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Evaluation of the Effectiveness of Radar Obstacle Detection Systems when Used on Industrial Lift Trucks

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EVALUATION OF THE EFFECTIVENESS OF RADAR OBSTACLE DETECTION SYSTEMS WHEN USED ON INDUSTRIAL LIFT TRUCKS

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This study addresses the application and the effectiveness of radar obstacle sensors for forklift trucks during reverse travel. Two different discriminating radar obstacle sensors with different outputs are evaluated. This study reviews the safety of human exposure to emissions from these radar sensors; documents the field of view obtained from experiments with the two systems; gives the results from experiments with sensors on lift trucks. The influence of obstacle reflectivity, composition and area on the size and shape of the radar detection zone are discussed. An experimental setup for measuring position and velocity of the obstacle crossing the truck path is described. The combination of obstacle sensors required for full coverage of the back of the lift trucks and the mounting height and angle are discussed.

DEDICATION

I would like to dedicate this research to my mother Mrs. Abosede Folusho Olarewaju and Dr. (Mrs.) Adebimpe Odetola whose sacrifices I appreciate. Also to my husband Olumide Folorunsho Odetola and my son Boluwatife Joshua Odetola who mean so much to me and gave me all the support I required to complete this study.

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INTRODUCTION

Background

Forklift trucks are the first choice for moving materials in factories and yards due to their versatility and the high density of people. Presently, 1% of factory accidents involve forklift trucks and 10% of these accidents lead to physical injuries (James 1984). Accidents involving lift trucks are usually blamed on operator errors but 25% of these accidents are usually caused by controllable environmental factors (Miller 1998). The operation of lift trucks therefore requires extra diligence during reverse travel because the stabilizing counterweight hampers the view and the operator must turn his or her head backward to get a better view.

The use of obstacle sensors on forklift trucks is relatively new. Girardi reviews the limitations of ultrasonic sensors for industrial lift truck applications in his paper SAE 96809 (Girardi, 1996). some of these limitations will apply to radar and optical sensors as well. The SAE standard "Discriminating Back-Up Alarm System Standard" required that these systems detect obstacles 100% of the time with not more than 10% inadvertent detection for them to be considered reliable (SAE J1741 June 1999).

Research Objective

The objective of this research is to evaluate two obstacle sensors, which operate on different principles, for application on industrial lift trucks. This evaluation includes: determining the field of view (detection zone) of the sensors; investigating the effect of obstacle orientation and shape on detectability; identifying any permanent blind spots; investigating the range in the size of objects that can be detected; determining the influence of obstacle material on detectability; determining the effect of rain and vibrations on the performance of sensors. The desirable detection range suitable with the steering geometry of lift trucks will be analyzed.

The stopping distance required to prevent collision for two different lift trucks at different speeds of travel will be estimated. This is necessary to allow enough distance between the truck and obstacle for the operator to prevent collision when the alarm sounds. Factors like operator and system reaction time will be determined as well. The results obtained from this research will be used to configure and mount obstacle sensors on industrial lift trucks. The occurrence of false detection will be noted during the course of the experiments.

Problems with Backup Alarms

Problems that may be encountered in the use of backup alarms/object detection systems include: habituation, filtering, ambient noise, dependency and fatigue. These factors will be discussed briefly

Habituation may occur when the operator or pedestrians get used to hearing the alarm and cease to recognize it as a warning signal. This may be addressed by reducing the frequency of false alarms so each warning is taken seriously. The warning signal may either be in form of sound or Light Emitting Diode (LED) display. The operator should always look over the field of travel to ensure that it is safe to backup. Filtering may occur if people condition their senses to respond only to warnings they consider important and ignore those that are less important. This is very dangerous because no warning signal should be ignored. This problem may be addressed by conducting safety drills often to see how people respond to warnings. Ambient noise is the noise level of the operating environment. If the ambient noise is very high then it might overshadow the sound of the warning. The obstacle sensors under study have warnings both in form of sound and LED indicators. The allowable ambient noise level should be at least 10 dB lower than the sound level of the alarm (SAE J994 August 1993). Dependency may occur when the operator gets accustomed to people responding to the alarm and leaving the forklifts' path of travel. The operator might become less vigilant under these conditions and may reduce the effort to ensure that the path of travel is clear. Habituation and filtering, mixed with dependency are a recipe for disaster. Fatigue simply affects the operator's response to a warning signal. Fatigue may lead to an increase in the actual stopping distance due to an increase in the human perception time and reaction time.

Radar Systems

Currently, there are several radar obstacle detection systems available for lift truck application but only two of these radar detection were investigated. These two systems operate on different principles and have different features described below.

Principle of Operation

The obstacle sensors use radio detection and ranging (RADAR) to extract information about the target's position. Radar systems transmit signals in form of electromagnetic waves from the antenna. The signal travels from the source to the target where it is reflected back to the receiver antenna. The difference in the parameters of the transmitted signal and the received signal are then used to extract information about the target. Information that may be obtained includes position, speed, height and size of target. The distance to the target is obtained from the time lapse between the received and the transmitted signal. The size of target is directly proportional to the power of the received signal. The relationship between these parameters used for radar devices is given by equation 1-1.

$$P_R = \frac{KP_T}{R^2} \tag{1-1}$$

Where,

P_R is the received power

P_T is the transmitted power

R is the distance to the target

K is the constant of proportionality that depends on the antenna gain, cross-sectional area of target and effective area of the antenna.

If the target approaches the antenna, the reflected signal increases in frequency. Conversely, the reflected signal becomes expanded due to an increase in frequency as the target moves away from the antenna. This is illustrated in Figures 1.1 and 1.2.

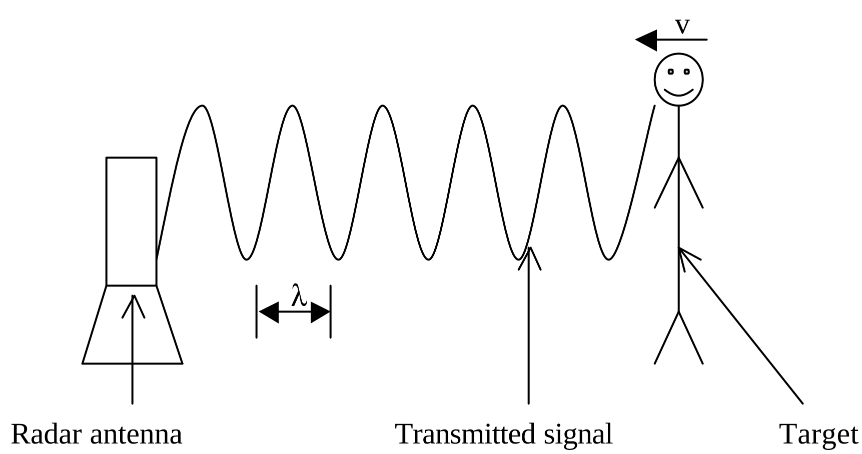

Figure 1.1: Transmitted signal from radar system with wavelength, λ

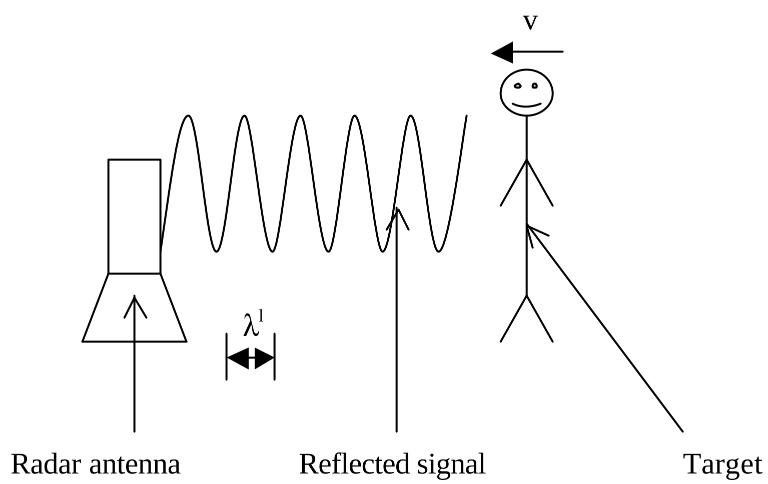

Figure 1.2: Reflected signal from target leading to a change in signal parameters: $\lambda > \lambda^1$

Radar systems may be continuous wave or pulsed radar. The main purpose of a pulse radar system is to locate, detect and measure the range of targets. The continuous wave (CW) radar systems are used to obtain velocity measurements of the target and the transmitter sends out signals constantly. The two systems used for this study represent the two systems described above. Both systems may be reconfigured to change some parameters, but the parameters that can be changed in each system differ.

Description of Sensors

Two different radar systems are used in this study. The first system is manufactured by Preco Electronics and the other by Sense Technologies.

The Preview Obstacle Sensor

The Preview obstacle sensor is manufactured by Preco Electronics and operates using the pulsed radar principle to detect both moving and stationary objects. This system gives the vehicle operator information about the distance to the closest object by visual indication of light emitting diodes (LED) and an audible signal. This system consists of three major parts, a 5.8 GHz radar sensor enclosed safely in a case, a display unit that may be mounted in the cab with the operator and an external backup alarm. The operator display provides a row of 5 LEDs that indicate the distance of the unit to the detected object. The number of LEDs illuminated depends on the distance to the detected object. If the object is close, more LEDs will be illuminated. The distance may be adjusted, but the maximum distance is 8 meters (26 feet). The system operates with a minimum voltage of 9.8 volts and a maximum of 33.0 volts.

The Guardian Alert Obstacle Sensor

The Guardian Alert is manufactured by Sense Technologies and the system operates using the Doppler radar principle. This system detects only when there is a relative movement between the sensor and the obstacle. The information about the distance to the closest object detected is given to the vehicle operator by visual indicators (LED) and an audible signal. This system consists of three major parts, which include a 10.525 GHz radar sensor pulsed at a 12% duty cycle. The sensor is a range-gated microwave Doppler radar enclosed safely in a case, a display unit that may be mounted in the cab with the operator, and an external backup alarm. The operator display provides a row of 3 LEDs that indicate the degree of danger for impact with the detected object. The combination of LEDs illuminated depends on the distance to the detected object. The distance may be adjusted, but the maximum distance is 35 feet. The Guardian Alert comes with heavy-duty lights that may be used with the LED, only one of these display units may be used at a time. The system operates with a voltage of 12 volts.

Settings of the Obstacle Sensors

The settings of an obstacle sensor are determined by how it is programmed, which is briefly described below. The settings of the sensor will determine the beep rate of the alarm, the detection range of the sensor, and the velocity of obstacles to be detected for the Doppler radar. The settings will influence the occurrence of false alarms also.

Settings of the Preview Obstacle Sensor

The Preview obstacle sensor can be programmed by configuring the sensor to suit the end user. Both the sensor and the display can be programmed. Some of the parameters that can be programmed are the sensor ID, the sensor type, the range, the pattern and the sensor calibration.

The sensor ID is used to identify each sensor in a multi-sensor detection system. The value of the ID can range from 1 – 254. The sensor ID is relayed to the Preview display, which uses this number to determine the acceptance of data from the sensor. The sensor type indicates the location of the sensor on the vehicle, and this information is also conveyed to the Preview display. The sensor range defines the length of the detection zone. Standard settings for detection range may be used or the sensor range may be customized. The pattern of the sensor defines the shape of the Preview sensor detection zone and the program has a predefined set of shapes. The predefined shapes are rectangular, cone and side patterns. The Preview enables the user to customize the pattern by allowing the entry of a sequence of 52 values that control this variable. The calibration of the Preview sensor serves as a means to get the sensor to overlook static objects that are part of the vehicle on which the sensor is mounted.

The Preview display properties that may be configured include the display ID, display type, maximum number of sensors, sensor IDs, LED mode and buzzer mode. The Preview display ID is the parameter used to identify each display in a multi-display detection system. The Preview display ID can range from 1 – 254. The display type indicates the location of the sensor on the vehicle from which the Preview display will receive information. Preview sensors will only receive data from displays that match the sensor type. In a multi-sensor detection system, the Preview display must be programmed to know the number of sensors it will receive data from. This number varies from 1 – 31 sensors. The in cab display can be configured to allow the audible warning signal (buzzer) and the LEDs to operate in certain scenarios. The buzzer can be turned OFF or allowed to operate while the vehicle is in reverse and the LEDs can operate in reverse only or continuously.

Settings of the Guardian Alert Obstacle Sensor

The settings of the Guardian Alert can be changed to suit specific applications by downloading programs furnished by the manufacturer. Programs are written by defining the sensor parameters. Parameters that may be customized by programming the Guardian Alert include: the number of ranges, the self test, Direction of Motion (DOM), Range (ft), Priority, Velocity (mph), Turn off seconds, Turn off inches, Alarm color and Alarm duration.

The "number of ranges" can vary from 1 to 8 and dictates the number of independent ranges that the user wants the sensor to detect obstacles. The "self test" can be turned either ON or OFF. Switching the self test ON makes the display beep once when the operator switches to the reverse gear to indicate that the sensor is functional. The DOM can either be turned ON or OFF and it is functional when it is ON. The DOM sensor parameter enables the sensor to be more discriminating about the obstacle detected. The sensor alerts the operator only if the distance between the truck and obstacle(s) detected is decreasing. With good programming, this will help decrease the occurrence of false alarms, i.e. alarms for situations which pose no danger.

The "Range" describes the radial distance from the sensor in which obstacles are detected. The Range value can vary from 1 – 35 feet. The Range works together with the number of ranges selected. Priority can vary from 1 – 10 with a default value of 5. The Priority parameter defines how fast the sensor detects an obstacle within a range gate and overrides previous decisions. Velocity is a very important sensor parameter for the Guardian Alert due to the fact that a Doppler sensor requires motion to identify an obstacle. The velocity parameter can vary from 0 –15 mph. The zero mph setting indicates that there is no velocity discrimination. The "Turn off seconds" defines how long the alarm is active after the relative movement between sensor and obstacle is detected. The "Turn off seconds" can be varied from 1 – 10 seconds. The "Turn off inches" defines the distance of sensor away from the point of obstacle detection to the obstacle, before the audible warning signal is stopped. The turn off inches can be varied from 1 – 24 inches if the DOM is ON.

The "Alarm color" describes the form of visual display, the LEDs. The LEDs may either be red or yellow and different colors may be assigned to each range gate. Alarm "duration" defines the beep and flash rate that the display applies to the alarms within each range gate as programmed by the user. This parameter ranges from 0 – 9.

A good understanding of the settings of these obstacle sensors is required. The detection range obtained from the sensors is determined by the settings of the sensors.

Literature Review

The Society of Automotive Engineers (SAE) has compiled a standard for testing discriminating backup alarms systems (SAE J1741 June 1999). This standard describes the test procedures for evaluating the performance of these detection devices. It also addresses the minimum detection area behind any machine, the system false detection requirements, and the audible and visual information presented to the operator. The standard also includes the operator system function test and maintenance procedures.

Johnson, Guy A. *et al* (1986) conducted a series of tests on different obstacle sensors for mining applications and reported the results in the United States Bureau of Mines Information

Circular 9079. The experiments were conducted with obstacle sensors with infrared, ultrasonic and Doppler technologies to evaluate their performance on mining equipments in 1986. These sensors were evaluated to see whether they were capable of detecting objects at the rear of mining equipment. From these tests it was concluded that Doppler radar technology was the best of the three different types of technologies. Doppler radar systems use the Doppler shift principle to detect objects. The detection zone of Doppler radar systems have the shape of a tear drop. From these experiments it was observed that the power output, sensitivity, reflectivity from obstacle, the shape of the antenna and the radar profile determine the detection range. The detection zone obtained for bigger, more reflective obstacles had a wider range. Some of the in-mine test demonstrated that a system that detects a person at a distance of 20 feet would detect a small car at 40 feet and a large metal building at several hundred feet. One advantage of Doppler radar sensors is, that it is not affected by lighting, rain, fog, wind or snow like the other sensors per this report.

Girardi, Walter J. (1996) performed experiments to analyze the limitations of ultrasonic sensors on lift trucks. The tests were conducted to check the ability of the ultrasonic sensors to eliminate false signals, eliminate habituation and reduce the amount of noise introduced into the environment by warning signals from these alarms. The test results detected a rectangular wood target (38 mm x 140 mm x 1219 mm), with the obstacle sensor mounted 1143 mm above the ground. The detection zone obtained was a cone 4318 mm in height; 1118 mm in diameter and vertex located 0.0348 mm from the face of the sensor. This conical shape limited the coverage directly behind the lift truck because a person in the 95% percentile crouched behind the truck would not be detected. The sensor detected objects 635 mm – 1753 mm above the floor longitudinally placed along the centerline of the sensor. The ultrasonic sensor has the potential to reduce the level of noise pollution created by the warning alarm. With centerline of the obstacle sensor mounted laterally 102 mm and 699 mm above the ground. The sensor detected objects 140 mm – 1257 mm above the floor longitudinally placed along the centerline of the sensor. The sensor centerline was located at 1143 mm above the floor and tilted 13.5^0 downward. At this position the sensor detected objects ranging from 51 mm – 1143 mm above the above the floor, located longitudinally along the centerline. Objects 1143 mm above the floor, not extending to the floor surface were not detected until they were within 0.0348 mm from the face of the sensor. Habituation problems remain the same and when the sensor was mounted too low the occurrence of false signals increased due to the detection of objects which were not detected when sensor was mounted at a higher position.

Ruff (2001) tested some collision warning systems including the Preview and the Guardian Alert obstacle sensors and gave the results in the National Institute for Occupational Safety and Health (NIOSH) Report of Investigations 9654. The test was performed on mining equipment in a graded test area approximately 60m by 30m. The obstacles to be detected were a three ton, four-wheel drive pickup truck and a man between 178 – 191 cm (70 – 75 inches) tall. The first sensor was mounted at a height of 1.3 m. If this sensor was mounted less than 1.3 m from the ground it would constantly detect the bed of the dump truck. The reliable detection zone for this human target extended from the sensor out to 9.1 m when placed in the rear of the truck. Some irregular detection was observed at the fringes of the detection zone. The reliable detection zone for the pickup truck covered the width of the dump truck and extended from the sensor out to 8.4m when placed in the rear of the truck. There were no false alarms when the truck was moved forward in a clear field. The detection zone of a cinder block ranged from 4.6 – 9.1 m away from the sensor. Lower mounting height caused this system to be more sensitive to object that were lying low. The second obstacle sensor was mounted 2.7 m high and tilted downward at 10^0. This obstacle sensor generated an alarm when the truck's gear was switched or when the brakes were applied suddenly. The detection zone of a person walking toward the stationary dump truck was 6.1 m from a distance close to the tires; the width of the zone was only 3 m. The detection zone of a slowly driven pickup truck was 10.7 m from a distance close to the tires, the width of the zone increased to 9.1 m. From this research it is observed that the mounting height and angle, the size of obstacle, the technology behind the operation of the sensor, and the composition and orientation of the obstacle will affect the detection zone of radar obstacle sensors.

Thesis Overview

This thesis is simply based on obtaining the field of view of the obstacle sensors under study and determining their reliability. Chapter II discuses the safety required for operation of the obstacle sensors and how they conform to the safety standards for radar devices. Chapter III discusses the stopping distance relative to the operation of the lift truck equipped with these sensors. It also discusses the use of the knowledge obtained about stopping distance in the configuration of the obstacle sensors. Chapter IV gives a description of the test for collecting data manually and automatically. A description of the data collection system and the devices that make up the data collection system is also given. Chapter V gives a description of the experimental procedures for obtaining the field of view of the two sensors both manually and automatically, and some procedures to mount the sensors on lift trucks to obtain the maximum detection zone with minimum occurrence of false alarms. Chapter VI presents the results of the field of view obtained from the manual experiments and automated experiments for both sensors. Finally, Chapter VII gives the conclusions and recommendations of this study.

CHAPTER II

RADIATION LEVELS OF OBSTACLE SENSORS

Introduction

The obstacle sensors in this study use radio frequency (RF) waves to detect the presence of objects within their range of coverage. One system uses Doppler radar, which requires relative motion between target and sensor, while the other system uses pulsed radar, which will sense objects in the field regardless of the relative velocity. The Institute of Electrical and Electronic Engineers (IEEE) and The Federal Communications Commission (FCC) have published rules and standards to ensure that radar devices are safe for human usage. This section presents the standard requirements relative to the emission levels of these two systems.

Standards Governing Human Exposure to RF Emissions

Radar systems must conform to IEEE or FCC standards before their usage is allowed. Each of these standards differs in the magnitude of the factor of safety. The guideline first adopted by FCC was in 1985 to evaluate the human exposure to Radio frequency (RF) emissions. The new guideline dated 1999 states the limits for Maximum Permissible Exposure (MPE) in terms of electric and magnetic field strength and power density for transmitters operating at frequencies between 300 kHz and 100 GHz.

Power density (W/m) is a measure of the power generated by a transmitter, while electric field strength is the strength of the electric field created by the transmitter (V/m). The magnitude of power transmitted varies with the distance from sensor as illustrated in Table 2.1. As the transmitted power increases, the distance to the limit also increases for a constant frequency of operation.

Table 2.1

ESTIMATED DISTANCES TO RF POWER DENSITY LIMIT

Frequency of operation: 144 MHz Controlled limit: 1 mw/cm^2 Uncontrolled limit: 0.2 mw/cm^2		
Transmitter power (watts)	Distance to controlled limit (meters)	Distance to uncontrolled limit (meters)
10	3.11	6.95
100	9.83	21.98
500	21.98	49.16
1500	38.08	85.14

The commonly used relationship between power and electric field strength is given by equation 2-1. A more accurate relationship between power and electric field strength depends on some additional factors. Free space impedance is 377 ohms.

$$\frac{PG}{4pD^2} = \frac{E^2}{120p} = \frac{E^2}{377} \qquad (2\text{-}1)$$

Where,

P is the transmitter power (watts)

G is the numerical gain of the transmitting antenna relative to an isotropic source

D is the distance from the electrical center of antenna to measuring point (meters)

E is the field strength (Volts/meter).

The new MPE limit includes some factor of safety. This limit is based on the exposure criteria quantified in terms of specific absorption rate (SAR). The basis for the limit is a whole-body averaged SAR threshold level of 4 watts per kilogram (4 W/kg), as averaged over the entire mass of the body. Expert organizations have determined that potentially hazardous exposure may occur at SAR greater than 4 W/kg.

One of these devices under study transmits and receives at a frequency of 5.8 GHz while the other transmits and receives at a frequency of 10.525 GHz. The safety of these devices is obtained by comparing the power density of RF emission to the MPE as required by the IEEE and FCC standards. This safety check falls under class B, which is MPE for uncontrolled environments. The environment is defined as “controlled” if all the people that will be exposed to the system are aware of the hazards involved with the emissions. If the people are not made aware of the hazards of exposure to the radio frequency waves, the environment is classified as “uncontrolled”.

The FCC standards for controlled and uncontrolled exposure are given in Table 2.2 and Table 2.3. These tables for these two standards differ in the factor of safety at higher frequencies of operation. This is due to the fact that the FCC limit combines the IEEE and other standards.

Table 2.2

FCC MPE LIMIT FOR CONTROLLED OCCUPATIONAL EXPOSURE (FCC, 1999)

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes)
0.3-3.0	614	1.63	(100)	6
3.0-30	1842/f	4.89/f	($900/f^2$)	6
30-300	61.4	0.163	1.0	6
300-1500	--	--	f/300	6
1500-100,000	--	--	5	6

Table 2.3

FCC MPE LIMIT FOR GENERAL POPULATION UNCONTROLLED EXPOSURE (FCC, 1999)

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes)
0.3-1.34	614	1.63	(100)	30
1.34-30	824/f	2.19/f	($180/f^2$)	30
30-300	27.5	0.073	0.2	30
300-1500	--	--	f/1500	30
1500-100,000	--	--	1.0	30

The FCC Technical Standard part 15 for uncontrolled exposure (class B) given in Field Strength is presented in Table 2.4. The limit is expressed in decibels. The relationship between microvolts per meter (μV/m) and decibels of microvolts per meter (dBμV/m) is given in equation 2-2.

$$20\log_{10}\left(\frac{\mu V}{m}\right) = dB\frac{\mu V}{m} \qquad (2\text{-}2)$$

Table 2.4

FCC TECHNICAL STANDARD GIVEN IN FIELD STRENGTH (FCC, 1999)

5.785 – 5.815 GHz	Spread Spectrum	1 Watt Output Power
	Field Disturbance Sensors	500,000 µV/m (114 dBµV/m) @ 3 m
	Any	50,000 µV/m (94 dBµV/m) @ 3 m

The IEEE standards for controlled and uncontrolled exposure are given in Table 2.5 and Table 2.6 shown below.

Table 2.5

IEEE MPE FOR CONTROLLED ENVIRONMENTS (IEEE, 1996)

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes)
0.003-0.1	614	163	(100, 1,000,000)	6
0.1-3.0	614	1.63/f	(100, $10,000/f^2$)	6
3-30	1842/f	1.63/f	($900/f^2$, $10,000/f^2$)	6
30-100	61.4	1.63/f	(1.0, $10,000/f^2$)	6
100-300	61.4	0.163	1.0	6
300-3,000	--	--	f /300	6
3,000-15,000	--	--	10	6
15,000-300,000	--	--	10	$616,000/ f^{1.2}$

Table 2.6

IEEE MPE FOR UNCONTROLLED ENVIRONMENTS (IEEE, 1996)

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes)	
0.003-0.1	614	163	(100, 1,000,000)	6	6
0.1-1.34	614	16.3/f	(100, $10{,}000/f^2$)	6	6
1.34-3.0	823.8/f	16.3/f	($180/f^2$, $10{,}000/f^2$)	$f^2/0.3$	6
3.0-30	823.8/f	1.63/f	($180/f^2$, $10{,}000/f^2$)	30	6
30-100	27.5	$158.3/ f^{1.668}$	(0.2, $940{,}000/f^{3.336}$)	30	$0.636\ f^{1.337}$
100-300	27.5	0.163	0.2	30	30
300-3,000	--	--	f /1500	30	
3,000-15,000	--	--	f /1500	90,000/ f	
15,000-300,000			10	$616{,}000/ f^{1.2}$	

The term “f” in the tables refers to the frequency of operation (Hz). These MPE limits specify the averaging time. This implies that it is permissible to exceed the recommended limits for short periods of time as long as the average exposure over the appropriate period specified does not exceed the limit.

Evaluation of Obstacle Sensors

The results of the safety evaluation of the Preview and the Guardian Alert sensors are presented below. Most RF safety limits are defined in terms of electric and magnetic field strengths as well as power density. But, for lower frequencies the limits are better expressed in terms of electric and magnetic field strengths values and the indicated power densities are actually “far-field equivalent” power density values (FCC OET Bulletin 56 4th ed, 1999).

Safety Evaluation of the Preview Obstacle Sensor

This device was evaluated for safety using the test results obtained from the manufacturer. This evaluation was based on the FCC standard – part 15 class B, for uncontrolled environment. Most part 15 emission limits are specified in field strength. This device has a peak field strength of 92.7 dBμV/m at a position 3 meters from the center of the antenna. The radar emission from this device is considered to be safe because the standard gives a maximum limit for field strength of 114 dBμV/m at 3 meters away from the centerline of the sensor.

Safety Evaluation of the Guardian Alert Obstacle Sensor

This device was evaluated for safety using the test results obtained from the manufacturer. The evaluation was based on the IEEE standard for uncontrolled environment. A duty factor of 1.0 is equivalent to continuous wave (CW) operation. This device in the CW mode transmits a total power that is less than 15 mW. This power is distributed within a coverage pattern of the radar sensor, and the maximum power density is 1 mW/cm^2 at a distance 0.05 m from the front of the device. This value reduces to 0.72×10^{-3} mW/cm^2 at a distance 1 m away from the centerline of the antenna. When operated in the pulsed mode (the normal operating mode), with a duty cycle of 5% these values become 50×10^{-3} mW/cm^2 and 0.036×10^{-3} mW/cm^2 respectively. The radar emission from this device is considered to be safe because the standard gives a maximum limit for power density of f/1500 mW/cm^2, which is 7.0 mW/cm^2 at a distance 0.05 m from the centerline of the sensor.

CHAPTER III

DISTANCE TO OBSTACLE, STOPPING DISTANCE, VELOCITY RELATIONSHIPS

Introduction

The obstacle sensors of this study are backup aids and not sole methods for rear collision prevention. The sensors only indicate the presence of a hazard at a given distance from the vehicle. The detection would be useless if sufficient time is not allowed for the operator to stop the truck before colliding with the detected object. The distance it takes to stop the vehicle in order to avoid collision varies primarily as a function of speed, the perception time, response time, reaction time and braking time, which is a function of coefficient of traction, braking torque, tire radius, vehicle weight distribution, etc. A study of stopping distance will establish the relation of the vehicle speed to the activation of the obstacle detector's signal. The use of this "stopping distance" will be different for the two sensors because they operate on different principles.

The Total Stopping Distance

The actual stopping distance is the distance a truck travels from the time the obstacle enters the sensor's detection range until the truck stops. Factors that affect the actual stopping distance include the initial velocity of the vehicle, the perception time, the response time, reaction time and braking time, which varies with drag. Taborek, Jaroslav J.(1957), stated in the series "Mechanics of vehicles" that air resistance has little effect on stopping distance except at higher initial speeds. When descending grades, it takes a longer time to stop due to gravity pull downhill as illustrated in Figure 3.1, which shows the forces acting on a vehicle when decelerating downhill. All of these factors are important parts of the actual stopping distance and are discussed in this chapter. The approximate theoretical stopping distance on dry clean asphalt, brushed concrete or an equivalent surface is given by Equation 3-1 from Safety Standards for Low Lift and High Lift Trucks (ASME 1993), where the drawbar drag force includes the retarding force between tire and road surface due to braking (F_B), the rolling resistance (F_{RR}), the component of gravity force parallel to the road surface (F_G), and any force externally applied to the truck due to pulling or pushing a load (P).

$$F_{RR} = C_R W \cos\theta$$

$$F_G = W \sin\theta \approx W \tan\theta = WG / 100$$

$$F_D = F_B + F_{RR} - F_G + P$$

Where,

W = Weight of vehicle plus pay load

C_R = Coefficient of Rolling Resistance

θ = Angle of Grade

G = Grade, %

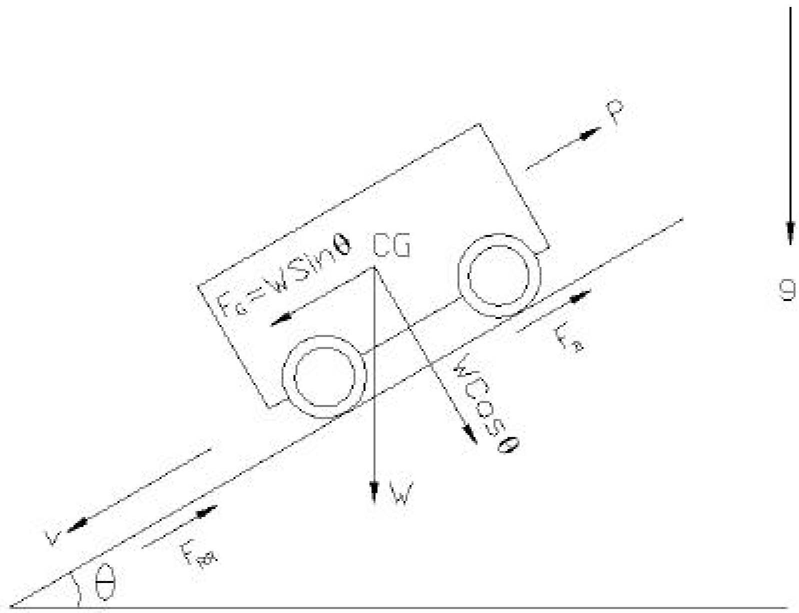

Figure 3.1: Forces acting on a vehicle moving downhill

$$s = \frac{3.34v^2}{D} \tag{3-1}$$

Where,

s = approximate theoretical stopping distance (ft)

v = velocity (mph)

D = drawbar drag (%)

Equation 3-1 is obtained as shown below.

D = Force of Drawbar Drag x 100 / Total weight of Vehicle, %

$$D = \frac{F_D}{W}100\% \tag{3-2}$$

Where,

F_D = force of drawbar drag, lb

W = weight of vehicle, lb

From Equation 3-2,

$$F_D = \frac{WD}{100} \tag{3-3}$$

From the Newton's laws of motion,

$$v_f^{\ 2} - v_i^{\ 2} = 2as \tag{3-4}$$

Where,

v_f = Final velocity, fps

v_i = Initial velocity, fps

s = Stopping distance, ft

a = Constant acceleration (The force to accelerate vehicle is assumed to be constant due to braking and grade).

From Equation 3-4 for a final velocity of zero, the stopping distance is:

$$s = \frac{v_i^{\ 2}}{2a} \tag{3-5}$$

Newton's law for force and acceleration of truck on grade,

$$a = \frac{F_D}{M} \tag{3-6}$$

Where,

g = 32.17 ft/sec^2, Gravity constant

M = W/g = Mass of truck

Substituting Equations 3-3 and 3-6 into Equation 3-5, gives the stopping distance:

$$s = \frac{100 v_i^{\ 2}}{2gD} \tag{3-7}$$

Substituting the value of g and doing some units conversion gives Equation 3-1. It should be noted that Equation 3-1 does not include the response, perception and reaction time. To include the perception time, the reaction time of the operator and the response time of the sensor, Equation 3-1 is modified by adding the distances covered during each of these times. The actual distance traveled before stopping is given by Equation 3-8.

$$S = vt_R + vt_p + vt_r + \frac{3.34v^2}{D} \tag{3-8}$$

Where,

S = actual travel distance, ft

v = speed of travel of the truck, mph

t_R = response time of sensor, sec

t_p = perception time of the operator, sec

t_r = reaction time of the operator, sec

Response Time

The "response time" is the time required for the obstacle sensor to detect the object in the detection zone and activate all warning systems (SAE 1999). The distance traveled during this time is a function of the initial speed of the truck and the response (detection) time of the sensor system. This distance is traveled before there is an indication of the hazard. The response time of these obstacle sensors are usually in milliseconds. For the Guardian Alert a highly reflective object gives a response time of approximately 16 milliseconds; however, a small object with low reflectivity could take about 128 milliseconds for response time or may not even sound the alarm. For the Preview, the maximum response time possible is 200 milliseconds. This is based on the eight 25 milliseconds sweeps for a detection signal. It takes a number of detections by the sensor before a response is sent to the display. Four detections are required for the Guardian Alert and eight for the Preview. This number affects the response time of the sensor. For an object with low reflectivity, the reflected signal might be so weak that the sensor loses the signal and the whole detection process will be started again.

The influence of response time of the sensor on the stopping distance of lift trucks is illustrated in Figure 3.2 for initial speeds of 16.6, 10 and 5 mph, and for t_p = 0.75 sec, t_r = 0.75 sec, D = 25 and G = 0. The increase in stopping distance is small due to the fact that the response time of the sensor is in milliseconds.

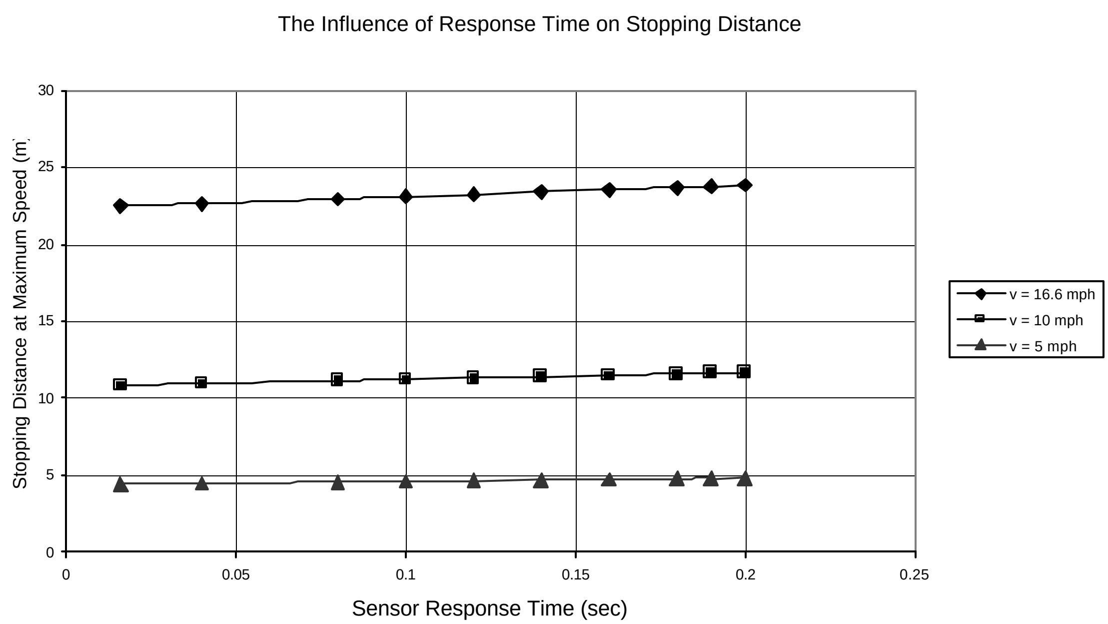

Figure 3.2: Stopping distance increases with sensor response time

Perception Time

The perception time is the time it takes the operator to see the hazard, and for him to recognize the situation as one that requires immediate action. Generally, perception time varies between 0.25 to 0.75 seconds (Safety Drive Training, 2002). The distance traveled during this time is a function of the velocity of the vehicle and the perception time. It is very important to look in the direction of travel during the operation of lift trucks because the earlier the hazard is recognized, the less the time required to stop the truck. Factors that can affect perception time include the condition of the operator. Tiredness, fatigue, concentration level, old age, alcohol, drugs and some medicines increase perception time. The influence of perception time on stopping distance of lift trucks for initial speeds of 16.6, 10 and 5 mph, and for $t_R = 0.20$ sec, $t_r = 0.75$ sec, D = 25 and G = 0 is illustrated in Figure 3.3.

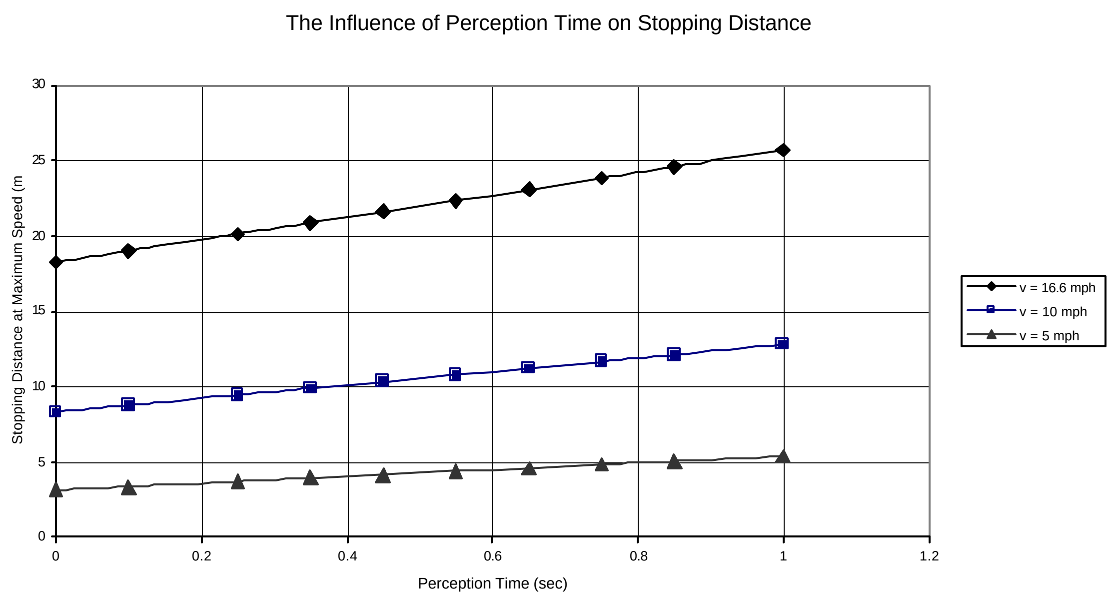

Figure 3.3: Stopping distance increases with perception time

Reaction Time

Some time elapses before the operator releases his foot from the accelerator and fully applies the brakes. This elapsed time is the operator's reaction time. Factors that can affect reaction time include the condition of the operator. Tiredness, fatigue, concentration level, old age, alcohol, etc. increase reaction time. Generally reaction time can vary between 0.25 to 0.75 seconds. The average reaction time for truck operators is 0.75 seconds (Girardi, 1996). The influence of reaction time on stopping distance of the lift trucks for a initial speeds of 16.6, 10 and 5 mph and for $t_R = 0.20$ sec, $t_p = 0.75$ sec, D = 25 and G = 0 is illustrated in Figure 3.4.

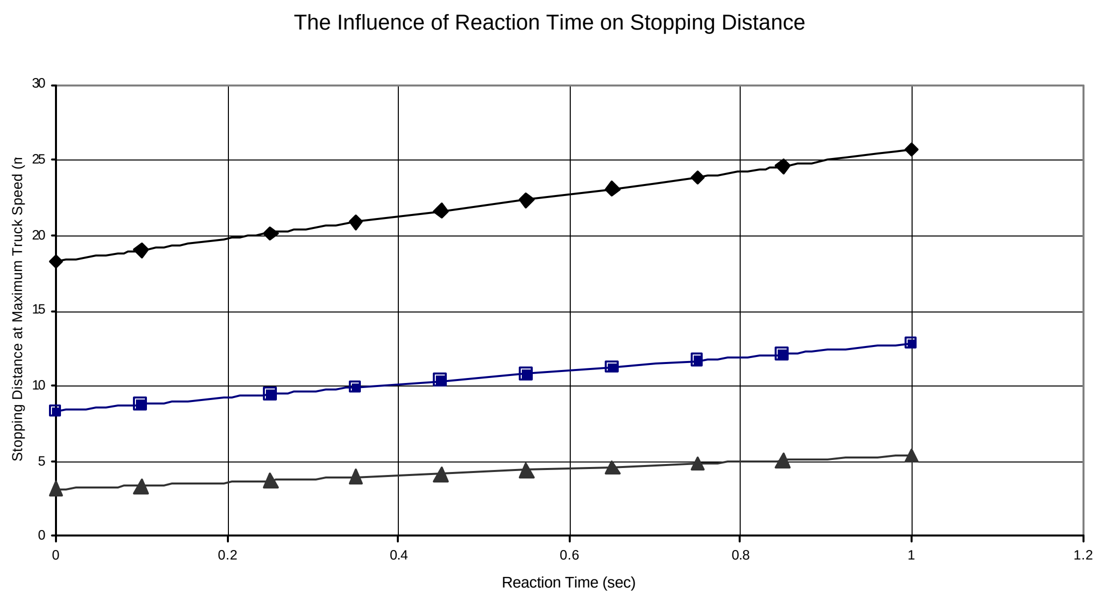

Figure 3.4: Stopping distance increases with reaction time

Braking Distance

This is the distance traveled before the truck comes to a rest, after the brakes have been fully applied. Factors that affect braking distance include vehicle speed, condition of tire/road interface (coefficient of traction and bumps), brake torque capacity, and the load on braking wheels. The greater the speed the longer the stopping distance required due to dissipation of higher kinetic energy. Braking distance is directly proportional to the square of the speed and inversely proportional to the drag force. The drag force is the resisting force developed between the tire and the road surface (rolling resistance and braking traction forces), which is augmented on inclined roadways by the component of the truck's weight force parallel to the roadway (F_G =

W Sinθ) and any drawbar pull or push forces. Excessive brake torque may cause the lift truck to tip over due to the high center of gravity and short wheelbase of this class of vehicles. Therefore, the brake torque for large trucks is limited to provide drag, D, of 20%. The braking distance is calculated using Equation 3-1. The "Drawbar Drag," D, includes the rolling resistance and friction force between the tire and road due to braking action. The value of D for forklift truck stopping distance evaluation is given in from Safety Standards for Low Lift and High Lift Trucks (ASME 1993) for $v \geq 8.33$mph maximum speed as D = 25%

The coefficient of traction between various roadway surfaces may be determined from Tractors and their Power Units (Barger, E. L. *et al*) as:

Table 3.1

THE COEFFICIENT OF TRACTION FOR DIFFERENT ROADWAY SURFACES

ROADWAY SURFACE	COEFFICIENT OF TRACTION
Concrete	0.68
Clay	0.58
Sand	0.42
Gravel	0.35

Effect of Speed on Stopping Distance

The effect of speed on stopping distance is very significant due to the fact that each component of stopping distance is a function of speed. If the best response time of the sensor is assumed to be 0.20 sec, the perception time is assumed to 0.75 sec and the average reaction time of a lift truck operator is assumed to be 0.75 sec, then the relationship between speed and stopping distance will be as shown in Figure 3.5 for different initial speeds. (t_R = 0.20 sec, t_p = 0.75 sec, t_r = 0.75 sec and G = 0).

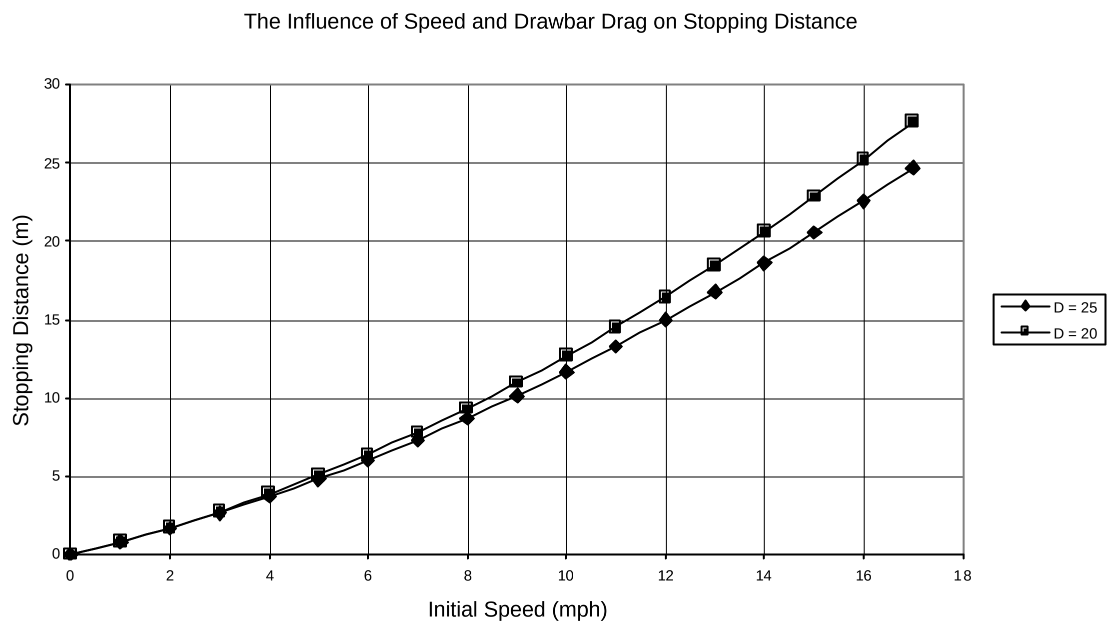

Figure 3.5: Stopping distance increases with initial speed values.

Dilich *et. al*. (2002), pointed out in their report "Evaluating Driver Response to a Sudden Emergency: Issues of Expectancy, Emotional Arousal and Uncertainty" that in the case of an emergency nobody can really predict what will happen. The settings of the alarm activation of the obstacle sensors require estimates of stopping distances. This study estimates the settings of distance between obstacle and sensor needed by an alert and skillful operator in order to stop the moving vehicle from an initial speed before the obstacle detected is hit. For example, if the maximum detection range for a human obstacle is set at 8 m, a vehicle with an initial speed of 8 mph or higher would strike the obstacle before the operator could stop if the operator's only warning was by the sensor. The setting of this distance at which the warning is sounded will vary with the application, operator, and truck.

CHAPTER IV

DESIGN OF TEST APPARATUS AND DATA COLLECTION SYSTEM

Introduction

Detection of an obstacle by the obstacle detection system is indicated by the activation of the LEDs. Hence, the performance of the system depends on monitoring the LED output.

The LED is energized when an obstacle is within the detectable range configured in the sensor. The "detectable range" for activation of the LED varies with the reflectivity and size of object being detected as well as the settings for the system. The LED may vary between "on" and "off" near the perimeter of the "detectable range" or cycle between range positions. Hence, the interpretation of results depends on the person observing the obstacle sensor and most likely will vary from one person to another. The interpretation of the number of LEDs energized is also subjective due to the fact that the duration of time that the LEDs stay on is difficult to quantify accurately. A computer controlled data acquisition system is designed to minimize these human errors in the recording of LED output. Some performance data is recorded without the computer controlled system and some with the computer controlled system.

Design of Apparatus

The obstacle sensors to be tested are mounted on stools with two spirit levels placed perpendicular to each other in the horizontal plane. The Preview is mounted on a stool with the centerline of the sensor about 25 inches from the ground. The Guardian Alert is mounted on a stool with the centerline of about 25.5 inches from the ground. The Preview is a larger system (7.56 inches high, 7.35 inches wide and 2.39 inches deep) than the Guardian Alert (3.00 inches x 3.00 inches x 1.50 inches deep). Figure 4.1 shows the mounting of the Preview sensor and Figure 4.2 shows that of the Guardian Alert. The test data may be manually collected from the devices of Figure 4.1 or 4.2 by viewing the LEDs as a pedestrian walks across the field of view of the sensor.

Figure 4.1: The mounting of the Preview sensor

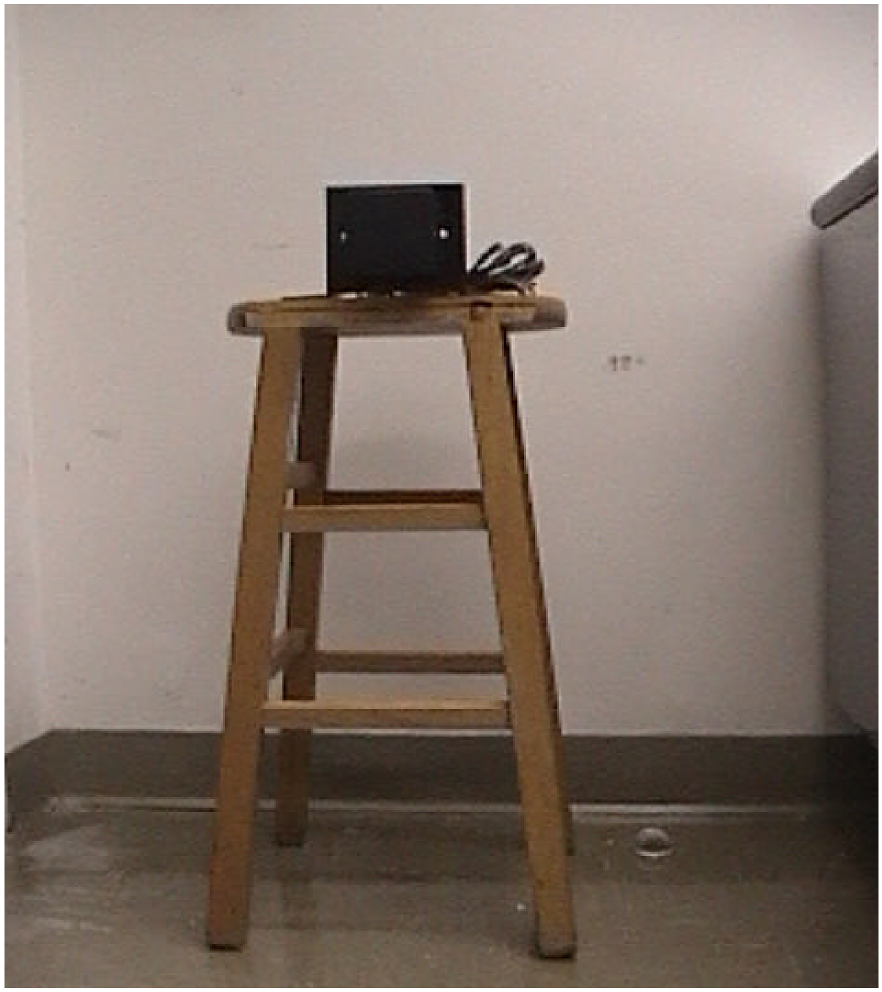

Figure 4.2: The mounting of the Guardian Alert sensor

Computer Controlled Test

In order to create a computer controlled test, the obstacle (pedestrian) is towed across the field of view by a cable, which rotates the pulley of Figure 4.3 and a rotary potentiometer. The position of the obstacle is defined as a function of voltage. In order to define velocity of the obstacle, the voltage defining position is recorded as a function of time. The position data (voltage) as well as data (voltage) indicating that an LED is “ON” or “OFF” are recorded by a computer controlled data acquisition system.

Obstacle Drive

The obstacle is pulled across the field of view by a wire cable per Figure 4.4. The apparatus used to run the experiments consists of a variable speed drill motor (1/2-horsepower) that provides the rotary motion required to wind a wire, which pulls the trolley carrying the test body (obstacle). The wire attached to the trolley is rolled on a 14.00-inch diameter pulley. A shaft connects the 14.00 inch pulley to the drill motor. The drill motor is held in position by bars connected to the test apparatus.

A ten-turn rotary potentiometer is used to obtain the displacement of the moving trolley that carries the obstacle. The output voltage from the potentiometer is proportional to the trolley displacement. The voltage across the potentiometer changes with the turns of the shaft as the wire winds up on the 14.00 inch diameter pulley as the trolley is pulled across the field of view of the sensor. Two rolling contact bearings support the 14.00-inch diameter pulley and transfer rotary motion to the friction clutch that limits torque on the potentiometer. A compression spring is used limit torque to the potentiometer.

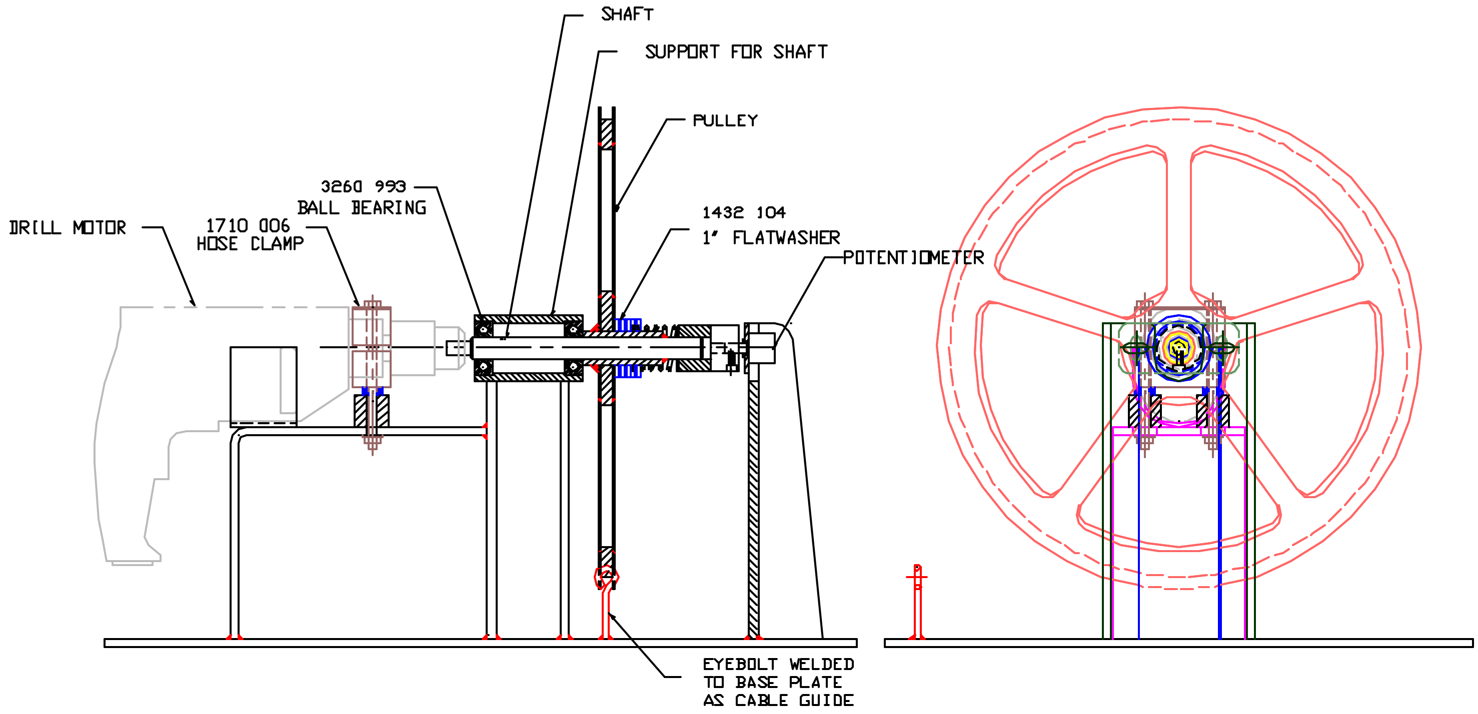

Figure 4.3: The side view of test apparatus; obstacle position drive

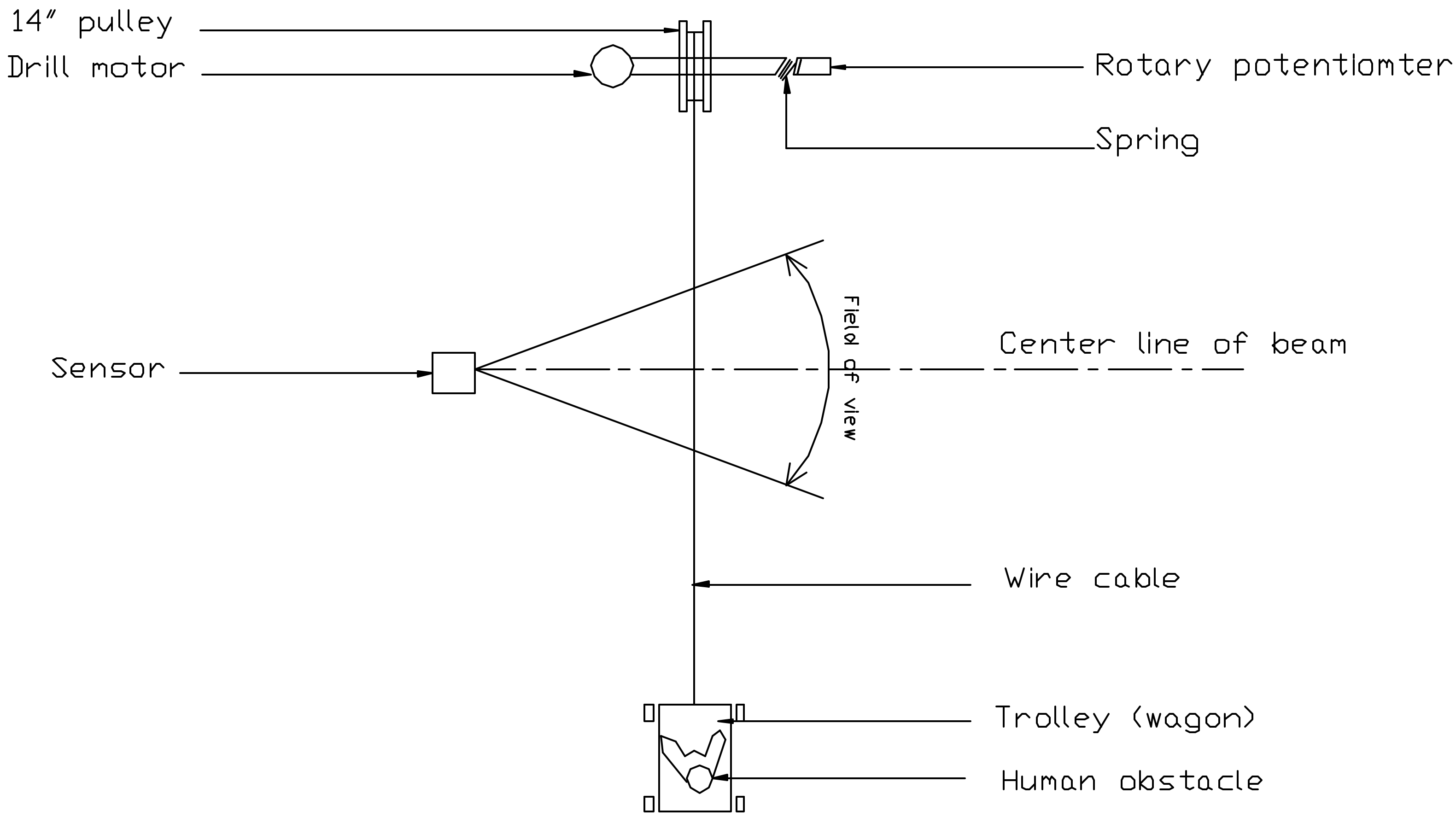

Figure 4.4: Trolley system with sensor position.

Data Collection System

The data acquisition (DAQ) system consists of a National Instruments DAQ card NI 6024 E installed in a personal computer, a National Instruments BNC-2110 shielded connector block, a potentiometer and the data acquisition software.

The wiring diagrams of the Preview and Guardian Alert obstacle sensors are illustrated in Figure 4.5 and 4.6. The potentiometer generates a voltage signal corresponding to the distance traveled by the trolley that rotates the 14.00-inch diameter pulley. The voltage signal from the potentiometer is fed into the connector block and measured. The DAQ system is controlled by the National Instruments LabView 6.1 program. The programs used for the Preview and the Guardian Alert obstacle sensors are shown in the Appendix. The signals sampled by the DAQ system as functions of time are:

1. Potentiometer voltage (trolley travel)
2. Voltage across each of the LEDs of obstacle sensor (five LEDs for the Preview and three for the Guardian Alert).

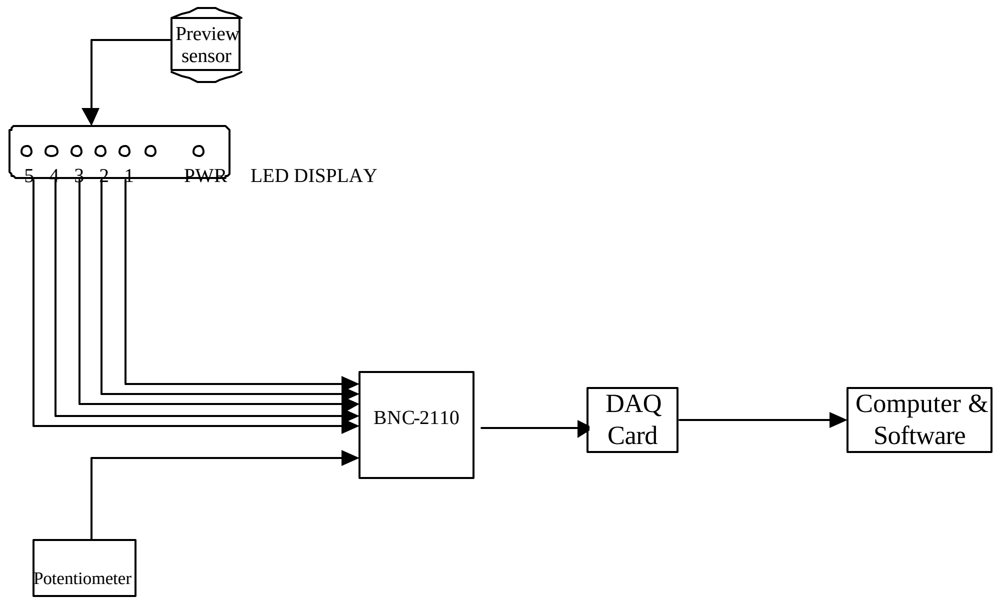

Figure 4.5: The Wiring diagram of the Preview and the connections of the data system

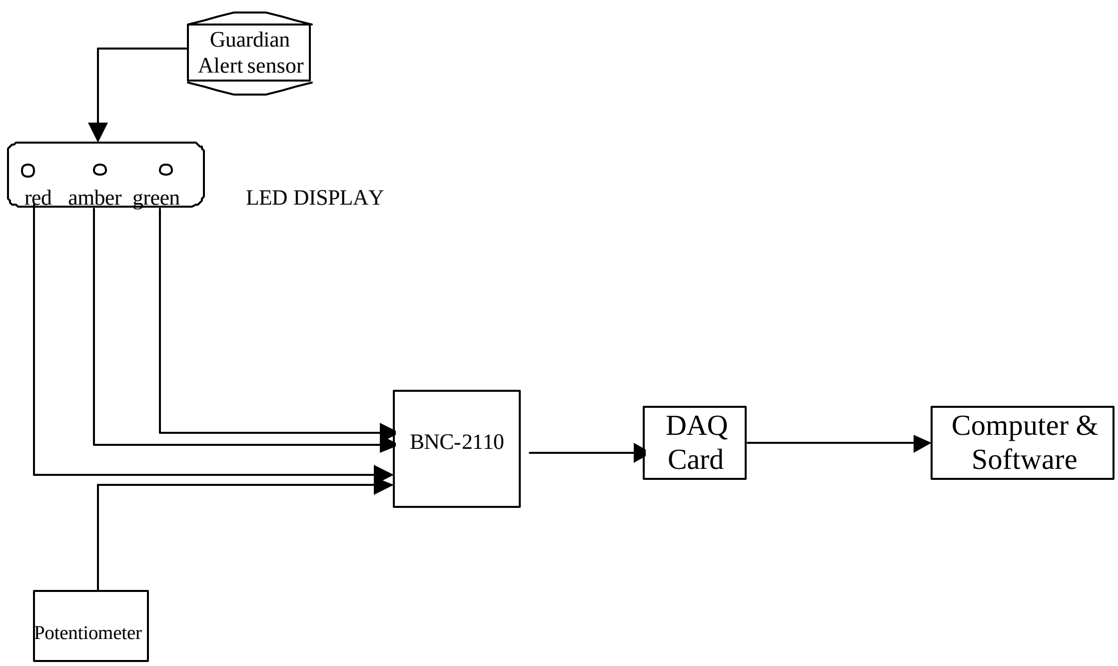

Figure 4.6: The Wiring diagram of the Guardian Alert and the connections of the data system

CHAPTER V

EXPERIMENTAL PROCEDURE FOR PERFORMANCE TESTING OF OBSTACLE SENSORS

Introduction

The detection range of an obstacle sensor is the area at the rear of the truck within which an obstacle should be detected by the sensor. The Guardian Alert obstacle sensor detects obstacles whose velocity relative to the truck exceeds some preset value when the distance between the truck and obstacle is decreasing. The Preview obstacle sensor detects obstacles independent of its relative velocity. The 3D-field of view of the sensors (i.e., the horizontal and vertical detection ranges of the sensors) is needed to design for proper location of the sensor on the truck. This field of view may be measured by experiment. This chapter describes the procedures for obtaining the field of view of the obstacle sensors. The field of view is determined manually and by an automated data collection system.

The test conducted on the Forklift trucks with these obstacle sensors have the sensors located to provide good coverage of the width and depth of the field of view for reverse travel based on data from the tests of sensors. The test area as specified by the SAE standard "Discriminating Back-up Alarm System Standard" SAE J1741 (SAE 1999) should be an open space with a smooth surface and no significant physical object within five machine lengths. Most of the manual test data are from tests performed indoors in a gymnasium that had a polished wooden floor or in a metal building with concrete floor. The data is for the two different devices, which were configured with different sensor settings and for different obstacle sizes.

Manual Measurements of the Field of View of Sensors

The manual tests on the device described above in section 4.2, but without the automated data acquisition system attached are described in this section. Tests are run for different configurations of the obstacle sensors. The obstacle sensor is placed at a reference point and the LED display is connected. Two spirit levels are used to ensure that the sensor is in a leveled position. A centerline is projected from the center of the stationary sensor and divided into increments at 0.5 m, 1 m, 2 m, 3 m, 4 m, 5 m, 6 m, 7 m and 8 m. The points of tests were chosen to conform to the SAE standard "Discriminating Back-up Alarm System Standard" SAE J1741 (SAE 1999). Tests are conducted by moving the target along lines perpendicular to the centerline at these increments.

The field of view of each sensor is obtained if the full detection range is split into two components, the horizontal and vertical detection range. The perimeter of the field of the field of view is obtained by plotting a line through the coordinates of the detection points on the perimeter. Detection points are coordinates of the obstacle's position when the system is actuated as the target moves into the field. The obstacle continues to move along this line normal to the centerline until all LEDs turn off and there is no detection as the obstacle moves out of the field. The points where detection is initiated and where detection is terminated are recorded after the experiment is completed.

Horizontal Detection Range of Sensors

The horizontal detection range for the Preview has the shape of a tear drop while that of the Guardian Alert has the shape of an irregular polygon. Objects out of the detection range will not be detected. This concept is best described graphically. The horizontal detection range of radar sensors is illustrated in Figure 5.1.

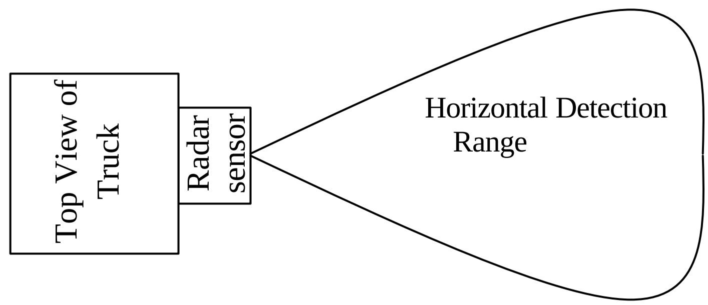

Figure 5.1: Figure showing the top view of the forklift truck and the horizontal detection range of a radar sensor.

Vertical Detection Range of Sensors

This describes the range in which obstacles will be detected by the obstacle sensor in the vertical plane. The vertical detection range may produce false alarms as the truck moves over undulating roadbeds. This concept is best described graphically. The vertical detection range of radar sensors is illustrated in Figure 5.2. The vertical detection range is obtained experimentally by installing the device with a 90^0 rotation about the centerline parallel to the ground. The results of the vertical detection range will be used to reduce the occurrence of the false alarms initiated by detecting the ground and to determine the minimum height of objects to be detected. The horizontal and vertical detection range work hand-in-hand to define the total volume of the field of view of obstacle sensors.

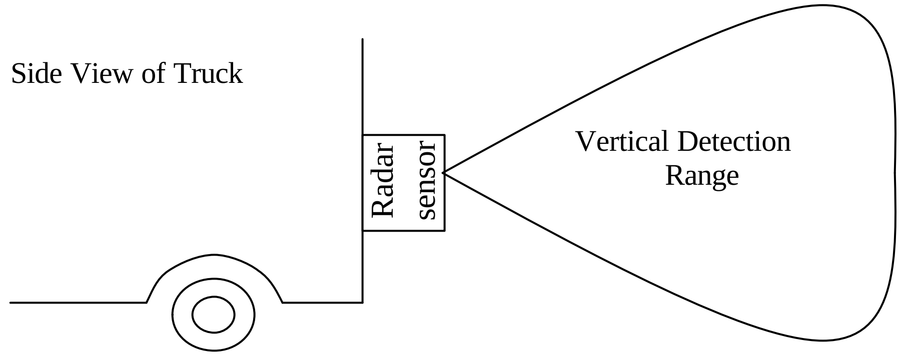

Figure 5.2: Figure showing the side view of the forklift truck and the vertical detection range of a radar sensor.

Automated Measurements of the Field of View of Sensors

The collection of data by an automated system is needed for the Guardian Alert obstacle sensor due to the dependence of this Doppler radar sensor on velocity, a vector and time dependent quantity. The Preview obstacle sensor measurement will benefit from the automated data collection system, but it is not required. The automated test is the same as the manual test procedure, except the obstacle is pulled through the field of view of the sensor at a constant velocity with a wire cable. The computer based data acquisition system records data for position versus time and data showing range signal lights as being ON or OFF versus time.

The procedure previously described in the section entitled " Manual Measurements of the Field of View of Sensors" is repeated with the automated data acquisition system for both the Preview and the Guardian Alert obstacle sensors.

Location of Sensor on Truck for Tests

The design for positioning of these sensors on the truck was simulated using the perimeter of the most conservative field of view given in chapter VI and CAD drawings of the sensors and lift trucks under study. The installed height of the sensor on the lift truck is very important because it will detect the ground if installed too low and will not detect obstacles close to the back of truck or close to the ground if installed too high. This simulation reduces the time spent on determining the "best" locations of these sensors on different trucks.

Location of the Preview on the Forklift Trucks

Three Preview sensors are mounted across the rear of the truck to obtain the desired width of field of view. The Preview is mounted on the lift truck TC 300S with the center of the sensor C, at least 0.33 m above the ground and tilted upward 9^0 per Figure 5.3. This should reduce the occurrence of false alarms. In the design for location of the Preview, the detection range data obtained from the smallest human (test body) is used. Three Preview sensors are spread across the rear of the truck to eliminate blind areas immediately behind the truck due to the teardrop shape of the field of view of each sensor. The outer sensors may be turned outward by 60^0 to include the path for a 90^0 turn within the field of view.

Location of the Guardian Alert on the Forklift Trucks

The Guardian Alert is mounted on the lift truck TC 300S at a height of 1.15 m from the ground and the sensor is centered at the back of the truck per Figure 5.4. This should reduce the occurrence of false alarms. In the design for location of the Guardian Alert, the average data for the horizontal and vertical detections are used. The rectangular pattern of the field of view of this sensor allows one sensor to cover the width of the truck. The position of the truck after a 90^0 turn is illustrated by the faint truck outline of Figure 5.4.

Tests of Obstacle Sensors on Actual Lift Trucks

The Sensors are installed on the lift trucks as described in the section entitled " Location of Sensors for Test". The Guardian Alert was mounted on the lift truck with the center of the sensor 1.15 m above the ground. Manual and automated tests are conducted to determine the detection zone at the back of the lift truck. The obstacle is pulled across the field of view of the obstacle sensor with a wire cable attached to the 14 in pulley diameter of the test apparatus at positions 0.5 m, 2 m, 4 m, 6 m and 8 m from the sensor.

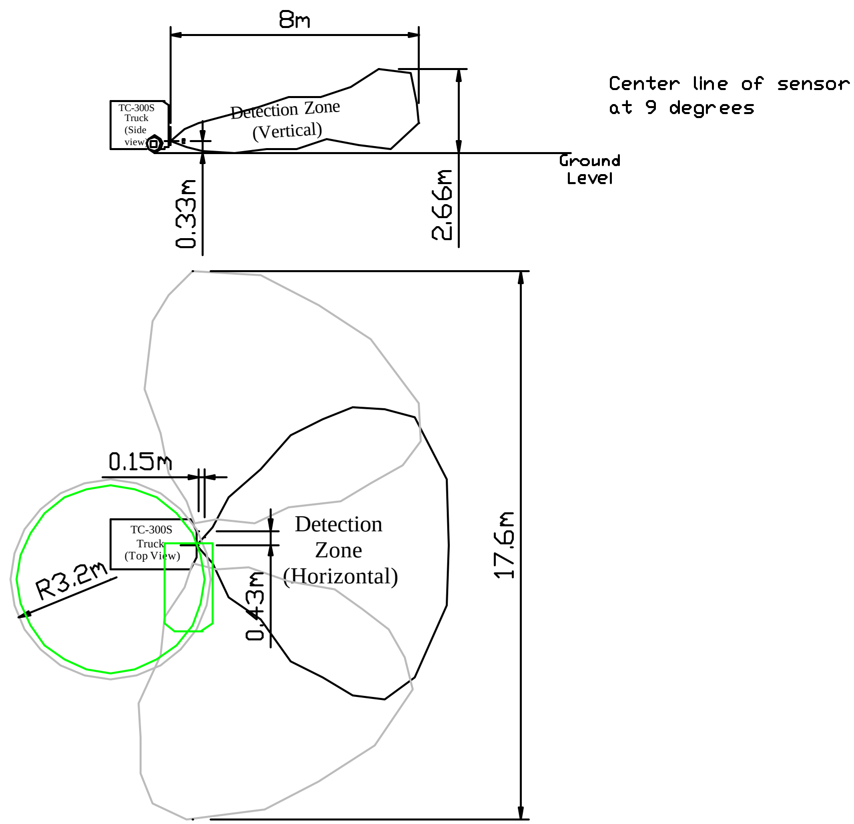

Figure 5.3: The position of three Preview sensors on TC 300S forklift. One is on the truck centerline and the other two sensors are located at 0.15 m ahead of the center sensor, 0.43 m from the truck centerline and rotated at 60^0 clockwise and counterclockwise respectively. The sensors are located with centers 0.33 m above the ground and tilted upward 9^0.

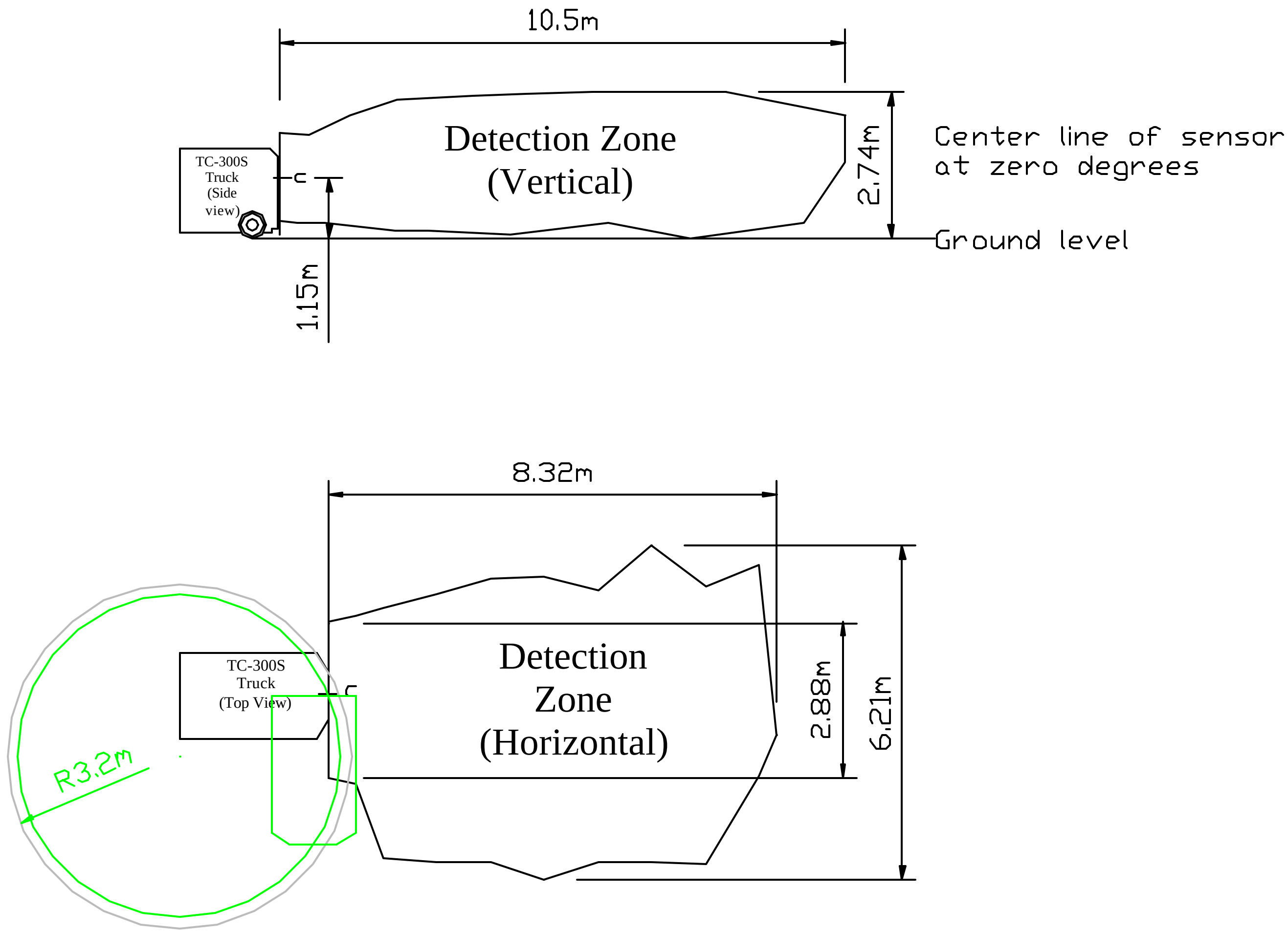

Figure 5.4: The position of the Guardian Alert on TC 300S forklift is located 1.15 m above the ground.

CHAPTER VI

EXPERIMENTAL RESULTS

Results Obtained from the Manual Tests

This section presents the results obtained from the manual tests of obstacle sensor performance using the procedures described in the section entitled "Manual Measurements of the Field of View of Sensors". The perimeter of the detection range is determined by having an obstacle move along a straight line from one side of the detection field to the other. The sensor is activated at the entrance into the field of view and is deactivated at the exit from the field of view. The results obtained from the DAQ system using the procedures described in the section entitled "Automated Measurements of the Field of View of Sensors" is presented in this chapter. The position (i.e. elevation and angle) in which the obstacle sensor is installed depends on the field of view desired and is limited by the actual field of view of obstacle sensors.

Horizontal Detection Range Results for the Preview Obstacle Sensor

The results presented in this section define the horizontal detection range of the Preview obstacle sensor. These experiments compare the horizontal detection range for different test bodies with different settings for detection patterns. The horizontal detection range data obtained for the sensor and display settings in Table 6.1 are presented in Figure 6.1. The same sensor and display settings are used, but with different sizes of test bodies. The test bodies include: a female 5'6" in height weighing 160 lbs and a male 5'7" in height weighing 180 lbs. It can be observed that the detection range for a bigger body is wider than that of a smaller body.

Table 6.1

PREVIEW SENSOR AND DISPLAY SETTINGS FOR RECTANGULAR PATTERN EXPERIMENT

Horizontal Detection Range test

Height of Sensor Center:		25 inches above ground level	
Preview Sensor Properties:		Preview Display Properties:	
ID:	1	ID:	1
Type:	Rear	Type:	Rear
Range:	26 ft / 8.0 m	Max sensors:	1
Pattern:	Rectangular	Sensor 1 ID:	1
Calibration:	4.0 ms	LED mode:	Forward and Reverse
Code Rev:	1.5	Buzzer mode	Reverse announce/detect
		Code Rev:	1.3

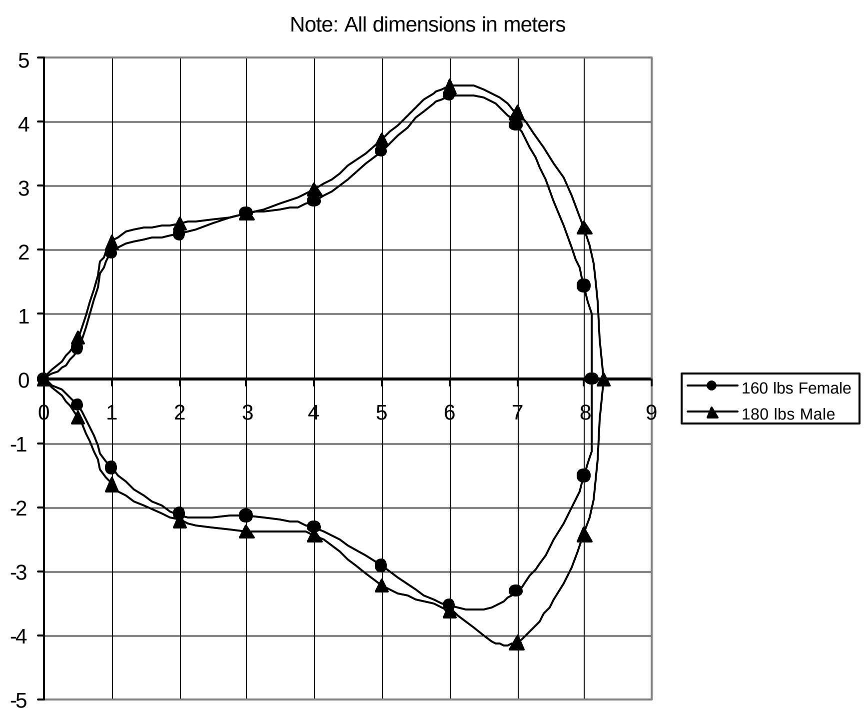

Figure 6.1: Comparison of the horizontal detection range of a rectangular pattern of a female 5'6" and a male 5'7" test bodies for Preview

The detection range data in Figure 6.2 are obtained when the sensor and display settings are per Table 6.2. The only difference from the prior test (Figure 6.1) is the pattern setting.

Table 6.2

PREVIEW SENSOR AND DISPLAY PARAMETERS FOR CONE PATTERN EXPERIMENT

Horizontal Detection Range test

Height of Sensor Center:		25 inches above ground level	
Preview Sensor Properties:		Preview Display Properties:	
ID:	1	ID:	1
Type:	Rear	Type:	Rear
Range:	26 ft / 8.0 m	Max sensors:	1
Pattern:	Cone	Sensor 1 ID:	1
Calibration:	4.0 ms	LED mode:	Forward and Reverse
Code Rev:	1.5	Buzzer mode	Reverse announce/detect
		Code Rev:	1.3

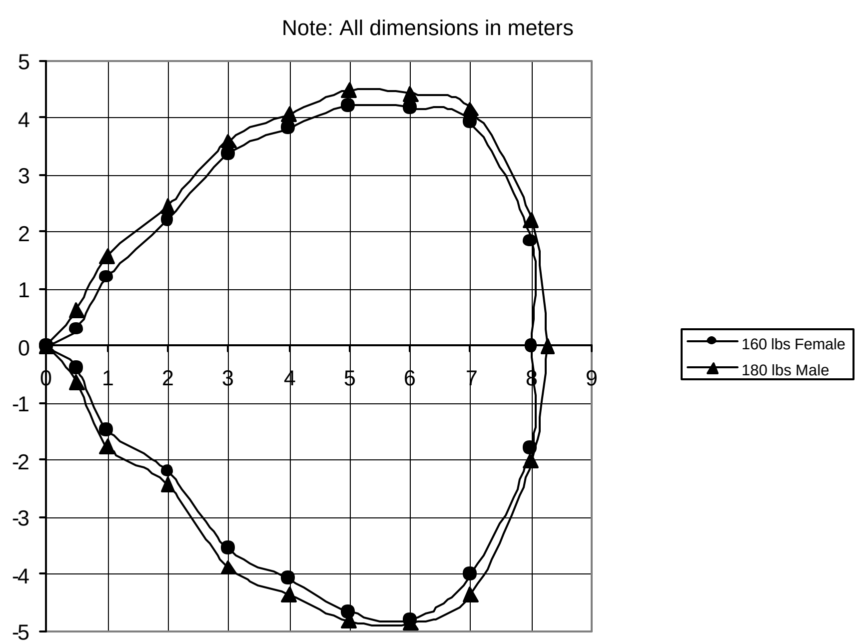

Figure 6.2: Comparison of the horizontal detection range of a cone pattern of a female 5'6" and a male 5'7" test bodies

Figure 6.3 shows the horizontal detection range obtained using a 5'6" high, 160 lbs, female test body for three different detection pattern settings: rectangular, cone and side. These results show that the detection range varies for each detection pattern setting in the sensor even though the test body is unchanged. The configurations of sensor and display are given in Table 6.3.

Table 6.3

PREVIEW SENSOR AND DISPLAY PARAMETERS FOR SIDE PATTERN EXPERIMENT WITH A 5'6" TALL, 160 LBS FEMALE

Horizontal Detection Range test

Height of Sensor Center:		25 inches above ground level	
Preview Sensor Properties:		Preview Display Properties:	
ID:	1	ID:	1
Type:	Rear	Type:	Rear
Range:	26 ft / 8.0 m	Max sensors:	1
Pattern:	Side	Sensor 1 ID:	1
Calibration:	4.0 ms	LED mode:	Forward and Reverse
Code Rev:	1.5	Buzzer mode	Reverse announce/detect
		Code Rev:	1.3

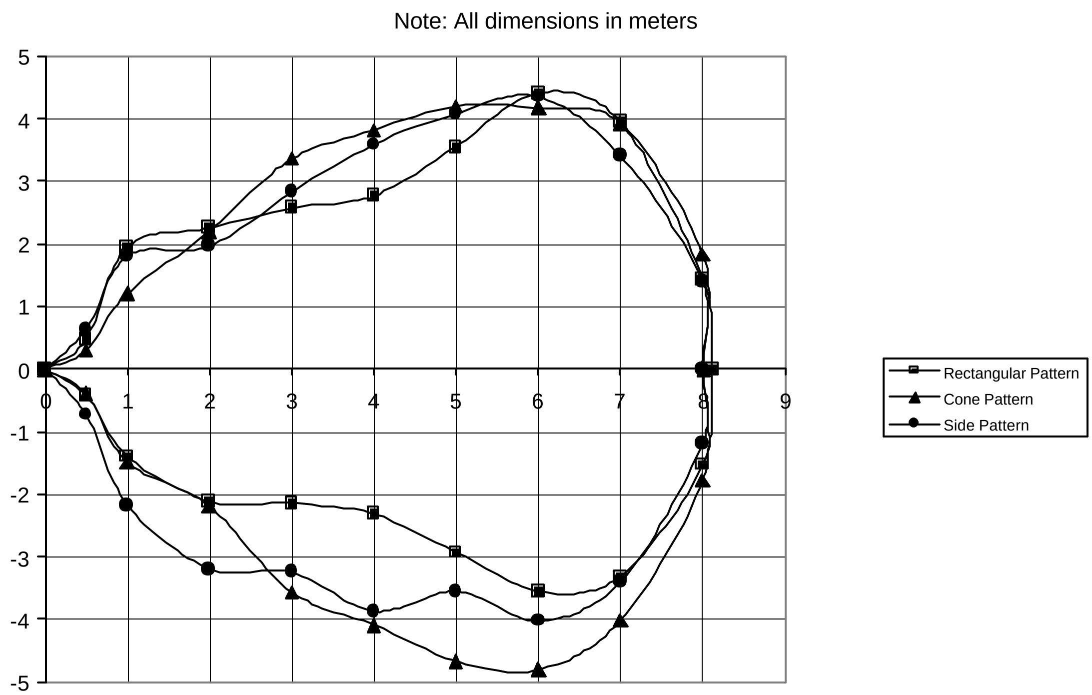

Figure 6.3: Comparison of the horizontal detection range of a rectangular, cone and side detection patterns for Preview.

A male test body 5'10" tall and 165 lbs in weight with the same sensor settings presented in Table 2 was used to compare the detection range obtained from human and some non-human obstacles. Only the last zone was used to run these tests as four LEDs were on continually during these tests, the last LED was used to monitor the detection zone. Walls in the test area caused the constant actuation of the four LEDs. The results obtained from these test are compared with that of a plywood test body with dimension 30" tall x 11.5" wide x 0.375" thick per Figure 6.4. The plywood was cut out in the shape of the upper torso of a human being with arms placed on sides. These results are presented in Figure 6.5.

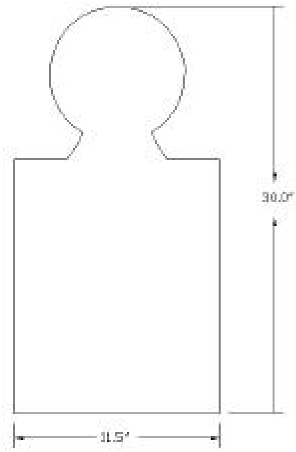

Figure 6.4: Plywood cut into the shape of the upper torso of the human being.

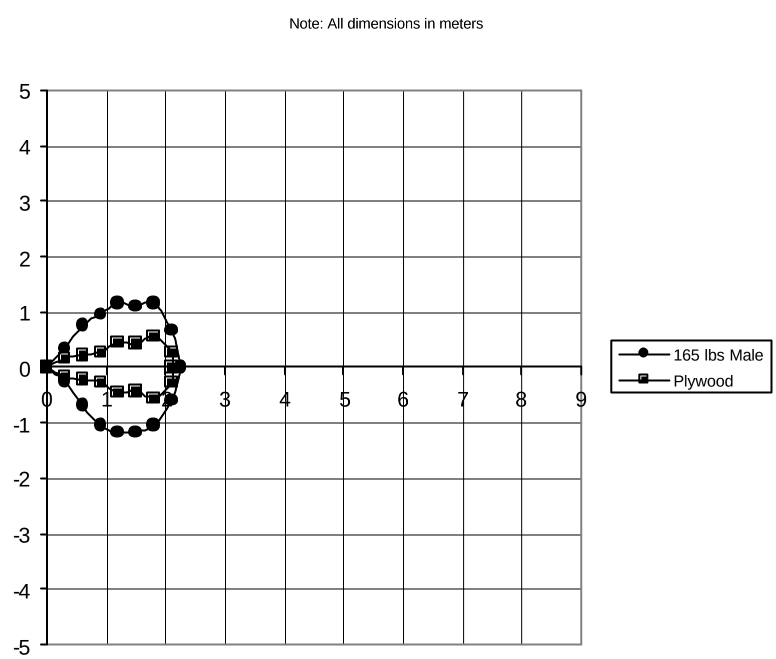

Figure 6.5: Comparison of the horizontal detection range of a cone detection pattern for a human obstacle and a plywood obstacle as detected by the Last zone only (i.e. the other four LEDs were ON continually) for Preview.

All results presented above, Figures 6.1, 6.2, 6.3 and 6.5 are presented without the subjectivity of how long the LED stayed on or if it blinked. Detection was recorded when the LED initially turned on. The subjectivity is due to the variation in the response time due to the composition and size of obstacle. This subjectivity was discussed in chapter IV. The results presented in Figures 6.6 to 6.8 shows the subjectivity in the interpretation of results. This simply means that sometimes, the LEDs switch from one to the other, or one lights up and then goes off, but then lights up again. The detection pattern configurations used for data of Figures 6.6 to 6.8 are given in Tables 6.1 to 6.3 respectively. A male body is used for the Figure 6.6 test.

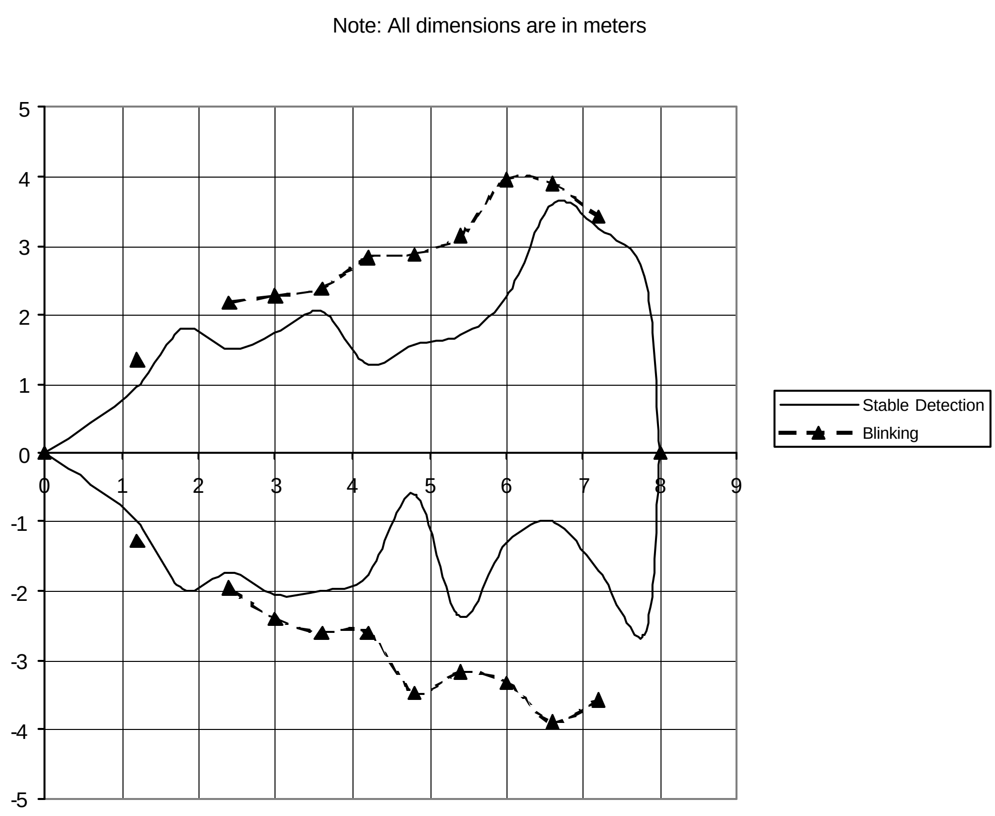

Figure 6.6: The horizontal detection range of a rectangular pattern of a male 5'10" tall test body based on observations of blinking LEDs as occurring at the fringe of the detection zone and of stable LEDs as occurring inside the detection zone for Preview.

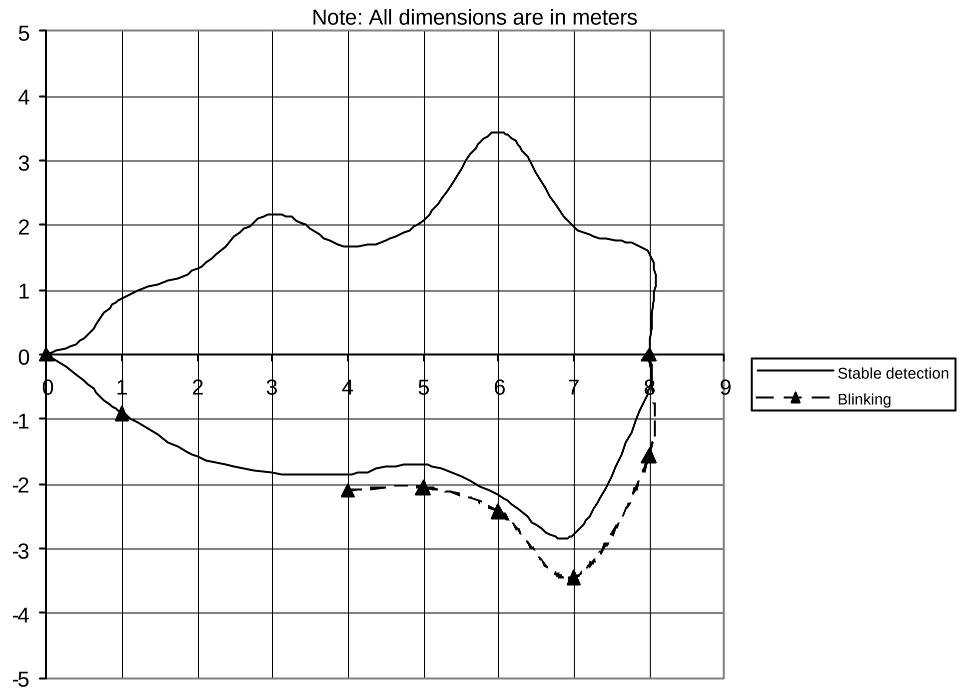

Figure 6.7: The horizontal detection range of a cone pattern of a female 5'6" tall test body based on observations of blinking LEDs as occurring at the fringe of the detection zone and of stable LEDs as occurring inside the detection zone for Preview.

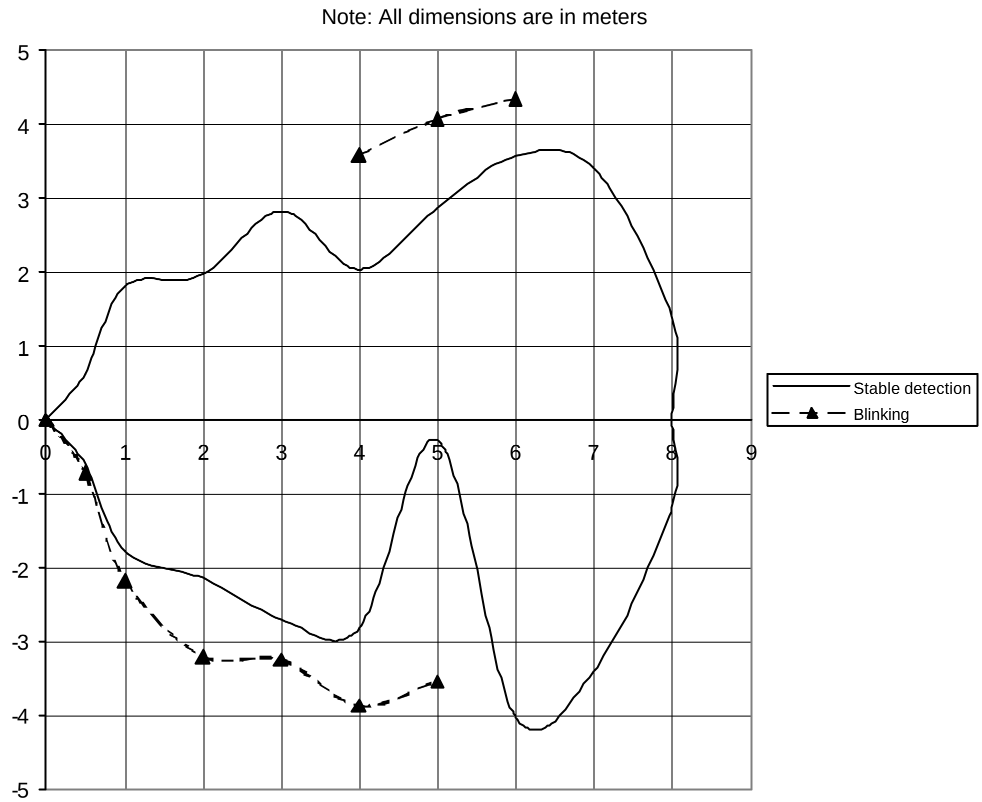

Figure 6.8: The horizontal detection range of a side pattern of a female 5'6" tall test body based on observations of blinking LEDs as occurring at the fringe of the detection zone and of stable LEDs as occurring inside the detection zone for Preview.

Vertical Detection Range Results for the Preview Obstacle Sensor

The results presented in this section define the vertical detection range of the Preview obstacle sensor. All results are presented in meters and the test bodies and the detection patterns are varied. The result obtained for a “last zone only” test is illustrated in Figure 6.13. The 5'10" tall test body is a male weighing 165 lbs and the 5'6" tall test body is a female weighing 160 lbs. The vertical field data of Table 6.4 shows the number of LEDs “ON” and their status [i.e. “stable (constantly energized), “switching” (blinking ON and OFF of one or adjacent lights alternately)] as the pedestrian walks across the field of view along lines located at various positions from the sensor. This data of Table 6.4 is plotted in Figure 6.12 with added data showing the location where the LEDs were initially energized, the location where the LEDs began to blink (or switch), and the location where the LEDs began a stable (constant) output. Other results obtained are illustrated in Figures 6.9 to 6.11.

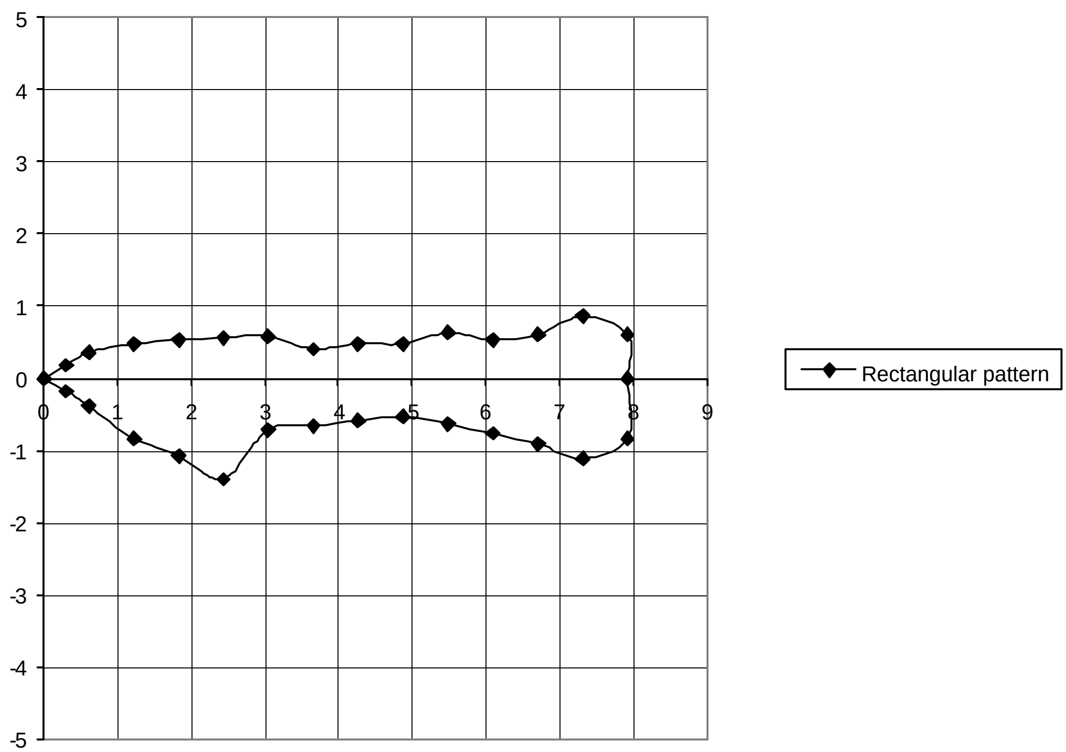

Figure 6.9: The vertical detection range of a Preview sensor for a rectangular pattern with a male 5'10" tall test body

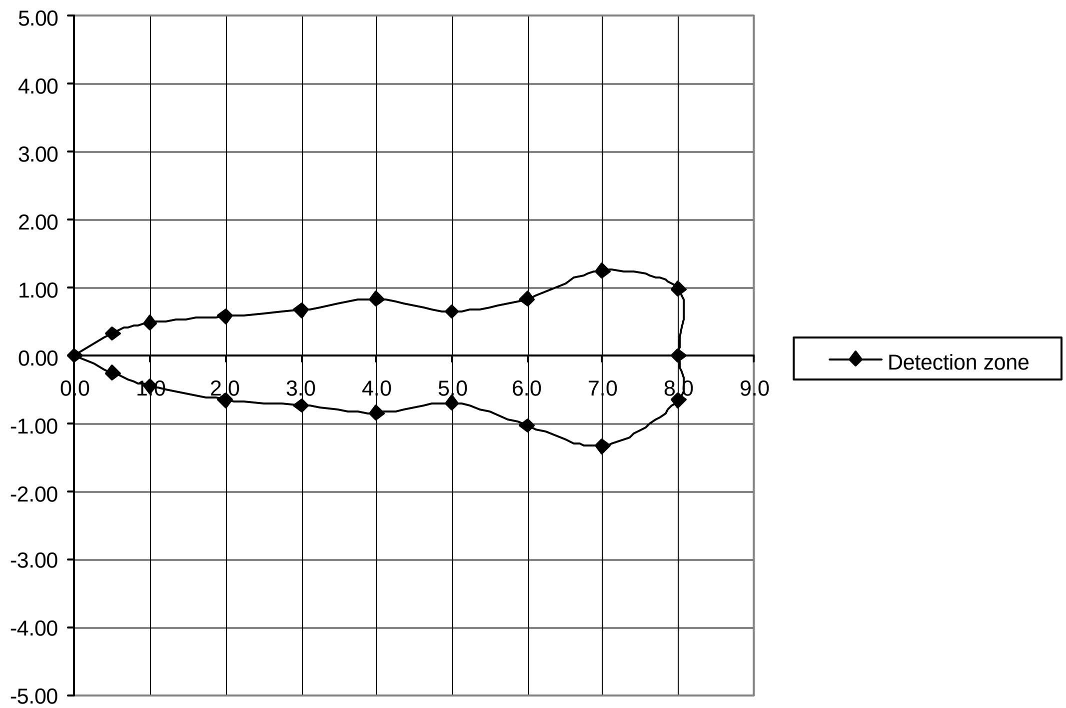

Figure 6.10: The vertical detection range of a Preview sensor for a cone pattern with a female 5'6" tall test body.

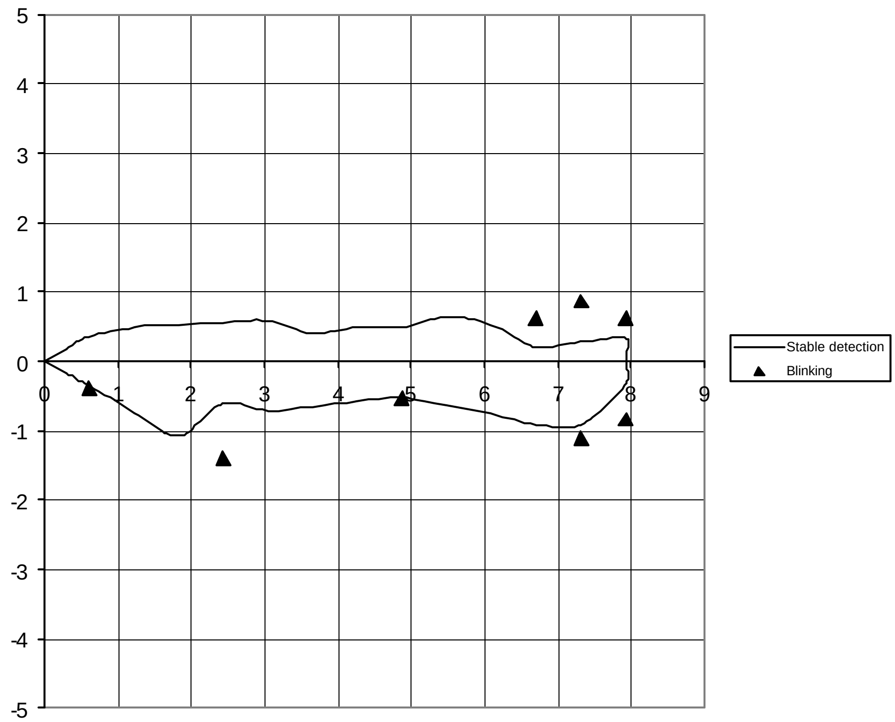

Figure 6.11: The vertical detection range of a Preview sensor for a rectangular pattern with a male 5'10" tall test based on observations of blinking LEDs as occurring at the fringe of the detection zone and of stable LEDs as occurring inside the detection zone.

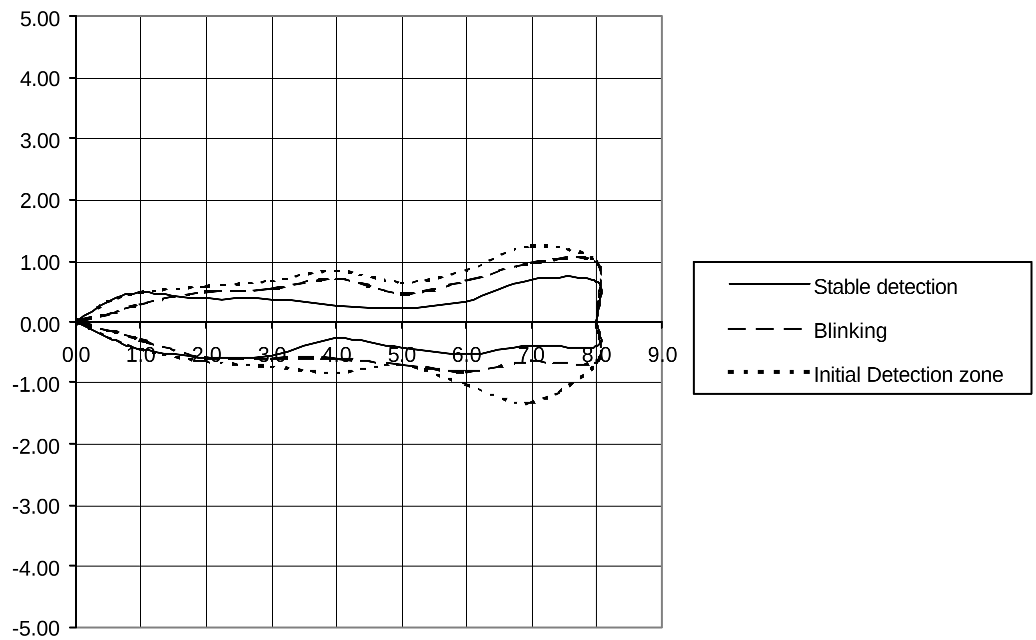

Figure 6.12: The vertical detection range of a Preview sensor for a cone pattern with a female 5'6" tall test body based on observations of blinking LEDs as occurring at the fringe of the detection zone and of stable LEDs as occurring inside the detection zone. The Initial Detection zone is the location of the first response.

Table 6.4

VERTICAL DETECTION RANGE NUMBER OF LEDS ACTIVATED FOR THE PREVIEW SENSOR FOR A CONE PATTERN AT POSITIONS SHOWN IN FIGURE 6.12

Position (meters)	Number of LEDs ON at centerline	Number of LEDs ON to the left of centerline	Number of LEDs ON to the right of centerline
0.0	5	5	5
0.5	5	5	5
1.0	5	4 (stable), 5: switching from 4 to 5	5
2.0	5	4, 5	4, 5
3.0	4	3, 4	3, 4: switching from 3 to 4
4.0	3	3	3
5.0	2	2 (stable), 3: switching from 2 to 3	2 (stable), 3: switching
6.0	2	1, 2: switching from 1 to 2 then OFF	2
7.0	1	1	1
8.0	1	1	1
Beyond 8.0	0	0	0

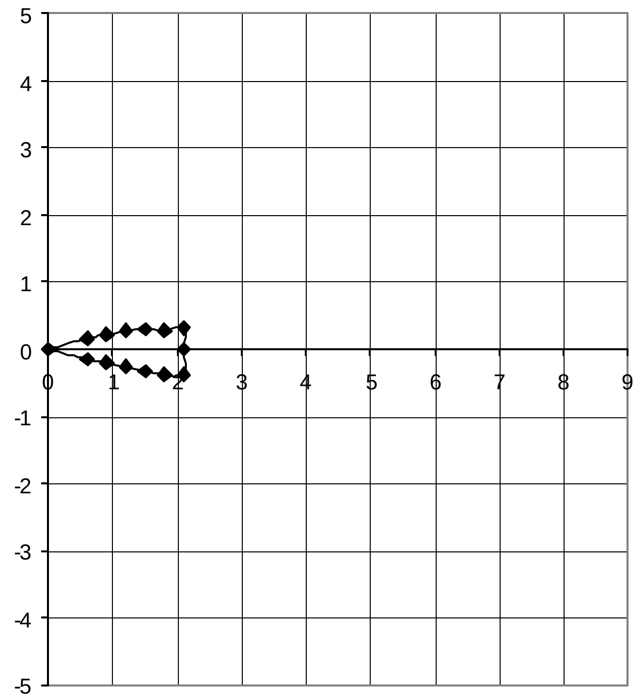

Figure 6.13: The vertical detection range of a Preview sensor for a cone pattern with a female 5'6" tall test body as detected by the Last zone only (i.e. the other four LEDs were ON continually).

Horizontal Detection Range Results for the Guardian Alert Obstacle Sensor

The results presented in this section define the horizontal detection range of the Guardian Alert obstacle sensor. All the results are presented in meters and the same test body is used for all the tests. The velocity discrimination setting of this sensor is varied.

The Guardian Alert sensor is programmed as illustrated in Table 6.5 for partial velocity discrimination. The test body for these tests is a female 5'6" tall weighing 160 lbs moving transverse to the sensor centerline at about 2 mph. The results for partial velocity discrimination are illustrated in Figure 6.14.

Table 6.5

GUARDIAN ALERT SENSOR PARAMETERS FOR PARTIAL VELOCITY DISCRIMINATION

Number of Ranges:	8						
DOM	ON						
Self Test	OFF						
	Range 0 - 35	Priority 0 - 10	Velocity MPH	TurnOff Seconds	TurnOff Inches	Color	Duration 0 - 9
Range 1	3	7	0	5	8	Red	0
Range 2	6	5	0	4	8	Red	1
Range 3	9	5	0	3	8	Yellow	2
Range 4	12	5	2	3	8	Yellow	3
Range 5	15	5	3	3	8	Yellow	4
Range 6	18	5	3	2	8	Yellow	5
Range 7	21	5	5	2	8	Yellow	6
Range 8	26	3	7	1	2	Yellow	7

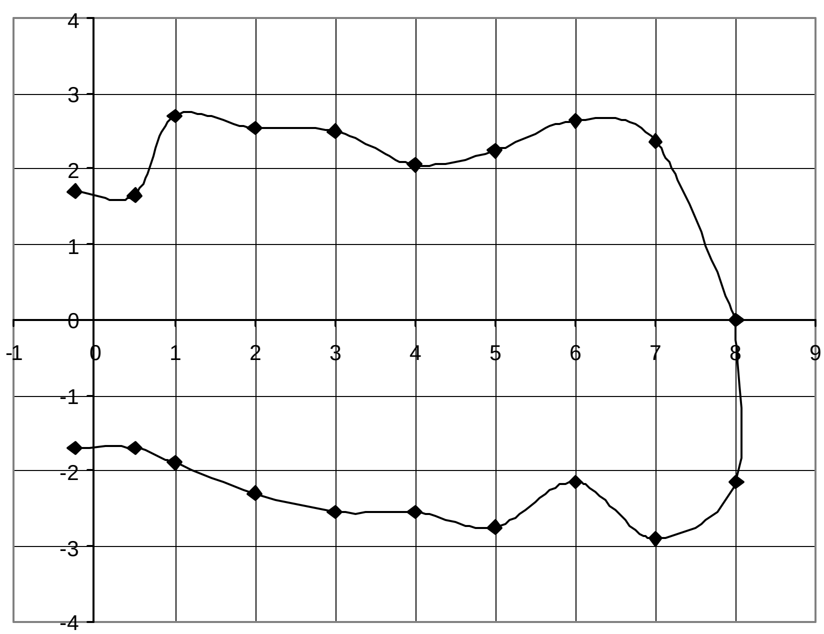

Figure 6.14: The horizontal detection range of the Guardian Alert sensor with partial velocity discrimination.

The average detection range obtained when the Guardian Alert sensor is programmed to have no velocity discrimination is presented in Figure 6.15. The program setting for the sensor is illustrated in Table 6.6. The test body for these tests is a female 5'6" tall weighing 160 lbs moving transverse to the sensor centerline at about 2 mph.

Table 6.6

GUARDIAN ALERT SENSOR PARAMETERS FOR NO VELOCITY DISCRIMINATION

Number of Ranges:	8
DOM	ON
Self Test	OFF

	Range 0 - 35	Priority 0 - 10	Velocity MPH	TurnOff Seconds	TurnOff Inches	Color	Duration 0 - 9
Range 1	3	7	0	5	8	Red	0
Range 2	6	5	0	4	8	Red	1
Range 3	9	5	0	3	8	Yellow	2
Range 4	12	5	0	3	8	Yellow	3
Range 5	15	5	0	3	8	Yellow	4
Range 6	18	5	0	2	8	Yellow	5
Range 7	21	5	0	2	8	Yellow	6
Range 8	26	3	0	1	2	Yellow	7

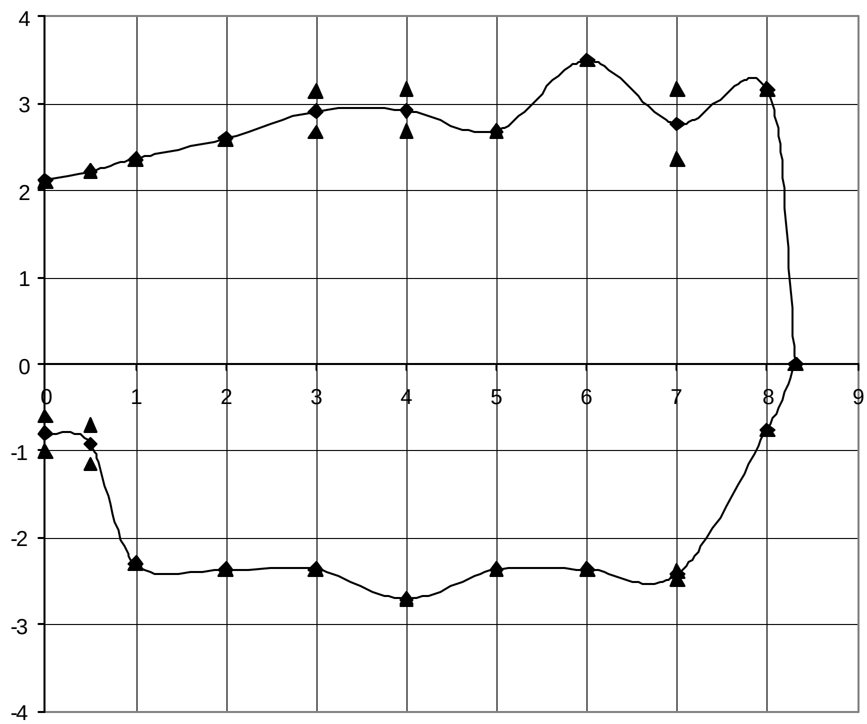

Figure 6.15: The horizontal detection range of the Guardian Alert sensor with no velocity discrimination.

Vertical Detection Range Results for the Guardian Alert Obstacle Sensor

The results presented in this section define the vertical detection range of the Guardian Alert obstacle sensor. All results are presented in meters. A female 5'6" tall weighing 160 lbs test body is used for all tests. The results obtained when the Guardian Alert sensor is programmed to have no velocity discrimination as illustrated in Table 6.6 are presented in Figure 6.16.

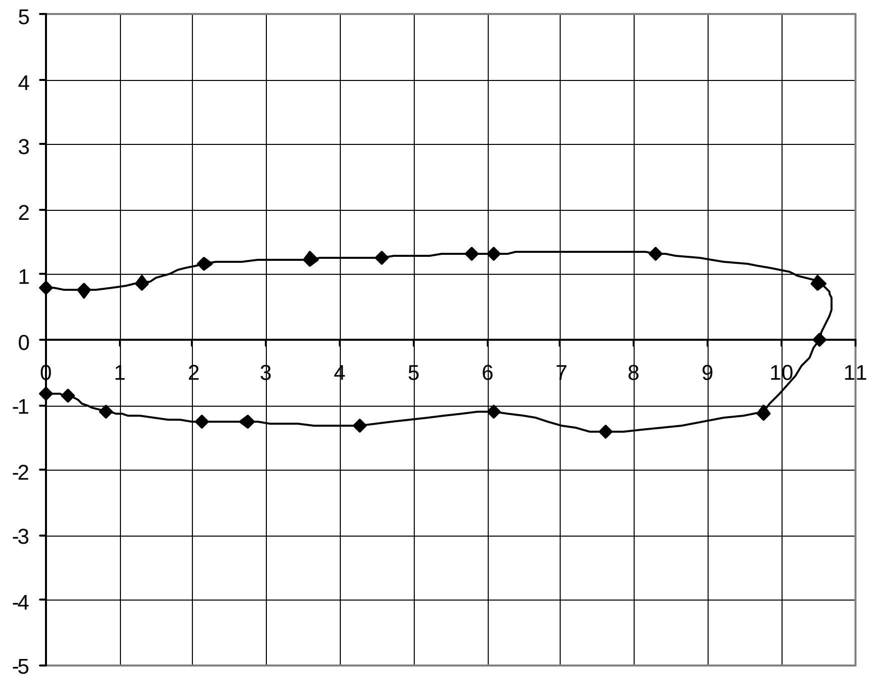

Figure 6.16: The vertical detection range of the Guardian Alert sensor with no velocity discrimination.

Results Obtained from the Data Acquisition System

The automated data acquisition system has the ability to regulate the speed of the human obstacle. The speed of the test could be obtained from the time elapsed and the distance traveled by the test body during each test.

The Preview was tested with the DAQ system on the stand with the configuration shown in Table 6.1. The test body for this test is a female 5'6" tall weighing 120 lbs. The results obtained for the response of the LEDs at a distance 1 m away from the sensor are illustrated in Figure 6.17. The Guardian Alert was tested with the DAQ system both on the stand and on the forklift with the configuration shown in Table 6.6. The test body for these tests is a female 5'6" tall weighing 120 lbs. The results obtained for the response of the LEDs at a distance 0.5 m away from the sensor when the Guardian Alert was mounted on the stand are illustrated in Figure 6.18.

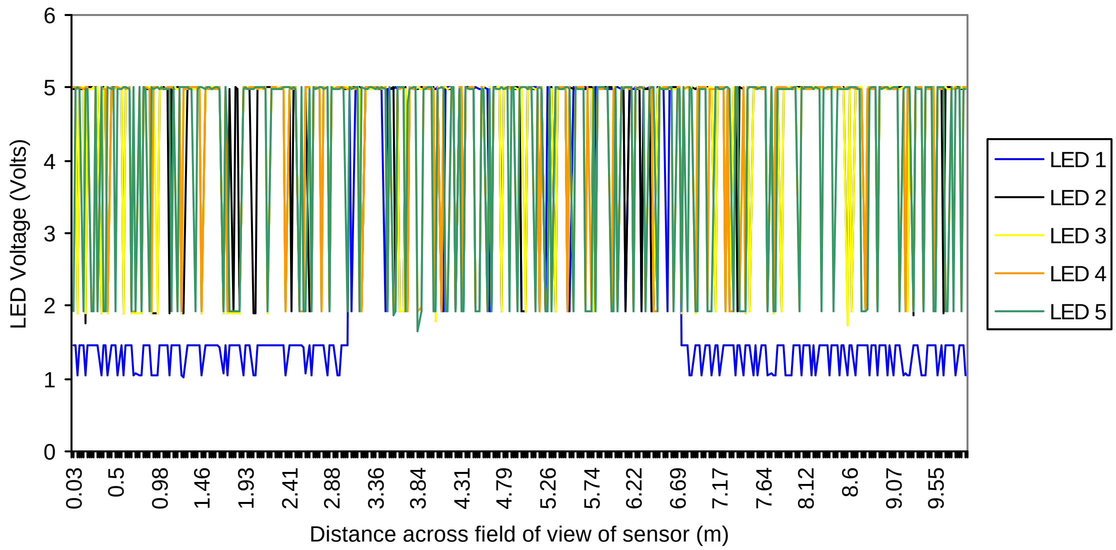

Figure 6.17: The response of the Preview LED sensors on a test stand when the pedestrian is at a 1 m distance away from the sensor as obtained from the data acquisition system.

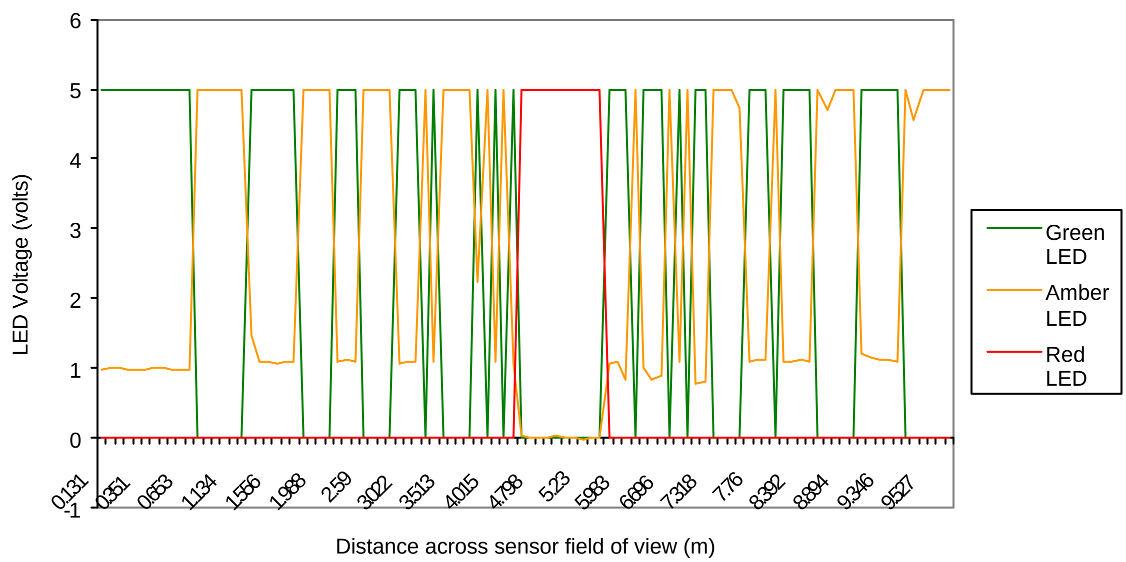

Figure 6.18: The response of the Guardian Alert LED sensors (with no velocity discrimination) on the test stand at a distance 0.5 m away from the sensor obtained from the data acquisition system.

Other Tests for Performance of Sensors

A plastic trashcan 32” by 12” was not detected at all by the Preview sensor at the sensor settings presented in Table 6.2. For a 5’10” human test body weighing165 pounds, lying on the floor parallel to the sensor centerline and about 2 meters away from the sensor, the Preview sensor did not detected this body. A 5’10” body weighing165 pounds lying on the floor, perpendicular to the sensor centerline and about 2 meters from the sensor, was not detected by the Preview sensor. The Preview sensor did detect this body when hands and legs were raised. The sensor was located 25 inches above the floor in a level orientation.

The influence of the angle of tilt of the sensors from the vertical plane normal to the vehicle centerline is investigated. The first test consisted of tilting the top of the test stand towards the rear until the sensors cease to detect the floor. Both the Preview and the Guardian Alert sensors and detect the wooden floor at some inclination. The Preview sensor was raised to a centerline height of 28.4 inches and tilted to an angle of $\tan^{-1}$ (3/28.4) to eliminate detection of the floor. This test furnished the motivation for mapping the perimeter of the vertical field of view by rotating the sensor 90^0 and having pedestrians move across the field of view.

For the 5’10” tall human test body weighing 165 pounds, lying on the floor on the truck centerline and about 2 meters away from the sensor, the Guardian Alert sensor did not detected this body. The Guardian Alert sensor did not detect this test body lying perpendicular to the centerline and about 2 meters from the sensor. The Guardian Alert sensor did detect this body when hands and legs were raised to about 20 inches above the floor. This sensor was mounted on the rear of the counterweight surface at 1.15 m above the ground.

The influence of rain on the sensors is indicated by the results of a test with the sensors “looking out” from the building doorway into a heavy rainstorm. The Guardian Alert detected raindrops during the test without the presence of an obstacle, but it gave a higher pitch warning signal when a human obstacle (a person) walked into the detection zone during this test. The Preview did not respond to raindrops, but detected only the human obstacle who walked into the detection zone during this test. Hence, the Guardian Alert gives a false signal but the Preview did not.

The Guardian Alert was locate on the side of a city street at a height 40 inches above ground level and faced perpendicular to the direction of vehicles. The Guardian Alert at 85 ft away from the roadway detected most trucks and the old cars, which were heavier than those designed for the modern day use. The Guardian Alert obstacle sensor did not detect any vehicle at 95 ft away from this roadway. The detection zone of the Guardian Alert sensor for a human test body 5’ 10” tall, weighing 165 lbs extended 28 ft away from the sensor. This test was not conducted for the Preview.

The Guardian Alert sensor was mounted on the lift truck with the center of the sensor 1.1 m above the ground level. This test was performed in a sheet metal building with concrete floor. The sensor was programmed to have no velocity discrimination as illustrated in Table 6.6. The test body for the test was a male 5'10" tall weighing 165 lbs. For this human obstacle the length of the detection zone was 14.588 m. This same test was conducted at a gymnasium with wood floor and brick walls with the same test body and the sensor mounted at the same height of 1.1 m. A comparison of the results obtained for the sheet metal building and the gymnasium is illustrated in Figure 6.19 and shows the detection zone for this human obstacle to be roughly 30% longer and 100% wider in the metal building. The detection range to the left of the sensor was not completed in the metal building due to the limitation in the size of the test site. A forklift truck that drove into the field of view of the Guardian Alert was detected at about twice the detection range of the human obstacle.

During the course of the tests, it was observed that the Guardian Alert sensor was sensitive to vibration. This observation led to the quantitative test of the Guardian Alert sensor for reaction to vibration. The test was performed using a mechanical shaker with known input amplitude at different frequencies. The response of the Guardian Alert to base vibrations is presented in Table 6.7.

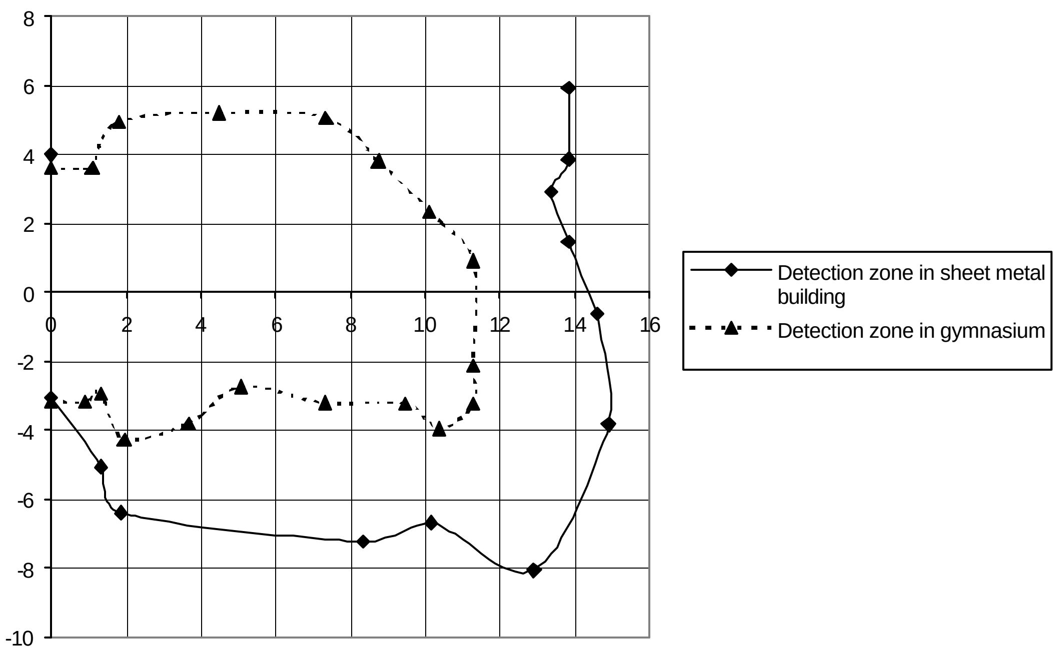

Figure 6.19: Comparison of the horizontal detection range for the Guardian Alert sensor with no velocity discrimination for tests in a sheet metal building and a gymnasium.

Table 6.7

THE RESPONSE OF THE GUARDIAN ALERT TO BASE VIBRATIONS

Frequency	Displacement of Sensor	Maximum Velocity of Sensor	Beeper Status
cps	inches	in/sec	
20	0.0000	0.0000	OFF
20	0.0092	1.1510	ON
20	0.0366	4.6041	ON
30	0.0000	0.0000	OFF
30	0.0092	1.7265	ON
30	0.0183	3.4530	ON

CHAPTER VII

CONCLUSONS AND RECOMMENDATIONS

The size, shape, composition and position of the obstacle and the position and orientation of the of obstacle sensor on the lift truck will affect the performance of obstacle sensors. The results obtained from this study help quantify how these factors and other considerations will affect the performance of obstacle sensors when used on lift trucks in reverse travel. The results of this study will aid in the positioning of these sensors on the truck to reduce blind spots and false warning signals. Although, as the results of this study demonstrate, the performance limitations of the sensors create a condition where blind spots and false signals cannot be completely eliminated.

The Influence of Sensor Position on Detection Range

The location of the sensor on the lift truck will influence the detection range in both the horizontal and vertical planes. Some of the considerations in locating sensors on a lift truck are illustrated in the following comments for a lift truck TS-300S. This illustration only considers the field of view and does not consider the design constraints.

For the specific lift truck tested, the vertical location for obstacle sensors should not be on top or at the bottom of the counterweight. If the obstacle sensor is placed at the bottom of the counterweight, more false alarms will be caused by the ground. If the sensor is placed on top of the counterweight, it will be blind to obstacles immediately behind the truck even when the obstacle sensor is tilted. The position of the obstacles that cannot be detected by the Preview and the Guardian Alert, when the sensor is placed on top of the counterweight of the lift truck are illustrated in Figures 7.1 and 7.2. Desirable vertical positions for the sensors are illustrated in Figures 5.3 and 5.4.

The location of the sensors in the horizontal plane should provide coverage of the rectangular (180 angle) area across the width of the rear of the truck and should provide coverage of the vehicle's path during the sharp turns typical of this class of vehicles. The Preview may need three or more sensors (depending on type of truck) at different positions in order to cover the full width of the truck, since it has an average angle of detection of 100^0. To achieve a detection pattern that only covers the width of the truck, one Guardian Alert sensor may be sufficient due to its ability to cover 180^0 angle of detection, but one sensor will not be sufficient to cover the width of the field of view for sharp turns in reverse. It is recognized that the necessity to arrange multiple sensors to cover areas, which may be entered by the truck during normal maneuvers may be impractical to implement in design. Figures 5.3 and 5.4 show the horizontal field of view of three Preview sensors and one Guardian Alert sensor during reverse travel. These figures also show the position of the truck after a 90^0 turn in green to indicate the inadequacy of the sensors warning of obstacles in the path before starting the turning maneuver and areas truck may enter during normal maneuvers. (This study only considers sensors at the rear of the truck. Therefore, it would not warn for a pedestrian standing beside the truck when the truck stops ahead travel an initiates reverse travel with a turning maneuver. The effect of overlapping detection ranges of multiple sensors was not investigated.

The Preview obstacle sensor should be installed at a height not less than 0.33 meters above ground level with the settings of the sensor configured to a cone pattern, this pattern seems to be the most appropriate. The choice of this pattern is determined by the relatively uniform shape of the perimeter of the field of view obtained from tests, which reduces the inconsistencies of detection created by the irregular shape at the base of the vertical detection range.

The Guardian Alert obstacle sensor should be installed at a height of 1.15 meters above ground level with a sensor setting of no velocity discrimination at detection ranges closer to the sensor but the choice of velocity discrimination at the remaining ranges will be determined by the application of the sensor (see Figure 5.4). Programming the sensor to have “no velocity discrimination” will increase the occurrence of false alarms because these obstacles will be detected irrespective of the relative speed of travel (Figure 6.15). However, obstacles close to the vehicle are in harm’s way and the extra false signals may be of less concern.

The sensor requirements may create a situation in that the detection range of sensors is affected by necessary protection of the sensor units from normal wear-and-tear of lift truck operation. The units may need to be recessed within the structural portion of the lift truck such as the counterweight. Any structure designed to house the sensors while protecting them from damage may affect the detection range.

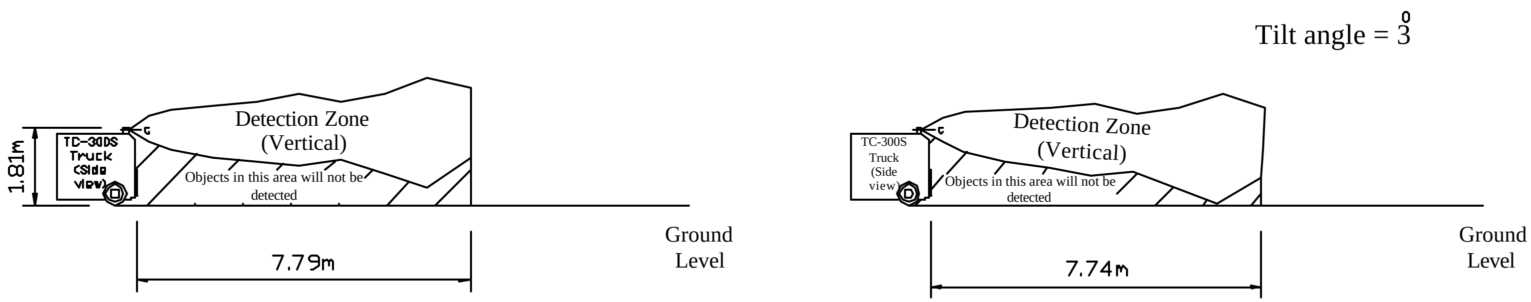

Figure 7.1: The Preview obstacle sensor with a conical field of view mounted on top of the counterweight of truck TC-300S.

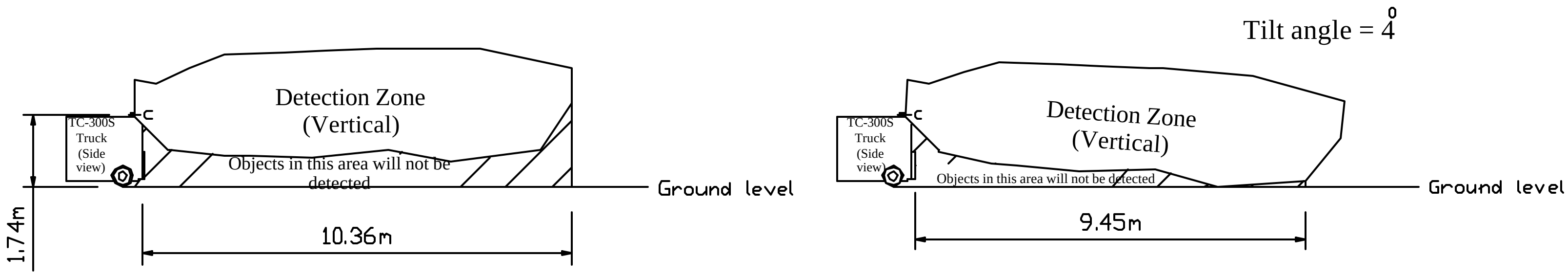

Figure 7.2: The Guardian Alert obstacle sensor with rectangular field of view mounted on top of the counterweight of truck TC-300S.

Stopping Distances

The approximate stopping distance at each initial truck speed can be obtained from Figure 3.5. The results obtained show that these obstacle sensors are not effective at the maximum speed (16.6 mph) of the lift truck. At speeds above 8.0 mph, if the maximum range setting of the obstacle sensor is 8m, the truck will impact a detected obstacle before the operator can stop the truck, assuming sensor response time is 0.2 sec, operator perception time is 0.75 sec operator reaction time is 0.75 sec and the drawbar drag is 25. This data is theoretical while assuming correct and accurate performance of the sensor system. Irregular pattern of the detection zone of the sensor, unreliable detection of some objects, inconsistent performance of operators, and some other factors may combine to create situations which may greatly reduce the maximum speed to prevent impact at this range setting.

The Influence of Composition, Size and Orientation on Detection Range

The detection range obtained is greater for a larger test body than a smaller one due to the higher reflectivity of the larger test body. It may be concluded that the size of the detection range will increase as the size of obstacle increases. Obstacles projecting larger surface area to the sensor field of view will be detected at farther distances than smaller areas due to the fact that larger surface area produces greater reflectivity. Therefore, the response time of the sensor will increase as the surface area of the obstacle decreases.

The composition of the obstacle also affects the detection range. Wood and plastic are not good reflectors of radar emissions: Human beings are good reflectors, but metal is even better.

The orientation of obstacles will affect the detection range. The sensor response time increases when the wide side of the test body is turned parallel to the sensor field of view. The detection range decreases when the wide side of the test body is placed parallel to the sensor field of view.

Environmental Effects on Obstacle Sensors

The results show that the Guardian Alert is sensitive to base vibration with high amplitudes of vibration, therefore this sensor should be mounted rigidly on a rigid base such as the counterweight. The Guardian Alert detects raindrops as distant obstacles, while the Preview does not detect the rain. This implies that false alarms will occur with the Guardian Alert during a rainfall. Tests under other environmental factors such as dust, snow etc. were not done.

Design and Settings of Obstacle Sensors

The detection range changes for different detection patterns for the Preview obstacle sensor.

The LED displays of both the Preview and the Guardian Alert sensors have good visibility. The warning signals of both the Preview and Guardian alert are audible, that of the Guardian Alert might be too loud for some applications. The tests show that only the RED and AMBER LED display may be configured and activated within certain range of the field of view of the Guardian Alert obstacle sensor, the GREEN LED is activated once an obstacle is detected within the maximum possible detection range of the Guardian Alert sensor.

Both the Preview and the Guardian Alert are sensitive to voltage variation; 12Volts was used during the experimental tests. Both the Preview and the Guardian Alert require a minimum of 10 volts for them to function properly.

Durability of Obstacle Sensors

The wiring of the system is very important. The wirings of the sensors should be strong, durable and easily accessible. The application of the sensors is on a lift truck where there is much vibration and rough terrain. The wiring of the Preview system is well designed, easily accessible, durable and therefore suitable for industrial lift truck application. A more rugged wiring design is needed by the Guardian Alert for lift truck application.

Closure

Safety of personnel is of primary concern. The operator of the lift truck is the dominant factor in providing a safe environment. The operator's skills, alertness and responsiveness, and vigilance are key factors. Skills may be improved by training, while alertness and responsiveness may be enhanced by life style. Also, the operator must use vigilance to protect those within his working path by path by keeping a clear view of the path of travel.

While obstacle sensors may be located on a lift truck to alert the operator of the presence of an obstacle within its path during reverse travel or turning, the sensor may augment the operator's visual sense in the dynamic environment by promoting the operator to apply extra caution when a warning occurs. However, the net effect on the safety of the environment can only be evaluated under strictly defined and limited operating conditions in specific applications. The RADAR type sensors of this study may be set to provide an alarm for warnings to occur at a set distance with some variations due to size of obstacles; however, obstacles of other sizes and compositions will initiate the alarm at significantly different distances.

For a given truck, the sensor locations and settings for a specific application should be coordinated with the stopping distance required for the operating speed to provide the desired field of view. The false signals may be excessive, making the device ineffective due to the frequency of the lift truck being in close proximity to other vehicles, equipment, aisles, etc. encountered in applications such as warehouses, lumberyards, and steel mills. A compromise must be made to limit sensor range setting and size of field of view to limit number of false signals due to walls, passing vehicles, etc. The vehicle speed may be limited by the sensor range and stopping distance. Because this study was based on static tests, it is recommended that the sensors be mounted on a lift truck as proposed and the response of drivers recorded to identify areas for added development, and to investigate the effectiveness of these sensors under actual conditions.

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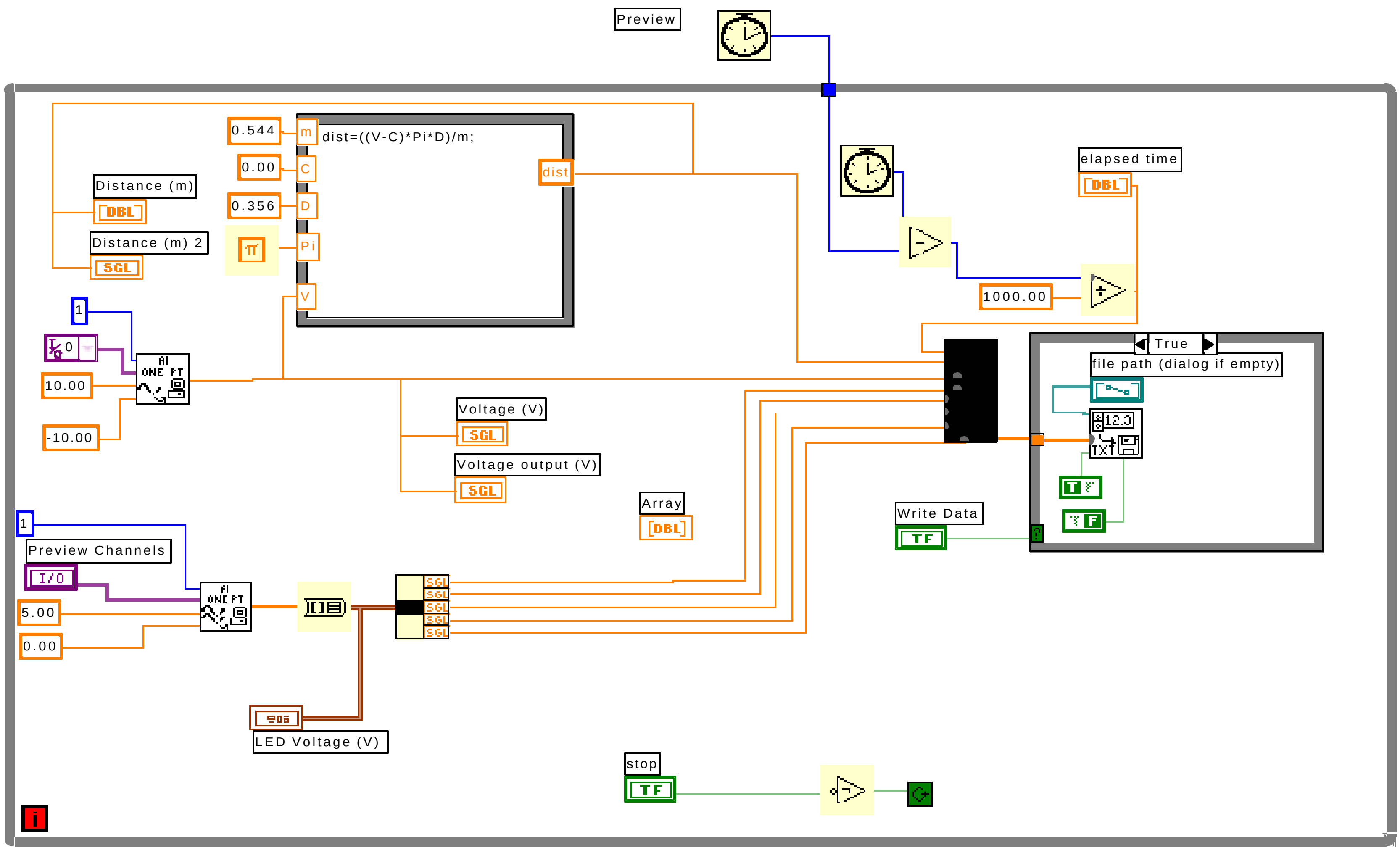
APPENDIX

LABVIEW PROGRAM FOR GENERATING AUTOMATED DATA


Preview
elapsed time
DBL
0.544
0.00
0.356
m
C
D
Pi
V
dist=((V-C)*Pi*D)/m;
dist
Distance (m)
DBL
Distance (m) 2
SGL
1
10.00
-10.00
Voltage (V)
SGL
Voltage output (V)
SGL
Array
DBL
1000.00
True
file path (dialog if empty)
Write Data
TF
1
Preview Channels
I/O
5.00
0.00
LED Voltage (V)
stop
TF