its focal depth is from 25 m to infinity. The detection range for a pedestrian is 300 m (Marinelli and Boulanger, 2000).

A second manufacturer, Volvo, announced that in the fall of 2002 they planned to release a new model (the XC90) with a NVES that is also based on a Raytheon IR-camera. However, this introduction was recently postponed and no new date has been given (Veznaver, 2002). Many other companies are also developing FIR systems, e.g., Autoliv together with Indigo is developing a system based on Indigo's new miniature IR camera (Autoliv, 2002). Fiat together with Bosch, CEDIP, Sofradir, and Vertex is working with a corresponding system within the DARWIN EU-project (Andreone et al., 2000).

In early 2002, a new, EU-supported research project called EDEL (Enhanced Driver's pErception in poor visibiLity) was started. Participants in this project are Fiat, Jaguar, Bosch, Osram, Hella, University of Karlsruhe, University of Genoa, and University of Siena. The technical approach is based on an NIR system, possibly with the assistance of other technologies (Andreone, 2002).

The Cadillac sensor is placed in the grill. This may be compared to the positioning of the sensors in four prototype NVES. The Autoliv sensor (FIR-HUD) is placed at the lower end of the windshield (Autoliv, 2002), the Jaguar camera (NIR-contact analogue) is placed just above the head of the driver (Ståhl et al., 1994), the Renault camera (NIR-contact analogue) is placed at the inside rearview mirror (Augello, 1993), and the Daimler-Chrysler camera (NIR-HDD) is placed high above the driver's eyes (Daimler-Chrysler, 2000).

The pictures presented in the HUDs are monochrome. The driver may easily modify the brightness of both the NIR and the FIR screens. It could be fairly easy to switch the polarity (negative or positive contrast). It would be an advantage if the driver could modify the contrast in the picture. Also, most systems allow the drivers to adjust the position of the virtual picture to match their respective eye heights.

The display is normally situated just below the driver's line of sight. However, there is talk of placing the display in the line of sight, which requires both identical scale and full contact (congruence) with the real scene. On the other hand, some displays are placed lower on the dashboard. The problem in all cases (except the contact analogue design) is that the driver has to visually scan both the real visual scene and the display, which can cause conflicts and interference.

The resolution of the NVES depends on the number of pixels of the IR camera image. NIR resolution is often better because cost per pixel is much higher in the FIR camera than in the NIR camera. The main cost associated with the FIR systems is the camera itself. The costs of the NIR systems include the camera, the IR projectors required to create an adequate display picture, and some form of solution to the glare problem. However, at this early stage, it is difficult to predict the relative costs of the two systems in a production stage.

The price for the only publicly available system (the Cadillac system) is about 5% of the total cost of the car. This price will likely go down with larger volumes and advancement of technology. The price is probably acceptable for buyers of luxury automobiles and heavy trucks, which are driven proportionally more in darkness than passenger cars. However, the price may need to be substantially reduced for small-car buyers.

4.5.2. Performance of the different systems

In principle, with opposing headlights, both the FIR and NIR systems may offer visibility distances to vertical human and animal targets that correspond to the visibility distances offered by high beams without opposing headlights (see Table 1). Consequently, the NVES potential to improve driver visibility conditions in normal night driving cannot be questioned. Moreover, as will be elaborated on below, only the NIR systems offer acceptable visibility of signs, markings, the road surface, and other cold objects. However, if special steps are not taken to reduce the amount of reflected illumination, the enhancement might even be too great, resulting in "blooming" (see below).

The MIR systems offer pictures, which work and look very much like the FIR systems (see below). According to Hahn (1994), FIR cameras are superior to MIR cameras in their capacity to show warm objects. To our knowledge, BMW is the only car manufacturer that evaluated night vision systems in this wavelength interval (Hahn, 1994). However, we will focus our attention on the NIR and FIR systems.

The NIR systems offer pictures that correspond closely to the normal scene. The visibility of everything is enhanced. The resolution is normally superior to the FIR resolution. However, oncoming headlights and retroreflective road signs create glare (blooming) on the screen. It is argued that the problem from headlights may be overcome by the use of band pass filters and a pulsed laser from the laser headlights (Holz and Weider, 1998).

The FIR systems offer pictures that do not look like the normal visual scene through the windshield. The FIR systems are mainly sensitive to relatively hot or warm objects. Humans, animals, and hot parts of vehicles (e.g., engine exhausts and radiators) are very visible, while road signs, road markings, the road itself, and the horizon have a lower visibility level. The difference between the FIR picture and the real scene may create confusion and misperceptions. In military applications, this has frequently been reported to contribute to crashes. FIR systems have higher atmospheric transmission than do the NIR systems (Hahn, 1994).

The FIR system displays have a special problem in that while the visibility of warmer objects is enhanced, the visibility of colder objects is often less than in direct vision. Therefore, drivers may have problems locating targets correctly in the road scene. By using both FIR and NIR systems, the images from the two sensors might be fused in an optimal way. This would, however, increase the costs.

Both systems are technically and economically feasible. However, the NIR systems are somewhat more complicated because they require both IR illumination and IR sensors. Furthermore, the blooming on the screen caused by oncoming IR projectors has to be reduced. Using band pass filters and projector pulsing however, increases the complexity of the system. Still, it is not quite clear how the glare of oncoming headlights will look on the screen. However, the NIR picture is created by means of an advanced digital signal processing procedure before it is presented to the driver. This offers future opportunities to enhance certain aspects (e.g., pedestrians) and suppress others (e.g., glare) (Barham et al., 2000).

On the other hand, the NIR picture will be easier to interpret than the FIR picture partly because the relative contrasts in the visual field will not differ too much from those in direct vision, and partly because the resolution of the NIR systems is superior. On the other hand, NIR systems normally suffer from glare-related problems. In the present situation (without NVES) glare is a consequence of very bright stimuli in the direct view. In NIR systems, glare (blooming) shows up in the display picture. There are methods to reduce the NIR glare and such methods should be implemented in order to make the NIR systems competitive in this respect.

Some targets look somewhat different with NIR systems than in the direct view. For instance, with NIR systems dark clothes and vegetation are brighter and snow is darker. On the other hand, the FIR picture is very different from what the driver sees in front of the vehicle. Warmer or hotter objects and areas show up with strong contrasts, while cooler objects or areas have lower contrast and are difficult to see. It is not the absolute temperature but the relative temperature that determines the level of contrast. This means that the surrounding snow is black and the clean road surface, which is cool, might still be considerably warmer than the snow and consequently visible. Some other targets, which are considered important in both day and night driving, such as road signs, road markings, side post delineators, cool parked cars, and retroreflectors, have lower visibility than warm targets.

Another way of expressing the situation is to say that it would probably be possible to drive at night with only the information presented on an NIR screen. Military studies indicate that in night driving this may even be preferred to direct vision (Padmos, 1995). But it would be more difficult to drive with only the information presented on an FIR screen. It would be harder to follow the road, to see the shoulders and the curves, and to detect and read the various signs. It would be more difficult to perceive the relative position of visible objects. The extent to which these problems can be reduced or solved by further development of the FIR systems remains to be seen.

The location of the sensor or camera is critical to obtain an acceptable picture of the road. If the sensor or camera is positioned low (e.g., in the grill), the perspective of the road will be less than ideal, especially when driving on vertical curves. It is acceptable to position the sensor at the driver eye height, and it is preferable to place it above the driver's eyes. Another aspect of camera position is that a lower position is more exposed to dirt. Glass interferes with the FIR wavelengths and cannot be placed in front of the sensor. Thus, the FIR sensor cannot be placed behind the windshield. This is not the case for the NIR camera.

4.5.3. The displays

In most head-up displays, the virtual picture is projected a few meters in front of the driver to avoid any accommodation problems when switching between the real traffic scene and the HUD picture. Most HUDs are placed just under the driver's direct line of vision so that the driver will not completely lose contact with the real traffic scene when looking into the HUD, and vice versa.

The fact that the driver will have to shift gaze between the real scene and the virtual scene is one of the major potential problems with NVES, a problem to which we will return to in Section 5.2.

The visual field covered by the display has to be large enough to accept reasonable horizontal and vertical curves of the road. In both systems (NIR and FIR), the brightness of the screen and the polarity of the contrasts may be varied. The positioning of the sensors (cameras) is critical for both systems. There are also a number of other human factors problems involved in the positioning of the screen and in the design of the picture on the screen.

The display itself offers a limited field of vision, normally 10 to 15 degrees horizontally and less than 5 degrees vertically. It is questionable if such a limited field of view is sufficient for normal driving (Mortimer, 1997). If the goal is to cover a wider field of vision, then the picture has to be scaled down. In contact analogue displays, the scale must of course be 1:1. But in NVES with separate screens the scale can be reduced to cover a wider field of view. A wider field of view has been tested and was preferred by drivers (Hollnagel, 2001 and 2002). The two fields of view compared in his study were 12° and 18° (corresponding to downscaling of 1:1.5 and 1:2). Of course, the resolution in the picture will suffer from downscaling, but that should not be serious if identification of the visual targets is not considered critical.

The reason for a wider field of view is that the road has horizontal and vertical curves and the goal is to be able to see far enough into such curves before entering them. This goal is analogous to the goal of some adaptive headlamps, which will move horizontally to improve visibility in curves. Another reason for a wider field of view is that, especially in urban areas, pedestrians and cyclists often approach the street at perpendicular angles, and drivers would benefit from being able to detect them during the approach phase. This problem is also present when pedestrians or bicyclists along the road are close to the vehicle and not within the relatively narrow angular range of the camera. A wider field of view would give drivers more time to prepare action and avoid emergency situations.

Head-down displays, which are normally placed in the dashboard, are not transparent, while contact analogue HUDs must be. HUDs that are placed just below the driver's line of vision may be more or less transparent. A reason for also making those HUDs transparent is that the HUD can be placed so close to the line of vision that the road is the background. Drivers will then have the ability to see through the screen if necessary. A reason for making the screens less transparent is that the brightness of the screen may be set to a lower, less disturbing level without losing clarity. Another reason is that in transparent screens a bright background may be visible through the screen, which makes the picture difficult to interpret. However, especially if the screen is not transparent, it must be positioned so that it does not obstruct any important part of the direct visual field, particularly on hillcrests.

In the NVES-equipped Cadillac, the virtual image is projected on the lower part of the windshield, straight in front of the driver. Consequently, the screen is transparent. The curvature of the windshield causes some distortion of the picture. This distortion could be eliminated by optical compensation or picture processing. Because drivers differ considerably in height, there is a control for adjusting the display so that the virtual image can be ideally positioned for each driver. Another possibility, an example of which was shown in the Volvo safety Concept Car at the North American Auto Show in January 2001, is to move the driver to the optimal observation point. The positioning and the design of the display controls (brightness, position, and possibly contrast) require additional human factors considerations, which are not dealt with here.

The two types of systems (FIR and NIR) provide very different pictures, each with advantages and with disadvantages. One possibility is to use both systems and merge the two pictures in such a way that the advantages of both systems (strong enhancement of living objects and a reasonable picture of the road) are reached without their respective disadvantages.

Based on this analysis of the technical possibilities it may be concluded that the available technology can do most of what we would like it to do. Technology poses no major problems for the development of NVES. The problem is what we want it to do. The current cost of NVES is a problem for most buyers of passenger cars.

4.6. Legislation and guidelines

There are a number of general guidelines concerning the design of new technologies, which should also be applicable for NVES. However, because the current regulations were written before the introduction of NVES, none of the regulations are directly relevant. In the U.S., the ANSI visibility requirement (ANSI, 1983) only refers to the transmission of the windshield itself, and does not seem to prevent any screen in front of the driver's eyes. A corresponding transmission requirement also exists in the European Union (EU, 1992). An additional requirement that might influence the design of future NVES appears to be the Vision Directive from the European Union (EU, 1977), which does not allow obstructing the driver's direct line of vision. If this requirement is applied to NVES, contact analogue NVES displays may not be feasible—at least not in the European Union. To our knowledge this question has not been tested and furthermore, in both cases (EU and U.S.), the manufacturer will probably have to prove to the regulators that *any* display considered will not cause problems.

4.7. Estimations of NVES visibility and safety potential

Lunenfeld and Stephens (1991) estimated that NVES could reduce night crash fatalities by 20 to 25%. The benefit in reduced congestion and driving time in the U.S. was estimated at $1.8 billion, though they do not explain how they reached these figures. Their statement about reduced driving time indicates that they expect NVES to make higher speeds possible. In our opinion, night driving speeds are already too high, and a further increase would not be good for safety.

There are several recent studies of visibility distances provided by NVES. Gish et al. (2002) used a Cadillac system in a field experiment and reported considerable visibility improvements for young drivers. Compared to visibility with standard low beams, young drivers increased their visibility distances by 65 to 150 m when using NVES with oncoming glare. Without glare and with older drivers, he found only marginal improvements of visibility. Gish et al. found that due to driver uncertainty of target location and the increased demand on driving created by the two visual tasks, the efficiency of the NVES was reduced to only 50-70%. Many of the older drivers did not use the NVES. However, this was probably more a question of motivation than capacity. Gish et al. also found target motion important for recognition, but not for detection.

Barham and coworkers (1995 and 1998) evaluated the Jaguar contact analogue NIR system. Their results show 50 to 60% increases in visibility distances compared to visibility with low beams on dark roads, and a 40% visibility increase in a dimly lit area. Ståhl et al. (1994) in their evaluation of the same NVES technology using exclusively older subjects found results comparable to those of Barham. Gish et al. (1999) studied object visibility in a field experiment using both younger and older subjects, and their results are also in line with the previous ones. The increase in visibility for the younger drivers ranged between about 31 and 60 m. The older drivers did not benefit as much in visibility.

Blanco et al. (2001) report that an FIR system offers about 250 m visibility distance to most warm objects. Martinelli and Boulanger (2000), using the Cadillac FIR system, report pedestrian visibility distances of 300 m, but without giving any description of the conditions. Hollnagel (2002), in a simulator study of an Autoliv FIR system, reports obstacle (pedestrian, dog, etc.) visibility of 400 to 700 m.

On the other hand, Ward et al. (1994), in a study using the Jaguar NIR system with contact analogue HUD, found no visibility improvements. As dependent variables, they used reaction time and number of misses, which are comparatively insensitive measures of visibility. Another possible explanation for the lack of visibility improvement in this study is that the drivers knew where the targets were because the test track was short, the runs were repeated frequently, and the number of alternative target positions was limited.

Driver subjective evaluations of NVES have been carried out in a number of studies (Gish et al., 2002; Barham, 2001; Ståhl et al., 1994; Hollnagel, 2001, 2002). Gish et al. obtained subjective ratings from three groups around the U.S. The results varied, but a majority was of the opinion that the tested Cadillac system was useful when driving on straight, unfamiliar, unlit, and/or rural roads. Visibility was enhanced particularly for warm objects in glare situations, but not for signs and road markings. The general opinion was that the system was easy to use and that the distraction potential would not be a major problem. However, inconsistent with these positive ratings, as many as 40% thought the system would offer little or no crash reduction potential.

Ståhl et al. (1994) collected subjective ratings in the field using the Jaguar NIR contact analogue NVES. Most of the subjects (75%) were very positive concerning usage, comfort, and safety. In a simulator study using the DARWIN research model (FIR with separate HUD), Barham (2001) received only positive reactions towards NVES from his subjects, both concerning ease of use and safety potential. In a simulator study using the Autoliv FIR system (separate HUD), Hollnagel (2002) also obtained generally positive evaluations. He compared two fields of view (12° and 18° horizontally) and found that the larger field of view was preferred. He also received several complaints that the display was hiding parts of the direct visual scene and about the identification and positioning of objects.

To get an indication of how large a visibility improvement NVES could make, we might make a simple comparison with the present situation. If we compare NVES visibility with the visibility offered by the present low-beam system with opposing low beams, we can say that NVES visibility is normally much better (e.g., Blanco et al., 2001). If we compare NVES visibility with the visibility offered by the present high-beam systems, we can say that they are often equally good. One of the problems with these simple comparisons is that older drivers often do not use NVES. There are indications that the main reason for this is that NVES require attending to dual tasks—a known problem for older persons. Consequently, they probably are not using NVES systems because they are avoiding dual-task situations. Ironically, older drivers should benefit most from NVES systems.

NVES can offer substantially improved visibility conditions. Most drivers are positive about NVES and would like to have them in their cars. Consequently, the net safety effect of NVES will be determined by the user friendliness of the system (especially for older drivers) and the potential risks of the systems (such as increased speed, increased workload, increased distraction, and cognitive capture –see Section 5).

5. POTENTIAL RISKS WITH NVES

Several factors that could cause potential risks to users of NVES have been mentioned briefly. Here we discuss in more detail the following issues:

- Driver characteristics (age, learning time, experience, and visual status)
- Visual interference (scanning behavior, distraction, glare, screen transmittance, importance of detection vs. recognition, importance of road vs. obstacle visibility, incongruent pictures, field of view, and signal detection)
- Driving interference (choice of speed, increased workload, cognitive capture, and variable lateral position)
- Traffic interference (mixture of vehicles having and not having NVES)
- Environment (weather, street lighting/no street lighting, and urban/rural)

5.1. Driver characteristics

The previously mentioned selective degradation theory (Leibowitz and Owens, 1997) states that object detection degrades more than road guidance in night driving. It furthermore states that older drivers suffer more from object degradation than younger drivers do. This is also shown in empirical studies (Blanco et al., 2001; Flannagan et al., 2000). Therefore, older drivers should benefit more than young drivers from enhancement of objects.

However, Gish et al. (2002), using the Cadillac FIR-system, showed that older drivers did not make use of the NVES as frequently as did young drivers. They estimated that the correlation between age and the percentage of trials in which NVES was used was r =-.62. However, the distribution was bimodal, with some older drivers using the NVES as much as younger drivers. But those older drivers who almost never used the NVES did not detect obstacles as frequently as younger drivers. Overall, while older drivers needed the NVES more than younger drivers did, they used it less.

There are several possible reasons for the age effect on the usage of NVES. The primary one is that night driving is more difficult for older drivers. They, like everybody else, give the highest priority to road information, and do not have much spare capacity to attend to the HUD information. Analogous results were obtained by Wolffelaar and Rothengatter (1990) concerning older drivers' lowered capacity to handle tasks involving divided attention. Another reason may be that as we get older, visual scanning behavior is over-learned, rigid, and hard to change.

Peripheral sensitivity decreases with increased eccentricity, especially so for older persons (Flannagan and Harrison, 1994). Consistent with this are the results of Kiefer (1998), who found that older drivers were better at detecting pedestrians when secondary-task information was presented via HUDs, as opposed to via HDDs.

Based on this analysis of older driver problems with NVES, a contact analogue system would be preferable. Drivers would not have to radically change fixation patterns between day and night, and between direct and indirect vision. Studies by Ståhl et al. (1994) indicate that this might very well be the case. In that study, older subjects (65 to 80 years of age) evaluated the effectiveness of the Jaguar contact analogue NIR system. A majority of the drivers were very satisfied with the system, both with ease of use and visibility improvement. However, as pointed out by Hahn (1994), a problem with contact analogue displays is that the different vibration characteristics of the camera and the driver might increase mismatch. Another problem with this display design is that conformity may vary with distance to the targets. A third problem is that the position of driver eye point is critical. Head movements may impair the contact analogue display.

Tsimhoni and Green (2002) extensively discuss the potential advantages of merging the pictures from two or more camera systems. This approach could be used with the two IR systems because the NIR and FIR systems and displays have different advantages and disadvantages. By merging the pictures from the two systems, a display with optimal characteristics could be obtained. Such a solution would, however, probably greatly increase the price for the NVES, and is not yet ready for the market.

Another way out of the problems with dual fixation tasks could be to let the technical system handle the signal detection, for instance by comparing the real-life picture with the enhanced-visibility picture and to signal the driver to scan the display only when a critical object is present. That would require picture recognition functions. A simpler alternative, applicable to the FIR systems, could be to display any hot objects that produce strong contrasts. In both cases, the signal detection task is taken over by the technical system and the driver would not have to scan the display if nothing was there. On the other hand, such a solution would introduce new problems relating to the reliability of the warnings and false alarms—a critical issue with all warning systems. The signal-to-noise ratio may not always be as simple as in a simple rural, two-lane situation (e.g., in an urban situation with many pedestrians on the sidewalk).

It is known from earlier studies of instrument panels that older drivers and drivers with visual correction have problems with the change of accommodation from far (from the traffic scene) to near (to the instrument panel). Therefore, the HUDs used in NVES normally have virtual pictures positioned a few meters in front of the driver. In the NVES studies covered in this report, the virtual picture has been placed from 3 to 25 m in front of the driver. Although in general this seems to be acceptable, Gish et al. noted that a few drivers wearing bifocals complained about focusing problems (Perel, 2002). They found it annoying to have to tilt the head down in order to view the display through the distant (upper) part of the lenses. Other visual problems might include reduced contrast sensitivity. Such problems should be an argument for and not against NVES, which aims to enhance target contrast. Driver visual status does not seem to pose any serious problems when using NVES.

NVES using separate screens introduce a new dimension to night driving. The driver has to view the direct scene but must also scan the display intermittently. There are at least two problems associated with the new driving situation. One is to adapt the scanning behavior, and the other is to learn what is shown and what is not shown in the NVES display. Gish et al. argue (Perel, 2002) that after about 20 minutes the drivers have adjusted to the new situation. According to a sub-study carried out by NHTSA within the Gish et al. project, users of NVES estimated that they needed about two hours of experience to become comfortable with using the display. Some drivers even estimated they would require three or more hours to use the display without problems. There are no data showing that the learning time would be longer for older drivers, but all experience favors such a hypothesis. It should be more difficult to break a routine that is very well established (over-learned). But probably the fixation pattern changes continuously, at least during the first two hours of driving with the system. It is, for instance, uncertain whether drivers who are not used to NVES will develop a stable fixation strategy during a few hours' use of the system when renting a car equipped with NVES.

The analysis in this section shows that older drivers constitute a special problem concerning NVES, especially for systems with separate displays. Another potential problem concerns the time needed to get comfortable with the system (the learning time).

5.2. Visual interference

The non-contact-analogue NVES displays have been compared with rearview mirrors as additional sources of information to be used intermittently. However, there are a number of differences between rearview mirrors and NVES displays. Rearview mirrors are used primarily in two situations:

- To check surrounding traffic before making a specific maneuver (e.g., a lane change or a turn)
- To routinely check surrounding vehicles in normal driving when not interfering with other tasks

In other words, drivers check rearview mirrors without interfering with the main tasks of driving. The NVES display has to be checked much more frequently because it is not possible to predict when and where an obstacle that will influence driving might appear. Also, the fixations on the NVES display may have longer durations because the scene is more difficult to interpret. The examination of the NVES display plays a direct role in the main driving task. Therefore, the potential for interference with the driving task is considerably larger for checking NVES displays as compared with checking rearview mirrors, unless these systems are used only when not interfering with the primary driving task. Studies have also shown that the scanning of the rearview mirrors decreased when NVES was used (Holz and Weidel, 1998). However, it is not clear whether this effect would persist after getting accustomed to NVES.

If the NVES offers a high quality, complete picture, there are indications that drivers would prefer driving by primarily using the display rather than the direct visual scene. One of the few eye movement studies carried out with NVES (Meitzler et al., 2001) indicates such driver preferences.

A related scanning problem associated with NVES (both contact analogue HUD and separate HUD) could be cognitive capture. This means that the focus on the HUD might attract so much attention that the chances of detecting obstacles and events that occur outside this view (e.g., a cyclist approaching from the side) would be considerably reduced. There is some experimental evidence for this hypothesis (Bossi et al., 1994; Lee and Triggs, 1976). According to a study by Holz and Weidel (1998) using a contact analogue NIR system, drivers showed a reduced number of glances in the rearview mirror when using the NVES. The reduction was 15 to 20%. That could be an indication of cognitive capture and/or increased workload. However, it could also be a consequence of getting used to a new system.

An option that has not been discussed very much is to simplify driver-scanning tasks by warning the driver when a critical target appears. In other words, let the system take care of the signal detection task and leave only the positioning and maybe the identification to the driver. Such a warning could be visual (e.g., a flashing icon) or it could be auditory. Then the driver would only have to scan the display when the warning appears, which would certainly reduce visual interference and distraction. In the display, the target could be further enhanced, perhaps by use of color. According to Watanabe et al. (1999), such a warning would not interfere much with direct observations of the traffic scene. Another possibility could be to only have the warning signal and not the display. Then the driver would have to search for the critical target in the real visual scene, which could be disturbing because it would not be visible in direct vision for some time. However, according to Roper and Howard (1938), high alertness in itself could approximately double the detection distance. The problem with this approach is that the reliability of the warning system would have to be very high in order not to create false alarms and a false sense of security.

Another scanning problem associated with the FIR system is that the direct view and the display picture look so different. Due to this conflict, there may be problems with interpreting the display picture. These interpretation problems, in turn, could increase the distraction caused by the display. There are reports (Foyle et al., 1990; Gish et al., 2002) of drivers who focus too much of their attention on the interpretation of the object and lose contact with the direct visual scene. Many relatively warm objects are irrelevant to driving tasks (e.g., exhaust pipes and radiators on cars) but are highly conspicuous in FIR system displays.

As mentioned earlier, the visual system seems to selectively degrade in night driving. Object detection degrades more than visual guidance (road visibility). Consequently, object visibility seems to be the primary visual component that should be enhanced. That speaks in favor of FIR systems, which enhance visibility of critical objects such as humans and animals, but do not or only marginally enhance the visibility of the stationary road scene. NIR systems enhance the visibility of all targets about equally. The positions of objects that become visible need to be correctly perceived. If an object is visible but not correctly located, the driver may hit it anyway because the distance was misinterpreted. This is similar to what has been observed for objects that become visible as silhouettes (Johansson and Rumar, 1964). The objects seem to hang in the air, with no contact with the ground. Therefore, the display must provide some road visibility to give drivers a frame of reference in which they can position the objects detected by means of the NVES display. A high road perspective (high location of the camera) should facilitate the correct positioning of the target.

With a good camera and an adapted display picture, it may be possible to present the road in a very simplified graphical form in the FIR display so the driver can position the object correctly in the road scene. To our knowledge, this has not been tried.

It is customary to describe the visual process concerning visibility of road signs in three consecutive phases:

- Detection
- Identification
- Interpretation

It is important to detect, to identify, and to read and understand the message on road signs. The question is: how important is it in night driving to go through the same phases concerning obstacles on the road, such as pedestrians? As stated in Section 4.3, detection at a safe distance is the most important task. Recognition or identification is extensively discussed and treated as a problem in the studies of Gish et al. (2002). Most likely, identification of objects is not as important for night driving as is detection. Identification does not in any radical way change driver tasks and behavior. Pedestrians, whether adults or children, or animals may behave completely unexpectedly and drivers are not helped much by an early identification or interpretation. Location and positioning of the object on or at the side of the road seems much more important. The knowledge of *where* the object is will change driver tasks and behavior.

As stated earlier in Section 4.5, it seems important for several reasons to have NVES displays that cover a reasonably large visual angle (at least 20 degrees horizontally). From a technical point of view, this can normally be achieved at the price of decreased scale and decreased resolution of the display picture. Such a decrease of scale rules out contact analogue displays, which must be to scale. Consequently, there is a choice to be made about whether to have a wide field of view or a contact analogue display. Because the NIR systems currently have a better resolution than the FIR systems, it might be easier to scale down an NIR display.

In one of the studies reported by Gish et al. (2002), subjects using the Cadillac FIR system mentioned that the HUD prevented them from direct viewing of the road scene when driving over hillcrests. However, the corresponding complaints were not received after driving other less hilly road geometries. Hollnagel (2002) also reports some complaints of that nature, though his studies were carried out in a simulator.

Several authors (Harrison, 1994; Ward et al., 1995; Mortimer, 1997) argue that even transparent screens might mask objects with the display picture itself, especially if the real scene is complicated. This speaks in favor of a separate HUD on top of the dashboard. If the display is not contact analogue the screen must not be positioned too close to the driver's direct line of vision, especially not if the transmission of the screen is low. Furthermore, there are reports that the contact analogue displays are not quite analogue at all distances.

One of the secondary reasons for introducing NVES is to decrease the effect of glare from oncoming vehicles. To what extent the NIR systems can avoid glare effects is not quite clear. The Renault NIR system used polarizing filters to avoid glare (Augello, 1993). DaimlerChrysler and Ford are using filters and pulsing IR illumination. The FIR system displays do not create any glare effects from oncoming vehicles. The question is to what extent the direct glare will reduce the visibility offered by the NVES displays. Contact analogue displays should be more sensitive to glare than the separate displays because they are closer to the real oncoming headlights. As a result, contrast in the pictures will decrease. What could be done in the displays is to enhance the contrast of critical tasks to make them less sensitive to glare. This is what the FIR systems automatically do for warmer objects.

Introducing a separate display could cause considerable visual interference. Some of the problems include eye fixation patterns, cognitive capture, incongruence of the display picture (FIR), difficulty in accurately positioning detected objects, and occlusion of direct vision. A contact analogue display would solve some of these problems, but it would introduce additional problems because it is technically more complicated and, furthermore, limits the field of view because it requires displays at a 1:1 scale.

5.3. Driving and traffic interference

A general safety concern when part of the driving task is simplified is how drivers will react to this change. As discussed in Section 4.4, compensatory reactions often lead to increased speed. But the reaction may also be decreased attention or effort. In all cases, a compensatory reaction might result in reductions in the safety effect of the measure in question.

Several studies have examined the effect of NVES on a driver's choice of speed, but the results are not conclusive. Ward et al. (1994) report reduced speeds (about 5 km/h) when using a Jaguar NIR contact analogue NVES. However, the speed variance increased with NVES. Their explanation is primarily that the NVES required greater mental workload. The results were the same even after one hour of driving. Gish et al. (2002) report a similar decrease of speed (about 5 km/h) when using a Cadillac FIR system with a separate HUD. His explanation for the decreased speed is similar to that of Ward et al. (1994). Hollnagel (2002), in a simulator study using Autoliv (FIR-HUD), found no significant difference in speed with and without the NVES.

On the other hand, other studies show an increase in speed as a result of using NVES. Stanton and Pinto (2000) studied speed with and without vision enhancement in a simulator. They found an increase in speed of about 20% when using the enhanced vision. Nilsson and Alm (1996) conducted a simulator study of driver speed choice in fog with and without a separate-screen HUD. They found a significant increase in speed chosen (about 50%), as well as in speed variance when using the vision enhancement system. One of the reasons for the strong speed effect in both of these simulator studies could be that the whole scene, including the road, was equally enhanced. Therefore, the drivers tended to rely on the display rather than on the direct view. Nilsson and Alm found no effect of VES on workload. Osaka (1987), in a study using artificially restricted fields of vision, found that the smaller the visual field, the lower the estimate of speed. Speed perception largely depends upon the visual flow over the retina in the peripheral field of view. The more reduced this field is, the more reduced the speed stimulation is. When peripheral information is reduced, speed estimation goes down. This could be another factor behind increased speed with VES.

Increased workload is another central issue when considering the potentially negative effects of NVES. Again, the results from experimental studies are inconclusive. Ward et al. (1994), using a Jaguar NIR contact analogue HUD, report significantly increased workload when driving with NVES. The two variables that increased markedly were mental effort and mental demand. As mentioned above, in a simulator study, Nilsson and Alm (1996) did not find any increase of workload with VES usage. As was the case in the differences in speed choice mentioned above, the differing results could be explained by either the full visibility of the road scene in the simulator study, or by the difficulty of interpreting the contact analogue scene. Overall, it is reasonable to predict that perfect contact analogue displays would cause the least increase in workload, followed by separate HUD screens. However, it may be difficult to achieve a perfect contact analogue system. Head-down displays should result in the highest workload increase.

One effect of increased visual distraction and/or increased workload could be a larger variation of lateral position on the road. In a simulator study, Barham (2000) found that only a few drivers had problems with lane keeping when using NVES. In a later study (Barham, 2001), he found that lane departures decreased by 25% when using NVES. In another simulator study, Hollnagel (2002) investigated the lateral distance in relation to the obstacle. He found that drivers made more marked evasive maneuvers without the NVES. His explanation is that with the NVES they had plenty of time to consider what they had to do and did not overreact. Without the NVES, they were surprised when they discovered the obstacle and overreacted. Padmos and van Erp (1996) compared road following behavior with direct view and with a camera view. Lateral position showed a larger variation with the camera view. This makes sense because lateral position is largely maintained by peripheral vision (Rumar and Marsh, 1998), and peripheral vision is diminished in displays.

Could a night traffic situation in which a proportion of the vehicles are equipped with NVES, while the others are not, create any problems? Yes, it could, if the behavior of the equipped drivers differed markedly from the other drivers, for instance, if they drive much faster or much slower, or if they suddenly brake for an object that the other drivers do not see. Another negative effect could appear if unprotected road users start behaving as if all cars were equipped with NVES, but these problems are estimated to be small.

The dual scanning tasks created by a separate display creates an increased workload for the driver. However, considering the inconclusive effects of NVES on speed, the increased workload probably counteracts the potentially increased speed due to the improved visibility.

5.4. General environmental situation

The focus in this report is on systems intended to enhance driver visibility conditions during night driving. However, night traffic is often carried out in conditions other than clear atmosphere and full darkness. How do the NVES function in adverse weather conditions such as fog, rain, and snow, and in traffic conditions with street lighting and distracting light sources?

Theoretically, NIR systems might be more susceptible to the negative effects of scattering in inclement weather, since they involve active sources and therefore are subject to scattering on both outgoing and return paths. In contrast, FIR systems use radiation produced at the viewed object itself, and therefore may be less affected. However, the practical effect of these differences has not been tested.

FIR systems are sensitive to relative temperature differences. Therefore, the darkest part in the picture will be the area with the lowest temperature, which is normally the sky. But snow also looks very dark using the FIR systems. That may cause the road to be more visible when it is surrounded by snow. In cold weather, pedestrians and cyclists wear more clothes, and animals have thicker fur. This will, however, have the effect that exposed legs, arms, and faces will show up even brighter. Whether this will influence the overall visibility of people and animals in FIR systems is not known. The clothing will also influence human visibility in NIR systems because of the normally lower reflectivity of cold-weather clothes.

Rain should not seriously influence the efficiency of FIR systems. The NIR systems should be more sensitive to rain, just as the road scene illuminated by headlights is comparatively sensitive to rain. Studies in a simulator by Lakshmanan et al. (1995) indicate that this is the case.

As stated above in Section 4.2, street lighting does not solve all of the problems associated with object visibility. In rainy or wet conditions obstacle visibility in areas without good lighting is seriously impaired. In fact, even road visibility sometimes becomes inadequate under wet road conditions. Street lighting does not hamper the effectiveness of FIR systems while NIR systems may show blooming around some street lighting sources. NVES could complement street lighting, especially for low-grade street lighting and under adverse weather conditions.

> There are no indications that NVES would not fulfill their purposes under adverse weather conditions and in street lighted areas. However, FIR systems could be slightly superior to NIR systems in adverse weather and in street lighted areas.

5.5. Estimation of the total safety effects of NVES

The positive visibility effects offered by NVES were described in Section 4.7. This improved visibility must be balanced with the potential risks to estimate the total safety effects of NVES.

According to the preceding analyses, the potential risks of NVES are related to how the enhanced visibility should be presented to the driver, in order:

- Not to increase speed
- Not to cause too much distraction
- Not to cause too much cognitive capture
- Not to increase workload too much
- To be useful to older drivers

In the late 1980s, European automobile manufacturers started a large research program to stimulate the introduction of ITS into European vehicles – the Prometheus program. One of the branches of this ambitious program was a group of European researchers who tried to estimate the effects of a number of systems proposed within the program, including proposals related to systems that could enhance driver visibility conditions in night traffic. In an estimation carried out within the Prometheus research program "PRO-GEN" (Färber, 1993), the potential risks were judged to be very serious. This influenced the estimation of the potential effect of various ITS functions. Their estimation of the potential safety effect of visual enhancement by image processing was quite low, varying from an accident increase of 1% to a maximum 7% reduction of accidents. Our position is that such estimations cannot be carried out without detailed knowledge of the functioning of the system(s). The functioning characteristics of NVES will determine whether the potential risks will have a strong or weak influence.

6. SUGGESTED FUTURE STUDIES

This section is primarily a synthesis of the previously described purposes of NVES (section 4) and the corresponding potential risks associated with NVES (Section 5). Section 6.1 offers a comprehensive list of general issues that are important for the future development of NVES. Section 6.2 presents a relatively focused subset of topics that could be studied in more limited research projects.

One of the major remaining questions concerning NVES is the existence and magnitude of the visual interference created by the introduction of the displays. A crucial methodology to study this problem is eye movement recordings. Such a methodology would also be applicable for studying other NVES issues, such as cognitive capture, peripheral detection, learning time, the benefit of warnings, etc.

6.1. Important research issues

NVES have great safety potential, but a number of problems must be solved before the full benefits can be realized. There are a number of remaining issues concerning NVES potential risks that have to be solved before NVES can be fully acceptable. The optimizing issues are analyzed in Section 4 and the potential risks in Section 5. The remaining issues include the following:

- Registration and analyses of driver eye movements during night driving with and without various NVES could, at least in part, answer many of the critical safety questions, such as:
    - o How does driver focus of attention change (cognitive capture) with the introduction of separate displays?
    - o How do different display types (contact analogue HUD, separate HUD, HDD) influence the scanning pattern?
    - o How does the learning process using the NVES displays develop?
    - o How do the two types of technologies (NIR and FIR) compare in scanning patterns?
    - o What effect does a target warning have on the scanning pattern?
- What may be the expected short and long-term learning time to use various NVESs in an effective way for younger and older drivers?
- Why do earlier studies show a large variation in visibility benefits?

- What is the relative importance of recognition and identification of objects on and alongside the road?
- Is speed choice directly related to visibility of the road? If so, in which way?
- What influence will enhanced object visibility have on driver choice of speed?
- Is there an optimal balance between strong object enhancement and weaker road enhancement where drivers can easily locate the objects but where they will not use the NVES for driving faster?
- The steering wheel movement in the 0.3 to 0.6 Hz band could be a sensitive measure for driving workload with and without NVES (e.g., Sivak et al., 2002). If so, this methodology could be used to compare various NVES designs (position of display, FIR or NIR picture, target warning and no warning, etc.)
- What effect does vertical and horizontal angular distance between the line of vision and the display have on NVES usage, workload, etc.?
- Are contact analogue displays congruent enough in different situations, and how sensitive are they to various disturbances (e.g., distance, head movements)?
- How could the usage of NVES by older drivers be increased? Could this performance be trained in any way?
- How large is the cognitive capture problem (the reduced capacity to detect peripheral objects and events)?
- What effect on detection distance would a simple warning system offer?
- How wide and high should the display field of vision be to make the NVES user-friendly for the driver in rural and urban areas?
- Which effects on driver perception do the incongruent pictures in the FIR display create?
- What effect does the scale of the picture have on detection and recognition distance?
- How could the FIR systems be improved concerning driver ability to position the obstacles in the road scene?
- What effect would height of the camera have on driver capacity to judge the positions of targets in the road scene?
- What effect would picture resolution have on target detection and recognition distance?
- In which part of the visual field should the display picture not be allowed to mask the direct view?

- How would target detection and recognition distance be affected by a driver control to modify contrast in the display?
- What effect would there be on detection and recognition distance from marking of the target by means of an icon or a color?
- How much does direct glare influence visibility of the scene in HUDs with separate screens?
- How much does direct glare influence visibility of the scene in contact analogue displays?
- How should occlusion and masking caused by a separate screen HUD be avoided?
- How will separate screen HUDs and contact analogue HUDs influence driver workload?
- How may the respective advantages of the FIR and NIR systems be combined without introducing their respective disadvantages?
- Does driver usage of NVES create problems in adequate lateral positioning of the vehicle?
- Do adverse weather conditions create any problems for the efficiency of FIR- and NIR-based NVES?
- What effect on object visibility would NVES have in streets with lower quality stationary lighting?
- What are the effects of pedestrian clothing on detection distance in FIR and NIR systems?
- Could the incompatibility of wide visual fields and accurate (1:1) scaling be overcome by presenting an image that is scaled 1:1 in the central visual field but which has gradually decreasing scale towards the periphery? (This would be similar to the inhomogeneous magnification in aspheric rearview mirrors, and might be achieved optically or electronically.)
- Does the night-driving pattern of NVES-equipped vehicles differ markedly from the night-driving pattern of non-equipped vehicles?

6.2. Specific, limited research problems

This list is a subset of the above general list. It is more specialized by focusing on specific issues that might be addressable in limited studies.

- The way drivers move their attention between the real scene and the display is crucial for the success of NVES. Eye movement recording is a methodology that can be used to study attention problems. A large number of questions could be answered by means of eye movement recording (e.g., cognitive capture, scanning pattern, learning process, comparison of various designs and technologies, the effect of warnings).
- There is no doubt that NVES have a considerable safety potential by increasing visibility during night driving. The size of these visibility benefits is not yet well established. It should be possible to compare the FIR seeing distances and/or the NIR seeing distances for dark clothed pedestrians with the corresponding high beam seeing distances.
- The display pictures using FIR and NIR technology look very different. The time it takes for drivers to interpret the two types of pictures could be compared in some limited studies.
- It has been suggested to have target warnings to reduce driver mental and visual task load in scanning the NVES displays. It could be possible to study the effect of such warnings in a limited study.
- The question of what should be presented in the NVES displays has not found its optimal solution (e.g., target/road, detection/identification, picture scale 1:1/wide angle field of vision, high resolution/wide angle field of vision, separate/contact analogue display, etc.). What could be studied in a relatively limited investigation is the relation between display scale 1:1 and scale 1:2 concerning detection distance and recognition distance.
- Driver reaction to the various improved visibility conditions should be further studied (e.g., choice of speed, attention level, and lateral position). In a limited study, the effect of NVES on lateral positioning of the vehicle could be investigated.
- How large is the distraction caused by a separate screen HUD? And how large is the extra workload? In a limited study, the steering frequency from 0.3 to 0.6 Hz (lane maintenance workload) for contact analogue and separate screen HUDs could be compared. A corresponding comparison could be made between FIR and NIR systems with the same and separate HUD screens.

- Will an NVES HUD influence driver detection of obstacles outside the HUD area (the cognitive capture problem)? In a limited study, the peripheral detection angles (simulated in the car) could be studied for one or two NVES.
- What is the learning time for various NVES? How is efficient scanning behavior developed? The learning time for one or two NVES could be studied in a limited investigation.
- Does pedestrian clothing have any effect on detection distance in an FIR-based system? This problem could be studied in a limited field experiment on a closed-track.

7. CRITERIA AND EVALUATION PROCEDURES FOR NVES

The evaluation of present and future NVES is a difficult task. The goal of this report is to start the discussion on how such an evaluation procedure should be designed. To begin with, an evaluation should be performance-based and not technology-based. How well the system works should be the main criteria, not how it is constructed and what it looks like. However, hypotheses are presented concerning which construction variables will influence the respective criteria. The criteria and the hypotheses suggested here have not been tested, and some are based on weak data or hypotheses. They must be extensively discussed and tested before being implemented in some kind of code of practice or standard. It is important to stress that this section is primarily written to start such a discussion. The variables and the limits mentioned below are clearly not ready for implementation.

A. First, the purpose of the system or equipment must be clearly defined because that should be the basis for the conditions in which the evaluation will be carried out.

   - Is it intended for the enhancement of obstacle and/or road visibility?
   - For which kind of obstacles should visibility be enhanced?
   - For which group of drivers is it intended (younger and/or older)?
   - For which type of vehicles is it intended (all cars/luxury cars/light trucks/buses/heavy trucks)?
   - Is it intended for rural and/or urban night driving?
   - In which weather conditions is it intended to function well (wet/rain/snow/fog)?

   It is, of course, up to the manufacturers to answer these questions. However, the preliminary assumption is that in most cases the manufacturer should be able to answer "for all" on all these questions, except the first one. If so, all testing should be carried out with older drivers (age 65+) because they would benefit most and, at the same time, they have most problems in using NVES. It is further suggested that although the NVES should primarily enhance warmer objects, enough of the road scene must be visible to make it possible for the driver to correctly locate the obstacle in the road scene.

B. The next step should be to evaluate the functioning of the system, with the form of evaluation depending to some extent on how its purpose has been specified. The main purpose, which is visibility enhancement, can now be specified as detection distance. Each detection distance should at least correspond to detection distance with standard high beams without oncoming glare, for older drivers and bright obstacles. According to Table 1, that distance is 200 m.

- Detection distances under glare from oncoming low beams at 50 m distance for large (0.4 x 1.5 m) and small (0.4 x 0.4 m) warm objects (human and animal targets)
- Detection distances under the same glare conditions for large (2.0 x 2.0 m) and small (0.4 x 0.4 m) cool objects (signs, dropped cargo, and parked cars or trailers)–if so specified.
- Then, visibility (detection) should be tested in the periphery of the display. Visibility should be at least 100 m (50% of the previous detection criteria) at 8° left and right in the horizontal plane.

C. It is suggested that the display should be a HUD (contact analogue or separate on top of dashboard). The virtual picture should be optically at least 3 m in front of the driver. The field of view in the display should cover, at a minimum, 20° horizontally and 5° vertically. The wide screen makes it possible for the driver to have enhanced visibility in curves, and of pedestrians and cyclists in urban areas. The 20° value is proposed partly from practical experience driving NVES, and partly because 18° has been tried with favorable effect. The scale in a contact analogue display must be 1:1. In a separate HUD, a scale between 1:1 and 1:2 is acceptable.

D. The position of detected targets should be correctly perceived. It is acceptable if distance estimation is within ±20% of the distance estimation with high beam illumination.

E. Ideally, there should not be a learning curve because the usage of the system should be self evident and intuitive (Barham et al., 1999). However, a learning time of one hour seems acceptable.

F. Masking of the direct scene should be evaluated. The separate screen must not mask road delineation beyond 15 m in front of the car or overhead road signs beyond 25 m in front of the car.

G. The use of NVES will probably increase the workload of the driver. This increase must not be too large. The first problem is to measure the workload. There is no generally accepted testing instrument for that purpose. But in several of the studies, the NASA-TLX-R has been used and it is suggested that, using that instrument, the difference in average composite value between driving with and without the NVES at night on a rural two-lane road should not exceed 25%. The workload could be reduced by using perfect contact analogue displays (if such displays can be achieved) or by only giving the driver a visual or auditory warning when a new, relevant object becomes visible in the display. Workload is not only negative; moderate workload may prevent fatigue and work against increased speed.

H. The risk of increased speed is often put forward as the major safety risk with NVES. The results from previous studies are inconclusive. No speed increase should be accepted when driving with NVES at night on a two-lane rural road. A speed decrease is acceptable. A hypothesis put forward in this report is that the more of the road that is visible in the display, the higher the probability of a speed increase. Another hypothesis is that the higher the workload, the lower the speed.

I. Cognitive capture caused by the NVES display is a difficult variable to measure. One way to approach the measuring problem could be to study the eye movements of drivers with and without NVES, while driving in real traffic. The reduction of fixations outside the display should not exceed 10%. An alternative approach could be to use a simulator and measure the angle at which an object entering from left and right will be detected with and without NVES. The detection angle should not be reduced more than 10°. One hypothesis is that the more of the road that is shown in the display, the more frequently drivers will look at the display and the stronger the cognitive capture factor will be.

J. One of the purposes of NVES is to avoid the negative visibility effects of glare from oncoming headlights. Therefore, the degree to which glare reduction works in the NVES should be tested. This could be done by means of a subjective methodology, for instance, using the de Boer glare index. In the same way, the glare caused by retroreflective signs, and the legibility of those signs, should be evaluated.

K. A number of specific requirements are important concerning the detailed characteristics of the display: brightness, contrasts, polarity, transmission, etc. These requirements are not treated here.

L. NVES controls should be tested concerning both position and design. This problem is not treated here, but it seems necessary to be able to have an on/off switch, to adjust the position of the HUD in relation to driver eye height, and to adjust the brightness of the display. It would be an advantage if the driver could also modify the contrast in the display.

8. CONCLUSIONS

The NVES is a potentially promising development. It is able to meet both the requirements of drivers and of society, which are sometimes different. However, the optimal designs have not yet been found. The estimates of traffic safety effects of NVES have a large range (predicted changes in accidents vary from +1 to -25% [Lunenfeld and Stephens, 1991; Färber, 1993), partly because of differing estimates of potential risk factors.

Some of the potential risks have not been fully investigated. Presentation of the enhanced visibility picture on a separate screen creates a number of problems because of the necessity for dual scanning. There are indications that this will influence attention to the primary task and increase driver workload and distraction. Many older drivers show low motivation and/or capacity to use NVES, though they would benefit more from it than younger drivers. Presenting the picture as a contact analogue image would solve some of those problems. But at the same time, it would unfortunately create new problems because a contact analogue display would require a narrower field of view in the display and introduce a number of new technical problems. The effect of NVES on driver choice of speed is inconclusive. If speed is increased, it might eliminate most of the potential safety effect. However, there are indications that if road visibility is not enhanced as much as obstacle visibility drivers will not increase their speed when using NVES.

Much of the analysis speaks in favor of a NVES that primarily enhances obstacles and only enhances enough of the road to make it possible for the driver to position the detected objects in the road scene. Analyses of crash risk indicate that it is primarily human and perhaps animal obstacles that should be enhanced. The scene presented must be wide enough to cover curves and crossings, to include approach and crossing behavior of humans and animals. This probably means a field of view of at least 20^{o}.

Table 2 list the main questions facing the future development of NVES, as well as alternatives and recommended answers. Table 2 illustrates two things – the large number of alternatives available, and the fact that the best solution for one NVES purpose is not necessarily the best solution for another purpose. For example, if we want to enhance pedestrians for all drivers, an FIR system with part-time presentation, warning, and icons on a separate HUD display seems to be preferred. If we want to enhance the road and road signs for older drivers, an NIR system with full time presentation and full sensor image on a contact analogue display may be best.

Table 2
The six main questions concerning implementation of NVES, possible alternatives, and recommendations.

Question	Alternatives	Recommendations
1. **What** kind of information should be presented?	The obstacles and/or the road with markings and/or road signs	Mainly warm objects but with enough road information for contrast
2. To **whom** should the information be presented?	• To professional and/or private drivers • To younger and/or older drivers	To all drivers (including older drivers)
3. **Which** technology should be used?	Heat sensitive FIR or generally sensitive NIR	Primarily FIR, maybe merged with radar or NIR information
4. **When** should the information be displayed?	Always (full time) or warned when target present or when asked for (part time)	If possible, warning when critical target is present
5. **How** should the information be presented?	As full image or as icons (of obstacle, signs, or road), maybe with a warning	If possible, icons for selected critical targets
6. **Where** should the information be displayed?	In a contact analogue display, in a separate HUD, in a HDD, or just a non-visual warning	Separate HUD about 5° below driver line of vision (or just the warning)

Behind questions 4 and 5 is the signal detection problem. If a reliable technical system for detecting the relevant signals could be designed, the scanning task and the workload of the driver would be substantially reduced. The driver would then only have to react to a warning signal by scanning the display or by slowing down. According to Roper and Howard (1938), a warning alone would increase detection distance by a factor of two, without any displayed vision enhancement system. However, such a system might introduce new problems of false security (leading to reduced attention) and false alarms (leading to reduced usage).

In order to start a discussion of how an evaluation procedure of present and future NVES should be designed, Table 3 contains a set of preliminary variables and the respective candidate limits. (For more detailed discussion, please see Section 7.) To repeat, these variables and their limits (criteria) are suggestions designed to start a discussion about the evaluation procedure. Most of the suggestions are based on comparatively weak data. Both the variables and their limits must be discussed, thoroughly tested, modified, and agreed upon before they can be established as a code of practice or requirements.

Table 3
Preliminary proposal for important NVES variables with candidate limits.

Variables	Limits or criteria
Purposes of NVES	• Explicitly stated and tested accordingly
Field of view and scale in display	• HUD • ≥ 20° horizontally • ≥ 5° vertically • Scale: 1:1 to 1:2
Detection distances for small and large, warm and cool objects	• Straight ahead: ≥ 200 m • 8° left and right: ≥ 100 m
Positioning of the detected object	• ± 20% of distance estimation on high beams
Masking of real scene	• No masking beyond 15 m for roadway • No masking beyond 25 m for overhead signs
Learning time	• ≤ 1 hour
Workload	• TLX-R, average composite difference ≤ 25%
Speed increase	• Not accepted
Cognitive capture (eye fixations or detection)	• ≤ 10% reduction of eye fixation patterns outside display, or peripheral detection reduction ≤ 10°
NVES controls	• Not treated, see handbooks

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