Research on Development and Application of Simulated Night Vision Enhancement Systems

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Abstract

Poor visibility due to darkness is believed to be one of the main causes for the high rate of night driving accidents.

Night vision enhancement systems (NVESs) have been developed to improve visibility at night through supplementing drivers’ direct vision with additional information shown on a display, rather than replacing drivers’ direct vision. Existing studies have shown that NVESs may increase recognition distance, but may also increase drivers’ mental and visual distraction (eyes-off-road). Each scan of the display of the night vision enhancement system involves some visual and mental cost to the driver. Automatic pedestrian warnings (APWs) have been integrated into NVESs with the anticipation of a minimized workload, improved performance, and further increased safety. However, NVESs still have a low popularity rate among vehicle owners and few drivers are fully aware of NVESs’ benefits in nighttime driving, i.e., extended visibility and excellent pedestrian detection ability. This could be due to the following reasons: (1) the price for a NVES is too expensive for many drivers; (2) most drivers are concerned about the distraction problem with any in-vehicle devices; and (3) a very complicated nighttime driving experimental environment is required for studying NVESs, making progress in the study of NVESs very slow.
This research focuses on developing an affordable and integrated experimental platform that can provide drivers using NVESs with a realistic nighttime driving experience. Study on both near-infrared (NIR) and far-infrared (FIR) NVESs’ overall benefits and driver distraction were conducted on this platform with the purpose of exploring both the advantages and disadvantages of current NVESs and making recommendation for future improvements.

A comprehensive review was first conducted on previous research on nighttime driving safety and NVESs, including the evolution of this system, the state of the art of the technology, and the application of NVESs to production vehicles. Previous research methods for evaluating drivers’ distraction and safety while using NVESs and other in-vehicle devices were also studied. A platform for simulating both NVESs and nighttime driving environments was then developed in a driving simulator. Twenty different hazard scenarios involving pedestrians and bicyclists (walking, running, jogging, standing or riding bike) were created in the simulated environment, aiming to capture the true traffic features in both the downtown and rural areas of the greater Boston area. The NVESs simulated in this study captured the characteristics of the current advanced NVESs on production vehicles of BMW, Mercedes Benz, and Audi. Twenty-four experienced drivers from Northeastern University (staff and students) participated in this study of NVESs. They used and tested NVESs systems in the Virtual Environments Laboratory and were required to complete two experimental trials, each individually. The twenty-
four subjects were divided into three groups of eight. Each group was tested against one of the following: (1) control-group without NVESs; (2) using NIR NVES; and (3) using FIR NVES. In addition, each participant drove in two different weather conditions – one in clear weather and the other in foggy weather.

All subjects reported that the simulations seem realistic and they showed significantly increased interest in purchasing a NVES for their own vehicle after the test. Significance at a 0.01 level of confidence has been done for each parameter. If two criteria, the response distance to stop the vehicle before hitting an object on the road, and detection accuracy, were used in evaluating the performance of the three different groups. The group that used FIR had the best performance in the foggy weather in terms of both statistically significant hazard detection distance and hazard detection accuracy differences, while the control group without NVESs had the worst performance. Though statistically insignificant, the result might indicate that NVESs’ performance in hazard detection won’t be affected by the weather conditions. Results also showed that NVESs’ performance in detecting hazard statistically varied as the hazard scenarios and hazard appearance distance changed. Test results on lane deviation and driver’s glance behaviors were not statistically different among the conditions, subjects that used FIR NVES spent more time looking at NVES’s display and failed in one criterion for drivers’ distraction by NHTSA. However, the result might still indicate that though the use of NVES did cause drivers’ visual distraction, it did not have a negative impact on drivers’ overall
driving performance in terms of lane keeping. Scores from NASA-TLX questionnaires also showed that drivers’ mental distraction in terms of mental workload was reduced when driving with the NIR system, but the difference was statistically insignificant. These results demonstrated that simulation provides a good opportunity to experience driving with a NVES, and also is a very good tool for conducting research on NVESs. Data analysis showed that instead of distracting drivers and degrading driving performance, implementation of current NVESs on production vehicles could actually improve drivers’ nighttime driving performance at an acceptable distraction level, especially in adverse weather conditions like fog.

Key Words: Night Vision Enhancement System, Automatic Pedestrian Warnings, Drivers’ Distraction, Hazard Detection, and Driving Simulator
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Chapter 1 Introduction

Nighttime driving safety is always of great concern as many severe and fatal crashes occurred at night (e.g., Mariani et al., 2002; Owens et al., 1996; Sullivan et al., 2001). The 2008 and 2009 Pedestrian Fatalities Analysis from the National Highway Traffic Safety Administration all reported that most pedestrian crashes occurred between 6 p.m. and 6 a.m. at nighttime. Despite various factors like alcohol, fatigue driving, and low environmental ambient light, drivers’ seriously reduced visibility, is considered to be the most important factor that contribute to the high rate of nighttime pedestrian fatalities as the most significant difference between driving during the day and night.

Human visual information processing is severely degraded in the dark or bad weathers (fog, rain and etc.) (Levine et al., 2006). However, most people do not realize that their visual ability is limited in low light conditions (Tyrrell et al., 2004). Studies show that drivers usually dramatically overestimated the visibility up to three times greater than the actual visibility. (e.g., Shinar, 1985; Tyrrell et al., 2003). Visual processes during driving can be divided into two rather separated subcomponents (e.g., Leibowitz 1977; Owens 1988): (a) peripheral visual processes, relevant for lane keeping and lateral control (e.g., Mourant et al., 1972; Summala et al., 1996); and (b) processes of central vision, responsible for object detection as well as recognition. Central vision is more sensitive to the intense light during daytime, and is severely impaired at night. Under the condition of seriously reduced visibility, drivers are more likely to have incorrect prediction of
pedestrians and other objects. Experiments and analysis show that most drivers do not realize the impending collisions and fail to perform any avoidance. Others may not have sufficient time to respond once they realized the unsafe condition (Tijerina et al., 1995). Consequently, drivers at night take a significant higher risk to involve in a crash compared to daytime for all age groups (John M. et al., 2005).

Night vision enhancement systems (NVESs) are primarily proposed and designed to enhance the visibility of road beyond drivers’ vision field, especially for pedestrians and animals on road (e.g., Rumar, 2002; Sullivan et al. 2001). It works by providing a reimaged view of the real road scene captured by an infrared sensor camera on a separate in-vehicle display to drivers, with a longer seeing distance beyond the reach of vehicle’s highlights. Researchers agree that the theories of NVESs can considerably improve drivers’ nighttime visibility and therefore increase the overall nighttime driving safety. Therefore automobile manufacturers have spent a considerate amount of effort enhancing this technology. However, some field and experimental studies have shown some negative effects resulted from NVESs, which are opposed to its anticipated improvements, such as a high mental workload (Gish et al., 1999), or even a worse detection rate (Kiefer et al., 1995), and questions on both visual and mental distraction resulted from drivers’ continuous scans on NVES’s display are raised. Due to the limitation of either near-infrared (NIR) sensor or far-infrared (FIR) sensors, some have complained that users are having hard time in either identifying the objects in display, or relocating the object’s position in the real scene. Either of these two problems can distract drivers from driving and increase drivers’ mental workload. In recent years, advanced real-time Automatic Pedestrian Warnings (APWs) techniques have been developed and
integrated into NVESs, aiming to improve the pedestrian detection performance at a lower drivers’ distraction. But it is not clear how they would change the drivers’ performance and visual behaviors as a driving-related in-vehicle device and whether the warnings would reduce drivers’ distraction, especially when they are facing a real hazard. Also, NVES’s performance under adverse weathers like raining, fog and etc., remained unclear. Moreover, tough NVES have been introduced to the production vehicle, as an upgrade option by many vehicle manufacturers since 2002, and the system are keeping updated as the techniques proceeded, the popularity rate is still at a low level. Besides the high cost of NVESs, many vehicle purchasers are not realized the benefits of having NVESs as they are lacking of real driving experience by NVESs. Some of them also worry about the potential drivers’ distraction like other in-vehicle devices.

The goal of this research was to provide drivers a real nighttime driving experience by NVESs, and build an experimental platform to conduct a complete study on the overall performance by multiple current NVESs in both clear and fog weathers at night, all by simulations. Impact of NVESs for different hazards by scenario and appearance distance was also evaluated. Recommendations relating to the future improvements for NVESs in terms of deducted drivers’ distraction and enhanced drivers’ hazard detection abilities were also discussed upon the results.

Measures of three formats were collected and analyzed: subjects’ visual behavior (eye movements); subjects’ vehicle control performance (as indicated by hazard detection performance and lane keeping tasks); and subjects’ subjective assessment of both mental workload and system rating.
Instead of using self-assembled NVESs and on-road closed track as most previously studies did, the experimental approach presented in this research was to simulate the infrared image effects on NVESs’ displays, including a FIR and a NIR NVESs prototyped from the current on-market products. Image effects of APWs were also simulated and integrated into NVESs in formats of both visual and acoustic warnings. Immersive nighttime driving environments of downtown and rural roads, including all the elements like roads, buildings, pedestrian hazards, hills, light lamps and etc., were also simulated. Effects of weather conditions of clear and foggy were applied to the virtual environmental as well.

This method is expected to be a promising approach to provide a better and complete evaluation of NVESs, because simulation is always considered as a faster, safer, lower cost approach without any sacrifice in experimental authenticity. This experimental platform, including both simulated NVESs and nighttime driving environments, can be extended to meet any field tests relating to NVESs.

It was assumed at the beginning of this study that the integrated platform of driving simulator and NVES’s simulation could well replace the on-road experiment by real NVES without sacrificing the experimental reality. It was hoped that vehicle owners could better accept NVESs after tests. By analyzing drivers’ eye movements and performance, concerns and questions on drivers’ distraction and NVESs’ sufficiency could be well answered, and improvements from future techniques on NVESs could be well evaluated. A well-designed NVES should enhance the detection distance for drivers
at an acceptable distraction level with a suitable visual strategy and affordable mental workload.
Chapter 2 Background and Related Research

2.1 Scope

The original idea of this study was inspired by the high concentration of traffic accidents in nighttime, the research popularization of night vision enhancement system (NVES) in recent years, and the questions brought on the current and future NVESs.

Nighttime driving is always of great concerns as many pedestrian fatalities were happened at night, mostly due to the drivers’ limited sight distance in the dark.

NVES was originally designed and developed to compensate drivers’ vision loss by supplementing drivers’ direct vision with additional information, particularly the front scene far beyond the reach of the headlamp. There are two main NVESs: the active, near-infrared (NIR) NVES that requires an IR source but give a complete picture of the scene in front of the drivers, and the passive, far-infrared (FIR) NVES that does not need an IR source but only enhance the visibility of relatively warm objects (people, animal, etc.). Automatic pedestrian warnings (APWs) have also been applied to NVES with the purpose of minimizing drivers’ distraction, improving performance and further increasing safety.

This research was mainly proposed to develop an immersive experimental platform for NVESs in a driving simulator. Both the effectiveness and distraction of different NVESs in detecting hazards and avoiding crashes under multiple weathers were compared.
Potential problems relating to NVESs and usability will be discussed based on the collected data.

A number of background variables are relevant to this research. These variables, which will be mentioned in the following paragraphs, concern information on:

- Nighttime driving safety and pedestrian crashes
- Visibility at night
- Theory and application of NVESs
- Research on NVESs: benefits and drawbacks
- Pedestrian warning technology and its uses
- Driving simulator for experimental study

2.2 Nighttime Driving Safety and Pedestrian Crashes

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 (Rumar, 2002). 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.

The General Estimates System (GES), compiled by NHTSA, provides a national database of all crashes. GES data reveals that more than 70 percent of all crashes occur during daylight. Thus, even though the number of fatalities during the day and at night is about
the same, the percentage of fatalities at night is higher, in general two to three times higher (Weber et al., 2001), and the rate of injuries is also disproportionately higher at night than the overall. The proportion of traffic fatalities at night does not vary as much as expected throughout the world. A typical figure for highly industrialized countries (U.S.) as well as for less industrialized countries (Senegal) is one third or less of all fatalities. However, in some countries the number could be much higher, for example, this number is 44%, 49%, 77% and 80% for Ukraine, Italy, Taiwan, and Cambodia, respectively (UN, 2000).

In conclusion, compared to daytime driving, severe and fatal crashes are more likely to occur at night (e.g., Sullivan & Flannagan, 2001; K. W. Gish, L. Staplin & M. Perel, 2002; Owens & Sivak, 1996; Kenneth S. Opiela, Carl K. Andersen & Greg Schertz, 2002). Various crash data from multiple countries all suggest that the highest potential risk that a driver could encounter at night is to hit a pedestrian– the risk of a pedestrian crash is about 3 to 6.75 times higher in darkness (e.g., Ferguson, Preusser, Lund, Zador, & Ulmer, 1995; Sullivan & Flannagan, 1999 and 2002).

In the year of 2008, the risk of pedestrian fatalities in US was almost twice higher in nighttime (66%) than daytime (34%). In 2009, the risk of pedestrian fatalities at night further increased to 71%. The diagrams shown in Figure 2.1 and Figure 2.2 indicate that most pedestrian fatalities happened between the period after sunset and before the next dawn, and the peak time starts from 4 p.m. till the midnight.
Figure 2.1 Pedestrian fatalities by time of day, 2008

Figure 2.2 Pedestrian fatalities by time of day and day of week, 2009
The rest of road users who get injured or killed in motor vehicle crashes were vehicle occupants (drivers and passengers), motorcycle riders, bicyclists and others (NHTSA, 2009). Among these people, bicyclists are considered to be the most vulnerable of all. They have the largest proportion of self-reported near-miss crashes compared to pedestrians, motorists and so on (Joshi MS, Senior V and Smith GP., 2001). Though bicycle trips accounts for only less than 1 percent of all trips in the U.S., two-percent of motor vehicle-related fatalities are involved with bicyclist, making bicyclist fatality at a high risk.

Night-time cycling has been shown to be more dangerous than cycling in daylight, with 40% of cyclist fatalities occurring at night despite much lower exposure rates than in the daytime (Jaermark S. et al., 1991). Though only 12% of cyclists reported that they ride at night, 35% of cyclist deaths occur in nighttime (e.g., Rodgers GB et al., 1995).

Although other human factors, such as alcohol/drug and fatigue, all contribute to a large proportion of total nighttime crashes, deteriorated lighting condition and drivers’ reduced vision at night play major roles in pedestrian and bicyclist crashes.

### 2.3 Visibility at Night

Study shows that the visibility provided by a NVES is usually much better than the visibility offered by the present low-beam system with opposing low beams (Blanco et al., 2001). It can be even as good as the visibility offered by the present high-beam systems.
The most significant difference between driving at day and driving at night is the limited visibility offered to drivers in the dark. The day/night illumination ratio is $10^5$, which means you can visibly see a person standing 304 m/1000 feet away in daytime, however, you can only see a person standing less than 76m/ 250 feet away at night (Farber, 2004). Under adverse weather conditions such as fog or raining, visibility is further reduced.

Drivers’ visual problem in detecting objects ahead is the most important factor for crashes involved with low contrast objects such as pedestrians, cyclists and animals (Wood et al., 2010). A more serious problem is that drivers might not be aware that their vision is reduced or impaired during nighttime driving (e.g., Rumer, 2002; Tyrrell et al., 2004).

Visual processes during driving can be divided into two separated subcomponents (e.g., Leibowitz 1977; Owens 1988): (a) peripheral visual processes, which are used to guide one’s movement and are relevant for lane keeping and lateral control at driving (e.g., Mourant et al., 1972; Summala et al., 1996); and (b) processes of central vision, which are responsible for object detection as well as recognition. Central vision is more sensitive to the intense light during daytime, and thus will deteriorate rapidly at night, while the peripheral vision does not decline greatly.

Initially, based on the idea of compensating for the loss of illumination at night, solution to the problem was to provide drivers with enough light intensity to illuminate the road scene at distances far in front of the vehicles, such as to enhance the headlight’s illumination, or to adjust the illumination of streetlights.
Means of having more efficient light sources to enhance the headlamp’s illumination could bring other problems such as causing glare, as light sources available did not match the speeds of the cars (e.g., Rumar, 2002; G. Benedict Maxwell et al., 2012). Many other efforts have been made to achieve good illumination without causing glare. Intelligent (adaptive) headlights, ultraviolet headlights, polarized headlights, etc., have been developed to improve this situation. However, each method has its own drawbacks, preventing their introduction to the public (Rumar, 2001).

Statistics data indicated that over half of pedestrian and bicyclist fatalities happened outside the illuminated area. And the total number of fatalities occurred on the illuminated road is almost three times higher than the road without light. Studies show that street lighting usually improves the visibility of the road but does not reliably improve object visibility. A more surprising finding was that pedestrian and bicyclist wearing bright color clothing may be more dangerous as if they incorrectly believe themselves to be more conspicuous to drivers at night (e.g., Jaermark S et al. 1991; JM Wood et, 2010). All the findings showed that none of the proposed methods above are practical and acceptable.

Consequently, researchers and manufacturers have turned to systems using radiation outside the range of the human visual system. The idea is to assemble a system to decode and process the radiation signals. Night vision enhancement related systems were primarily used in military contexts in mid-80s with the purpose to detect the enemy in dark conditions (Tsimhoni & Green, 2002). 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 on vehicles. Night Vision Enhancement Systems were first marketed for civilian vehicles in 2000, as an option on the GM Cadillac model.

2.4 Theory and Application of Night Vision Enhancement Systems

2.4.1 Evolution of NVESs

NVES offers a solution that can extend a driver’s ability to see objects down the road without increasing glare to other road users. NVESs work by providing a reimaged view of the real road scene on the display. The display can be a contact analogue with the real scene in front of the driver or it can be a separate display (Rumar, 2002). The screen might be a head up display (HUD) shown on the windshield, a separate screen on top of the dashboard, or a head down display (HDD) with a screen integrated into the dashboard. Information showed on display is captured and processed by an infrared camera installed in the front of the vehicle, thus allowing drivers to see the road condition and objects in the path that may otherwise be missed due to poor illumination or bad weather conditions.

Two major sensor technologies, the NIR sensor and FIR sensor, are applied in the development of NVESs: the NIR NVES and the FIR NVES. The NIR sensor system, or
active night system, which requires both infrared sources and infrared sensors, has the ability to sense objects with heat wavelengths within a range between 780 nm and 3000 nm. The FIR sensor system, or passive night system, which requires only infrared thermal sensors, has the ability to sense objects with heat wavelengths of 6000 nm to 16000 nm (Sullivan et al., 2003). Since then, both NIR and FIR sensor-based NVESs have attracted the attention of numerous researchers and world leading automobile manufacturers.

Technique of APWs was newly introduced and integrated into NVESs with the purpose of minimize drivers’ distraction, improve performance and further increase safety. The theory of APWs is to provide drivers with visual warnings or/and acoustic warnings when a pedestrian is detected by NVES. Visual cues work by generating a pedestrian icon on the display (Figure 2.3) or highlighting the position of pedestrian in a colorful square on the display (Figure 2.4). Acoustic cues usually come out in the format of an alarm sound accompanied by the visual warnings.

![BMW's NVES with pedestrian detection icon](image)

**Figure 2.3 BMW's NVES with pedestrian detection icon**
In the year of 2000, the first passenger vehicle on the consumer’s market that had an IR-based night vision enhancement system -- the 2000 model GM Cadillac DeVille, was brought into market (Martinelli & Seone, 1999). Since then, NVESs have been available for vehicles from various manufacturers, such as Audi, BMW, Mercedes Benz, Honda, Volvo, etc., either as factory option or as after-market add-ons. Based on the appearance of APDWs, the developing course of NVESs on vehicles can be divided into two phases – 1st generation: NVESs without APDWs before 2005, 2nd generation: NVESs integrated with APDWs after 2005.

Figure 2.5 shows the landmarks for both NIR and FIR NVESs.
Figure 2.5 NVESs landmarks (NIR, FIR and Pedestrian Detection)

Picture Sources:  
http://www.carfinancing.net  
http://www.clublexus.com  
http://www.autozine.org  
http://www.auto-power-girl.com
2.4.1.1 NIR NVES Landmarks

In the year of 2002, Toyota introduced its first production automotive NIR Night view on Lexus. Two separate headlamps illuminate the road with near infrared light. A windscreen top-mounted camera, designed to precisely pick up reflected radiation, can give a viewpoint close to drivers. The radiation signal is then processed and sent to a Head-Up display (HUD) positioned on windshield. A greyscale image is produced and pedestrians, cyclists and other obstacles are highlighted clearly at an early stage. In 2008, Toyota updated its Night View systems with a new feature, which highlights pedestrians and presents them in a box on the display. Two additional cameras were also added to the locations of the left and right mirrors to produce a broadened view for drivers.

Mercedes-Benz introduced the Night View Assist to the market in 2005. The system works in the same way as the Toyota’s product in 2002 except the position – a Head-down display (HDD) on the dashboard. In 2009, Mercedes-Benz released its newest Night View Assist Plus to the public. In this version, Detected pedestrians are highlighted on the display by means of a specially developed pedestrian-detection function.

2.4.2.2 FIR NVES Landmarks

In 2002, the only vehicle in production with a NVES was the Cadillac, which is equipped with an FIR system, which is based on a Raytheon IR-camera and a Delphi-developed HUD. The camera has its maximum sensitivity at a temperature of 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/230 feet. The camera is focused at 125 m/410 feet and its focal depth is from 25 m/82 feet to infinity (Rumar, 2002). The detection range for a pedestrian is 304 m/1000 feet (Marinelli & Boulanger, 2000).

In fall 2005, BMW introduced BMW Night Vision to its vehicles. This system processes far infrared radiation. The far infrared radiation minimizes non-essential information by placing a greater emphasis on warmer objects like pedestrians and animals. It allows for a detection range up to 304 m/1000 feet and can avoid dazzle from headlights, road lights and similar intense light sources. In 2008, BMW redesigned its Night Vision system by adding a pedestrian detection function. Thus the system will flash a caution symbol on the display and head-up-display when it detects pedestrians.

Volvo unveiled its first Night Vision system in 2002. It has a 50-percent wider field of view and a deployed combiner mirror head-up display (HUD) that folds flush into the dashboard when not in use. Volvo promoted its latest vision safety system with pedestrian detection and a full auto brake to pedestrians in 2010. The system uses newly developed dual-mode radar, which has both laser and infrared sensors, to assure a more stable and broadened detection view. If a pedestrian is walking into the vehicle’s path, the system will warn the driver first, and the vehicle’s full braking power will be automatically switched to active mode if the driver fails to respond in time. The system can only recognize pedestrians who are 80 cm tall and upwards.
Audi also introduced its optional night vision assistant with highlighting of detected pedestrians. This system scans the area in front of the vehicle with the aid of a thermal imaging camera and highlights any pedestrians detected in a yellow box at distances of between approximately 15 and 90 m (50ft and 295ft). If the system determines that there is a risk of a collision between the vehicle and the detected pedestrian, the color of the highlighting turns red and an audible warning sounds.

2.4.2 Research related to the Implementation of NVESs

Various studies have carried out on the application of NVESs. Since the 1940s they have been primarily used in military contexts (e.g., Johnson, 2004; Tsimhoni & Green, 2002), but for a decade or longer, there has been a broad discussion about their automotive application – are NVESs beneficial? Some studies have already examined the benefits of target detection performance by NVESs under realistic driving conditions. Research on NVESs can be divided into two phases: first generation of NVESs – the period before the appearance of APWs; second generation of NVESs – the period after the appearance of APWs.

2.4.2.1 First generation of NVESs

Though some studies showed contradictory results in respect of some particular obstacle detection (tire treads) and age group. Gish, Staplin and Perel (1999) concluded from their data that there is a high probability of overlooking critical targets in a visually demanding display because both tasks, driving and target detection, depend upon the same visual
resources and thus interfere with each other. Similarly, Ward et al. (1994a) found no significant difference in target detection time between control group that not used NVESs and experimental groups that used NVESs. Gish et al. (1999) found that older drivers did not benefit from using NVESs as they were reluctant to use extensive information shown on the extra display. Kiefer (1999) reviewed the literature on the target detection and concluded that drivers would have a better detection performance without a NVES. Blanco et al. (2001) found that tire treads and a child’s bicycle, which are hard to see using thermal imagery, were detected at shorter distances than with low-beam headlamps.

Most studies showed that NVESs could bring visible evidence and positive effects in improving drivers’ detection performance. Gish et al. (1998), using a NIR VES, found an increase in detection distance of small targets from 90m (295ft) to 120m (394ft) and of large targets from 120m (395ft) to 180m (590ft). Similarly, Staahl et al. (1995) and Barham et al. (1998, 1999) found that the use of an NIR VES increased the mean detection distance of a pedestrian from 61m (200ft) to 95m (312ft) and for a few older drivers from under 30m (98ft) to over 100m (328ft). An increase was also observed in detection distance of an adult dummy from 24m (79ft) to 63m (206ft) and for a child dummy from 19m (62ft) to 47m (154ft). Blanco et al. (2001a, 2001b) found the IR thermal imaging system allowed drivers to detect most objects at a longer distance than any of the conventional headlamps (210m vs. 150-180 m). Rosler et al. (2006 and 2007) invited experts to heuristically evaluate the NVESs. Results indicated that all experts considered NVESs as a very promising and worthwhile tool to assist drivers and to increase safety under impaired visual conditions.
Studies showed convincingly that NVES is beneficial to drivers by offering considerable improvements of visibility and obstacle detection during night driving, consequently the research on NVES has switched to the implementation of NVES.

By finding possible alternatives and recommendations for solving those questions, Rumar (2002) proposed preliminary for important NVES variables with candidate limits (Table 2.1) and stated that pedestrian detection should be the primary objective of any night vision system.
Table 2.1 Preliminary proposal for important NVES variables with candidate limits

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

A great deal of research and experiments were conducted upon finding answers to the six questions. 1) What kind of information should be presented? 2) To whom should the information be presented? 3) Which technology should be used? 4) When should the information be displayed? 5) How should the information be presented? 6) Where should the information be displayed?

Most studies can be categorized into three topics: performance of different NVESs: FIR versus NIR, visual distraction and mental workload.
In principle, both the FIR and NIR systems offer a longer visibility distance to the front scene compared to low/high beams, and pedestrian detection distance was enhanced as well (Tsimhoni et al., 2004). However, neither of the two sensors (NIR or FIR) is conclusively better and both sensors have some advantages as well as drawbacks. For example, if enhancing pedestrian detection is more desirable for all drivers, an FIR system with part-time presentation, warning, and icons on a separate HUD display seems to be preferred. If enhancing the road and road signs are more desirable for older drivers, an NIR system with full time presentation and full sensor image on a contact analogue display may be the best option (Rumar, 2002).

Tsimhoni (2004) compared detection distances for pedestrians in both systems using matched stimuli and found that detection distances by FIR were overwhelmingly greater than by NIR.

Table 2.2 shows some related image and cost comparisons between the technologies of the two sensors.

**Table 2.2 Comparison between NIR and FIR systems**

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIR</td>
<td></td>
</tr>
<tr>
<td>1. A greater effectiveness in pedestrian detection because the heat radiation from pedestrians is more obviously in far infrared source. (Tsimhoni et al., 2004; Lim et al., 2010);</td>
<td>1. Pictures on display may change unpredictably (Parkes et al., 1995);</td>
</tr>
<tr>
<td>2. No illumination required and no glare effects in image;</td>
<td>2. Problems in interpreting pictures (Brickner, 1989);</td>
</tr>
<tr>
<td>3. A longer detection range approximately to 304m (1000ft) (twice as NIR);</td>
<td>3. Difficulties in matching the picture to the real world (Rumar, 2002);</td>
</tr>
<tr>
<td></td>
<td>4. Cooler objects like road surface, snow and etc., could not be detected by the sensor and displayed on the screen;</td>
</tr>
<tr>
<td></td>
<td>5. Monochrome thermal image looks</td>
</tr>
</tbody>
</table>
4. More stable performance under adverse weather conditions;
6. Roadway signs and other bright objects are dim;
7. Costly (Schweiger et al., 2010)

| NIR | 1. A more realistic image with a higher resolution; |
|     | 2. Easier to interpret; |
|     | 3. Monochrome image has normal contrast pattern; |
|     | 4. Road signs visible in image |
|     | 5. A lower system price; |
|     | 6. A smaller sensor that can be mounted to rearview mirror; |
|     | 7. A better performance in warmer conditions. |

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 both the drivers’ visual and mental distraction. (Rumar, 2002)

Measurements of vehicle’s speed, lane keeping, NASA-T LX questionnaires, eye movements, etc. are used to study drivers’ distraction and mental workload associated with NVESs (eg., Barham et al., 2001; Hollnagel et al., 2001; Nilsson et al., 1996; Stanton et al., 2000; Ward et al., 1994, ; Rumar et al., 2002, Mahlke et al., 2007; Bi et al., 2009; Kim et al. 2010). Results from NASA-T LX revealed that although it is the conception of the drivers that the dual scanning task would result in increased workload, they actually did not find much difference in workload between driving the roadway that with and without NVESs. Other studies argued that vehicle’s speed should also be included in examining drivers’ workload as a higher speed suggests a lower workload.
and might eliminate most of the potential safety effect by NVESs.

Kim et al. (2010), evaluated drivers’ glance behaviors in detecting pedestrians while using NIR and FIR NVESs. They conducted experiments in a driving simulator with a real vehicle. Recorded movie clips of the night-vision enhancement system were showed at the center console of the vehicle, synchronized movie clips of the front view of the vehicle was also projected on the simulator’s screen in front of the participant sitting in the vehicle. An eye tracker was used to record the real-time eye movement. Results showed that the search time and mean number of glances varied with the types of sensors used (FIR system has less glances in detection), but no conclusive remarks can be made on the effects on both visual and mental distraction.

2.4.2.2 Second Generation of NVESs

From a heuristic evaluation (Diana et al., 2006, 2007), experts suggest a possible method of reducing distraction by presenting only the relevant information (pedestrian, cyclists, animal and etc.) on the display. Inspired by this method and supported along with the innovative technical support, intelligent APW technology have been developed and integrated into NVESs to categorize the image contents and inform the driver in a different way than by showing an analogue video image. The system can generate an optical or acoustical signal to alarm drivers to an identified object at an early stage. It is much likely that drivers’ distraction can be greatly reduced and obstacle (pedestrian) detection can be further enhanced in this way (Tsimhon et al., 2004).
A great number of studies were concentrated on evaluating the newly improved NVESs that combined with APDWs (e.g., Tsimhoni et al., 2005; Kallhammer, 2009; Tsimhoni et al., 2007; Mahlike et al., 2007; Bertozzi et al., 2004; Rumar, 2002, Lim et al., 2010). Warnings are presented in format of visual, acoustic, tactile or their combinations in their research. The conclusion from these studies as well as studies by other researchers was that APWs should help both NIR and FIR NVESs to be further effective in increasing object detection distance, but the effect on reducing drivers’ workload and distraction were inconclusive for the new NVESs, and different methods of warnings would result in different drivers’ performance. It is suggested that further substantial advancement in information presentation and selection is essential to reduce drivers’ workload and support information processing.

Diana et al. (2006, 2007) conducted an evaluation study on six NVESs, which differed in type and position of the displays used to present either analogue far or near infrared sensor information. A heuristic evaluation by experts and an experimental field study with experienced drivers were performed separately. Results indicated that all relevant requirements are met by NVESs that are positioned at an unobtrusive location and are equipped with functions for the automatic identification of objects and for event-based warnings. The earlier a warning can be generated by the system, the sooner drivers can react, and the longer distance can be gained from a hazardous object on the road.

The Transportation Research Institute (UMTRI) at University of Michigan extended its 2004 research and conducted a series of studies on the performance of APWs for NVESs (Tsimhoni, Flannagan & Minoda, 2005 and 2007).
Tsimhon et al. (2005) compared the detection performance with a highlighted square on detected pedestrians at two different distances -- 75m and 150m, to the ones without highlighted warnings. Drivers’ workload was also evaluated in the form of glance duration and frequency. Results showed that longer warning distance at 150 m increased the mean detection distance of pedestrians, but warning at 75m had the potentials to decrease the detection distance. However, drivers’ workload was not significantly reduced, as subjects continued to sample the display frequently (about every 3.0 s). They suggested that a stronger warning would have reduced the need to sample the display frequently, thus reducing workload. Kallhammer (2009) also argued that the addition of APDWs did not decrease the workload significantly.

Later in 2007, Tsimhon et al. (2007) presented a simple pedestrian icon (a stronger warning) as a replacement of highlighted square to be used in a night vision system, and to partially test its effectiveness. The display consists of a pedestrian icon that shows up when there are pedestrians near the future path of the vehicle in less than 150m. Though the results showed improvements in both pedestrian detection and detection accuracy, it did decrease subjective workload.

Brown et al. (2010) presented a study that was conducted on a driving simulator setup to test the effectiveness of different combinations of three warning modes (visual, auditory and tactile). Results indicated that the inclusion of a visual warning cue appears to have a negative impact on old drivers’ performance. For old drivers aged between 65 and 74, single modal warning conditions of auditory only and tactile only are more effective than the dual-modal conditions of auditory-visual and tactile-visual.
Systems with APWs can highlight pedestrians, thus conveying their importance to the drivers. They are expected to be effective for rare events because they draw the drivers’ attention whenever there is a pedestrian ahead. Once a pedestrian has been detected, there is almost no need for the driver to look again at the display because the pedestrian is already highlighted. Interruption during the event is therefore expected to be minimal. There is still a potential for negative impact because the display is regularly on and drivers may tend to look at it more often than necessary to avoid pedestrians, animals, and cyclists. Possible problems with automation may arise if the driver becomes overly reliant on the system’s ability to detect pedestrians.

### 2.4.3 Weather Impacts on NVESs’ Performance

Another major issue that needs to be considered but is always ignored and restricted due to their complexity and experimental cost is NVES’s performance and stability under different weather conditions. Night traffic is often carried out in conditions other than clear atmosphere and full darkness. Therefore, how the NVES functions in adverse weather conditions such as fog, rain, and snow will need to be examined.

Of those adverse weather conditions, fog is a weather condition that is not as common as other weather conditions. To draw a comparison, rain occurs in the United States 29 percent of the time during a year on average, while fog occurs only 6 percent of the time; however, fatality rate in fog weather is higher, indicating that more problems are encountered during this weather condition. Snow condition was not evaluated in this study because snow will cover the lens of the IR camera.
Supported by Federal Highway Administration, Virginia Tech Transportation Institute in 2005 conducted an empirical test on visual performance of six visual aid systems on the Virginia Smart Road testing facility (closed track) during adverse weather conditions (i.e., rain, snow, and fog) in the daytime. The study in foggy weather evaluated drivers’ ability to detect and recognize pedestrians while using the different NVESs, including an IR system and other advanced high beam systems. Each participant was also asked to complete a subjective performance rating following his/her experience of each NVES. Results showed that though in fog weather the detection distance of IR NVES was largely reduced compared to clear weather, it still had the longest detection distance and the best system satisfactory among all the systems.

However, it is unclear whether drivers will be in favor of using NVESs in fog weather at night, as the mental and visual demands should be further enhanced, though NVES has a longer visibility distance. Also, it is unknown which system, FIR or NIR, would be practically better than the other one, though FIR NVES is said to be superior to NIR system (Rumar, 2002) because APWs may compensate for the loss of stability under adverse weather conditions for NIR systems.

2.5 Driving Simulator for Experimental Study

Driving simulation has been offered as a method of evaluating the functional design, ergonomics, cognitive demands and safety of in-vehicle information system interfaces. Simulation is appealing since it provides a safe environment for conducting such testing.
The National Advanced Driving Simulator (NADS) in East Liberty, Ohio, is the most technically sophisticated driving research simulator in the world. It provides a unique research tool to safely conduct fundamental and highly focused research into wide ranging driver-vehicle-environment issues including those associated with drivers’ distraction. Previous research has made significant progress in understanding some of the fundamental issues associated with drivers’ distraction. However, the inability to carry out research under realistic and highly demanding conditions, has limited progress in this area. The NADS facility will offer a unique capability to study this issue in a setting that does not compromise drivers’ safety, but allows drivers to experience a wide range of demands associated with driving conditions (e.g., traffic, weather), drivers’ states (e.g., fatigue, drugs) and tasks (e.g., cell phone, navigation). It further provides the opportunity to assess the distraction potential associated with various in-vehicle technologies (e.g. user interfaces) under identical driving conditions, which would not be possible using on-road studies.

Driving simulators are used for entertainment as well as in training of drivers’ education courses taught in educational institutions and private businesses. They are also used for research purposes in the area of human factors and medical research, especially under conditions in which it would be illegal and/or unethical to place drivers, to monitor drivers’ behavior, performance, and attention and in the car industry to design and evaluate new vehicles or new advanced driver assistance systems. Studies of drivers’ distraction would be dangerous and unethical (because of the inability to obtain informed consent from other drivers) to do on the roads; therefore driving simulator is used in this research.
The main question on driving simulator is whether it can provide an accurate model of behavior in the real world.

Research from both NHTSA (2010) and other institutions (Wang, 2008) had confirmed that fixed based driving simulation is a safe method of assessing task interaction and performance that provides valid estimates of on-road behavior and distraction for the type of in-vehicle devices.

NHTSA even developed a series of recommended criteria to assess the distraction potential of secondary tasks performed using in-vehicle information systems in production vehicles or portable electronic devices for the simulator study. Some of the recommended criteria would be used in this study.

Tough driving simulator is considered as a suitable method in evaluating in-vehicle devices, especially for the issues on drivers’ distraction, it is not popular used in research relating to NVESs. Tsimhoni (2005) conducted a simulator study by both assembled FIR and NIR NVESs. The scenarios in this study were just recorded video clips. Hollnagel (2003) and Brown (2010) used both simulated scenarios and simulated NVES images in evaluating the target detection performance by NVESs. Results from on-road tests by NVESs were almost of the same trend as ones from simulator study, but simulator study was more flexible and easier to conduct compare to on-road test.
Virtual Environment (VR) Lab in Northeastern University was established in early 90’s with the purpose of building realistic virtual driving environment and conducting drivers’ behavior-related research on it.

We have two PC-based driving systems in the lab: Vehicle Turning Driving Simulator (shown in Figure 2.6) with 180 degree field of view (FOV) and a single computer monitor with a steering wheel & accelerator pedal from Microsoft Force (shown in Figure 2.7). We use VC++, OpenGL and Unity3D to build our scenarios. An advanced ASL eye movement camera (shown in Figure 2.8), which can provide real-time visual feedback and record eye movement data, is also equipped in the VR Lab.

We have successfully developed virtual driving environment of city downtown, rural road, highway and city suburb. Research on evaluating driving skill, drivers’ distraction and drivers’ hazard perceptions were carried out using the built environment and existed devices. A series of achievements has been accomplished and a number of papers have been published in the past decade.

Drivers’ distraction study with in-vehicle devices had been carried out in VR Lab. Eye movement like distraction time percentage, fixation time and scan path were analyzed. And design suggestions in avoiding drivers’ distraction were presented.

The research presented here is partially inherited from the previously achievements. A series of experiments had been conducted for assessing drivers’ driving performance and skills under a number of carefully developed realistic scenarios. Various real-time data,
both (vehicle control data acceleration, brake value, gas value, lane deviation etc.) and physiological measures (heart rate, galvanic skin response) are recorded and analyzed using evaluation criteria. Previously field study includes:

- Experiment 1: evaluate the driving skills of novice and experienced drivers in the lane-change scenarios;
- Experiment 2: evaluate the driving skills of divers in the pedestrian scenarios and assess the performance;
- Experiment 3: evaluate the driving skills of the wounded drivers and assess their capabilities for driving;
Figure 2.6 Advanced vehicle turning driving simulator

Figure 2.7 Microsoft Force
Figure 2.8 ASL eye movement camera

2.6 Summary

This Chapter reviews the backgrounds of nighttime driving and NVES in the areas of: Nighttime driving safety and pedestrian collisions; Visibility at night; Theory and application of NVESs; Research on NVESs: benefits and drawbacks; APWs technology and uses; Driving simulator for an experimental study.
Existing main questions concerning implementation of NVES in terms of performance and distraction can be concluded as following:

1) What kind of information should be presented: detected pedestrian or complete road information?

2) To whom should the information be presented: old/young, novice/experienced?

3) Which technology should be used: FIR, NIR, or APDs?

4) When should the information be displayed: at the point of detection or at the point of danger?

5) How should the information and warning be presented: visual, acoustic, tactile or their combinations?

6) Where should the information be displayed: windshield or extra display?

Though a great deal of research has evaluated the questions on NVESs, they were usually incomplete due to the limitation in hardware, resources, environment, subjects, cost etc.

According to the concentrations and facilities limitation, this study was intended to develop a virtual experiencing and testing platform that can conduct tests based on those existing concerns. We hope the virtual platform can provide drivers with a real experience of NVES, and provide researchers with a more flexible and extensible method in carrying out studies on NVES. Therefore, NVESs can be better analyzed, designed and served for us.

Experimental tests would be conducted on this platform with our own interests in both driving performance and drivers’ distraction, by both NIR and FIR NVESs, as there has
not yet been research that does a comprehensive study on the overall benefits gained from current NVESs. Also, we’d like to examine the effects of weather conditions on NVESs. Drivers’ distraction would be another major issue in this study as none of the previous work has fully explored this main disadvantage from NVES. Moreover, on a virtual platform, hazards of all scenarios and multiple appearance distances can be much easier to accomplish compared to previous research. Therefore we’d like to know NVES’s impact on hazards in terms of hazard scenarios and appearance distance.

In order to evaluate drivers’ distraction and NVES’s overall benefits, we will describe the NVES test design theory in the next Chapter, which will also have requirements for the platform development. The virtual platform design is introduced in Chapter 4. The human subject experiment is detailed in Chapter 5. In Chapter 6 and Chapter 7, experimental data has been analyzed and a final conclusion has been accomplished.
Chapter 3 Related Description of Virtual Platform

3.1 Test Hypotheses

Our experimental tests were carried out on our experimental platform. Test design decided the requirements for platform development and simulation. Measurements of the tests were based on the previously research in this area, and by NHTSA’s recommended method and criteria for driving simulator study.

It was assumed in this study:

1) Experimental results from simulator study are reliable;
2) All NVESs have perfect detection of pedestrian and bicyclist;
3) All potential hazards are assumed to collide with main vehicle if drivers fail to respond as required.

It was hypothesized at the beginning of this study:

1) NVESs will increase detection distance to the potential hazard at which drivers were able to respond, especially by FIR NVES;
2) NVESs will increase hazard detection accuracy, especially by FIR NVES;
3) Adverse weather condition like fog will decrease the NVESs performance in hazard detection and accuracy, especially for NIR NVES;
4) NVESs’ hazard detection performance will vary by hazard scenarios and hazard appearance distance;
5) APWs presented at different times in different formats can reduce drivers’
distraction, and warnings appeared earlier on NVES would lead to a better hazard
detection performance;

6) NVESs will bring some distraction to drivers at a suitable level that would not add
extra problem.

3.2 Simulation Analysis

The idea of the test was to let subjects drive inside an immersive nighttime driving
environment with/without NVESs. Along the route that subjects was to drive, there were
a series of hazards in formats of pedestrians and bicycle riders. The subject’s primary
task and responsibility was to drive safely (avoid collisions) and make sure his/her
vehicle stay in the center of the lane that it is travelling in. For secondary task, subjects
were required to detect these potential hazards as soon as possible in order to avoid
hazard collisions.

Simulations were mainly composed of four factors: 1) driving environment, 2) potential
hazard (driving scenario), 3) NVESs and APWs, 4) main vehicle (driver’s vehicle).

Most previously researches required drivers to verbally report the hazard, which was not
a regular habit when driving. Drivers’ direct reaction to a hazard while driving is to steer
away, to slow down the speed, or to alarm the pedestrian. Therefore subjects were
instructed to press on the brake pedal when they detected a hazard as an action of
deceleration, tough the vehicle’s speed would not actually slow down.
3.2.1 Nighttime Driving Environment Design

At night, the majority of pedestrian and bicycle collisions occurred at downtown or rural road with low light conditions. Driving on highway takes a higher possibility of colliding with vehicles, road debris and other stationary constructions rather than pedestrian. As this research was more focused on vehicle’s collision with pedestrian and bicycle, driving environment simulated both downtown and rural road, which was connected by a 90-degree curve road.

The downtown environment was prototyped on the area around Prudential Center in Boston. Figure 3.1 shows the real vertical view of the selected downtown area. Figure 3.2 shows an intersection view on Boylston Street at night.

![Figure 3.1 Boylston street vertical view](image-url)
Besides roads and intersections, all other environmental elements, like moving vehicles, buildings, shops, road lamps, road barriers, vehicles, trees, bus stations, fire trucks and etc., were included in the scene. Both curve and straight roads were simulated without considerations of the road elevations.

In the rural environment, the road type was unlit two-lane asphalt with a gravel shoulder, and with sparse residence houses, schools, fire station and farms along the road. In the city downtown environment, the road type was mostly four-lane asphalt with a raised curb and was lighted by the road lamps and building’s light, where the outer lane was a parking lane. There was a high concentration of traffic, apartment buildings, and commercial structures along the road. The road was constructed with gentle turns and periodic intersections. The primary route of travel was along the “main” road, with no turns necessary.
Weather condition is another main factor that typically increases crash risk. Driving in adverse weather like rain or foggy has a higher rate of severe pedestrian collisions, as drivers’ visibility will be further impaired by the weather. Drivers’ visibility at night for pedestrian is 45 – 76 m (150 – 250 feet) with low beam in clear weather, and will decrease to a lower level (depending on the density of fog) in foggy weather even if the fog light is on. This study set the visibility in clear weather up to 76 m/250 feet by subjects’ eyes, in fog up to 60 m/200 feet. Details on the environment simulation will be expanded in Chapter 4.

3.2.2 Hazard Design

Once the environment was configured, hazards were implemented. With simulation, we can create any hazard as designed.

The most common types of pedestrian crashes are pedestrians crossing a roadway not in a crosswalk (53%) and pedestrians that has exited a vehicle prior to the event (13%), followed by pedestrians who are crossing at intersections (10%). Pedestrian behavior is the first contributing cause of over 80% of the pedestrian crashes.

Any pedestrian or bicyclist that appeared in the scene was defined as potential hazard in this study as they all had the possibility to collide with the main vehicle. Subjects were required to detect the hazards with a proper response as quickly as they can.
National report reveals that most pedestrian crash fatalities are occurred at non-intersections or on urban roadways. And they summarize that most collisions with pedestrians and bicycles are happened on road facilities of: 1) roadway; 2) bike route; 3) marked and unmarked crosswalk; 4) sidewalk; 5) shoulder; 6) walkway.

Based on the report, pedestrian hazard actions can be classified into the following types: 1) cross at intersection with or without signal, use or not use crosswalk; 2) not in roadway; 3) stand in roadway; 4) fall into path of vehicle; 5) walk from parked vehicle; 6) cross mid-block no/in crosswalk; 7) walk in road with traffic.

Bicyclist hazard actions can be concluded into several types as well: 1) ride with traffic; 2) cross or enter traffic; 3) turn into vehicle path traveling in same direction; 4) turn into vehicle path traveling in opposite direction; 5) cross diagonally; 6) fall into path of vehicle.

A total of 20 hazard events were developed according to the most frequent crash actions and locations, and the prototypes of the hazards were extracted from the recorded driving videos. Each hazard had an initial scenario and would involve some actions like running, walking, standing, jogging and riding bicycle. In total, 10 running, walking, jogging pedestrians were defined as moving hazards in this study, 5 people riding bicycles for cycling hazards, and 5 standing pedestrian as standing hazards. Table 3.1 concluded the hazard prototypes by scenario and location.
Table 3.1 Hazards by Scenarios and Locations

<table>
<thead>
<tr>
<th>Hazard Type</th>
<th>Initial Locations</th>
<th>Scenario and action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Right side of the road, Left side of the road, Center road, intersections</td>
<td>Walking across street, walking along the roadside toward/backward main vehicle</td>
</tr>
<tr>
<td>2</td>
<td>Right side of the road, Left side of the road, Center road</td>
<td>Running across street, running along roadside</td>
</tr>
<tr>
<td>3</td>
<td>Right side of the road, Left side of the road, Center road, intersections</td>
<td>Standing still</td>
</tr>
<tr>
<td>4</td>
<td>Right side of the road, Left side of the road, Center road, intersections</td>
<td>Cycling across street, cycling along roadside</td>
</tr>
</tbody>
</table>

Hazards were placed along the driving route at different locations with three levels of appearance distance in environment: less than 100 m (328 feet) at an average of 75 m (246 feet), 100 – 200 m (328 – 656 feet) at an average of 150 m (492 feet), and longer than 200m at an average of 250m. Ten were located in the downtown environment, and ten were located in the rural road environment. Simulations of hazards will be described in Chapter 4.
Only drivers’ detection ability of hazards was analyzed in this study, so we assumed all hazards (people) acting mechanized movement without any response, which meant that the pedestrian or bicyclist had no subconscious behaviors such as to avoid oncoming vehicles, response to the driver and etc. It was anticipated that NVESs could improve the drivers’ performance in detecting and avoiding hazard collisions.

3.2.3 Main Vehicle Design

Main vehicle is the vehicle that the subject drove. In a simulator study, the simulated vehicle in the driving environment reflects the dynamic system of the main vehicle, and driver’s cabin in driving simulator provides the mechanical model of the main vehicle. This paragraph will describe mechanical model of the main vehicle.

The driver’s cabin inside simulator, equipped with active feel on steering, brake, accelerator pedal, was the mechanical model of the main vehicle in this study. The visual system featured one front visual channel with a field of view of 60 degrees. A 65-inch display was used for the rear channel.

Most previously research required drivers to fully control the vehicle, however, speed is the unstable and unpredictable parameters while driving. Any change in the vehicle’s speed by drivers can affect the collision results even if drivers detected the hazards. Thus the result of NVESs’ effectiveness should be analyzed in a model composed of all the attributes. A simple analysis on hazard detection distance and time would not be enough to draw or support any conclusions.
In this study, subjects drove at a constant speed of 25mph. 25 mph is considered as a regular speed driving in city or rural road at night. A fixed speed eliminated any other factors that would add the uncertainty and unforeseen to the result. Results and analysis on hazard detection distance are more persuasive and precisely as the speed can be predicated. Once the driver started driving, vehicle automatically speeded up to 35 mph, and remained at this speed till end of the experimental trial. Tough the speed was fixed, and brake and gas pedal did not have any effect on vehicle’s speed, drivers were required to press the brake pedal once a hazard was detected. The distance between the vehicle and hazard at this time was recorded as the detection distance for this hazard. Drivers were also requested to rotate the steering wheel to make sure the vehicle stays in the center of his lanes, and to avoid any not-a-hazard event in the scene.

3.2.4 Night Vision Enhancement System Design

As stated in the previously paragraphs, instead of assembling a physical Night Vision Enhancement System as other researches did, this study chose to simulate the far and near infrared image and automatic pedestrian warnings on a monitor, based on the prototypes of the most advanced NVESs on market. Compared using a real NVES, simulation is a more economical and flexible way to carry out this research.

The infrared image can be approached by the implementations of 3D graphic software. Details on image simulation will be expanded in the next Chapter.
Appropriate information on NVESs is needed for infrared images’ prototyping and simulation. High-end vehicle brand, like Mercedes-Benz, BMW, Audi, Honda, Volvo and etc., all equipped their vehicles with advanced NVESs nowadays, which represent the most on-edge technique of NIR and FIR NVESs, and automatic Pedestrian Detection systems. For this study, the simulations of infrared images and warnings were mostly prototyped from the specifications of NVESs available on Mercedes-Benz, BMW and Audi. They use far, near sensor and image recognition technology for producing video image on an in-vehicle display. Information would be collected from the recorded videos of infrared images for the real systems. Some modifications would be added to finalize the prototypes.

Figure 3.3 shows BMW’s night vision assist system’s display, which locates at the center of vehicle’s dashboard. This system processes far-infrared radiations, which allows for a range of 300 m or nearly 1,000 feet, and avoids "dazzle" from headlights, road lights and similar intense light sources.
Figure 3.3 BMW's NVES

Figure 3.4 shows the in-vehicle picture of Mercedes-Benz’s night vision assist system’s display. Infrared image captured by camera is represented on a head-down display (), which takes the place of conventional instrument panel behind the steering wheel, just in front of the driver. This system processes near-infrared radiations ranged of 150-200 meters or 500-650 feet.
Figure 3.4 Mercedes-Benz ‘s NVES

Figure 3.5 and Figure 3.6 shows APWs on Audi’s NVES’s display when a pedestrian is approaching. Once detected, the pedestrian is highlighted in yellow as a warning (Figure 3.5). If the detected pedestrian moves into your path, they are highlighted in red with a warning sound (Figure 3.6), signifying a possible critical situation.
Figure 3.5 Detected pedestrian highlighted in yellow box

Figure 3.6 Detected pedestrian highlighted in red box
Above pictures indicate display’s settings, like size (length*width), position on dashboard (center or left), position to a driver’s head (head down or head up) and etc. varies from system to system. However, instead of focusing on examining human factors on system’s design like display’s size, position and so on, this study are more concentrating on the result from image effect and all these factors that could influence the result should be eliminate. So all NVESs display are simulated in the same size and placed on the same position for drivers.

Position: A head-up display takes possibility of blocking drivers’ visual field or any instrumental panels, so a head-down display positioned on the center of dashboard, which is on the right bottom of drivers’ front view accordingly, should be a more considerable choice and it’s also more popular among in-vehicle displays compared to other positions. Figure 2 shows the location of the simulated NVES display inside the simulator.

Automatic Pedestrian Warnings Design:

A detection method was developed and applied to the simulated systems based on it.

1) Once the hazard appeared on the display (304 m (1000 feet) away for FIR system for all weather conditions, 182 m (600 feet) away for NIR system in clear weather, 122 m (400 feet) away for NIR system in foggy weather), it was highlighted in a yellow square;

2) If the driver does not detect the hazard, yellow square will turn into a red one with a beep sound when the distance between the vehicle and hazard approaching to less than the stopping distance at the current speed. Even if the pedestrian is walking out of your path at this time, you cannot predict whether he/she will walk back to your path at any time. Instead of judging the pedestrian’s direction as a
evidence to decide whether it should be further warned, this study calculate the distance between the hazard and the main vehicle to make the warning decisions.

3.3 Measurement Design

This test used a mixed between/within-subject design. NVES’s sensor type (FIR and NIR) was between subject variable, and weather conditions and hazards as a within-subject variable. Measurement is designed based on the factors.

Various data would be recorded throughout the experimental trials. Performance data like vehicle’s position, steering wheel angles, hazard detection distance and etc., was automatically recorded in the program. A Canon camera (Figure 3.7) was used to record subjects’ visual behaviors by capturing their looking directions and durations. Figure 3.8 indicated the camera’s position in the test. Subjects’ subjective ratings and comments on both NVES and visual platform were collected in formats of questionnaires and reports.

Figure 3.7 Platform interactions
Measurements of hazard detection distance and hazard detection accuracy would be analyzed to evaluate NVES’s detection performance. Hazard detection distance was defined as the Euclidean distance to the relevant pedestrian hazard at brake response. The onset of brake response was defined as the point at which the brakes were pressed after the appearance of the current hazard. Hazard detection accuracy was calculated as the ratio of the number of valid detection and the total number of hazards. Detection was validated by detection distance and appearance of hazard.

Measurements of drivers’ distraction would include subjects’ visual behaviors and other relating variables. Analysis on drivers’ distraction would base on the recommended criteria of Dynamic Following and Detection Protocol with Benchmark (DED-BM) for drivers’ distraction study in a driving simulator. Duration of individual eye glances away from forward road view, sum of individual eye glance duration away from forward road view, standard deviation of lane position, percent of visual targets detected, visual
detection response time and etc. will be calculated from the recorded visual behavior video. The Acceptance Criteria was:

1) 85% of individual glance duration less than 2.0 seconds;

2) Mean of individual glance durations less than 2.0s;

3) Sum of individual eye glance durations less than or equal to 12.0 seconds;

4) Lane deviation less than 3.7m.

Measurements of subjective reports were also conducted in formats of system rating, NASA-TLX questionnaires and system comments, which were served as extra data for drivers’ distraction study.

### 3.4 Summary

This Chapter first introduces the hypotheses of the NVES test. Then theoretical and technically describes the simulation planning in terms of: 1) driving environment, 2) hazard (driving scenario), 3) NVESs and APWs, 4) main vehicle and 5) measurements. Subjects drove a simulated main vehicle in both downtown and rural environment in either fog or clear weather in dark. One third of the subjects did not have NVESs. The rest of the subjects were using NVESs while driving. Besides task of safe driving, they also need to detect the 20 hazards in the scenario as soon as possible and perform the detection action of pressing brake pedal. Measurements of drivers’ performance and visual behaviors would be recorded. Platform design and simulation will be expanded in the next Chapter based on the idea of test desig
Chapter 4 Virtual Platform Design

4.1 Overview

This virtual platform is primarily designed to simulate the different effects of multiple NVESs in an immersive nighttime driving environment with a maximum degree of fidelity and realism. Thus subjects can have a realistic nighttime driving experience by NVESs and further help us to evaluate the distraction by NVESs. Figure 4.1 displays the interactions among the virtual platform, driving simulator and the user.

Having realized additional research associated with the NVESs will be needed in the future (Rumar, 2002), our virtual platform doesn’t limit to the current research purpose – simulate realistic NVESs, evaluate hazard detection performance drivers’ distraction upon the simulated NVESs, but also can extend to the future studies. The characteristics of this virtual platform are its opening nature, low system cost, adaptive quality, expansiveness and supporting rapid prototype.

Figure 4.1 Interactions between subjects and platform
This virtual platform is mainly composed of two parts: simulations and hardware. Simulations are run on hardware. Hardware includes driving simulator, computers, displays and a router.

Simulations are composed of two systems: virtual environment and NVESs. A local area network was established for a one-way communications and information synchronization between the two systems as they were run on separate computers. Computer for virtual environment sends main vehicle information out, and was set as the host. Computer for NVESs receives main vehicle information, and was set as the client.

The remaining paragraphs in this Chapter are specified in the following aspects: simulation tools; simulation of virtual environment; simulation of NVESs and hardware settings.

Figure 4.2 Virtual platform compositions
4.2 Development Tools

The development of computer graphics has been driven in part by the pursuit of photorealistic rendering. Advanced 3d environment and 3d modeling development tools have become the primarily choices in building virtual environment in recent decades. We use Unity for simulations, and Cheetach3D and Google Sketchup for 3d modeling.

4.2.1 Unity

Unity (www.unity.com), an integrated game engine for creating 3D video games and other interactive content like architectural visualizations, is an integrated development environment with hierarchical, visual editing, detailed property inspectors and live scene preview (Figure 4.3). Its advances in rendering, lighting, physics, programming and networking can best match the requirements for developing our platform.
Rendering and lighting systems in Unity come with 100 shaders ranging from the simplest (Diffuse, Glossy, etc.) to the very advanced (Self Illuminated Bumped Specular, etc.). It also has a state-of-the-art deferred rendering pipeline, which means tons of dynamic lighting. Its excellence in both rendering and lighting make our nighttime virtual environment and infrared images look more realistic.
Figure 4.4 A night scenario produced in Unity Pro

Unity provides refined in-editor tools to carve, raise, and lower sweeping and mountainous terrains. Its proficiency in trees, bushes rocks and grass make the development of virtual environment easier. Unity's terrain engine is fully integrated with the Beast lightmapper and therefore we use it to light buildings and road lamps in the environments.

The physics components of wheel collider and rigidbodies enable the main vehicle to act like a real car. The Wheel Collider is a specifically designed collider for grounded vehicles. It has built-in collision detection, wheel physics, and a slip-based tire friction model.
Scripting makes the simulation alive. Unity supports three scripting languages: JavaScript, C#, and a dialect of Python named Boo. All three are equally fast and can interoperate. We choose JavaScript as the scripting language.

Networking is also required in our virtual environment as we communicate between the host computer and the client computer. Built-in State Synchronization in Unity is a good choice. With the State Synchronization, game object position, velocity, animation, and anything else can be synchronized between players using a delta compression algorithm or uncompressed unreliable strategies.

With the purpose of producing a more accurate representation of the external nighttime driving environment in which the main vehicle and its human operator are immersed, NVESs and nighttime virtual driving environment are simulated in Unity3D.
4.2.2 Cheetah3D and Google Sketchup

Cheetah3D and Google Sketchup are powerful and easy 3D modeling, rendering and animation applications runs Mac OS X. 3D models were partly from online resources and were modified in Cheetach3D or Google Sketchup. The rest of 3D models were made by Virtual Environments Laboratory at Northeastern University.

4.3 Simulation of Virtual Environments

As stated in Chapter 3, virtual environments are composed of a downtown environment and a rural road environment. We have several steps in building a virtual environment: 1) construct road; 2) add environmental elements; 3) place hazards; 4) place main vehicle; 5) script the environments.

4.3.1 Road Construction

Figure 4.6 displays the vertical road views of real downtown environment and simulated downtown environment. The area in red circle is the main downtown environment with several intersections. Yellow circle indicated the start point for the main vehicle in virtual environment. The main road that drivers drove in is a four-lane lighted road. Figure 4.7 shows a textured intersection in downtown environment.

The rural road is two-lane unlit road and is connected to the downtown environment by a 90° curve road. Area circled in green in Figure 4.8 is the rural road. Figure 4.9 shows the textured rural road. Yellow square is actually a school bus.
Figures in 4.3.1 are captured under high ambient light for clearer views. In experimental drives, ambient light is set to a low value to achieve the effects of nighttime driving.

Figure 4.6 Vertical views of downtown environment
Figure 4.7 Intersection in downtown

Figure 4.8 Perspective of virtual environment
Figure 4.9 A school bus is driving on rural road

4.3.2 Environmental Elements Additions

Environmental elements are extracted from the environment surroundings in the recorded videos. Table 4.1 lists out all the environmental elements in the virtual environment.
Table 4.1 Environmental elements in virtual scenarios

<table>
<thead>
<tr>
<th>Environmental elements</th>
<th>Downtown</th>
<th>Rural Road</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trees,</td>
<td>Trees,</td>
</tr>
<tr>
<td></td>
<td>Buildings and shops,</td>
<td>School,</td>
</tr>
<tr>
<td></td>
<td>Traffic signs,</td>
<td>Fire station,</td>
</tr>
<tr>
<td></td>
<td>Traffic lights,</td>
<td>School bus,</td>
</tr>
<tr>
<td></td>
<td>Vehicles,</td>
<td>Fire truck,</td>
</tr>
<tr>
<td></td>
<td>Bus stop,</td>
<td>Road signs.</td>
</tr>
<tr>
<td></td>
<td>Road barriers,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Road lamps,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fire truck,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parking lot.</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.10 displays a comparison of real scene and simulated scene in downtown environment. In the scene, we can see road lamps, intersection, buildings, bus station and etc. As displayed in the real scene, nighttime downtown environment usually has a good lighting system, however, lighting is a very costly rendering in simulation. The program will run slow if two many lights are added. Without a sacrifice in realism, we use the light baking technique to bake the light into textures. Figure 4.11 displays a baked texture of a building. This texture is applied to the lighted building in Figure 4.10.

Other environmental elements that require consideration are night effect and weather conditions. Render settings in Unity have both lighting and fog properties. A nighttime skybox material with stars and moon is applied to render a nighttime sky effect. Figure
4.12 displays the properties in rendering settings for night and fog effects. However, built-in fog effect is only applied to the scene in depth, so a textured sphere shadered in transparent/vertexlit is placed around the main camera to receive a look-like-fog views. Figure 4.13 shows the finalized foggy scene from the vehicle.
Figure 4.10 Comparison of real scene and simulated scene
Figure 4.11 Light-baked texture of a building
Figure 4.12 Rendering settings properties for fog and night effects

Figure 4.13 Foggy view from main vehicle
4.3.3 Hazard Placement

20 Hazards are simulated and placed into the virtual environment. 3d models of hazards are downloaded from internet and are modified in Cheetah3d.

Hazards are placed along the driving route at different locations with three distance ranges: less than 100 m (328 feet) at an average of 75 m (246 feet), 100 – 200 m (328 – 656 feet) at an average of 150 m (492 feet), and longer than 200 m (656 feet) at an average of 250 m (820 feet). Ten hazards are placed in the downtown environment, and the others are placed in the rural road environment.

Based on the designs of hazards in Chapter 3, we have created 20 hazards with different actions at different positions. Some hazards are created by the same model with different actions at different positions. Table 4.2 lists out the properties of the hazards. Figure 4.14 – Figure 4.18 shows several typical hazards with different actions.

<table>
<thead>
<tr>
<th>Hazard NO.</th>
<th>Initial Position</th>
<th>Initial Scenario</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Road shoulder</td>
<td>Woman standing behind a parked vehicle on right</td>
<td>Walking across the roadway</td>
</tr>
<tr>
<td>2</td>
<td>Road shoulder</td>
<td>Woman standing on the right of the road with her child</td>
<td>Standing still on road shoulder</td>
</tr>
<tr>
<td>3</td>
<td>Marked Crosswalk</td>
<td>Woman standing on the left of the road under traffic light</td>
<td>Walking across the road</td>
</tr>
<tr>
<td>4</td>
<td>Bicycle Lane</td>
<td>Man riding bicycle</td>
<td>Cycling on the right of the road</td>
</tr>
<tr>
<td>5</td>
<td>Road shoulder</td>
<td>Man riding bicycle</td>
<td>Cycling across the road</td>
</tr>
<tr>
<td>6</td>
<td>Marked Crosswalk</td>
<td>Man standing on the pedestrian lines on the left of the road</td>
<td>Walking across the road</td>
</tr>
<tr>
<td>7</td>
<td>Road shoulder</td>
<td>Woman standing behind</td>
<td>Walking across the road</td>
</tr>
<tr>
<td></td>
<td>Location</td>
<td>Action Description</td>
<td>Activity Type</td>
</tr>
<tr>
<td>---</td>
<td>-----------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>8</td>
<td>Center of the road</td>
<td>Man standing on the right of the road</td>
<td>Walking across the road</td>
</tr>
<tr>
<td>9</td>
<td>Road shoulder</td>
<td>Man riding bicycle on the left of the road</td>
<td>Cycling across the road</td>
</tr>
<tr>
<td>10</td>
<td>Road shoulder</td>
<td>Woman standing on the right of the road</td>
<td>Standing still</td>
</tr>
<tr>
<td>11</td>
<td>Parking lot</td>
<td>Man standing on the left of the road (parking lot)</td>
<td>Running across the road</td>
</tr>
<tr>
<td>12</td>
<td>Road shoulder</td>
<td>Woman standing on the right of the road</td>
<td>Walking on the roadside</td>
</tr>
<tr>
<td>13</td>
<td>Center of the road</td>
<td>Child standing on the center of the road</td>
<td>Standing Still</td>
</tr>
<tr>
<td>14</td>
<td>Road shoulder</td>
<td>Man riding bicycle on the left of the road</td>
<td>Cycling across the road</td>
</tr>
<tr>
<td>15</td>
<td>Road shoulder</td>
<td>Woman standing on the left of the road</td>
<td>Walking across the road</td>
</tr>
<tr>
<td>16</td>
<td>Road shoulder</td>
<td>Man riding bicycle on the right of the road</td>
<td>Cycling on the roadside</td>
</tr>
<tr>
<td>17</td>
<td>Road shoulder</td>
<td>Woman standing on the right of the road</td>
<td>Standing Still</td>
</tr>
<tr>
<td>18</td>
<td>Road shoulder</td>
<td>Woman standing in front of the school bus on the left of the road</td>
<td>Walking across the road</td>
</tr>
<tr>
<td>19</td>
<td>Road shoulder</td>
<td>Man standing on the right of off-road</td>
<td>Running across the road</td>
</tr>
<tr>
<td>20</td>
<td>Road shoulder</td>
<td>Child standing on the right of the road</td>
<td>Standing still</td>
</tr>
</tbody>
</table>
Figure 4.14 Hazard of pedestrian walking across the street from right side

Figure 4.15 Hazard of pedestrian walking across the street from left side
Figure 4.16 Hazard of bicycle rider cycling across the street

Figure 4.17 Hazard of pedestrian running across the street
4.3.4 Main Vehicle Placement and Settings

Main vehicle in the virtual environment is actually a 3d model of an Audi car. Vehicle’s control panel, except for steering wheel, is removed. To simulate the front scene captured by subject’s eyes, main camera is attached to the vehicle with a field of view up to 30°. Figure 4.19 shows the camera’s setting in Unity. Four wheel-colliders are separately attached to the four tires of the vehicle to simulate the traction model of real vehicle tires. Figure 4.20 shows the wheel collider’s setting in Unity.

Vehicle’s mechanical outputs like brake value, steering wheel angles and gas pedal value are read from joystick. A joystick is an input device consisting of a stick that pivots on a
base and reports its angle or direction to the device it is controlling. Figure 4.21 shows an input axes for brake pedal.

One of the main concerns on the vehicle is how to accurately simulate the low beam effects. Unity provides four types of built-in lights. Built-in spotlights shine from a point in a direction and only illuminate objects within a cone - like the headlights of a car. We use two spotlights to animate the low beam in this study. Visibility by low beam is up to 76m. Figure 4.22 shows the vehicle’s low beam effects in a vertical view. The small image shows on right bottom of Figure 4.22 displays the low beam effects in vehicle’s view. Vehicle’s functions and output are controlled via scripts.
Figure 4.19 Main camera’s setting

Figure 4.20 Wheel collider’s setting
Figure 2.21 Joystick setup for brake pedal

Figure 4.22 Vehicle’s low beam light

4.3.5 Virtual Environment Scripting
Upon the completion of previous steps, a static virtual environment is well built. The remaining question is - how to make this virtual environment alive and work for our research purpose. Scripting is the best answer.

Different scripts are used to achieve the required functions of environmental elements control, hazard control, hazard detection, vehicle control, data recording and host setup.

Environmental elements control: most environmental elements are set to be static in this study, however, dynamic objects like traffic lights and any other moving vehicles are controllable. Scripts are used to calculate the distance between dynamic objects and the main vehicle. Critical values are conditional selected on objects’ types. Take the traffic lights for example, if the distance is getting equal to or less than a critical value of 30m, traffic lights turns into green. 150 m (492 feet) are the critical value for moving vehicles.

Hazard control: Hazards are imported with animations and are detected by the subjects. Therefore the main work for scripting is to make these animations controllable by hazards, to receive detection information from subjects and to record detection performance. Whether a hazard appears or not depends on the distance between the hazard and the main vehicle. Scripts calculate this distance and compare it with the appearance distance. Three hazard appearance distances are defined in Chapter 3. If subjects detected a hazard and the distance was getting lower than appearance distance, this hazard was activated with its animation. Besides appearance distance, we also included disappearance distance in this study. If the distance became shorter than the
disappearance distance, the detection of this hazard was recorded as a failure by system. If subjects successfully detected a hazard, information of detection position, detection time, detection distance, hazard name and etc. was automatically recorded by the system.

Hazard detection: Brake pedal value is read from a joystick. The main scripting method of hazard detection is to access the joystick, read the value of brake pedal, judge whether a hazard is detected or not and send the judgment back to both hazard.

Data recording: Vehicle real-time data like its position and lane deviation is calculated and recorded inside the program per frame, hazard detection data like hazard name, detection distance, detection time is recorded and updated when a hazard is detected. All those run-time data is output and recorded into different .txt files and stored in application folders with specific paths.

Host setup: A local area network is established to communicate between virtual environment and NVES’s display, by script. Vehicle running on host computer and vehicle running on client computer should move simultaneous. A component of built-in network view is added to the main vehicle on host computer.

We enable State Synchronization for the given Network View by choosing Reliable Delta Compressed from the State Synchronization drop-down. Then we set the vehicle’s transform data as the observed property that will be synchronized. A script is used to read
the observed value by calling the function of OnSerializeNetworkView(). Figure 4.23 displays the network view settings.

![Network View Settings](image)

**Figure 4.23 Network view settings**

### 4.4 Simulation of NVESs

Another computer runs the simulations of infrared images displayed on NVESs and works as the client in our local area network. The simulation here is actually the same version as virtual environment running on the host computer, like road constructions, environmental elements, hazards and etc., with different textures and settings. Transformations of the NVES’s camera follow the transformations of main vehicle on the host computer by State Synchronization. We will describe the differences in the following paragraphs.

Main vehicle is invisibly existed in the virtual scene for NVESs as all the components are removed except for the camera. Camera’s settings are modified to achieve the views captured by chosen NVESs. Introduced in Chapter 3, the NVESs on BMW and Benz are prototypes for FIR and NIR simulations in this study. Simulated APWs follow the specifications of APWs on Audi. Abundant videos and pictures of those systems can be
found online. Simulations of NVESs take those resources as simulation templates and extract useful information from them. Table 4.3 specifies the properties and image effects of the two NVESs. Figure 4.24 and Figure 4.25 show the comparisons between real systems’ images and simulated images in our platform.

For APWs, once detected, the pedestrian is highlighted in yellow as a warning (Figure 4.26). If the detected pedestrian moves into your path, they are highlighted in red with a warning sound (Figure 4.27), signifying a possible critical situation.

Table 4.3 Simulation properties of NVESs

<table>
<thead>
<tr>
<th>Field of view</th>
<th>FIR NVES (BMW)</th>
<th>NIR NVES (Benz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of view</td>
<td>36°</td>
<td>36°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Visibility</th>
<th>304 m (1000 feet) in both foggy and clear weathers</th>
<th>152 m (500 feet) in clear/ 122 meters (400 feet) in foggy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image effects</td>
<td>• Monochrome thermal image looks glowing;</td>
<td>• Monochrome image has normal contrast pattern;</td>
</tr>
<tr>
<td></td>
<td>• Roadway signs and other bright objects are dim;</td>
<td>• Road signs visible;</td>
</tr>
<tr>
<td></td>
<td>• No glare effects in image;</td>
<td>• Glare/image blooming from oncoming lights;</td>
</tr>
<tr>
<td></td>
<td>• Unchanged image effects in foggy.</td>
<td>• Produces image of any object reflecting IR;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Less visibility in foggy.</td>
</tr>
</tbody>
</table>
Figure 4.24 Comparison of real infrared image on Benz and simulated infrared image on NIR NVES in clear weather
Figure 4.25 Comparison of real infrared image on BMW and simulated infrared image on FIR NVES in clear weather
Figure 4.26 Comparison of real APWs on Audi and simulated APWs effect on FIR NVES in clear weather (yellow)
4.6 Hardware System Configuration

Hardware of this platform includes a fixed-base driving simulator, a Mac Pro (4 GB memory; 2 Quad-Core Intel Xeon; NVIDIA Geforce 8800 GT), a Macbook Pro (4 GB memory; Intel Core 2 Duo; NVIDIA GeForce 320M), a HITACHI projector and a router. The virtual environment runs on the Mac Pro and is projected to the curve screen of driving simulator via HITACHI projector. Infrared images run on Macbook Pro and are displayed on its screen. The router connected the Macbook Pro and Mac Pro via a local area network.
4.7 Summary

Based on the test design and requirement, this Chapter describes the platform simulation from both hardware and software supports. Simulation methods and properties of both NVESs and APWs are discussed in details. Simulation effects are presented in a series of figures. With the establishment of virtual platform, we will carry out the experiment on this virtual platform in the next Chapter.

The system architecture manages and controls the simulations of virtual environment and NVESs. The basic architecture consists of modular software subsystems and databases coordinated by the program that provides inter-subsystem data communicate and real-time scheduling function. This system consisted of six subsystems: NVESs system for multiple simulated NVESs; visual system for built scenarios; vehicle dynamics system for driving operations; object system for simulated detection targets in the scenarios; data recording system for recording driving behavior and eye movement data; audio system for intimated sound in a nighttime driving environment.
Chapter 5 Experiment Methodology

5.1 Experimental Settings

The experimental test was conducted on a virtual platform in an advanced driving simulator at the Virtual Environment Laboratory (Figure 5.1).

Figure 5.1 Advanced driving simulator
The simulator consists of a fully realistic vehicle dynamic system: driver’s cabin, steering wheel, gas and brake pedals. For this study, a simulated nighttime driving environment was ran on a Mac Pro (4 GB memory; 2 Quad-Core Intel Xeon; NVIDIA Geforce 8800 GT), and projected onto a curved screen with a resolution of 1280*960 pixels. The visual system featured one out of three front visual channels with a field of view of 60 degrees. Simulated night vision enhancement systems (NVESs) were run on a Macbook Pro (4 GB memory; Intel Core 2 Duo; NVIDIA GeForce 320M) and displayed on the screen with a resolution of 600*800 pixels. The rest of the screen was set to black color. The size of the display and screen setting were chosen to resemble a six-inch in-vehicle display. The display was positioned to right of the subject’s horizontal line of sight, varying to some extent with the height and posture of the subject.

A Canon camera was used to record the drivers’ visual behavior data. After seated in the driver’s cabin, subjects were asked to look at the front scene and begin training. Meanwhile, camera was on and set to a position suitable to record the drivers’ eyes, but it didn’t start recording at this moment. Once subjects finished training, the camera started to record the subjects’ eye movements.

The red circle in Figure 5.2 indicates the location and direction of the camera. Figure 5.3 and Figure 5.4 shows pictures (videos) captured by the camera. In Figure 5.3, subject was looking at the NVES. In Figure 5.4, subject was looking at the front scene.
Figure 5.2 Camera’s position
Figure 5.3 Eyes looking at NVES

Figure 5.4 Eyes looking at front scene
5.2 Participants Selection

Twenty-five subjects were enrolled in this study. The participant’s session would be terminated if he/she drove out of the traffic lanes more than twice in the training trial. Also, it was decided a priori that participants pressing the brake paddle before the appearance of potential hazards more than twice in either experimental trial would be dropped from the study. As a result, one participant was enrolled but dropped from the study for a total enrollment of 25 to achieve the required sample of 24 participants.

The final sample consisted of twenty-four subjects (mean age = 36 years, range = 25 to 55 years; 12 male, 12 female). All subjects held a valid drivers’ license and are experienced drivers. The average reported driving experience was 15 years. All drivers drove at least 5000 miles per year and at least 1000 miles at night per year. None of the subjects had any record of night collisions. One subject reported to know the concept of NVESs, and 3 subjects reported to know the concept of automatic pedestrian warnings. However, none of them had tried either NVESs or Pedestrian detection systems before.

All of subjects have 20/20 or corrected to about 20/20 vision. Subjects were collected from Northeastern University, including students, staff and professors. Each subject was paid an honorarium of $20 for participation in the whole research.
5.3 Experiment Design

This experiment was a mixed between/within-subjects $3 \times 2$ factorial experiment producing a total of $(a)(b) = (3)(2) = 6$ treatment combinations (Table. 1).

One of the independent variables, factor A, was the type of NVESs, consists of $A = 3$ levels – Base without NVES, Far-infrared (FIR) NVES, and Near-infrared (NIR) NVES (designated a1, a2, and a3); dependent variable - factor B, consisted of $B = 2$ levels – Clear weather and Fog weather (designated b1 and b2).

Table 5.1 Six treatment combinations

<table>
<thead>
<tr>
<th>B levels</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>BASE-Clear</td>
<td>NIR-Clear</td>
<td>FIR-Clear</td>
</tr>
<tr>
<td>B2</td>
<td>BASE-Fog</td>
<td>NIR-Fog</td>
<td>FIR-Fog</td>
</tr>
</tbody>
</table>

To avoid memorization of the simulated scenarios (carryover effect) for the participants, six treatment combinations were divided into three groups (table 2). Each group contained two treatment combinations. The orders of the treatment that the participants drove were balanced across the subjects in each group. S1 and S2 in table 2 presented the experimental trials with different orders in each group. The numbers in the table indicated the orders of treatment combinations in each group.
To reduce the variation of nuisance variables from condition to condition, twenty-four subjects were divided into six experimental trials by the method of block randomization. Table 2 shows the representative for different NVES trial in different groups. The numbers in the table indicate the order of trials for each group.

**Table 5.2 Representative for different NVES trial**

<table>
<thead>
<tr>
<th>Groups</th>
<th>Clear Weather</th>
<th>Fog Weather</th>
<th>Clear NIR NVES</th>
<th>Fog NIR NVES</th>
<th>Clear FIR NVES</th>
<th>Fog FIR NVES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group1 BASE (Night)</td>
<td>S1</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group2 NVES (Night)</td>
<td>S1</td>
<td></td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td></td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group3 NVES at Fog (Night)</td>
<td>S1</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

**5.4 Experimental Procedure**

For each subject, the experiment consisted of a briefing, training phase, test phase and a debriefing.

Upon arrival at the Virtual Environments Laboratory, subjects signed a consent form, filled out a background and pre-test simulator sickness questionnaire (SSQ) form. In briefing, subject was given a short orientation about the goals of this study and the duration of sessions. Also he/she was instructed to drive in the simulator and press the
brake pedal as soon as they detected any pedestrian or cyclist, and to continue driving in the same lane.

Each subject had a 2-minute training trial on a straight road and a curved road to gain familiarization with the driving simulator and to assure his/her ability in driving. Vehicle’s speed was fixed, but subjects were required to control the vehicle via braking pedal and steering wheel, per the instructions.

At the beginning of test trials, subjects were instructed that:

“A driver needs to detect potential hazards in order to avoid collisions. Along the route you are about to drive, there are many pedestrians and bicycle riders that are potential hazards.

Whenever you see a potential hazard, press on your brake pedal as soon as possible.

Your primary responsibility is to drive safely and make sure your vehicle stays in the center of the lane that it is traveling in. If your vehicle leaves the roadway, please try and get back on the roadway as soon as you can.”

Subjects use NVESs would be further informed, “In the display to the right of your steering wheel, the night vision enhancement system (NVES) will be automatically on when you start driving. Looking at the NVES’s display can help you detect the potential hazards. You should look at the NVES display as much as possible to detect hazards as quickly as possible.”

Upon completion of practice, the test phase started. Subject was required to complete two 4-minute experimental trials. Subjects’ eye movements and driving performance data
were recorded. Immediately following completion of test phase, a post-test SSQ form, systems rating form and NASA_TLX questionnaire were administered. In debriefing, subjects were thanked, paid for their participation.

5.5 Variable Definitions

Collected data from the test is analyzed in the next Chapter. A repeated measures analysis of ANOVA and t-test are performed for the following dependent variables. Significance at a 0.01 level of confidence has been done for each parameter.

a. Hazard detection distance – defined as the straight-line distance between the vehicle and the pedestrian when detection was reported.
b. Missed hazard – defined as a hazard failed to be detected by the subject;
c. Lane deviation – defined as the distance between the vehicle and center of the road;
d. Off-road glance frequency and mean duration – calculated as the mean time interval between off-road glances and the mean durations of a glance;
e. Total eyes-off-road time – calculated as the cumulated time of eyes-off-road in a trial;
f. Off-road glance duration in the final 5 seconds before detection – calculated as the cumulated time of looking off-road in the final 5 seconds before a successful hazard detection;
g. Number of off-road glances longer than 2 seconds – defined as the total number of off-road glances longer than 2s in a trial;

h. Subjective evaluation of the mental workload (NASA_TLX), system effectiveness ratings.

5.6 Summary

According to the experiment design, 24 subjects are involved in this experiment. They drive the virtual main vehicle in virtual environment with/without NVESs. Subjects’ data are then collected throughout the experiment and discussed in the next Chapter.
Chapter 6 Experiment Data Analysis

A repeated measure ANOVA and T-test were used in data analysis. A significance level of $p<.01$ was adopted for all data analysis reported in this thesis.

6.1 Hazard Detection Distance

6.1.1 Hazard Detection Distance by Treatment Groups

The analysis results for detection distance at the onset of brake response are shown in Table 6.1. A repeated measures ANOVA of detection distance revealed that there was significant main effect from NVES type, $F(2, 21) = 35.45$ (critical $F = 5.78$), $p < .01$ (Figure 6.1). The distance values in the figure were average among all hazards, and therefore were not representative of particular hazard events. The blue columns in Figure 6.1 show the difference in distance to the hazard at brake response by system types. The mean detection distance by the group that used FIR NVES (146.72 m/481.36 feet) was statistically longer than the group that used NIR NVES (95.65 m/311.68 feet) and the base (no NVES assisted) group (59.64 m/195.67 feet).
Table 6.1 Mean Hazard detection distance (m) by treatment combinations

<table>
<thead>
<tr>
<th>NVESs</th>
<th>BASE</th>
<th>NIR</th>
<th>FIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEATHER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clear</td>
<td>61.23</td>
<td>94.55</td>
<td>132.99</td>
</tr>
<tr>
<td>Fog</td>
<td>58.05</td>
<td>96.74</td>
<td>160.45</td>
</tr>
</tbody>
</table>

Although clear weather detection distance tended to be greater than that of fog weather, the main effect of weather conditions, $F(1, 21) = 1.21$ (critical $F = 8.02$), and the interaction between NVES type and weather conditions, $F(2, 21) = 1.39$ (critical $F = 5.78$), were not statistically significant.

Figure 6.2 displays the hazard detection distance categorized by system types in different weather conditions. Though a paired t-test revealed ($t = -1.31$, $p = 0.231$) that generally
there’s no significant difference between clear and foggy weathers, it is very interesting that subjects assisted by FIR NVES in foggy weather have a statistically visible longer detection distance (160.45 m/526.41 feet to 132.99 m/436.32 feet, p < .01) than the ones assisted by the same system in clear weather. Meanwhile, the differences for other systems under different weather conditions were not visible.

A possible explanation to this result is that drivers’ visibility distance can be improved according to the NVES’s visibility visual guidance distance. System’s visibility visual guidance distance varies among different systems and conditions. Assisted by FIR system, drivers’ sight distance can be extended to 304 m/1000 feet at most. For NIR, this distance was extended to 200 m/656 feet at most. And for those drives that not use NVESs, visibility is limited to 110m at most.
For NIR systems, though the sensor’s detection distance was limited to 200m and the pictures on the display were getting blurred, the hazard detection distance in fog remained almost the same as in clear weather. This may suggest the hazard detection function of NIR NVES won’t be affected by weather conditions.

The yellow horizontal line in Figure 6.2 indicates the second warning (hazard is highlighted in a red square, accompanied by a beep sound) in the distance measurement. Subjects that used FIR NVES can always detect the hazard before it is warned on the display. The mean hazard detection distance for NIR systems were almost the same value as the second warnings.
6.1.2 Hazard Detection Distance by Hazard Scenario and Appearance Distance

Hazards of different scenario might result in different hazard detection distances. Figure 6.3 shows the detection distance for 20 hazards. Each column represents the mean detection distance for each hazard of six treatment combinations. Hazard 9 (Man riding bicycle on the left of the road, appeared 100 m/328 feet ahead) has the shortest detection distance of 45.34 m /148.75 feet and hazard 16 (Man riding bicycle on the right of the road, appeared 300 m/984 feet ahead) has the longest detection distance of 127.97 m/419.85 feet.

Figure 6.3 Mean hazard detection distance (m) by hazards
6.1.2.1 Detection by Hazard Scenario:

Table 6.2 displays the mean hazard detection distance by hazard scenarios and NVES types. Data shows a significant difference by hazard scenarios ($F(2, 42) = 11.36$ (critical $F = 5.15$), $p < .01$), and also by interaction between NVESs & hazard scenarios ($F(4, 42) = 8.28$, critical $F = 3.80$, $p < .01$). Mean detection distance was greatest for the static hazard (standing hazard) (108.95 m/358 feet). Figure 6.4 shows the difference in distances to the hazard at brake response by hazard scenarios. Driving either with or without NVES, mean detection distances for moving hazard (99.33 m/325 feet) and cycling hazard (95.79 m/314 feet) were both significantly different from standing hazards; however, there’s no significant difference between moving and standing hazards. These results show that, as intended, compared to static hazards without any movement or activity, dynamic hazards with some actions provided a more difficult detection level as represented by the distribution of distances at braking onset for the hazards.

**Table 6.2 Mean hazard detection distance (m) by hazard scenarios and NVESs**

<table>
<thead>
<tr>
<th>Hazard Scenarios</th>
<th>NVESs</th>
<th>BASE</th>
<th>NIR</th>
<th>FIR</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moving</td>
<td>BASE</td>
<td>60.63</td>
<td>95.70</td>
<td>141.67</td>
<td>99.33</td>
</tr>
<tr>
<td>Standing</td>
<td>BASE</td>
<td>51.17</td>
<td>110.27</td>
<td>165.40</td>
<td>108.95</td>
</tr>
<tr>
<td>Cycling</td>
<td>BASE</td>
<td>55.46</td>
<td>96.73</td>
<td>135.19</td>
<td>95.79</td>
</tr>
</tbody>
</table>

Figure 6.5 displays the effects of interaction by NVESs and hazard scenarios to hazard detection distance ($F(4, 42) = 8.28$, critical $F = 3.80$, $p < .01$). For hazards in any
scenario, all had the longest detection distances by FIR NVES, and shortest detection distances to hazards when driving without NVES. For both FIR and NIR NVESs, detection distance of static hazards was significantly longer (p < .01) than the other two dynamic hazards. However, in conflict with that result, when driving without NVES, drivers had a better detection performance for hazards in motion than hazards in static. It may suggest that: drivers are more capable of detecting and recognizing a hazard without any movement showing on NVESs’ displays; when driving without NVES, hazards in motion are easier to be perceived by drivers.

The result may be related to the theory of NVESs in how they detect the objects and how they display the pictures on screen. A static object would be easier to detect both heat-based FIR sensor and reflection-based NIR sensor, and pictures of static objects would be easier to recognize.
Figure 6.4 Mean hazard detection distance (m) by hazard scenarios
6.1.2.2 Detection by Hazard Appearance Distance:

Based on the test design, 20 hazards can be divided into 3 groups by their appearance distances: 1) appearance distance less than 100 m/328 feet on an average at 75 m/246 feet; 2) appearance distance between 100 m/328 feet and 200 m/656 feet on an average at 150 m/492 feet; 3) appearance distance larger than 200 m/656 feet on an average at 250 m/820 feet. Table 6.3 shows the mean hazard detection distance by NVESs and hazard appearance distance.
Table 6.3 Hazard detection distance (m) by hazard appearance ranges

<table>
<thead>
<tr>
<th>APP Range</th>
<th>NVESs</th>
<th>BASE</th>
<th>NIR</th>
<th>FIR</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>100m</td>
<td></td>
<td>51.883</td>
<td>58.041</td>
<td>75.883</td>
<td>61.936</td>
</tr>
<tr>
<td>100-200m</td>
<td></td>
<td>57.961</td>
<td>105.493</td>
<td>148.786</td>
<td>104.080</td>
</tr>
<tr>
<td>200m and beyond</td>
<td></td>
<td>61.163</td>
<td>109.829</td>
<td>159.190</td>
<td>110.061</td>
</tr>
</tbody>
</table>

Analysis found a main effect of hazard appearance distance $F_{(2, 42)} = 69.23$ (critical $F = 5.15$), $p < .01$. Figure 6.6 shows that a hazard’s detection distance increased significantly if it appeared at a farther distance from the driver.

The interaction between hazard appearance distance and NVES type was also significant, $F_{(4,42)} = 14.16$ (critical $F = 3.80$), $p < .01$ (Figure 6.7). This difference was more pronounced for the FIR ($F_{(2, 14)} = 31.40$, critical $F = 6.51$, $p < .01$), and NIR NVESs ($F_{(2, 14)} = 41.93$, critical $F = 6.51$, $p < .01$), however, both NIR and FIR NVESs showed not-so-significant results on comparisons of hazard appearances ranging between 100-200m, and beyond 200m.

Drives that used FIR NVES had the longest mean detection distance for hazards appearing at any distance, mainly because FIR provided subjects with the longest visibility range than any other systems. Also by FIR, some subjects might feel they can see the road far ahead and possibly scan more frequently on NVES’s display. When a hazard appeared within 100 m, there’s no visible difference between using or not using...
NVESs. However, when a hazard appeared farther than 100 m, the detection ability was enhanced greatly by NVESs versus that not by NVESs, F (1, 14) = 97.31 (critical F = 8.86), p < .01.

![Mean Hazard Detection Distance](image1)

**Figure 6.6** Mean hazard detection distance (m) by hazard appearance range

![Mean Hazard Detection distance](image2)

**Figure 6.7** Mean hazard detection distance (m) by hazard appearance ranges and NVESs
The interaction between hazard appearance distance and weather conditions was not significant at p < .01, however, if we consider p < .05, F (2,42) = 4.66 (critical F = 3.22) (Figure 6.8), the result is statistically significant. When the appearance range is less than 100 m/328 feet, subjects drove in clear weather were able to detect hazards earlier than those in fog weather, but the difference was not significant (t = 0.398, p = 0.694). When the appearance range increased to 100 m/328 feet, subjects drove in fog had a longer detection distance than those in clear weather. This difference increased when appearance distance ranged longer than 200 m/656 feet (p < 0.01).

Figure 6.8 Mean hazard detection distance (m) by appearance ranges and weather conditions

6.2 Missed Hazards

6.2.1 Missed Hazards by Treatment Groups
Table 6.4 shows the average number and percentage of missed hazards for each treatment combination. Overall, both FIR and NIR systems had visibly improved the proportion of missed hazards. Subjects drove in foggy weather without NVESs failed to detect 3 hazards on average. On the contrary, subjects that used FIR NVES in foggy weather only missed an average of 0.63 hazards. Drivers in foggy weather that not used NVESs had the lowest sight distance as well as an unclear front scene, so it’s not surprising a large quantity of hazards were missed.

Interestingly, by either FIR or NIR systems, subjects in foggy weather missed fewer hazards than in clear weather. Based on the average missed hazards, Figure 6.9 shows the mean percentage of missed hazards by NVESs and weather conditions. However, differences among the conditions were not statistically significant.

**Table 6.4 Average missed hazard number by NVESs and weather conditions**

<table>
<thead>
<tr>
<th></th>
<th>BASE</th>
<th>NIR</th>
<th>FIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEAR</td>
<td>2.50 (12.50%)</td>
<td>1.75 (8.80%)</td>
<td>1.63 (8.10%)</td>
</tr>
<tr>
<td>FOG</td>
<td>3.00 (15.00%)</td>
<td>1.00 (5.00%)</td>
<td>0.63 (3.15%)</td>
</tr>
</tbody>
</table>
6.2.2 Missed Hazards by Hazard Scenarios and Appearance Distance

For total missed hazards, figure 6.10 shows that only 13% were pedestrians walking or running on the road. 42% of total missed hazards were pedestrians standing roadside, and 47% were bicyclists.

Subjects also indicated that based on the total missed hazard number, only 25% appeared at a distance less than 100 m/328 feet. This proportion increased to 37% when hazards appeared at a distance longer than 200 m/656 feet, and to 38% when hazards appeared between 100-200 m (328 – 656 feet) (Figure 6.11).

However, the difference among conditions of hazard scenarios and hazard appearance distance was not statistically significant.
Figure 6.10 Proportions of missed hazards by hazard scenarios

Figure 6.11 Proportions of missed hazards by hazard appearance distance
6.3 Visual Behavior

In experimental groups by NVESs, subjects’ visual behaviors were recorded and would be analyzed as follows:

1) Eyes off road duration – defined as the duration of a glance from the moment the eyes leave the forward scene to the next moment they re-look towards the forward scene;
2) Glance frequency: defined as the inverse of time interval between consecutive glances.

Eyes-off-road duration was analyzed in formats of: 1) total time of eyes off road duration; 2) eyes off road duration in the interval from 5s before the detected hazard; 3) the number of glances lasting longer than 2s

6.3.1 Total Time of Off-road Glance

Though the needed time to complete a trial varied from trial to trial and subject to subject, the accumulation time of eyes off road duration were calculated starting from the trial beginning and ended at the time when the subject passed the last hazard. Figure 6.12 shows accumulation of off road glance durations as a function of NVESs and weather conditions. There was a trend for durations to be longest when FIR system was used to assist subject drove in fog weather and shortest when the NIR system was used to assist
subject drove in fog weather. The differences among conditions, however, were not statistically significant in this experiment.

![Mean Total Time Glance Off-Road](image)

**Figure 6.12 Total time (s) of off-road glance by NVESs and weather conditions**

### 6.3.2 Off-road Glance Duration in the Final 5s before Detection

Based on the hazard appearance distances in this study and the nature of visual behavior in object detection, the eye active detection time for a hazard was defined as the period of final 5s before the hazard was detected. Hazards that failed to be detected were excluded from this analysis.

Figure 6.13 shows the duration of off-road glances in the final 5s as a combination of NVESs and weather conditions. Drivers in clear weather spent almost the same time
duration on NIR (2.36s) and FIR (2.36s) systems in the final 5s. However, in foggy weather, duration by NIR NVES decreased to 2.30s, and duration by FIR NVES increased to 2.54s. But the differences among the conditions were not statistically significant.

![Mean Duration](image)

**Figure 6.13** Mean duration (s) of off-road glance in the final 5s by NVESs and weather conditions

Classified by hazard scenarios, differences among the conditions are also not statistically significant. Figure 6.14 displays the off-road glance duration in 5 seconds as a function of hazard scenarios and NVESs. The pedestrian walking and running moving hazards have the shortest duration of 2.25s. However, standing still bicycle riding pedestrian hazards have a significantly longer off-road duration of 5 seconds – 2.47s for standing hazards, and 2.44s for cycling hazards.
Figure 6.15 indicated the statistically significant main factor of hazard appearance distance, $F(2, 14) = 10.01$ (critical $F = 5.15$), $p < .01$. Hazards appearing less than 100 m/328 feet had a shorter mean duration than hazards appearing longer than 100 m/328 feet.

Figure 6.14 Off-road glance duration (s) in final 5s by hazard scenarios
6.3.3 Number of Off-road Glance Duration Longer than 2 seconds

NHTSA estimates that a driver whose attention is taken off the road for two seconds becomes twice as likely to be in a crash. In this experiment, we examined the behavior of eyes off the road for two seconds as the behavior of attention off the road. This glance is defined as a distraction glance in this research. Figure 6.16 reveals the average number of distraction glances as a combination of NVESs and weather conditions. All combinations had an average number of distraction glances more than 9 times. The FIR system in foggy weather had the largest quantity of distraction glance, and NIR system in clear weather has the smallest number of distraction glances, but the differences among conditions were not statistically different.
Figure 6.16 Mean number of off-road glance longer than 2 seconds by NVESs and Weather conditions

6.3.4 Glance Frequency

Figure 6.17 shows that on average, subjects glanced at the display every 3.83 seconds when used FIR NVES in clear weather, and every 4.43 seconds when used NIR NVES in clear weather, but the differences among conditions were not statistically significant.
6.4 Lane Deviation

Lane deviation was used as a substitute measurement of test participant performance and distractions. The width of the road simulated in this environment followed the U.S. Interstate Highway System’s standard: 12ft (3.70m) for a single lane width. The width of the main vehicle in this research was 5.92ft (1.80m). If the vehicle was drove off the road, the system automatically recorded this fault and warned the subject with an instruction. However, for 24 subjects, none of them had driven the vehicle off the road. Figure 6.18 revealed the trend of lane deviation variation as a function of systems types and weather conditions. Though there’s some decrease and increase in different conditions, there’s no statistically significant difference among all conditions.
6.5 Subjective Rating of Mental Workload

Subjective ratings of workload were collected using NASA_TLX (Hart and Staveland, 1988). NASA_TLX is a multi-dimensional subjective workload rating technique that is commonly used to evaluate workload. Subjects rate their workload on six scales representing mental demand, physical demand, temporal demand, performance, effort, and frustration level. Their ratings are then combined, using weights or by simple addition, into a NASA_TLX score that represents overall workload. The results reported here are based on the unweight addition of ratings on each scale (Moroney et al., 1992).

Figure 6.19 shows the effect of systems on NASA_TLX workload scores. Subjects rated the mental workload 35.10 when not using NVESs. Though not significant, workload
was reduced to 25.52 by NIR NVES, but remained almost unchanged by FIR NVES (34.06).

![Mean Score Graph](image)

Figure 6.19 Mean NASA-TLX scores

### 6.6 Subjective Rating of System Effectiveness

Subjects were asked to rate the effectiveness of the night vision enhancement system used in his/her own experimental trials by completing a post-system questionnaire.

Subjects had to answer several questions relating to the system effectiveness and ease of use. Each answer was given on a seven-point rating scale with 1 = “poor,” 4 = “neutral,” and 7 = “Excellent.” Results showed that FIR NVES was rated a higher score than NIR NVES, however, the difference was not statistically different.
Subjects were also asked to make their own comments on night vision enhancement systems by expressing their own feelings of both advantages and disadvantages from the NVESs. Almost all the subjects confirmed that the NVESs were very helpful in detecting obstacles in early stage and to take action. They also like the yellow outline, red outline and sound warning to indicate the levels of danger. Some of them felt that NVESs were very beneficial, especially during bad weather. However, either FIR system users or NIR system users, they all said it was distracting for them to switch the gaze between the road ahead and the extra NVES screen.

6.7 Summary

Underlying this experiment was the premise that the primary purpose of night vision enhancement systems should be capable to enhance the visibility of people-related hazards at an acceptable level of drivers’ distraction. Parameters relating to hazard detection and drivers’ distraction data were analyzed in the previously paragraphs.

The simulated NVESs in this study effectively assisted subjects in detecting and responding to hazards in both clear and fog weathers. Subjects experienced the benefits of NVESs and showed their interests in purchasing the NVESs for their own vehicle. Tough the subjects did feel different level of distraction brought by NVESs, and some of visual behavior data cannot meet NHTSA’s distraction criteria, their performance suggested that they were not overwhelmed by the added distraction.
6.7.1. Both NIR and FIR night vision enhancement systems are beneficial in hazard detection performance, and FIR NVES is superior to NIR NVES.

There are mixed findings when evaluating the impact of the NIR and FIR NVESs on improving drivers’ safety in terms of hazard detection and avoidance.

Both hazard detection distance and number of missed hazards by NVESs type confirmed the hypothesis that NVESs could help drivers with hazard detection in terms of a faster response and higher detection accuracy.

Looking at the distance to hazard at the brake response by NVESs type, we saw that subjects assisted by either FIR or NIR NVES responded statistically sooner to hazards, and therefore were less likely to have collisions or fatalities, compared to control group without NVESs. As expected, on average, FIR NVES had the longest mean hazard detection distance of 146.72 m/481.36 feet, which was 1.5 times of NIR system (96.65 m/317.09 feet) and triple value of control group that not used NVESs (59.64 m/195.67 feet). The differences were statistically significant (p< .01).

Looking at the number of missed hazards by NVESs type, tough not statistically significant, we found that subjects by FIR NVES is more likely to miss less hazard (1.13 on average), and this number increased to 1.38 when by NIR system, and further increased to 2.75 when not using NVESs.
Comparing both detection distance and the missed number together, FIR system had the best hazard detection and response performance with the longest value of distance and minimum number of missed hazards. NIR system had the second best performance with a less detection distance and missed more hazards. And control group that not used any NVES had the worst performance with the shortest detection distance and maximum number of missed hazards. A possible explanation to this result is that drivers’ visibility distance can be improved according to the NVES’s visibility visual guidance distance. System’s visibility visual guidance distance varies among different systems and conditions. Assisted by FIR system, drivers’ sight distance can be extended to 304 m/1000 feet at most. For NIR, this distance was extended to 200 m/656 feet at most. And for those drives that not use NVESs, visibility is limited to 110 m/361 feet at most.

Current test may underestimate the real-world benefits of the both NVESs and APWs in terms of how the systems might affect general preparation to respond to and avoid a pedestrian. The present experiment measured only the effects of the hazard detection distance and accuracy. In real world driving, when a hazard is appeared and highlighted in the display, drivers would begin some avoidance responses to pedestrians before they are visible - e.g., slowing down, being prepared to steer, or brake.
6.7.2 NVESs’ performance will not be degraded in foggy weather, and the hazard detection performance is even better in foggy weather by FIR versus in clear.

On the other hand, when we considered the hazard detection performance by weather conditions, the result was contrary to the original hypothesis at some points, especially for groups that used FIR system.

It is believed that weather conditions, such as heavy fog or rain, can modify the thermal footprint of bodies, limit the effectiveness of infrared systems (M. Bertozzi et al., 2003), the hypothesis here is that though the NVESs would be affected in foggy weather, NVESs could still fulfill their purposes, meanwhile, drivers’ detection performance by NVESs would be degraded in foggy weather compared to clear weather. Subjects confirmed that in foggy weather, NVESs improved the hazard detection performance in terms of detection distance, however, the data also showed some conflicting results. When driving by NIR system, hazard detection distance in foggy weather was slightly higher than in clear weather. And this trend was enlarged when driving assisted by FIR system, hazard detection distance statistically improved from 132.99 m/436.32 feet in clear weather to 160.45 m/526.41 feet subjects assisted by FIR NVES in fog weather. Tough it confirmed the previously assumption that FIR systems could be slightly superior to NIR systems in adverse weather (Rumar, 2003), this result was opposed to the hypothesis that hazard detection performance would degrade from clear weather to foggy weather when using NVESs.
The superiority of FIR NVES in foggy weather may theoretically due to that FIR NVES uses radiation produced at the viewed object itself and the information captured by sensor camera is less affected in fog weather. Subjects will spend more time looking at the display and therefore result in a considerable improvement of hazard detection distance. Results on parameters of glance behaviors strongly support this explanation. Subjects that used FIR NVESs in fog weather: 1) had the longest off-road time; 2) accumulated duration on display in active scanning period was the longest; 3) had the maximum number of off-road glance with a duration longer than 2s.

Another main factor that can contribute to this result is vehicle’s speed, however, we do not consider it in this study.

6.7.3 NVESs’ hazard detection performance vary by hazard scenarios
and static hazard may be easier to be detected by the commercial

NVESs currently on the market.

Considering the hazard scenarios, it is hypothesized that NVESs can reduce the collision rate of both static and dynamic hazards, which was represented as the detection distance and the number of missed hazards.

These results show that, as intended, detection distances of hazards at all scenarios—walking pedestrians, running pedestrians, jogging pedestrians, standing still pedestrians and people riding bicycles, increased statistically significantly from driving without NVESs to driving with NVESs. Meanwhile, tough the difference was not significant,
when using NVESs versus not using NVESs, the missed number decreased for hazards of all scenarios. And no visible difference was discovered in missed number between the NIR and FIR systems by hazard scenarios.

A very interesting phenomenon was that when driving without NVESs, subjects responded to the dynamic hazards faster versus static hazards, however, this trend reversed when using NVESs (both green lines and red lines) as the static hazard had the longest detection distance, and FIR NVES was more pronounced. This result revealed that when using NVESs, compared to static hazards without any movement or activity, dynamic hazards might provide subjects with a more difficult detection level as represented by the distribution of distance at braking onset for the hazards.

6.7.4 NVESs are more sensitive in detecting the hazards appear in longer distances beyond drivers’ vision field versus hazards appear in closer distances within the eyes.

Looking into the data of hazard detection performance by the hazard appearance distance, as expected, NVESs worked better for improving the detection of hazard appeared out of subjects’ vision field versus the hazard appeared within subjects’ vision field. The difference was statistically significant. However, a longer visual guidance did not always bring a significant enhancement in hazard detection distance.

Figure 6.20 shows the relationship between hazard detection distance and the hazard appearance distance by different NVESs. When hazards appeared off subjects’ vision
field with an average of either 150 m/492 feet or 250 m/820 feet, mean detection distance by FIR was triple longer than by baseline trials, and by NIR was twice as baseline trials. Tough FIR had a visual guidance up to 304 m/1000 feet; however, subjects may have some problems in identifying the highlighted hazards shown on display when they were far away from the vehicle as the dimension of hazard on display was inversely proportional to its distance to the vehicle. This result suggests that a warning of a detected hazard may not be needed until the hazard is dimensional identified on the display. Road information displayed on the NVES’s screen limited to a certain distance might potentially increase the efficiency of the system and reduce the cost.

![Mean Hazard Detection Distance](image)

*Figure 6.20 Mean hazard detection distance (m) by appearance ranges and NVESs*
6.7.5 Drivers’ distraction by NVESs largely exists in terms of both visual distraction and mental workload, especially for FIR NVES; however, drivers’ performance may not be necessarily affected by drivers’ distraction.

Though the level of drivers’ distraction due to performing a task using an in-device inherently depends upon the personal characteristic and capabilities of the drivers, the data from 24 participants can average out individual differences and reveal drivers’ distraction upon the NHTSA Guideline criteria and other variables.

Tough statistically insignificant, total glance-off road duration by drivers with FIR NVES tended to be about 13% greater than with NIR NVES. The result may be related to the scanning problem associated with FIR NVESs, as the direct view and the display picture look so different. Many relatively warm objects are irrelevant to driving tasks but are highly conspicuous in FIR system displays. This conflict might result in new problems in interpreting the display picture. These interpretation demands, in turn, could increase the distraction caused by FIR. There are reports (e.g., Foyle et al., 1990; Gish et al., 2002) on drivers who focus too much on the interpretation of the object and lose contact with the direct visual scene. Driving with eyes-off-road can be considered as blind driving. However, even for the group that had the greatest mean eyes-off road time (124.54s), the average eyes-off road time (6.23s) for a hazard was only half of 12s, which is defined as the maximum glance duration away from the roadway for a task by NHTSA Guidelines criteria. Therefore, all NVESs tested in this study passed this criterion.
Another recommended criterion for measuring drivers’ distraction from visual manual tasks on a time-based acceptance is that the number of glances with duration longer than 2.0 seconds should less than 15% of total number of glances.

Though not conditional statistically significant, results indicated that while detecting hazards, as a function of NVESs type and weathers, the average number of single eyes-off-road glance with duration longer than 2 seconds was up to 10 times for each trial, which accounted for about 13% of total glance of eyes-off-road. And the minimum number of 9 times, which accounted for 12% of the total number of glances, was associated with of the scenario of using NIR in clear weather. The group that used FIR in fog weather had the largest number of 13 times in a trial, which accounted for 19% of total number of glances. Though the maximum percentage criterion was only exceeded in the case using FIR in fog weather, large percentage (14% on average) of off-road glance with durations longer than 2 seconds still indicated a severe visual distraction. Even though the NIR display can restore the front scene with a high resolution, subjects still need to spend time and attention in looking, interpreting and searching for the information on display. Future research should try to solve the high visual distraction problem caused by NVESs.

One factor of increased visual distraction and/or increased workload could be a large variation of lateral position on the road (Rumar, 2002). Results indicated that no driver drove off the road in this study, confirming that no drivers had problems with lane keeping when using NVESs, and there’s no statistically significant difference between groups that used and not used NVESs. For NVESs trials, NVESs did improve drivers’
lane keeping performance in clear weather. However, this improvement degraded as the weather turned into fog weather. Also lateral position showed a larger variation by the group that used NVESs although no drivers drove off the road. This makes sense because lateral position is largely maintained by peripheral vision (Rumar and Marsh, 1998), which diminished in displays.

NASA-TLX questionnaire and self-reported system comments further evaluated this uncertainty by comparing the results between NVESs and non-NVESs trials. Though subjects admitted the advantage of NVESs in detecting hazards and exploring the information of road ahead, one characteristic they complained most about NVESs was the dual-scanning requirement.

Results of the NASA-TLX showed no difference in general system appraisal. Additions of NVESs did not statistically add or reduce drivers’ mental workload according to NASA-TLX scores. Though statistically insignificant, average scores decreased from 35.10 by using no NVESs, to 34.06 by using FIR NVESs, and further down to 25.52 by using NIR NVESs. Two factors may have contributed to this result: (1) subjects were given the experimental instructions to find hazards as soon as possible; and (2) subjects attempt to do well in the experiment. Therefore the mental workload was potentially reduced by the assistance of NVESs. It is likely that in real-world situations, drivers would not be as vigilant and would not keep their workload at high levels continuously unless prompted by an automated system. Thus the workload would likely be further decreased in real driving when using NVESs.
This result confirmed the hypothesis that subjects using NVESs experienced less mental workload than subjects using no NVESs. The benefits gained from using NVESs in detecting hazards had greatly compensated for the increased mental workload raised by the dual-scanning requirement. Moreover, workload was rated higher when in fog weather than in clear weather, and this difference was more obvious when comparing groups that used and not used NVESs. This confirmed that in a more difficult night driving condition, such as in fog weather, mental workload was considerably increased, especially for the ones with the display from a camera view (Rumar, 2002).

Besides the recommended four criteria, other off-road glance behavior like subjects’ glance frequency can also reflect drivers’ distraction, although the effects were insignificant. It was found that on average, subjects glanced at the display every 4.13s by NIR NVES and 3.99s by FIR NVES. A lower glance frequency might suggest a less drivers’ distraction.

Subjects averagely spent around 25% of their time looking off road on the display for a trial. However, this number doubled to almost 50% in the final 5 seconds before a successful detection. A longer duration of eyes-off-road indicated a higher drivers’ distraction. When driving in clear weather, both FIR and NIR systems had the same glance duration of 2.36s in the final 5 seconds. However, when driving in fog weather, glance duration increased to 2.54s when using FIR and decreased to 2.30 when using NIR. Results might suggest that subjects relied more on FIR NVES in foggy weather compared to NIR NVES.
Results from two recommended time-based assessments by NHTSA Guidance and other eye movement data showed that though the NVESs did bring both visual and mental distraction by requiring drivers to switch their eyes and concentrations off road frequently with long durations, especially when using FIR NVESs. However, a conclusion could not be drawn on whether the NVESs would impact drivers’ safety in terms of drivers’ distraction by simply analyzing these two criteria. On contrary to the previously non-driving-related secondary tasks as operating the entertainment system, typing mobile message, etc., tasks performed by NVESs actually provide drivers with useful information for primary driving task. Therefore, it is much likely that the road and pedestrian information provided to drivers by a NVES could compensate the distraction it causes. Thus drivers’ driving performance might not degrade, as they might feel comfortable about performing dual-scanning task though they are required to look at the other display.

6.7.6 Virtual platform is a reliable and promising method to conduct NVESs related research by bringing maximal flexibility and versatility to the researchers, and by providing subjects with more realistic experiences by NVESs without any safety issues.

Experimental results described in the previous paragraphs have proven the value and reliability of the developed virtual environment in this study. With the developed virtual environment, this study brought the real potential hazards to subjects, which were much different from the detection targets in previous research. Potential people related hazards
of all scenarios: walking, running, jogging, standing and riding bike, were all simulated in our virtual environments. Moreover, analysis on drivers’ distraction were based on the overall results from drivers’ visual behavior, mental workload and driving’ performance.

One of the biggest challenges in this study was to develop a realistic virtual platform in terms of nighttime driving environment and NVESs images. Averagely, subject scored 5.5 points for the realism of virtual platform on a 7-point scale, indicating that they are satisfied with the reliability of the virtual platform.
Chapter 7 Conclusion and Future Work

7.1 Conclusions

This study aimed to develop a prototypal and extensive virtual platform to provide drivers with a realistic driving experience using night vision enhancement systems (NVESs) at low cost. Overall benefits gained from and drivers’ distraction caused by both near infrared (NIR) and far infrared (FIR) NVESs were evaluated and discussed based on the results from the experimental study on the developed virtual platform.

The experimental results and subjective reports validate the realism and research value of the developed virtual platform. The results show that the experience with the virtual experimental platform greatly increased drivers’ confidence in using NVESs.

The experimental data indicates that commercial NVESs currently available on the market can have a positive impact on improving both driver and pedestrian safety by allowing drivers to respond at a longer distance with a higher accuracy. It appears that NVESs are more statistically beneficial in improving drivers’ performance in foggy weather; while in clear weather the benefits are not as obvious as those for the case in foggy weather. This phenomenon is more pronounced for FIR NVESs. Moreover, subjects commented that they were more satisfied with their performances when using NIR NVESs in clear weather and FIR NVES in foggy weather. Overall, although FIR NVESs are more effective than NIR NVESs as FIR NVESs have a longer visual guidance
and more stable performance in foggy weather, NIR NVESs with a more realistic picture are preferred in clear weather conditions.

The exploratory analysis of glance behaviors and subjective questionnaires suggests that subjects are vigilant and more distracted when using NVESs. However, the distraction may not necessarily have a negative impact on drivers’ performance. According to drivers’ distraction criteria for driving simulator study by NHTSA, FIR NVESs had a higher distraction rate than NIR NVESs and failed to pass one criterion because over 15% of the tested subjects have glance duration longer than 2.0 seconds. Results from NASA_TLX questionnaires further reinforce this result as subjects rate higher scores of mental workload when using FIR NVES versus using NIR NVES. However, subjects’ good lane-keeping performance suggests that distractions brought by NVESs may not necessarily affect the drivers’ overall driving performance.

Based on the results from this study, it can be concluded that commercial NVESs currently available on the market can help enhance the drivers’ performance and safety while keep drivers’ distraction to an acceptable level. Future study on NVESs should still focus on reducing the mental distraction from NVESs and improving overall performance in hazard detection. For NIR NVES, research efforts should be focus on how to improve its hazard detection performance, while for FIR NVES the focus should be on how to reduce drivers’ distraction caused by the system.

A new technique for future NVES, the sensor fusion technique, is also recommended. This technology produces a sensor that combines the advantages of both NIR and FIR
sensors. Assisted by this new sensor, NVES is expected to provide drivers at least with the following features: (1) a realistic, stable and easy-recognizing infrared image; (2) a longer detection distance; and (3) a steady performance under any weather conditions. An experimental test of sensor fusion NVESs on virtual platform allows researchers to evaluate this new technology in advance. An image produced by sensor fusion technique is shown in Figure 7.3 as an example. Figure 7.1 and Figure 7.2 are the same view on NIR and FIR NVESs.

![Figure 7.1 NIR NVES view](image-url)
Figure 7.2 FIR NVES view

Figure 7.3 Sensor-fusion NVES view
7.2 Contributions

According to the experimental results and conclusions, the main contributions of this study can be summarized as follows:

1) Innovatively used a simulation method to restore the infrared images of both NIR and FIR NVESs;

2) Developed a driving simulator-based virtual experimental platform with rich scenarios of regular driving backgrounds and potential hazards; and the platform (both driving scenarios and NVESs’ images) can be extended to meet any image-based experimental test for NVESs or other in-vehicle devices;

3) Completely evaluated drivers’ hazard detection performance and drivers’ distraction in a more realistic driving environment which covers both downtown and rural roads, and confirmed based on experimental results that NVESs can greatly improve drivers’ hazard detection skills in dark and adverse weather conditions although they also cause high drivers’ distraction;

4) Analyzed drivers’ distraction in terms of visual behavior and mental workload and found that mental workload was raised from the visual behaviors of dual-scanning requirement. However, this study also found that visual behaviors of scanning at display actually enhanced driving performance.
7.3 Future Work

An ideal and reliable user experience could be an on-road test that uses a real NVES in a real production vehicle at night. However, considering the high cost associated with on-road tests and safety issues, simulation could be a better alternative for conducting studies that focus on the NVESS’ performance and potential drivers’ distraction. The research presented in this thesis innovatively simulated a virtual platform that can provide subjects with a realistic driving and hazard detection experience by commercial NVESs currently available on the market. Being able to simulate rich scenarios of realistic hazards that are practical impossible to achieve in on-road tests into the platform is a significant advantage of this developed platform. Besides, the use of this platform can help avoid the safety concerns related to the on-road tests.

However, due to the limited time, resources and facilities availability, this study is restricted in some areas, discussing in the following.

- Only two types of commercial NVESs currently available on the market were simulated and tested;
- Only people related hazards were simulated in the virtual environment. Other hazards like animals were not considered in this study;
- Only hazard detection distance and accuracy were used as for hazard detection performance by NVESs. Other performance in avoiding hazard, such as braking, rotating the steering wheel etc., were not examined.
• Only city downtown and rural road environments were simulated. Other environments with high population, such as city suburban, were not considered.

• The test was designed such that only one person appears on the display at one time. However, multiple people can appear in one scene in a real situation;

• Only NVESs with APWs were tested. A group of NVESs without APWs can be included;

• Only subjects’ performance, visual behaviors and mental workload at the time they initially started using NVES were tested. It is possibly that his/her performance would be changed as the long term effects, and a better visual strategy may be developed as they get used to the system.

According to the conclusions and limitations of this study, future work of this research will firstly focus on enriching and improving the scenarios of the developed virtual platform to include the city suburban and highway in addition to the scenarios that have been developed.

With the improved the platform, we recommend that further studies on NVESs carried out on this platform with the following emphases:

• NVESs by FIR sensor, NIR sensor and fused-sensor should be studied and compared with the specifications in hazard detection performance, visual behavior and mental workload;

• Different approaches of visual, auditory, tactile warnings and their combination should be studied. In particular, drivers’ distraction and mental workload by
different warnings should be compared. Questions on when the warnings should be produced and with which detected objects should be alarmed should be analyzed. A good developed alarm strategy should be able to automatically alarm at a proper time and completely cover all the possible events that need to be alarmed;

- Young and old drivers should be included as the subjects of the study;
- Automatic warnings for non-pedestrian hazards, mainly animals, should be tested. Methods that can improve the warnings of dynamic hazards to drivers should also be considered and studied;
- The long-term effects of exposure to the NVESs should be studied in terms of driving performance, user satisfaction, visual behavior and mental workload.
References


Rumar, K. (2002). Night vision enhancement systems: what should they do and what more do we need to know?. (No. UMTRI-2002-12) (p. 52). University of Michigan, Ann Arbor, Transportation Research Institute.


Related Publications & Academic Activities

*Simulation of Infrared Thermal Imaging in a Virtual Environments Driving Simulator.*


*Using Scenarios to Evaluate Driving Skills?* Linzhen Nie, Poster, Research and Scholarship Expo 2010, March 24, 2010, Northeastern University, Boston, MA, USA.


*An Experimental Study of In-Vehicle Displays,* Linzhen Nie, Poster, Research and Scholarship Expo 2009, Poster, March 24, 2009, Northeastern University, Boston, MA, USA.
Appendix 1: Consent Form

Northeastern University, Department of Industrial and Mechanical Engineering
Name of Investigator(s): Ronald Mourant, Linzhen Nie
Title of Project: Research on the Development and Application of Simulated Night Vision Enhancement Systems

We would like to invite you to take part in a research project. The purpose of this research is to simulate and evaluate the current automotive Night Vision Enhancement Systems (NVESs), which are intended to give drivers a better view of the road ahead during nighttime driving. The purpose of the study is also to make recommendations for the future NVESs.

You must be at least 25 years old to be in this research project. In addition, you must also have a valid driver’s license and be an experienced driver (minimum 2 years’ driving experience, around 5,000 – 8,000 miles per year and have nighttime driving experience) and have normal or corrected to normal vision.

The study will take place at Virtual Environment Laboratory and will take about 40 minutes.

If you decide to take part in this study, we will ask you to fill out a background form, answer a series of questions on simulator sickness and drivers’ distractions, and discuss your opinions about NVESs. You will complete one practice session in the driving simulator to familiarize yourself with the driving environment, followed by two testing trials. There will be a break between the first and second tests. During all sessions your eye-movements will be recorded by a video camera and your driving performance data will also be recorded.

The possible risks or discomforts of the study are minimal. You may experience some simulator sickness, which may include slight dizziness and nausea. If at any time during the study you experience discomfort, please indicate this verbally or stop the test and the study will be terminated immediately.

There are no direct benefits to you for participating in the study. However, your answers may help us to learn more about NVESs and their effects on nighttime driving safety.

Your part in this study will be handled in a confidential manner. Only the researchers will know that you participated in this study. Any reports or publications based on this research will use only group data and will not identify you or any individual as being of this project.

The decision to participate in this research project is up to you. You do not have to participate and you can refuse to answer any question. Even if you begin the study, you may withdraw at any time.

You will receive $20 at the end of experiment.

If you have any questions about this study, please feel free to call Linzhen Nie, 617-800-3963, linz.nie@gmail.com, the person mainly responsible for the research. You can also contact Prof. Mourant, 617-373-3931, the Principal Investigator.
If you have any questions about your rights in this research, you may contact Nan C. Regina, Director, Human Subject Research Protection, 960 Renaissance Park, Northeastern University, Boston, MA 02115. Tel: 617.373.4588, Email: irb@neu.edu. You may call anonymously if you wish.

You may keep this form for yourself.

Thank you.
Linzhen Nie
Appendix 2: Background Form

Name: ___________________ Date of Birth: ______________

Gender: ________________

Driver’s License Issued Date: ________________

On-the road nighttime (after 4 pm) driving miles per week: ________

Do you know the concept of night vision enhancement? Yes No

Do you ever try a night vision enhancement systems? If so, please describe the system and your experience with it.

Do you know the concept of pedestrian detection system? Yes No

Do you ever try a pedestrian detection system? If so, please describe the system and your experience with it.

Do you have some nighttime crashes? If so, please describe each of them.
Appendix 3: Simulator Sickness Questionnaire

SYMPTOM CHECKLIST

Pre-exposure instruction: please fill in this questionnaire once more. Cross below if any of the symptoms apply to you now.

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<th>Slight</th>
<th>Moderate</th>
<th>Severe</th>
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<td>Difficulty concentrating</td>
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<td>Mental depression</td>
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<td>Blurred vision</td>
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<td>Dizziness eyes open</td>
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<td>Dizziness eyes close</td>
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<td>Vertigo</td>
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<tr>
<td>Visual flashbacks</td>
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<td>Faintness</td>
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<tr>
<td>Aware of breathing</td>
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<td>Stomach awareness</td>
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<td>Loss of appetite</td>
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<tr>
<td>Increased appetite</td>
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<tr>
<td>Desire to move bowels</td>
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<tr>
<td>Confusion</td>
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<td>Burping</td>
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<td>Vomiting</td>
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<td>Other</td>
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Please specify the other symptoms you experienced.
Appendix 4: Post-System Questionnaire

Subject Number ______

Using the seven point scale provided please answer the following questions by placing an ‘X’ on the lines below.

1. How realistic was your simulator experience as compared to real world driving?

   1    2    3    4    5    6    7
   Poor Neutral Excellence

2. How useful were the Night Vision Enhancement Systems (NVESs) in your driving?

   1    2    3    4    5    6    7
   Poor Neutral Excellence

3. How clear and understandable was your interaction with the NVESs?

   1    2    3    4    5    6    7
   Poor Neutral Excellence

4. How easy were the NVESs to use?

   1    2    3    4    5    6    7
   Poor Neutral Excellence

5. How helpful were the NVESs in recognition of pedestrians?

   1    2    3    4    5    6    7
   Poor Neutral Excellence

6. How much likely will you get the NVESs in your own car?
7. How much distraction you feel while using NVESs?

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<th>4</th>
<th>5</th>
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<td>No</td>
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<td>Definitely</td>
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<td>Strongly</td>
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<td>Neutral</td>
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8. What did you like about the NVESs?

9. What did you dislike about the NVESs?

10. Which NVESs you like best and describe the reasons.
Appendix 5: NASA_TLX Questionnaire

**NASA Task Load Index**

Hart and Staveland’s NASA Task Load Index (TLX) method assesses workload on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

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<tr>
<th>Name</th>
<th>Task</th>
<th>Date</th>
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</table>

**Mental Demand**

How mentally demanding was the task?

- Very Low
- Very High

**Physical Demand**

How physically demanding was the task?

- Very Low
- Very High

**Temporal Demand**

How hurried or rushed was the pace of the task?

- Very Low
- Very High

**Performance**

How successful were you in accomplishing what you were asked to do?

- Perfect
- Failure

**Effort**

How hard did you have to work to accomplish your level of performance?

- Very Low
- Very High

**Frustration**

How insecure, discouraged, irritated, stressed, and annoyed were you?

- Very Low
- Very High
Appendix 6: Poster of an Experimental Study of In-vehicle Display

An Experimental Study of In-vehicle Displays
Linzen Nie, Ne Chen and Yingai Lin
Virtual Environments Laboratory
Intelligent Human-Machine Systems Laboratory

Application of In-vehicle display systems
- In various display systems, with the integration of computer and embedded information system technology, have been successfully adopted in vehicles.

Study Objectives
- Prepare for distraction associated with in-vehicle displays by setting different tasks and using different in-vehicle display systems.
- Compare different driving behaviors by setting different tasks and using different in-vehicle display systems.
- Compare different vehicle display systems.

Experimental Design
- Rear-screen on the primary task driving will be affected by secondary tasks (e.g., performing tasks while in vehicle display systems).驾驶过程中任务的后屏影响将受影响的次级任务（例如，在车辆显示系统中执行任务）

Study Considerations
- The vehicle is placed in driving environments with high visibility. However, results are not repeatable because of various uncertainties in the real driving environment.
- The vehicle is driven with good control of the driving environment and ensures safety unexpectedly.

Virtual Environment Lab
- What we do?

Method
- Participants
  - Staff or students at NU with valid driving licenses
  - 24 participants between 25-32 years old
  - 3 groups, each group has 8 participants

Apparatus
- An Experimental Study of In-vehicle Displays

Specifically Designed Tasks For the Distraction Study
- Tasks to study the navigation, radio, and radio sub-systems

Experiment Procedure
- Training Procedure
- 1 minute testing video
- A series of guided instruction using the system

Results and Conclusions
- Results focus on whether, based on different tasks and different systems, in-vehicle systems distract the driver and affect their driving performance. Of particular interest is the distraction levels corresponding to different design characteristics of the systems.

Conclusion
- Alternative display systems distract drivers by reducing the time drivers spend looking at the driving environment.
- In-vehicle display systems distract drivers by reducing the time drivers spend looking at the driving environment.

Future work
- Alternative display systems distract drivers by reducing the time drivers spend looking at the driving environment.

Acknowledgement
- Thanks to the Prof. L. xinchen; thanks to the vehicle display systems. Thanks to the Prof. L. xinchen; thanks to the vehicle display systems.
Appendix 7: Poster of using Scenarios to Evaluate Driving Skills

Using Scenarios to Evaluate Driving Skills
Lincheng Nie
Virtual Environments Laboratory
Department of Mechanical and Industrial Engineering

3-D Real-time Driving Simulators
3-D Real-time Driving simulators are used for entertainment as well as in training drivers, education courses taught at educational institutions, and private businesses. Industrial simulators are used to train employees through realistic, interactive scenarios, to monitor driver behaviors, performance, and attention. The car simulator uses simulators in design and evaluation new vehicles and advanced driver assistance systems.

Training
Research has shown that driving simulators are powerful tools to enhance and deliver educational training for new drivers, especially for the elderly and disabled. There are various types of driving simulators that are being used, such as fixed-base, low-fidelity, and high-fidelity simulators.

Entertainment
Beginning with the groundbreaking game Formula One Legends released in 1998 for the PC, 90% of the most popular racing games use some level of driving simulators. In the world of entertainment, driving simulators are being used, i.e., car, truck, bus, and train simulators.

Research
Driving simulators are used as research facilities for many purposes. For instance, in the domain of transportation, they are used for traffic safety studies.

Human Control Strategy (HCS)
A more general HCS model should be developed and a more accurate evaluation criteria should be applied. More scenarios should be implemented, like weather conditions (snow, rain, etc.).

Evaluation Criteria
A rule-based method, similar to the Group Method of Handling Data (GMDH), is used to analyze driver performance and to develop a driving skill model. The driving skill model is based on the driver's output (driving skill).

Horns Control Strategy (HCS)
In a chaotic, stochastic, and probabilistic process, developing a good analytic model of human behavior is extremely difficult. We use HCS to simulate dynamic human behavior.

What we have done
Experiments
A series of experiments have been conducted for assessing driver's driving performance and skills under a few carefully developed realistic scenarios (shown above). Various risk factors, such as vehicle control data instability, lane deviation, speed variation, and road conditions, are tested using static and dynamic physical simulation models. The performance of the driver is evaluated using several criteria, such as reaction time, braking distance, and overall driving performance.

Future work
Further research will be conducted on the development of advanced driving simulators and the integration of various real-time simulation systems to enhance the realism of the simulation environment.

Acknowledgment
This research is supported by the National Science Foundation through the Virtual Environments and Human-Centered Computing program.

http://www.coe.neu.edu/research/velab/velab/home.html