Detecting stalled or slow-moving vehicles at night by Optical Sensing - a feasibility study

by

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Abstract

In developing countries and areas without adequate infrastructure, a system that can work towards automobile accident reduction without heavy infrastructural dependence or in-vehicle installation will have a shorter implementation time and thereby function sooner. Road studs are a common feature used for road delineation at night. Incorporating intelligence into road studs to detect stalled or slowly-moving vehicles can greatly reduce fatal night car accidents, which have a much higher frequency rate than those occurring during the day. This research aims at investigating its feasibility through optical sensing.

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Chapter 1

Introduction

1.1 Background

Safety is an issue which cannot be over-emphasized, especially in the transportation industry. When vehicle accidents happen, human lives are lost and enormous amounts of money is usually spent. Engineers and Scientists have been constantly working towards improving safety on the roads. Intelligent Transport Systems (ITS) promise very rewarding results in terms of accident reduction and prevention. Though promising, it would take many years, probably decades, before implementation can be substantial.

Of the three modes of transportation, road transportation is by far the most ubiquitous, the other modes being air and water. This is due to the relative ease of setting up a road network. Water transportation usually makes use of an existing natural water channel. Air transport requires special infrastructure for safe takeoff and landing, which is usually expensive to setup and maintain.

No doubt, road transportation has facilitated life in various respects but when road crashes occur, the associated costs of such crashes can be enormous. In the year 2010, the price for car crashes in the US amounted to $871 billion dollars, including loss of life and lowered quality of life due to injuries [5]. Such amount clearly shows that any expenditure on safety is clearly justified.

In addition, the fatality rate of vehicle passengers is about three times higher during the night than during the day [39]. This higher frequency is attributed to various factors such as higher alcohol usage at night than during the day, over-speeding, less use of seatbelts, fatigue, glare from oncoming vehicle headlights, lower range of visibility, inadequate road signs, etc. Hence, any effective measure towards reducing vehicle passenger fatality at night will greatly reduce the overall fatality rate of vehicle accidents.

Since the invention of the automobile in the 18th century, the automobile has evolved over the years in terms of its operation. Of particular interest are some of the safety features aimed towards preventing accidents and minimizing injuries and loss of life, when accidents occur. Safety features in today's cars vary a great deal, usually depending on the cost of the car. However, features such as front airbags, seatbelts with pretensioners,etc., are standard across board. A more detailed review on some of these features is presented in the next chapter.

Two very important phenomena in preventing car collisions are reaction time/distance and braking/stopping distance (see figure 1.1). Reaction time can be described as the amount of time that elapses between when a car driver sees, appreciates or notices a hazardous situation (or obstacle) and then takes an action to prevent a collision or accident. During this reaction time, the car covers a distance known as the Reaction distance, which can be obtained by multiplying the speed by the time, assuming constant speed. Braking distance is the length of travel for a car to come to a standstill from a particular speed after the brakes are applied. In most cars in use today, it is the driver that performs an action to prevent a collision. In essence, if a driver fails to make a timely response to a hazard ahead, a collision may be unpreventable. Braking distance is affected by a host of factors among which include brake system condition, vehicle speed, road conditions, tire condition, vehicle weight, suspension, etc. The most incisive factor is speed. A vehicle moving at 100 mph will require a longer distance to come to a standstill than one moving at 60 mph, all other things being equal.

In the past, passive safety systems, such as seat belts and airbags, protected passengers during a car crash. In recent times, emphasis is being laid on active safety systems that are aimed towards crash prevention. This is in consonance with the popular saying which goes thus: "Prevention is better than cure". These active safety systems are commonly referred to

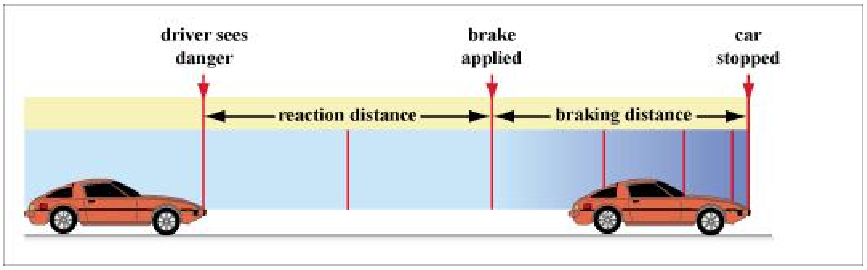

Figure 1.1: Reaction and Braking Distance
(Source: http://www.hk-phy.org/contextual/mechanics/kin/eq_mo01_e.html 09-10-14, 1:30pm)

as Advanced Driver Assistance Systems (ADAS). Some of the systems fast gaining popularity today include Forward Collision Avoidance (FCA) systems, Blind Spot detection warning systems, Parking Assist systems, Lane departure warning and others.

FCA systems are of particular importance as cars travel at much higher speeds in the forward direction, compared to other directions. Various implementations are in use today and constantly being developed. Common implementation includes the use of Radar, Sonar or video cameras to detect a vehicle/obstacle ahead and obtain relative velocity between the two vehicles, or vehicle and obstacle, in order to predict the possibility of a collision. This implementation has the major drawback that the obstacle along the vehicle's path of travel has to be within line of sight of the traveling vehicle. In addition, the obstacle needs to be within the range of the vehicle sensors for it to be detected. This can easily lead to insufficient driver reaction times, especially at night or along curved single-lane or two-lane roads without adequate road shoulders. Other implementations include the use of various vehicle sensors and information exchange over communication links from either vehicle to vehicle (V2V) or vehicle to infrastructure (V2I) [33].

A prominent feature used to prevent accidents at night are road reflectors in various forms. Generally, cars have reflectors as part of the rear lights to notify oncoming vehicles at night of their presence. Also, road signs are reflective in nature for easy visibility at night. Road studs are also becoming commonplace today, especially in developed countries. Road studs come in various forms including those that have only a reflective portion. These are popularly known as “cat’s eyes”. Other forms include those that are solar-powered with Light Emitting Diodes (LEDs) [20]. Whenever road studs are used, they are usually few meters apart, within line of sight of each other. LED road studs provide illumination visible from up to 900m, compared to reflective cat’s eye which is limited to 90m [28]. The major purpose of the road studs is for lane delineation purposes. Recently, other features/functions are being included in them to improve vehicle safety on the roads. Some of these include vehicle detection, incident detection, hazard warning and weather monitoring [9]. LED road studs with added functions are commonly referred to as Intelligent Road Studs (IRS). IRS are usually hard-wired to other systems to enable them function appropriately. Unfortunately, this limits their use to areas where adequate infrastructure is available. In developing countries, advanced infrastructure is not always available and there is the need for a solution that is both flexible and easy to install in terms of cost and complexity [20]. Vehicles can be detected using magnetic field disturbances in the earth’s surface caused by metals present in the vehicles [4][18]. A shortcoming of this approach can be caused by large vehicles passing close to the sensors, thereby leading to false readings. Also, the earth’s magnetic field could vary from time to time [27].

To further improve the reliability and accuracy of this detection method in IRS at night, lights from vehicles can be detected through optical means.

1.2 Purpose

This report is aimed at presenting results and findings arising from investigating the possibility of detecting stalled or slowly moving vehicles at night with minimum infrastructural dependence through measuring the variation of headlight intensity of the concerned vehicles. This possibility is being investigated as it is mandatory all over the world for car vehicles to have their headlights on at night and under low-lighting conditions. This makes it theoretically possible to detect the presence of a car through the use of a light detector at night. This detection method may be included in IRS that can detect vehicles through magnetic field sensing, which coupled with wireless communication ability, can be used in implementing an effective FCA system.

1.3 Scope

In carrying out the study and experiments, only cars, small trucks and sport-utility vehicles were utilized for the experiments. Experiments were carried out under dry conditions with minimal light reflection from road surfaces. Some of the experiment runs were carried out near traffic lights where moving cars and stopped vehicles could easily be observed. Fog, rain or other low visibility environmental conditions were not considered for the experiments.

1.4 Document Layout

This thesis is organized into five chapters, followed by a bibliography and a set of appendices. Chapter 2 provides background information on road crashes and its higher frequency at night. It also briefly describes some of the current ways of accident prevention. The second subsection gives a brief description of accident causes, including why accidents could occur more frequently at night. Also, the concepts of Reaction and Stopping distances are further explained. ADAS and vehicle detection systems are also briefly described. The car headlight beam is also described.

Chapter 3 explains the materials used for the experiments and the methods employed.

Chapter 4 provides the results of the experiments and discusses them.

Chapter 5 provides a conclusion and future work.

Chapter 2

Literature Review

Since the invention of the motor vehicle, scientists and engineers have been constantly working towards its development to improve its efficiency, reliability and safety. Safety is a very important aspect as "every year nearly 36,000 people are killed and more than 3.5 million people are injured in motor vehicle crashes, making it the leading cause of unintentional injuries and death for people between the ages of 1 and 33"[7].

In this chapter, causes of car crashes are briefly discussed.

2.1 Causes of Car Crashes[2]

Factors that could lead to a car crash can be grouped into three major categories, namely: **Driver, Vehicle and Environment**.

2.1.1 Driver related causes

These can be further classified into recognition, decision, performance and non-performance errors. As shown in Table 2.1, it can be observed that recognition error has the highest percentage of 40.6%, followed by decision error. Hence, if a driver recognizes a hazard in time, a crash may be avoided.

2.1.2 Vehicle related causes

These are crashes which occur as a result of failure of some part(s) of the vehicle(s) involved. These are as shown in Table 2.2. It is clearly seen that the most frequent vehicle related cause is tire failure.

Table 2.1: Reasons for Car Crashes attributed to Drivers[2]

Reason for Crash		Weight (%)
Recognition Error	Inadequate Surveillance	20.3
	Internal Distraction	10.7
	External Distraction	3.8
	Inattention (i.e. daydreaming,etc.)	3.2
	Other/unknown recognition error	2.5
	Subtotal	**40.6**
Decision Error	Too fast for conditions	8.4
	Too fast for curve	4.9
	False assumption of other's action	4.5
	Illegal maneuver	3.8
	Misjudgment of gap or other's speed	3.2
	Following too closely	1.5
	Aggressive driving behavior	1.5
	Other/unknown decision error	6.2
	Subtotal	**34.1**
Performance Error	Overcompensation	4.9
	Poor directional control	4.7
	Other/unknown performance error	0.4
	Panic/freezing	0.3
	Subtotal	**10.3**
Non-Performance Error	Sleep, actually asleep	3.2
	Heart attack or other physical impairment	2.4
	Other/unknown critical nonperformance	1.6
	Subtotal	**7.1**
Other/unknown driver error		7.9
Total		**100**

Table 2.2: Reasons for Car Crashes attributed to Vehicles[2]

Reason for Crash	**Weight (%)**
Tires failed or degraded/wheels failed	43.3
Brakes failed/degraded	25.0
Other vehicle failure/deficiency	20.8
Steering/suspension/transmission/engine failed	10.5
Unknown	0.5
Total	**100**

Table 2.3: Reasons for Car Crashes attributed to the Environment[2]

Reason for Crash		Weight (%)
Roadway	Slick roads (ice, loose debris,etc.)	49.6
	View Obstructions	11.6
	Signs/Signals	2.7
	Road Design	1.4
	Other highway related-condition	9.8
	Subtotal	**75.2**
Atmospheric Conditions	Fog/rain/snow	4.4
	Other weather-related condition	4.0
	Subtotal (Weather)	4.5
	Glare	16.4
Total		**100**

2.1.3 Environment related causes

These are contributory factors to crashes which are external to the vehicle(s) concerned. These can be roadway or atmospheric conditions [2]. Table 2.3 outlines some of these causes. It can be observed that slippery roads, such as ice and loose gravel, carried the highest weights. This is in agreement with the common knowledge to exercise extra care when driving under rain or snow conditions.

2.2 Car Crashes at Night

In the US, about half of passenger vehicle occupant deaths due to crashes, happen at night [39]. "Per mile driven, the nighttime fatal involvement rate for drivers of all ages was 4.6 times the daytime rate"[25]. Night-driving thus presents some peculiarities which lead to higher frequency of car crash fatalities than day-driving. Some common direct causes of car crash fatalities at night are discussed in the following:

2.2.1 Disuse of Restraints(seat-belts)

It is common knowledge that seat-belts are to be worn at all times by vehicle passengers. It is in fact a law in all states in the US (except New Hampshire) for seat-belts to be worn

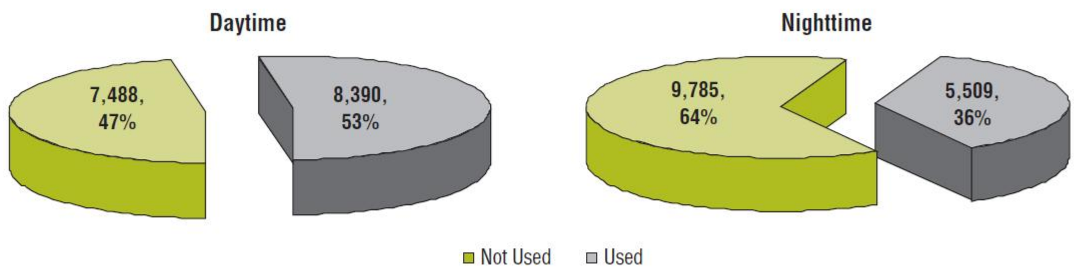

Figure 2.1: Passenger Vehicle Occupant Fatalities in 2005 by Time of Day and Restraint Use (Source: `http://www-nrd.nhtsa.dot.gov/Pubs/810637.PDF` 09-10-14, 1:30pm)

when operating a motor vehicle [8]. A study carried out in 2005 by the National Highway Traffic Safety Administration (NHTSA) showed that about 64% of people killed through car crashes at night did not use restraints (see Figure 2.1) [39]. In contrast, less than half of such people failed to use restraints during daytime. This could be due to the relative difficulty of being observed by law enforcement officers at night, than during the day.

2.2.2 High Blood Alcohol Concentration (BAC) Levels

Blood Alcohol Concentration can be defined as the quantity of alcohol contained in a person's blood, measured in weight per unit volume. At times, this measurement is converted to a percentage. Alcohol easily affects a person's sense of reasoning and judgment as it travels directly to the brain through blood [30].

Figure 2.2 shows Car Crash Deaths by time of day and BAC. It can be clearly observed that alcohol use contributed to more deaths at night than during the day. Table 2.4 shows the way people typically react to some BAC levels. It can be clearly observed that the higher the alcohol concentration level in a driver's blood, the higher is the likelihood of a car crash.

2.2.3 Speeding

We live in a fast-paced society where people want things done quickly. Unfortunately, this does not usually turn out well when it comes to driving a motor vehicle. Driving a

Table 2.4: The ABCs of BAC - A Guide to understanding Blood Alcohol Concentration and Alcohol Impairment [3]

BAC	Typical Effects	Predictable Effects on Driving
0.02 %	1. Some loss of judgment 2. Relaxation 3. Slight body warmth 4. Altered mood	1. Decline in visual functions (rapid tracking of a moving target) 2. Decline in ability to perform two tasks at the same time (divided attention)
0.05 %	1. Exaggerated behavior 2. May have loss of small-muscle control (e.g., focusing eyes) 3. Impaired judgment 4. Usually good feeling 5. Lowered alertness 6. Release of inhibition	1. Reduced coordination 2. Reduced ability to track moving objects 3. Difficulty steering 4. Reduced response to emergency driving situations
0.08 %	1. Muscle coordination becomes poor (e.g., balance, speech, vision, reaction time, and hearing) 2. Harder to detect danger 3. Judgment, self-control, reasoning, and memory are impaired	1. Concentration 2. Short-term memory loss 3. Speed control 4. Reduced information processing capability (e.g., signal detection, visual search) 5. Impaired perception
0.10 %	1. Clear deterioration of reaction time and control 2. Slurred speech, poor coordination, and slowed thinking	Reduced ability to maintain lane position and brake appropriately
0.15 %	1. Far less muscle control than normal 2. Vomiting may occur (unless this level is reached slowly or a person has developed a tolerance for alcohol) 3. Major loss of balance	Substantial impairment in vehicle control, attention to driving task, and in necessary visual and auditory information processing

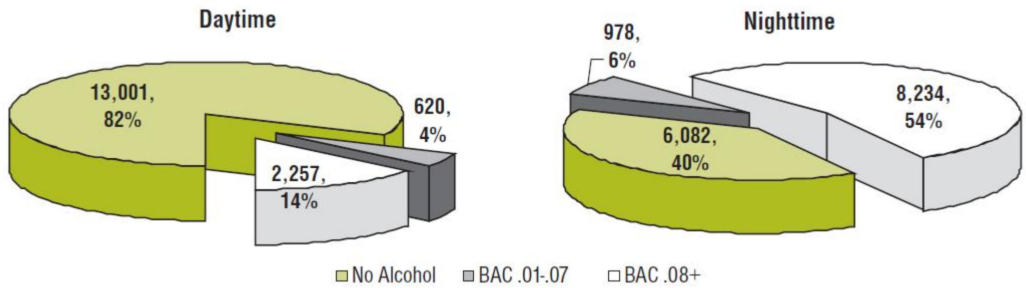

Figure 2.2: Passenger Vehicle Occupant Fatalities in 2005 by Time of Day and BAC Level in the Crash
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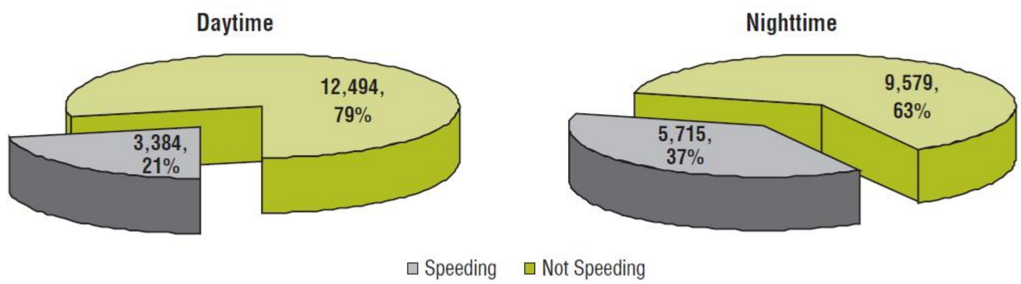

Figure 2.3: Passenger Vehicle Occupant Fatalities in 2005 by Time of Day and Speeding
(Source: `http://www-nrd.nhtsa.dot.gov/Pubs/810637.PDF` 09-10-14, 1:45pm)

motor vehicle at high speeds can be fatal. In fact, "Speeding is one of the most prevalent causes of car accidents today according to the U.S. Department of Transportation"[31].

In the year 2005, speeding accounted for about 37% of car-crash deaths at night compared to about 21% of such death during the day (see Figure 2.3).

2.3 Reaction and Stopping Time/Distance

These two concepts were introduced in Chapter 1 and would be further explained here. As mentioned earlier, speed directly affects both reaction and stopping distances. The faster a vehicle moves, the more distance it covers within a unit time. For example, a vehicle traveling at 70 miles per hour (mph) covers 31.29 meters (m) in a second, while one traveling at 100 mph covers 44.70 m in a second.

2.3.1 Reaction Time/Distance

It is necessary for a car driver to respond to a road hazard in a timely manner to prevent a crash. The time that elapses between when the driver sees or appreciates a hazard and actually responds is known as Reaction time. During this time, it is generally assumed that the speed of the vehicle remains constant. Hence, multiplying the speed by the reaction time yields the Reaction distance. This is a very important factor in FCA system design, as it contributes towards the computation of Time-to-Collision (TTC) and Safety braking distances, which are two quantities that FCA systems use in deciding whether there is a hazard ahead of a traveling vehicle or not [6]. Reaction time/distance of a driver to a particular situation depends on a lot of factors, among which includes:

- **Various available alternatives**: In case a driver traveling along a road needs to respond urgently to a situation, the time it takes to analyze the situation and its alternatives will affect the eventual reaction. For example, a driver suddenly encountering a road blockage may decide to try to avoid it or try to stop without a collision [38].

- **Ease of distinction between various situations**: In this case, the ability to differentiate the various happenings in the vicinity of the driver will likely affect the eventual response/reaction time. As an illustration, a driver who fixates his eyes on a semi-truck about to join a major highway may not see that the vehicles ahead are slowing down as a result of a speed zone ahead and thus have his or her available reaction time shortened [38].

- **Accuracy of the reaction outcome**: Depending on the resulting action, a driver may take a while to figure it out. In a situation where a car is following another too closely, if the one ahead suddenly slows down, the driver behind may be unable to respond accurately by also braking and this could result in a crash [38].

- **Thinking involved**[38]: The length of time a driver needs to think about a situation will directly affect the corresponding reaction.

- **Past experience of the driver**: A driver who has been previously exposed to various situations when driving, is likely to react/respond faster upon encountering similar situations than one who is not as exposed.

- **Current state of mind and health of the driver**:A distracted driver is not likely to react as quickly as one who is focused. In addition, a healthy and fit driver is likely to react faster than one who is not.

Reaction times vary from person to person, and also the situation but benchmarks of 1.5 seconds and 2.5 seconds are used for road design considerations and car-crash investigations [1]. In [6], Reaction time was broken into three components namely Reflection time , Judgment time and Action time, with corresponding time ranges of (0.44-0.52 seconds),(0.15-0.25 seconds) and (0.15-0.4 seconds) respectively.

Pressure Buildup Distance/Time

Due to the fact that there is some free pedal play in most vehicle brake pedals, this factor may also be considered before braking commences. "The pressure buildup distance is the distance of vehicle travel during the initiation of braking action to the full setup of the braking pressure"[6]. The value of this time may range from 0.3 to 0.75 seconds [6].

2.3.2 Stopping/Braking Distance

After the driver upon appreciating a hazard ahead, has decided to stop the vehicle and pressure is fully built in the brake system, the time that elapses between when the vehicle starts braking and eventually stops is the Stopping/braking time. The vehicle covers a certain distance during this time referred to as the braking distance. Factors which affect a vehicle's stopping distance include:

- **Speed** [11]: The higher the speed of a vehicle, the longer the stopping/braking distance will be, given a constant deceleration. This can be deduced from the mechanics equation:

$$v^2 = u^2 + 2as \tag{2.1}$$

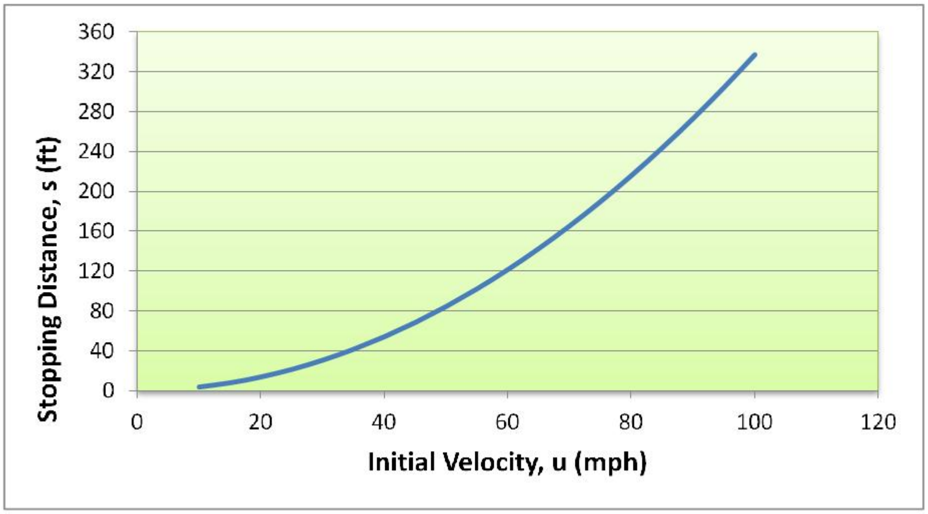

Figure 2.4: Stopping Distance against Initial Velocity at constant deceleration of $32ft/s^2$

where v = final velocity, u = initial velocity, a = acceleration (negative when decelerating), and s = distance covered. Upon making s the subject of the formula, we obtain:

$$s = (v^2 - u^2)/2a \tag{2.2}$$

where $v = 0$ and a is negative (i.e. deceleration), we obtain:

$$s = (u^2)/2d \tag{2.3}$$

where d = deceleration. Looking at equation (2.3) above, it can be clearly seen that the distance covered s, is directly proportional to the initial velocity/speed u, and inversely proportional to the rate of deceleration d.

A plot of distance, s covered against initial velocity u, at a constant deceleration d of $32ft/s^2$ is as shown in Figure 2.4.

-**Slope/Grade of the Road**[11]: Considering Figure 2.5, it can be observed that the factor $mgsin\theta$ is acting in the opposite direction of the vehicle travel. This factor adds up to the braking force and thus reduces the stopping distance of the vehicle compared to the other

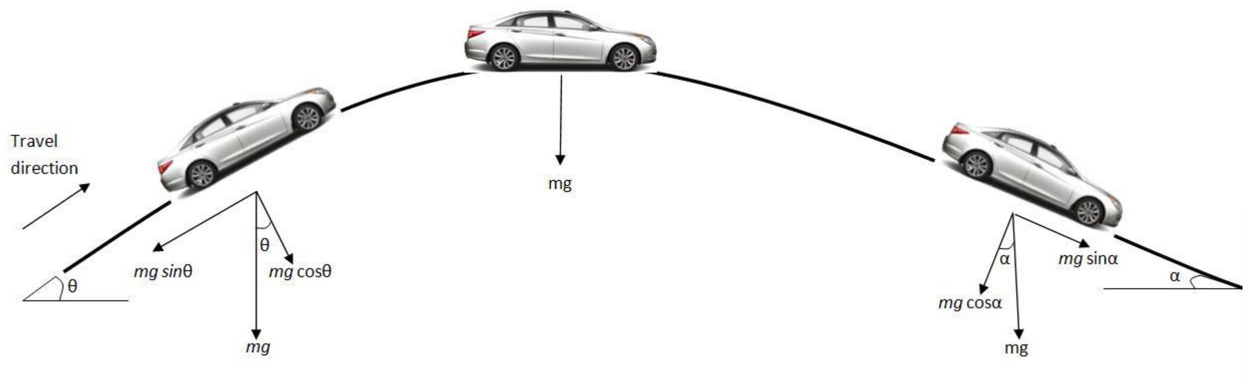

Figure 2.5: Effect of Gradient/Slope on Braking/Stopping Distance

two cases shown. When the vehicle is going downhill, the factor $mgsin\alpha$ reduces the effect of the braking force, thus making the stopping distance large.

-**Frictional Resistance between road and vehicle tires**[11]: A vehicle with badly worn tires will generally have a larger stopping distance than one that has tires with good thread depths. This is as a result of the frictional force between the tires and the road. Similarly, stopping distance for a particular vehicle on a wet icy road will be larger than on a dry road.

-**Vehicle Weight**[29]: Usually the heavier a vehicle is, the more the required stopping distance. This is due to the momentum (mass x velocity) of the vehicle.

-**Braking system**[29]: The efficiency of the vehicle braking system affects its stopping distance. A vehicle braking system is usually composed of many components, which include the pedal, brake fluid, master cylinder, brake lines, brake pistons, brake pads or shoes, discs and others. A deterioration of any of these components could lead to increased stopping distances and in some cases, inability to stop a vehicle thus resulting in a car crash.

-**Tire pressures**[29]: This directly affects a vehicle's stopping abilities as an under-inflated or over-inflated tire will affect the way the tire contacts the road surface. This could lead to excessive heat buildup which could ultimately affect the car's stopping ability. In addition, the car could become unstable as a result of unbalanced tire pressures and stopping ability would be affected.

-**Suspension system**[29][14]: The suspension system of a car is made up of components such as shock absorbers, control arms, stabilizer bars/links, bushings, subframe supports, etc. All these components ensure that the vehicle is well supported and stable when driven. Failure of any of these components could lead to instability and thus increase stopping distance of the vehicle. As an illustration, a worn out shock absorber could affect the way the tire contacts the road and thus affect the stopping ability of the vehicle.

Equation (2.4) shows an expression for the braking distance of a moving vehicle from speed V to a complete standstill [40, 10].

$$D_b(x) = \frac{\gamma W}{2gC_{ae}} \ln(1 + \frac{C_{ae}V^2}{\eta_b(\mu + f_r)W\cos\theta_s \pm W\sin\theta_s}) \tag{2.4}$$

where,

$D_b(x)$: braking distance of moving vehicle to speed zero

γ : equivalent mass factor

W : vehicle weight

g : acceleration due to gravity

C_{ae} : $(\rho * A_f * C_d)/2$

ρ : mass density of air

A_f : vehicle area

C_d : coefficient of aerodynamic resistance

V : vehicle speed

η_b : brake efficiency

μ :road adhesion coefficient

f_r : rolling resistance coefficient

θ_s : road slope angle with horizontal

$\pm$: positive for vehicle moving uphill, negative for vehicle moving downhill.

Figure 1.1 on page 3 summarizes the whole process with the pressure buildup distance occurring between the reaction and braking distances.

2.4 Advanced Driver Assistance Systems (ADAS)

Embedded systems can be found in many electronic devices and can be found in virtually all new cars today. In cars, this takes the form of Electronic Control Units (ECUs) which control specific functions in the car. Some of these systems found in cars include air-conditioning systems (climate control), security alarm systems, comfort modules, power and memory seats, supplemental restraint systems (SRS) and others. Real-time car systems aimed at preventing or avoiding accidents are known as Advanced Driver Assistance Systems (ADAS)[35]. Some ADAS systems help prevent major accidents while others help prevent minor ones. The following sections describe some of these systems in more detail.

2.4.1 Cruise Control

Cruise control is a feature found on some vehicles that keeps the vehicle moving at a particular speed (set by the driver) without throttle input from the driver. In earlier vehicles, this was controlled by the use of a mechanical device called a Centrifugal governor [37]. In recent vehicles, this is controlled electronically through an embedded system. Two main benefits of this kind of system are reduction of driver fatigue on long drives, and increased fuel economy [35].

2.4.2 Adaptive Cruise Control

With the Cruise control system, the vehicle would maintain the set speed regardless of the external conditions of the car and could be cancelled by either pressing the brake pedal or pressing the cancel button. Recent developments have led to Adaptive Cruise Control (ACC) systems.

In the ACC system, the vehicle has a range of sensors which detect other vehicles coming within their range. The system responds by autonomously applying the brakes and reducing acceleration in order to follow a vehicle ahead at a user-defined time-gap or distance [35].

Table 2.5: Car Manufacturers ACC sensor type and year first offered[35]

Manufacturer	**Sensor Type**	**Model Year Offered**
Toyota	Laser	1998
Jaguar	Radar	1999
Lexus	Laser	2001
Mercedes-Benz	Radar	2001
Saab	Radar	2002
Volvo	Radar	2002
GM	Radar	2004
Chrysler	Laser	2006
Ford	Radar	2009

The inclusion of external vehicle sensors and autonomous braking increases the complexity of the ACC system when compared to the earlier cruise control system.

Various car manufacturers make use of different sensors in their ACC implementations. Radar and Laser sensors are commonly used. Laser sensors are cheap due to their small sizes but have the disadvantage of being inaccurate under adverse weather conditions. Radar sensors have a farther range but usually cost more and are bulky [35, 17]. Table 2.5 shows some sensor types used by some car manufacturers and the years offered. Advances in semiconductor technology has enabled these radar sensors to be packaged in small sizes which can fit just about anywhere in front of a car [36].

The ACC system in some Audi cars can pinpoint detected cars to within a range of 10cm in distance and 0.1^0 in displacement from their axes of motion. The system determines how near or far other cars are by using the Doppler effect (the effect that causes the sound from a coming train to increase as it approaches one and then fade away as it recedes into the distance). The Audi ACC system can track 33 objects at a time. The system gives minor warnings to the driver through alarms and dashboard lights. Further alert include sharp autonomous braking as the situation demands [36]. Figure 2.6 shows some features of the ACC system found on a 2012 Audi A8.

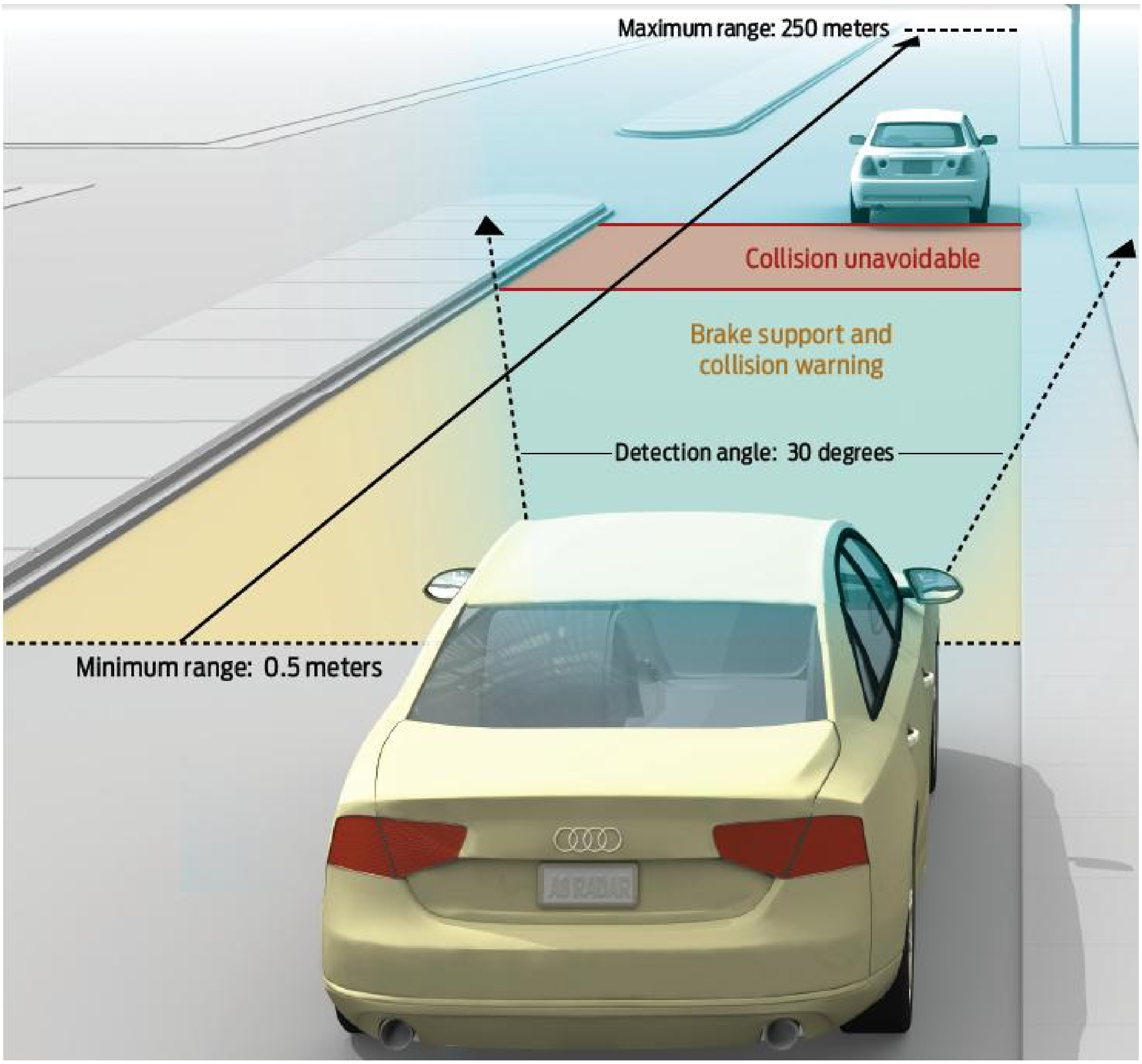

Figure 2.6: Adaptive Cruise Control (ACC) system on the 2012 Audi A8 [36]

Table 2.6: Car Manufacturers Lane Departure Warning (LDW) System trade names [35]

Manufacturer	System Name
Audi	Lane Assist
BMW	Lane Departure Warning
Ford	Lane Departure Warning System
GM	Lane Departure Warning
Honda	Lane Keep Assist System
Kia	Lane Departure Warning
Mercedes-Benz	Lane Keeping Assist
Nissan	Lane-Keeping Support
Toyota	Lane Monitoring Support

2.4.3 Precrash Systems [35]

These are systems that can detect and alert a car driver when an accident is about to happen. These systems also use radar or laser sensors, as well as video cameras in some cases. Their effects include ensuring that the brakes are fully prepared for maximum braking, seat adjustment for optimum support, tensioning seatbelts for optimal restraint, and in some cases, windows and sunroof are automatically closed. The effects and designs vary from one car manufacturer to the other.

2.4.4 Lane Departure Warning (LDW)Systems [35]

These systems ensure that the driver of a vehicle does not make unintended lane changes. The system checks if the vehicle is getting into another lane without the use of a turn signal. The lack of use of a turn signal could indicate inattentiveness or carelessness of a driver. The system could alert the driver through alarms or through vibration of the steering wheel. Some vehicles combine the displays of their ACC and LDW systems into one display for easier and faster driver readability. Different car manufacturers have varying names for their LDW implementations. Table 2.6 shows some of the various manufacturer implementation trade names.

2.4.5 Blind Spot Information System (BLIS) [35]

Blind spots are areas on the sides of a vehicle that cannot be seen by the driver through the mirrors, but only by turning the head away from the front of the car to the sides. The system was first introduced by Volvo. It usually notifies the driver of a vehicle in the blind spot through visual and/or audible alerts. Common implementations make use of sensors mounted in the rear wheel wells, bumper sensors and cameras mounted in the side mirrors.

2.4.6 Autonomous Parking Assistance System

These systems help to steer cars into parking lots, especially assisting drivers fit their cars into tight parking spaces. "The typical system uses a vehicle surrounding radar array to find parallel, diagonal, or perpendicular parking spots" [35]. The system will steer the vehicle into the available parking space while the driver controls the pedals and gear selection with guidance from a Human Machine Interface (HMI) [35]. Figure 2.7 on page 22 demonstrates Ford's *Active Park Assist* system.

2.4.7 Drowsiness Detection System [35]

This system can detect a change in the driving patterns arising as a result of loss of concentration/alertness. It responds by visual and/or audible alerts. It aids in reducing sleep-related car crashes. Some manufacturers use cameras to tract driver eye movements while others monitor the vehicle movement for erratic patterns.

2.5 Intelligent Transportation Systems (ITS)

This involves the use of Information and Communication Technology in various transport systems. This includes all in-vehicle communications, vehicle-to-vehicle (V2V) communications, and vehicle-to-infrastructure (V2I) communications /citeetsiintelligenttransport. ITS also makes use of Navigation systems such as Global Positioning System (GPS). ITS

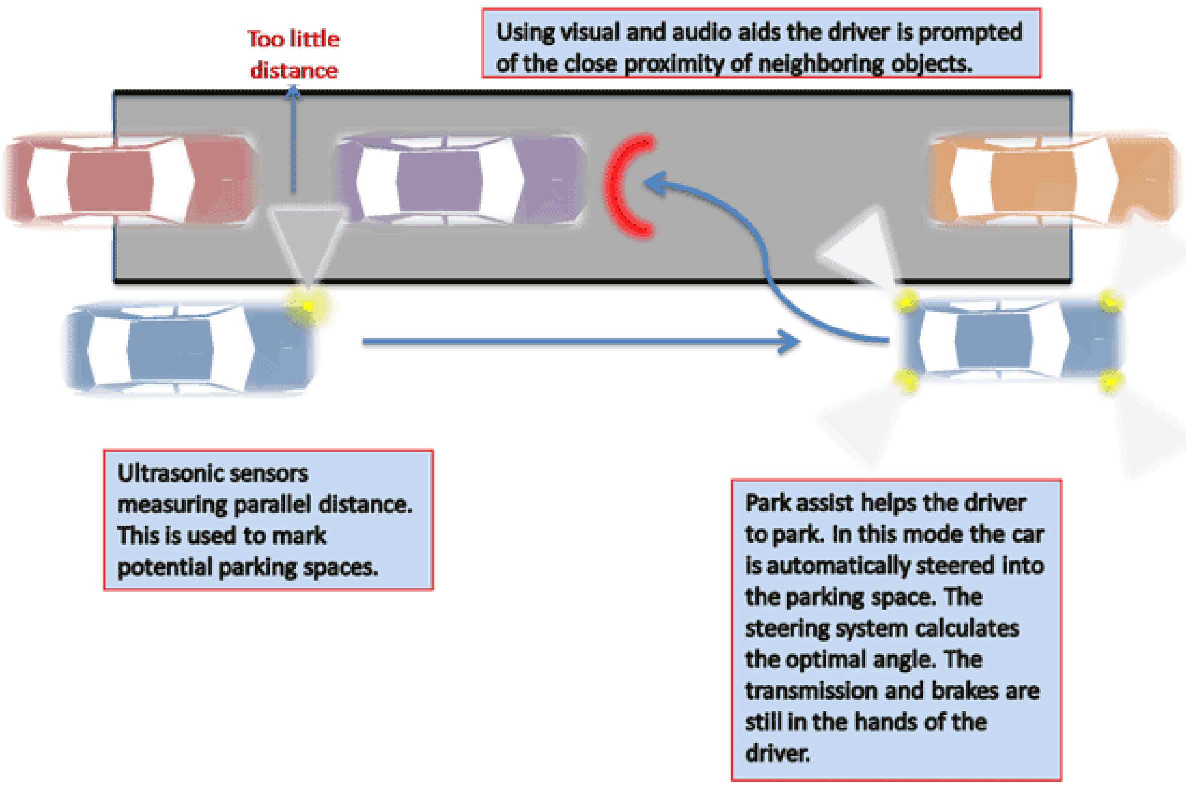

Figure 2.7: Ford's Active Park Assist System[19]

usually relies on various radio services for communication and other special technologies [15]. Figure 2.8 shows some feasible implementations of ITS.

There is a lot of on-going work and research into the development of ITS as it promises a lot of efficiency, in addition to enhanced safety of transportation systems. It will ultimately create a huge network of various transport components where each component can easily communicate with the other. This will have obvious advantages regarding safety, as vehicles will be able to easily communicate with each other and also with various infrastructure. Looking at Figure 2.8, it can be seen that collision avoidance features can be easily added, toll collected more efficiently and emergency services easily obtained.

Some ITS capabilities have already been implemented by some car manufacturers. For example, General Motors (GM) equipped some of its vehicles with a feature called OnStar. OnStar has the ability to provide Emergency, Navigation, Security and Vehicle Diagnostics

Figure 2.8: Intelligent Transportation System (ITS) [16]

features as necessary for the car user [22]. Automatic tolling systems have also been installed on some major US highways.

ITS systems promise very good results when implementation levels are high. This could take a couple of decades as research is still ongoing to develop some key components of the various subsystems. For instance, various implementations of Inter-Vehicle Communications (V2V) are still being experimented upon.

2.6 Road Studs

Road studs are devices used to delineate road edges and center-lines. Initially, reflective cat's eyes were used but electronics advancements have led to the creation of Solar-powered Light Emitting Diode (LED) road studs [20]. Solar road studs can provide illumination from distances ten times farther than reflective cat's eyes (900m compared to 90m) [28]. Figure 2.9 on page 25 shows the basic components of a Solar LED road stud. Solar LED road studs are basically maintenance-free as their internal batteries get recharged during the day and their power consumption levels are low due to low power levels of LEDs. Figure 2.10 shows a road well-delineated by LED road studs.

Solar LED road studs can be hard-wired together to a central controller (e.g. traffic management system). This can greatly improve their capabilities because they can provide dynamic capabilities suitable for various situations. This can be particularly useful during road construction, congestion periods and also as a driver safety aid to provide advanced warning of danger ahead [23]. The down-side of hard-wired road studs is the infrastructural demand required. This may not be available and cost-effective, especially along roads that are not tolled.

In [20], a wireless road stud network model was constructed. The architecture of the model is as shown in Figure 2.11. The model can only function properly where there is availability of required infrastructure such as reliable internet access, cellular service and

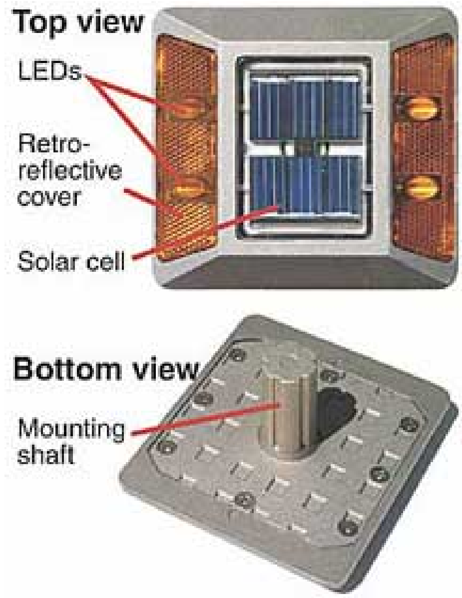

Figure 2.9: **Basic Components of a Solar LED Road Stud**
(Source: `http://www.sliwo.com/IMAGES/SRS2.jpgits)` accessed on 09-30-2014, 1:00pm

Figure 2.10: **Two-Lane Road Well-Delineated by LED Road Studs**
(Source: `http://solarpathusa.com/wp-content/gallery/lightmark-t/lightmark01.jpg` accessed on 09-30-2014, 12:50pm)

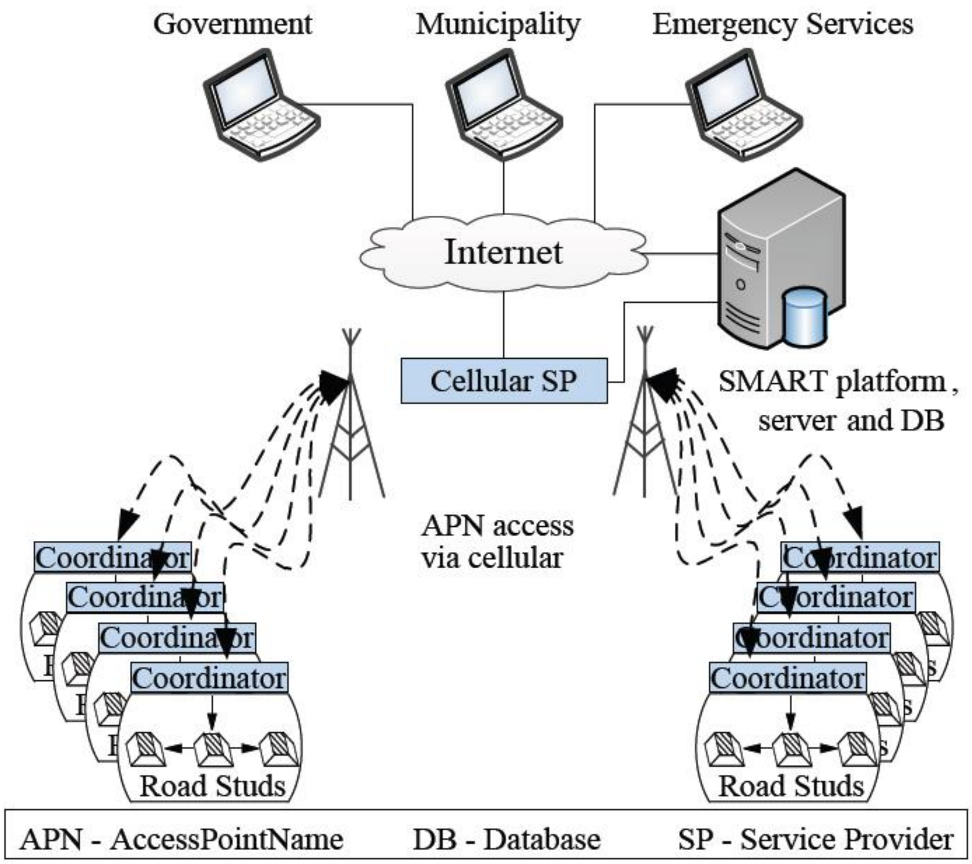

Figure 2.11: System Layout of Remotely Controllable Wireless Road Stud Network [20]

power. This may not be available along some roads, especially in developing countries, thus rendering the system unusable in such areas.

In [34], an intelligent system that makes use of Solar LED road studs connected wirelessly was developed. Each road stud has an infra-red sensor and light sensor to detect the presence of vehicles. Once an oncoming vehicle is detected, the road stud switches from a power-saving mode to an active mode. In the active mode, the LED (red in this case) is switched on and then a message is sent to the next node (road stud) for it to also be lit. This message is sent in a forward direction along the car line of travel for the corresponding road studs to be lit. The road stud LEDs go off after a definite time period. The system is as shown in Figure 2.12. This system provides clear lane delineation as the car travels and also conserves power by lighting only when a vehicle is detected. However, the system does not provide advanced

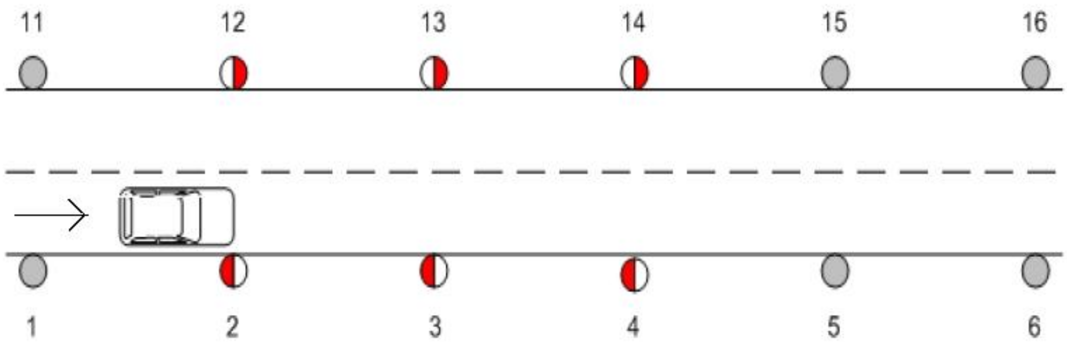

Figure 2.12: Road Nail System with communication between immediate neighboring studs [34]

warning in case of a hazard ahead and only one LED color can be produced (red in this case).

2.7 Vehicle Detection Systems

Various reasons call for the need to detect vehicles plying roads. Some reasons include traffic management, safety, and statistical purposes. Vehicle detection and monitoring forms the backbone of Intelligent Transportation Systems (ITS) since they help in collating data on the vehicular part of ITS [26].

A typical vehicle detection and surveillance system usually consists of three parts: 1.)the transducer, 2.)the signal-processor, and 3.)the data-processor. The transducer carries out the actual detection of the vehicles and is usually in close proximity to the vehicles on the road. The signal processor transforms the received output from the transducer into electrical signals, which are then sent to the data-processor for final conversion into forms understandable by the traffic management system [26].

According to [26], vehicle detectors can be divided into in-roadway and over-roadway versions. As the names imply, in-roadway designs are embedded in the road or in direct contact with the road, while over-roadway designs lie above the road surface at a certain height and not in direct contact with the road. Table 2.7 shows various in-roadway detectors and some applications. Table 2.8 shows various over-roadway detectors and some applications.

Table 2.7: In-roadway Vehicle Detectors and Applications [26]

Detector	Applications
Pneumatic Road Tube	1. Short-term traffic counting 2. Vehicle classification by axle count and spacing 3. Planning and Research studies
Inductive Loop	1. Vehicle passage 2. Vehicle presence 3. Vehicle count 4. Lane occupancy
Magnetic Sensor	1. Various traffic flow parameters (such as vehicle count, speed, lane occupancy) 2. environmental monitoring of road surface temperature 3. wetness or dryness of road surface
Piezoelectric Sensor	1. Vehicle classification by axle count and spacing 2. Vehicle weight measurement 3. Speed measurement 4. Weigh-in-motion
Weigh-in-motion (Bending Plate, Piezoelectric, Load cell, Capacitance mat)	1. Highway planning 2. Vehicle classification by axles 3. Vehicle weight enforcement

Table 2.8: Over-roadway Vehicle Detectors and Applications [26]

Detector	Applications
Video Image Processor	1. Vehicle presence, flow rate and occupancy 2. Speed and density 3. Travel time
Microwave radar	1. Vehicle presence, passage and volume 2. Lane occupancy 3. Vehicle speed and length 4. Traffic queue monitoring
Infrared Sensor Active (Laser radar) & Passive	1. Traffic signal control 2. Traffic volume and speed 3. Pedestrian detection 4. Vehicle presence at traffic signals 5. Vehicle classification, length and occupancy
Ultrasonic Sensor	1. Vehicle count 2. Vehicle presence 3. Vehicle occupancy
Passive acoustic array sensor	1. Data collection 2. Traffic volume 3. Lane occupancy 4. Average traffic speed

Magnetic Sensor Detector

In the design of a vehicle detector system that requires very little infrastructural dependence, over-roadway detectors are not usually considered because of their large dependence on infrastructure (power, mounting poles, communications lines, etc.). From the variety of in-road detectors, the only feasible option that can cover vast road areas is the Magnetic sensor type, as used in [18]. There is a large variety of magnetic sensor technologies. A detailed review can be found in [21]. [27] provides more information on the Anisotropic Magnetoresistive (AMR) magnetic sensor, which can be easily suited for vehicle detection with little infrastructural dependence, as shown in [18]. Some of the drawbacks of the AMR sensor are its temperature dependence, sensitivity to orientation, noise and amplifier requirement. To overcome these drawbacks, circuit complexity has to be increased to ensure accuracy, at the cost of increased power requirements [27].

2.8 Vehicle Headlamp

All motorized vehicles are mandated to have headlamps mounted in front of them to provide light for night-driving or as daytime running lights (DRL) to provide presence-awareness to other road users during the day. Engineers have constantly been working on headlamp improvements because of the higher frequency of fatal accidents at night. Figure 2.13 shows the basic components of a car headlamp. Recent car headlamps have multi-reflector surfaces with a plain glass surface instead of a lens with prisms to redirect the light [32].

Some types of headlamps used on automobiles include Sealed Beam, Composite, High-Intensity Discharge (HID), Bi-xenon and Light Emitting Diodes (LEDs). The sealed beam versions are not in common use anymore, as they require replacement of the whole lamp assemblies if their filaments burn out. Composite, HID and Bi-xenon headlamps have replaceable bulbs. LED headlamps are gaining popularity in vehicles as they consume very

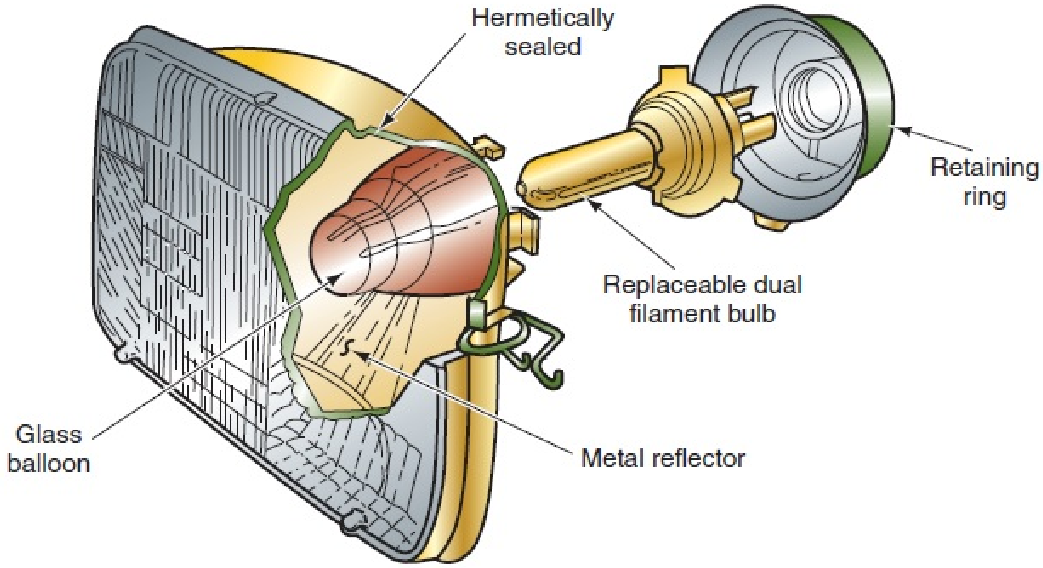

Figure 2.13: Basic Components of a Car Headlamp [32]

little power and can be powered by pulses which are imperceptible to the eye to further improve their efficiency.

Figure 2.14 shows the light intensity patterns of halogen bulb and HID headlamps. It can clearly be seen that the HID headlamp has a much better coverage than the halogen bulb. Since light travels in a straight line, headlights do not generally follow road curves except the vehicle is equipped with headlamps that can swivel in the direction of vehicle steering wheel turn. This has limited effectiveness as the field of view is usually restricted around curves and hills or valleys.

Vehicle headlamps have low and high beam outputs. Low beam is to be used to reduce or control the glare towards other road users. If the glare is not controlled, it could easily lead to a car crash as the driver could be blinded temporarily. Low beams cast most of their light on the ground, far and wide enough to provide forward visibility at a safe distance. On the other hand, high beams cast most of their light straight ahead of the vehicle, thus increasing its reach. However, this produces a lot of glare to other road users and should only be used in their absence.

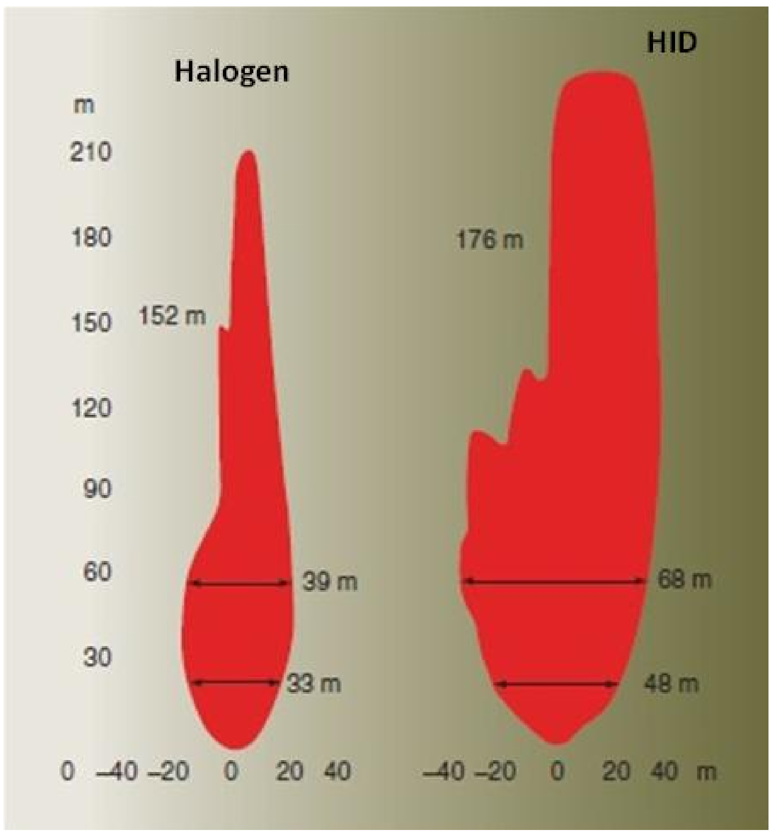

Figure 2.14: Comparison of Halogen and HID lamp light intensities [32]

Chapter 3

Materials and Methods

3.1 Experiment Setup

The main reason for this study was the determination of the feasibility of accurately detecting a slow-moving or stalled vehicle at night, through optical sensing, by using only the vehicle headlights. Other methods as mentioned in the previous chapter can be employed but one that can easily be integrated into an IRS, was investigated here. Figure 3.1 shows the basic components of the experimental procedure.

The power source used for the experiments was a laboratory AC/DC power source which was set to the required constant 5V output. The power source was connected to a truck (for mobility to test sites) that had an in-built inverter. The Optical sensor used was a PDV-9008 Light-Dependent Resistor (LDR) (see appendix A for specifications) in a circuit as shown in Figure 3.2. The resistor-divider arm was set up so that as the light intensity on the LDR increased, its resistance decreased, and thus increased the voltage drop across the 26.8kΩ resistor. The voltage drop across the 26.8kΩ resistor was then connected to an Oscilloscope / datalogger. The datalogger used was computer-based. It was obtained by

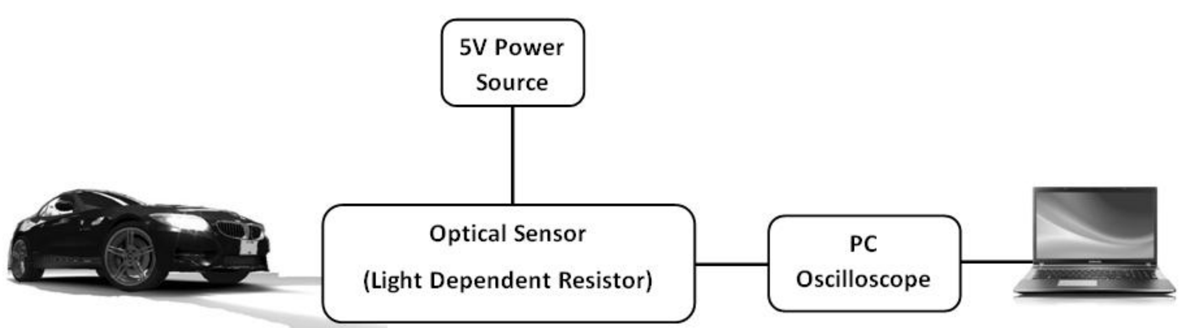

Figure 3.1: Experiment Setup

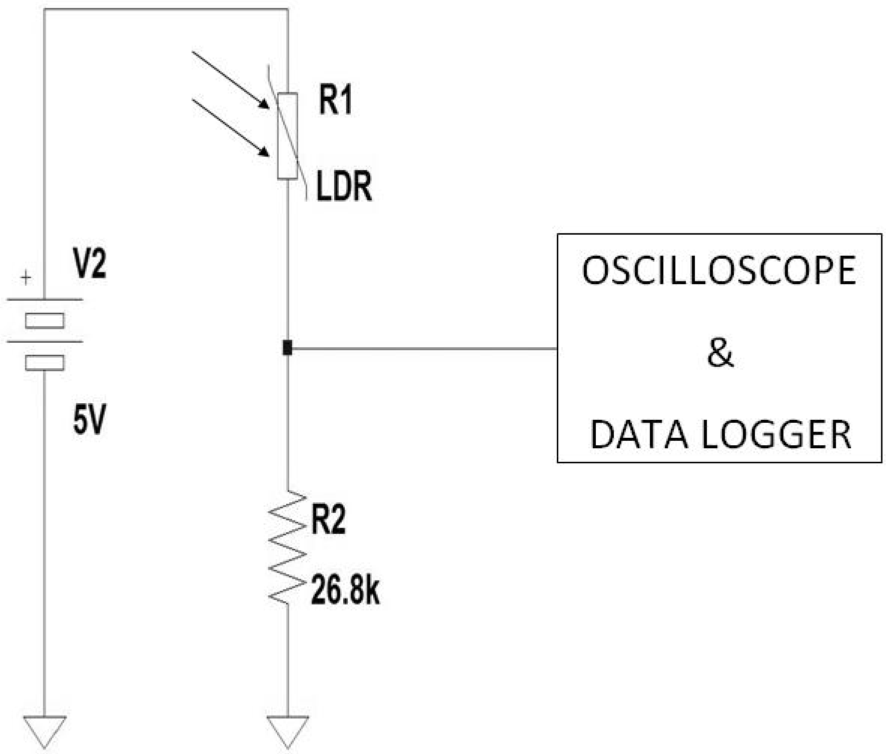

Figure 3.2: Optical Sensor Circuit

connecting the ADC-200 PC Oscilloscope / datalogger, by *Pico Technology*, to a computer through a Parallel cable (see appendix B for the ADC-200 datalogger specifications).

The LDR and 26.8kΩ were mounted on a breadboard, with the LDR tilted facing the vehicle headlights. Low resistance cable (3-wire core) was then used to provide power to the divider circuit and also connect the output to the datalogger. This was possible because the resistance of the cable wires was small compared to the very high resistance of the data logger. Tektronix P2200 passive probe was used to measure the output of the sensor (see Appendix C for specifications).

Figure 3.3: Experiment setup for sensor output with varying distance

3.2 Procedure

The breadboard was positioned in the direction of the right vehicle headlight low beam. A lit parking lot devoid of any other cars was used for the initial experiment readings. Using a tape measure, the distance of the sensor to the headlight was varied by moving the vehicle in small increments towards the sensor from about 200ft and appropriate readings were taken on the PC using the datalogger software. The setup was as shown in Figure 3.3.

Also, the vehicle was driven at speeds of 5mph, 10mph and 20mph respectively, towards the light sensor and appropriate waveform measurements taken.

The setup was then taken to a traffic light and was mounted by the roadside (on a curb about 6 inches high) by the side of a 4-lane road and appropriate measurements were taken. It was also mounted on the white stop line, in the middle of a lane, at a traffic intersection. The chosen location was as shown in Figure 3.4 with the mounting positions shown with

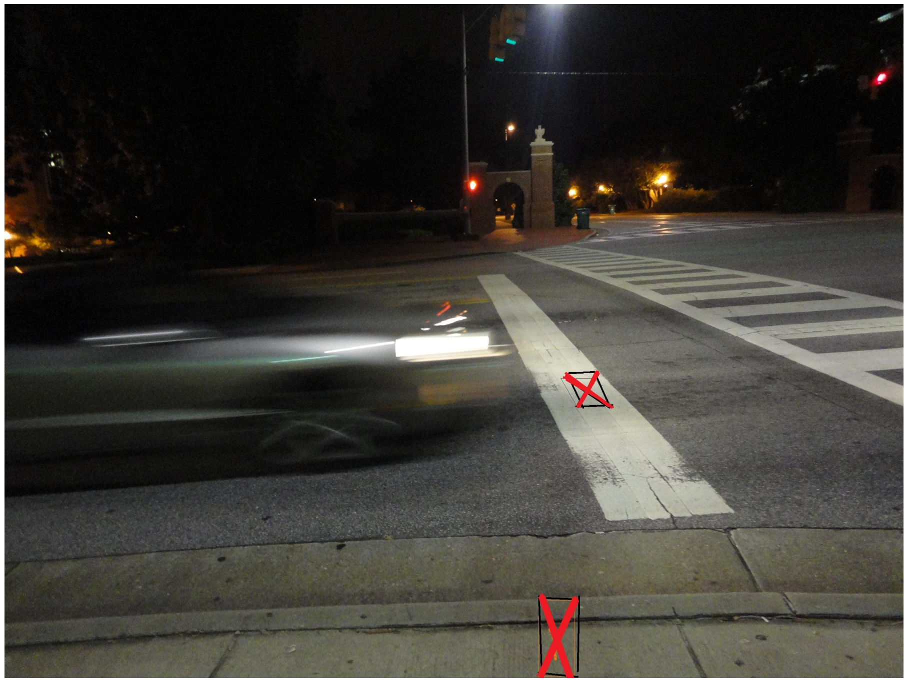

Figure 3.4: Experiment setup positions at traffic light - “X” marks positions

the red x-signs. The traffic light measurements provided the opportunity to observe actual situations of slowly-moving or stalled/stopped vehicles.

Chapter 4

Results and Discussion

4.1 Parking Lot Experiments

4.1.1 Variation of Voltage Output with Distance from Optical Sensor

The result was as shown in Figure 4.1 on page 37 at a sampling rate of 200Hz. It can be observed that the voltage output initially increased at a steady rate till it reached its peak (about 2.6V) at around 20ft. This was due to the fact that the car headlights being at a height of about 3.5 ft off the ground, do not fully shine on the sensor until the car was backed off from the sensor a distance of about 20ft. After 20ft, the light intensity diminishes and then falls off as the car recedes further. The small increments as the voltage output dropped from its peak value are due to light reflecting off the ground surface and light from the 2nd headlight reaching the sensor. At 190ft away from the sensor, the output voltage was measured to be 0.100V. With the headlights set to full beam at 190ft, the output voltage was measured to be 1.118V. This difference in output clearly shows the effect of using low and high beams during night driving.

At 120ft away, the voltage measurement was about 0.24V. This clearly indicates that the sensor could pick up the presence of a vehicle about 120ft away on a level and straight road.

4.1.2 Output waveforms at varying vehicle speeds

Results obtained were as shown in Figures 4.2, 4.3 and 4.4 for speeds of 5mph, 10mph and 20mph respectively. Upon comparing Figures 4.2, 4.3 and 4.4, it can be observed that the tooth-like portions are identical except that the widths of the bases reduced as the speed

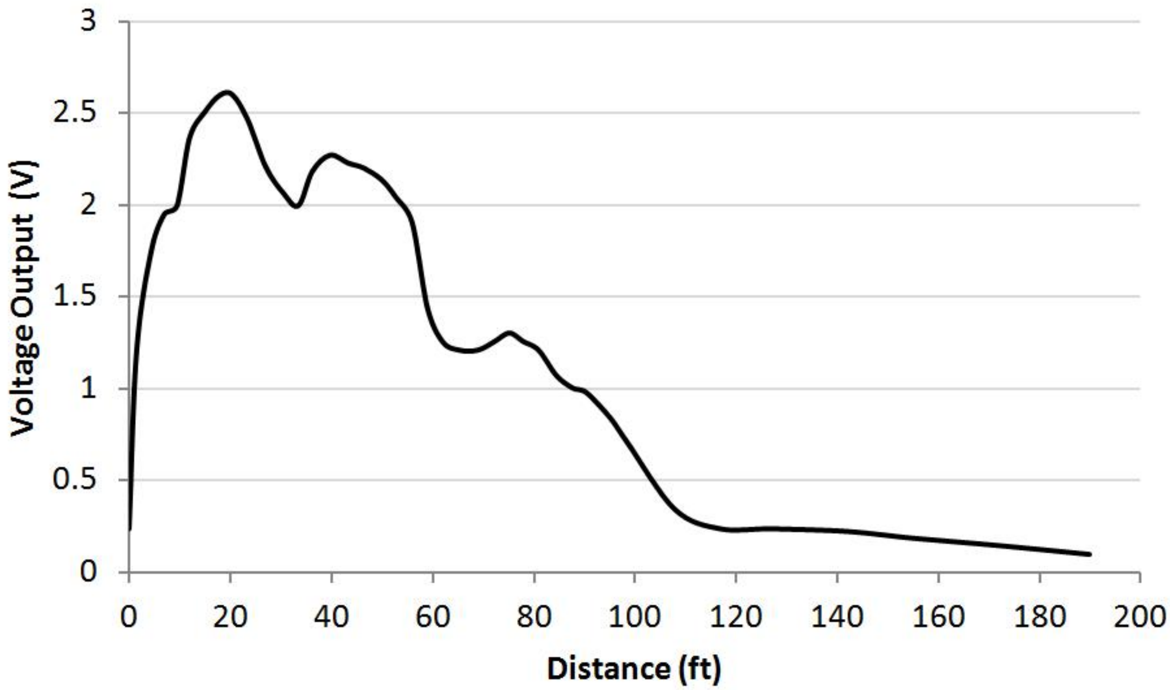

Figure 4.1: Variation of voltage output with distance from headlight

of the car increased. This was because as the vehicle speed increased, the duration of light incident on the sensor reduced. The little small humps before the big tooth in each case were probably due to the effect of both headlights before the vehicle got really close to the sensor.

In Figure 4.4, at around the 110s point the vehicle was stopped and the driver got out of the car. This led to the first step down in the curve due to the change in vehicle height as the driver stepped out. The output remained relatively constant till the driver passed in front of the headlight, thus creating the dip in output voltage. Afterwards, the headlight was turned off thus causing the output to drop to the quiescent value.

In addition, it can be observed from Figures 4.2, 4.3 and 4.4 that the quiescent values of the curves never dropped to zero. This was because the vehicle never went over the sensor but passed beside it. In essence, there was always some light incident on the sensor after the vehicle passed by.

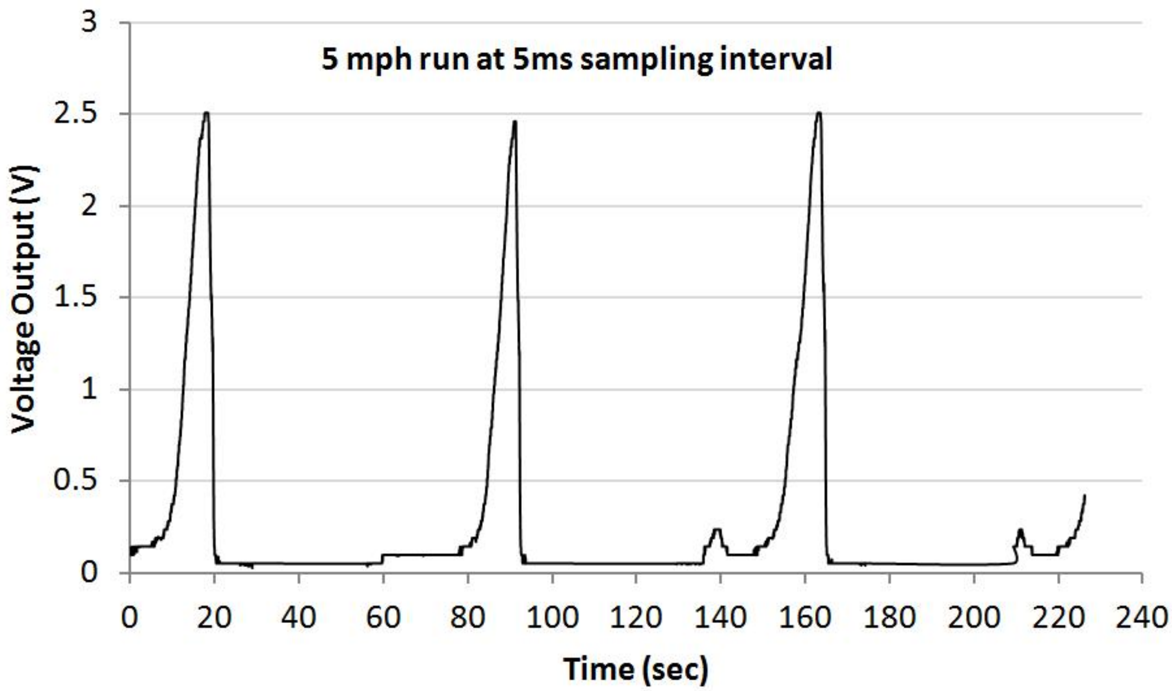

Figure 4.2: Light sensor output for vehicle moving at 5mph

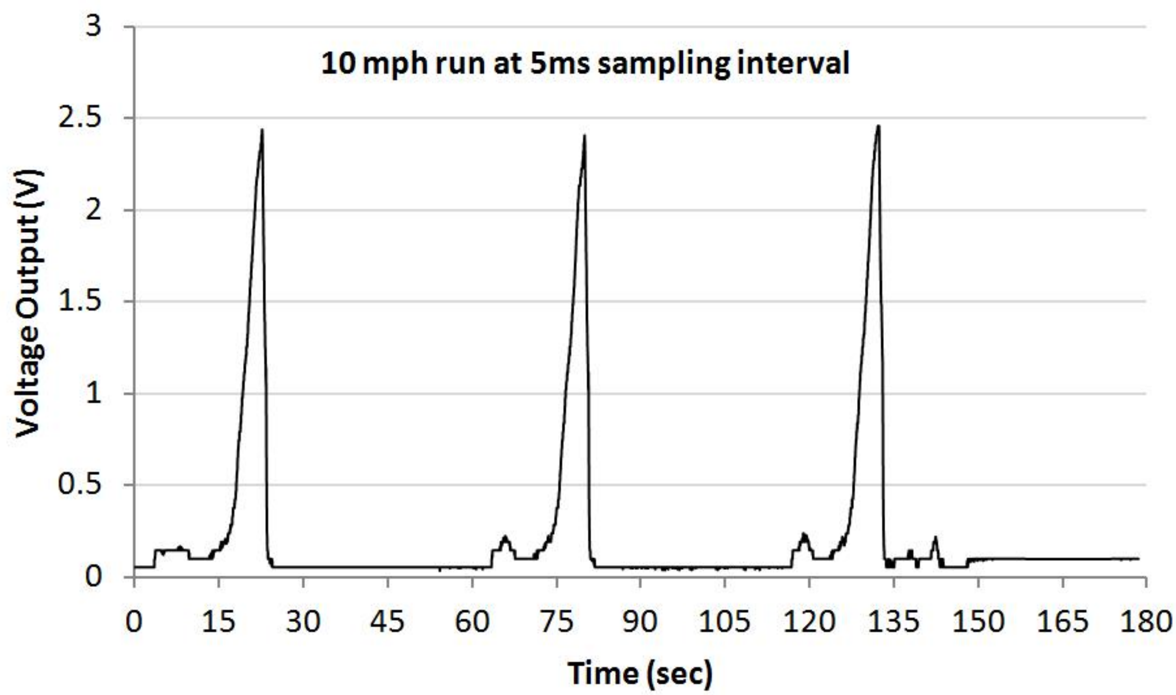

Figure 4.3: Light sensor output for vehicle moving at 10mph

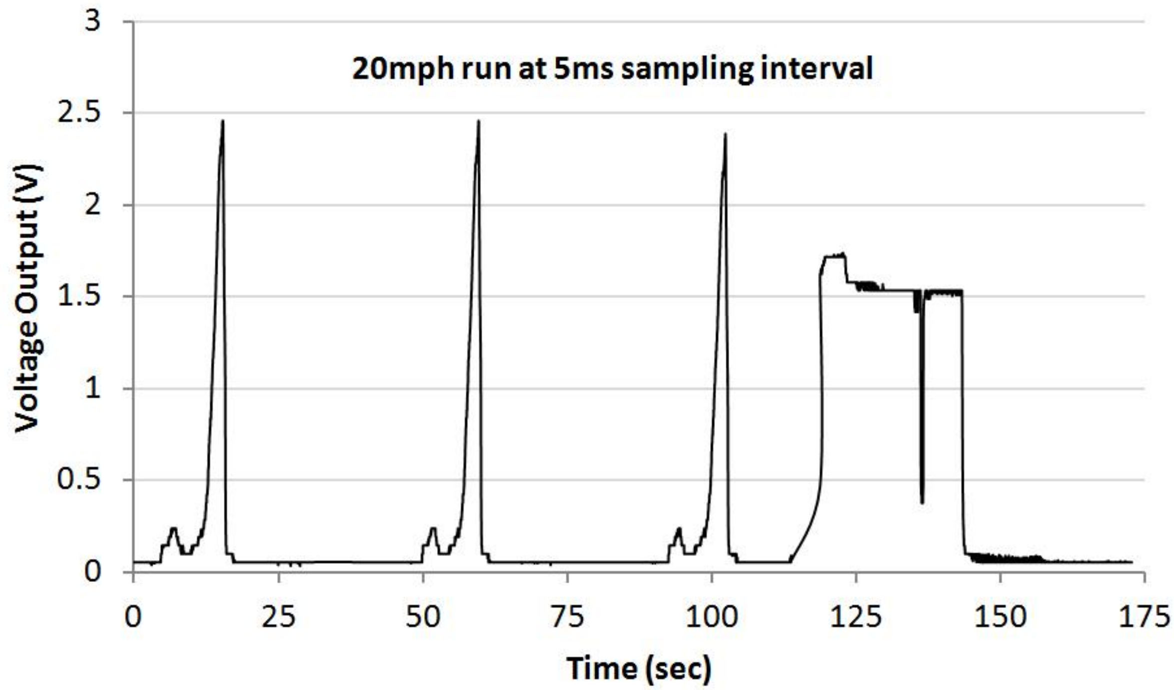

Figure 4.4: Light sensor output for vehicle moving at 20mph (At 120 s, vehicle is stopped; person walks between vehicle and sensor at approximately 135s.)

4.2 Traffic Light Experiments

As can be observed in Figure 3.4 on page 35, the sensor could detect lights from either the inside or outer lane. In addition, the sensor also detected ambient, street lighting.

4.2.1 Light sensor mounted by 4-lane road on curb

At a sampling frequency of 40Hz (25ms sampling interval), the result was as shown in Figure 4.5. For a sampling frequency of 100Hz, the result was as shown in Figure 4.6. Upon comparison of Figures 4.5 and 4.6, it can be seen that they both have baselines very close to 0V.

From Figure 4.5, for 135≤t≤200sec, cars were at a standstill at the traffic light. The pulse observed within the region was probably due to turn signal from one of the cars. Furthermore, it can be seen that the waveform is not constant but has ripples. Increasing the sampling frequency from 40Hz to 100Hz reduced these ripples, as shown in Figure 4.6. The

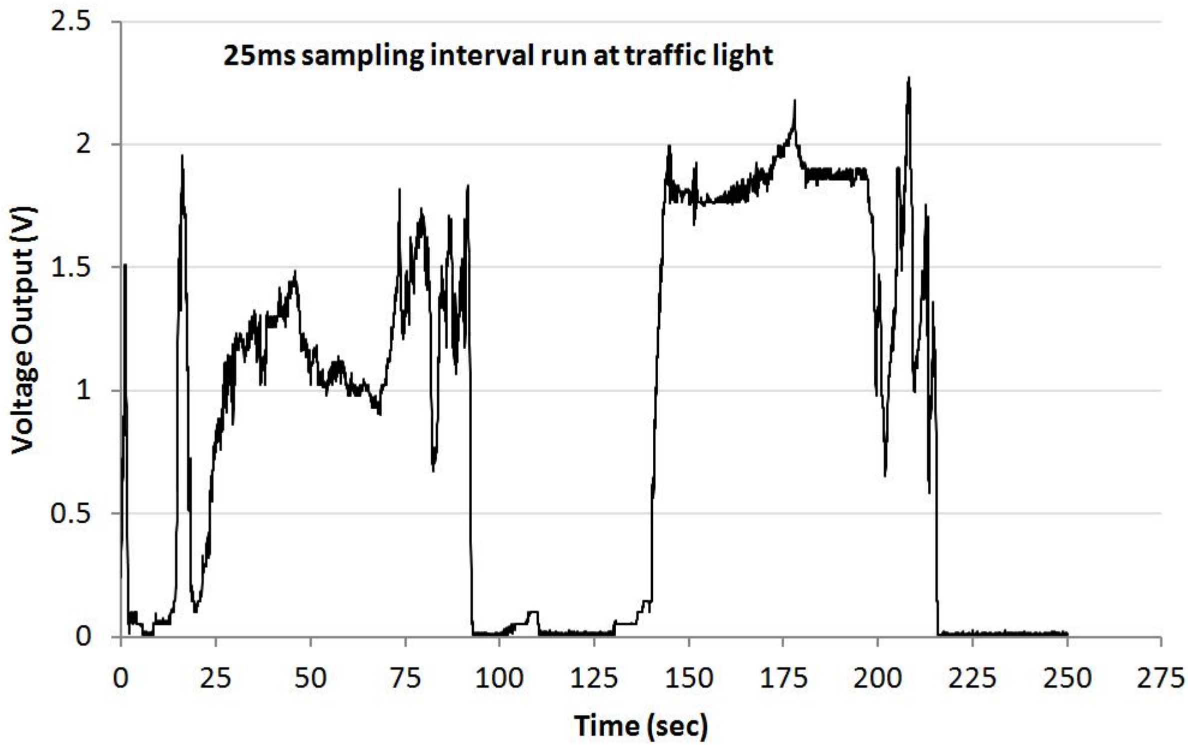

Figure 4.5: Light sensor output at traffic light (40Hz sampling frequency)

more ripples observed with the 40Hz sampling frequency were probably due to interference from the surrounding power lines operating at a frequency of 60Hz. It could also be attributed to the wires from the sensor to the oscilloscope acting as antenna and picking up unwanted signals. It can clearly be observed from Figures 4.5 and 4.6 that the waveforms remained relatively constant when the vehicles were stationary, as depicted in regions 135≤t≤200sec and 47≤t≤82sec respectively.

With sampling frequency increased to 200Hz, the results were as shown in Figures 4.7, 4.8, 4.9 and 4.10. It can clearly be seen that smoother curves were obtained, with higher baselines of about 0.3V. Looking at Figures 4.8 and 4.9, in the ranges 80≤t≤120sec and 70≤t≤95sec respectively, vehicles at the traffic light were at a standstill. Due to the position of the sensor on the curb, it was sometimes crossed over by pedestrians on the sidewalk thus leading to unwanted drops in output. No doubt, by merely observing the waveforms one could reliably tell the presence or approach of a vehicle towards the optical sensor.

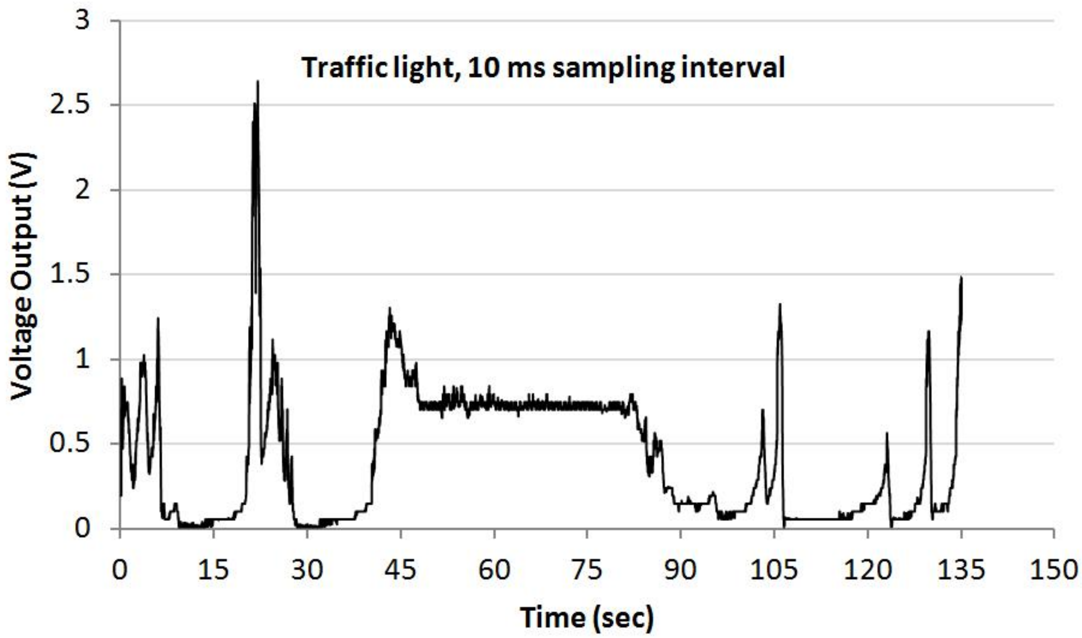

Figure 4.6: Light sensor output at traffic light (100Hz sampling frequency)

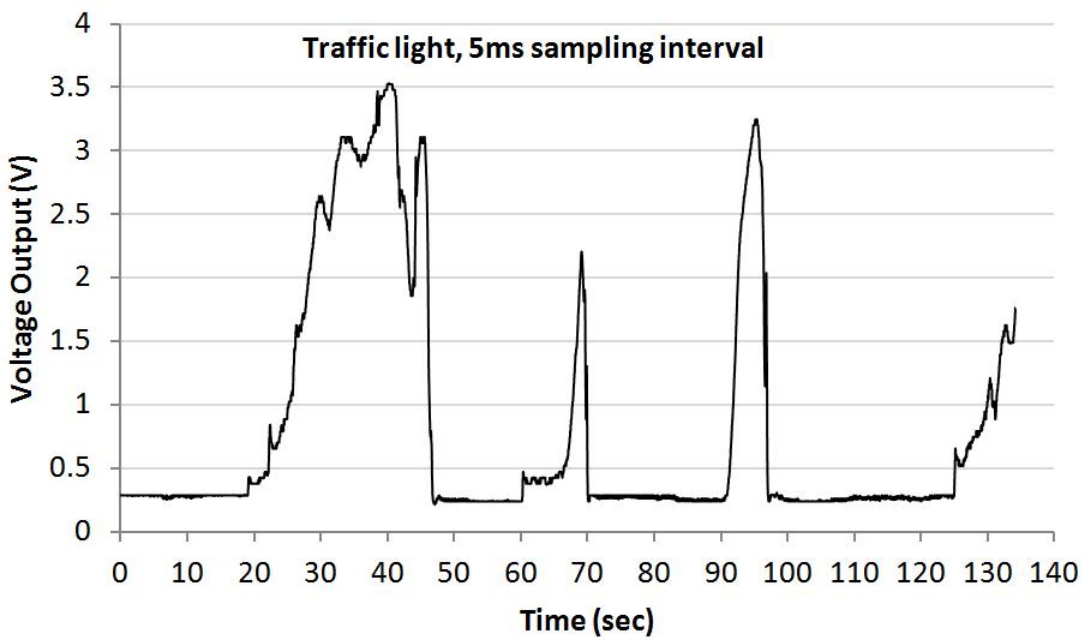

Figure 4.7: Light sensor output at traffic light (200Hz sampling frequency) - 1st run

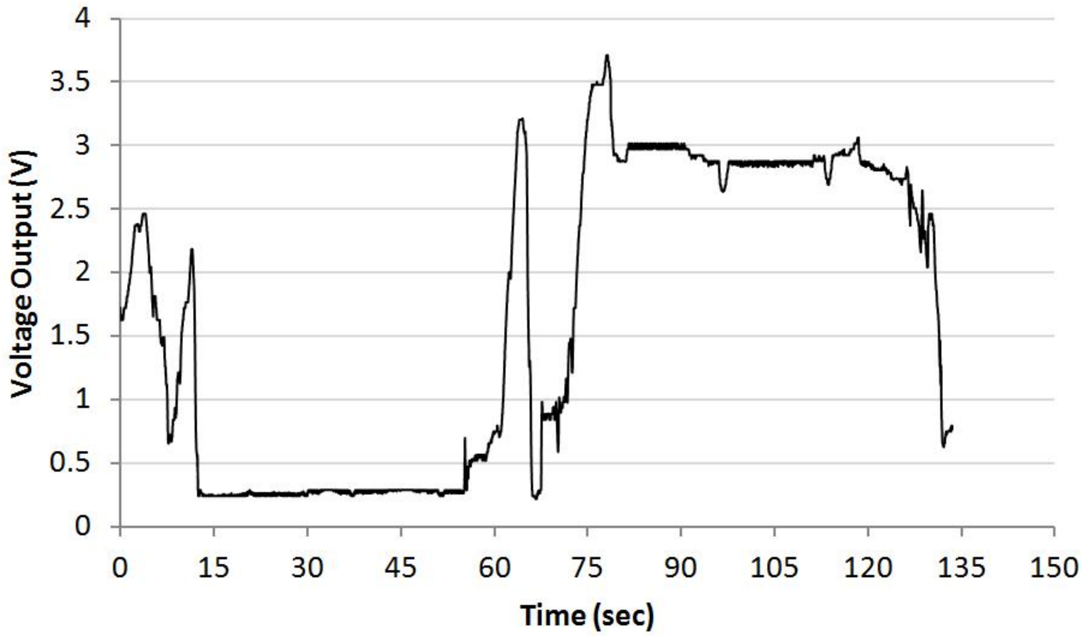

Figure 4.8: Light sensor output at traffic light (200Hz sampling frequency) - 2nd run

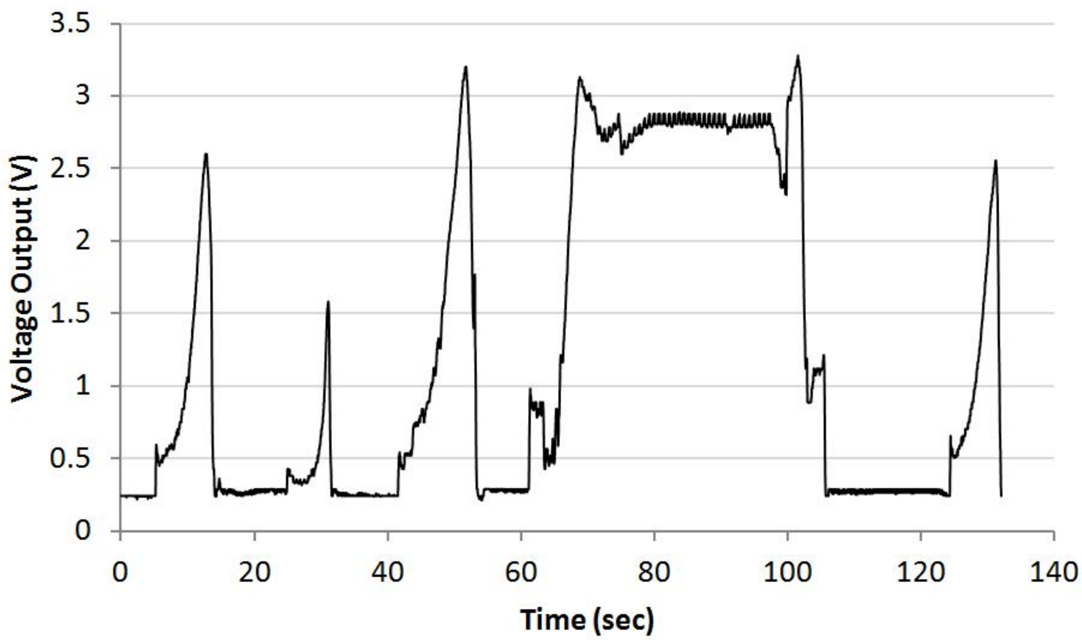

Figure 4.9: Light sensor output at traffic light (200Hz sampling frequency) - 3rd run

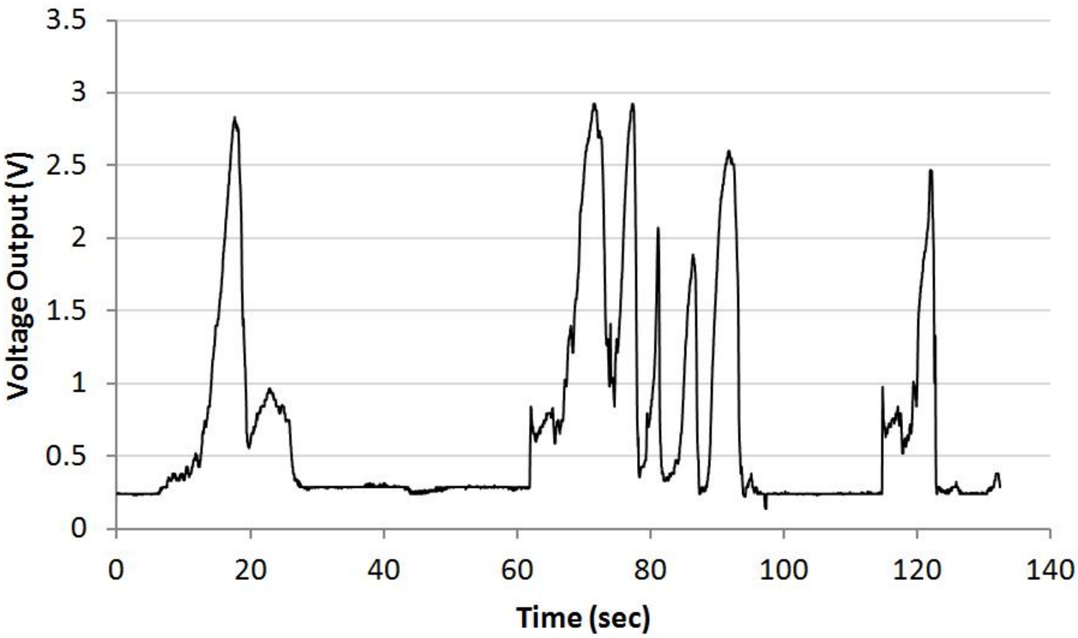

Figure 4.10: Light sensor output at traffic light (200Hz sampling frequency) - 4th run

4.2.2 Light sensor mounted in middle of outer lane on white stop line

At a sampling frequency of 200Hz, the results were as shown in Figures 4.11, 4.12 and 4.13.

From Figure 4.11, it can be observed that the curve exhibits less ripple compared to when the sensor was placed on the curb. In addition, the baseline is also a little higher. In the regions 0≤t≤8sec and 107≤t≤124sec, the curve is relatively constant. This was so because vehicles were stopped at the traffic light.

Figures 4.11, 4.12 and 4.13 show drops to zero at certain times. This occurred at those times when vehicles passed directly over the sensor, thus shielding it momentarily from any light.

Figures 4.12 and 4.13 show peaks of above 4V. This was because the light falling on the sensor was more as a result of both headlights, due to the sensor being in the middle of the lane, compared to the situation when it was by the road-side on the curb. Also, vehicles

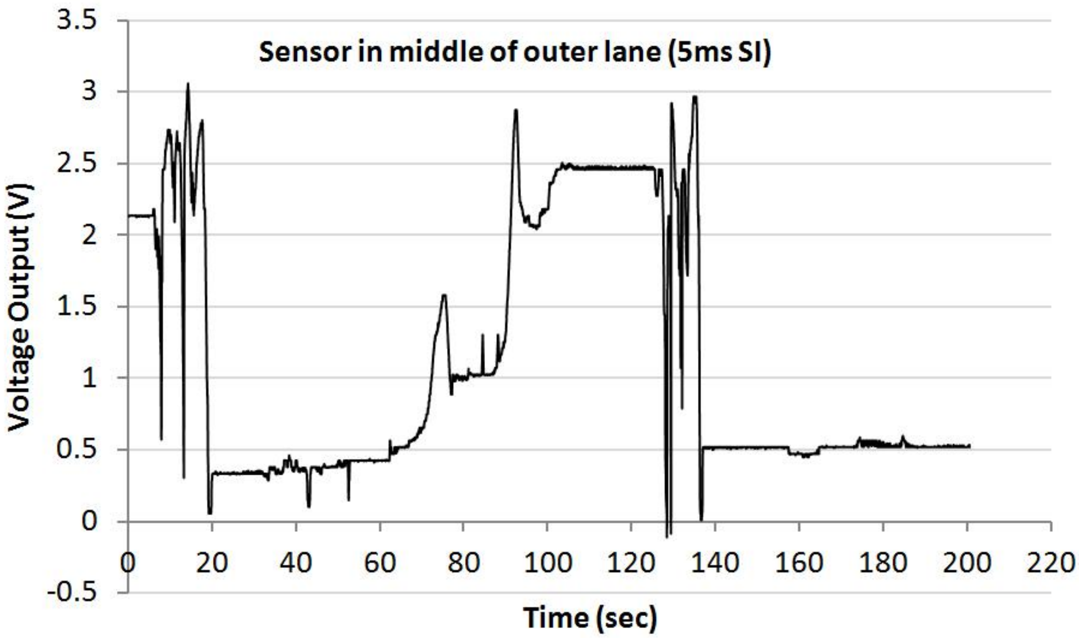

Figure 4.11: Light sensor output from mid-lane position - 1st run

with very bright headlights (probably High Intensity Discharge (HID) lights) and fog lights in use, produced higher sensor voltage outputs.

With the sensor in the middle of a lane, more accurate results could be obtained. However, this position would prevent the road stud positioned in this way from being used to delineate lanes.

After the first experiment run, the sensor was run over by a vehicle but due to its simple and rugged nature, its function was not impaired. This proved that it didn't require a very special enclosure, as long as it had adequate light exposure in the required orientation.

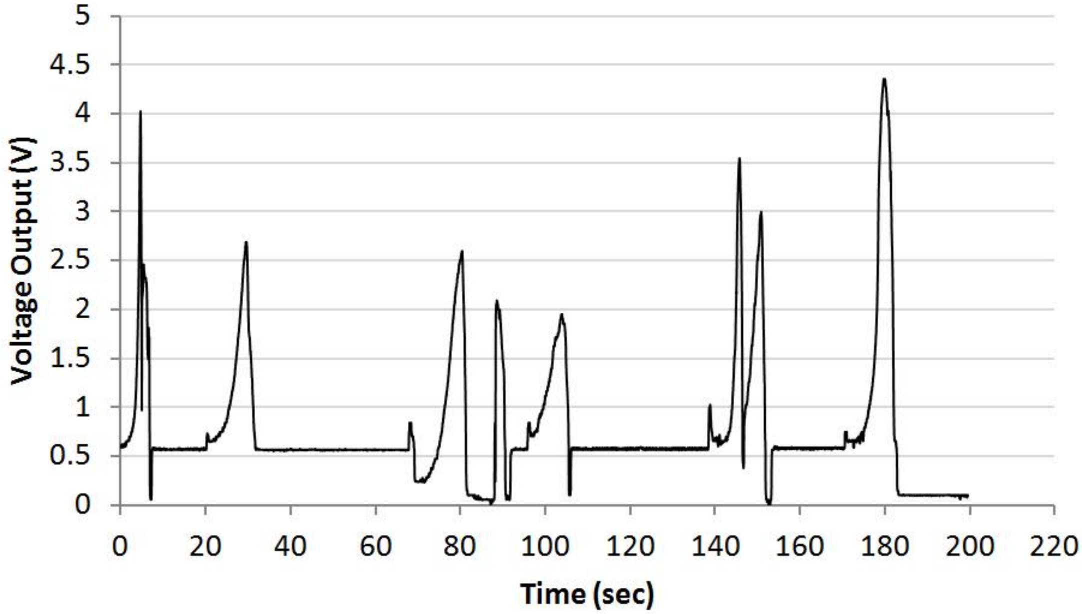

Figure 4.12: Light sensor output from mid-lane position - 2nd run

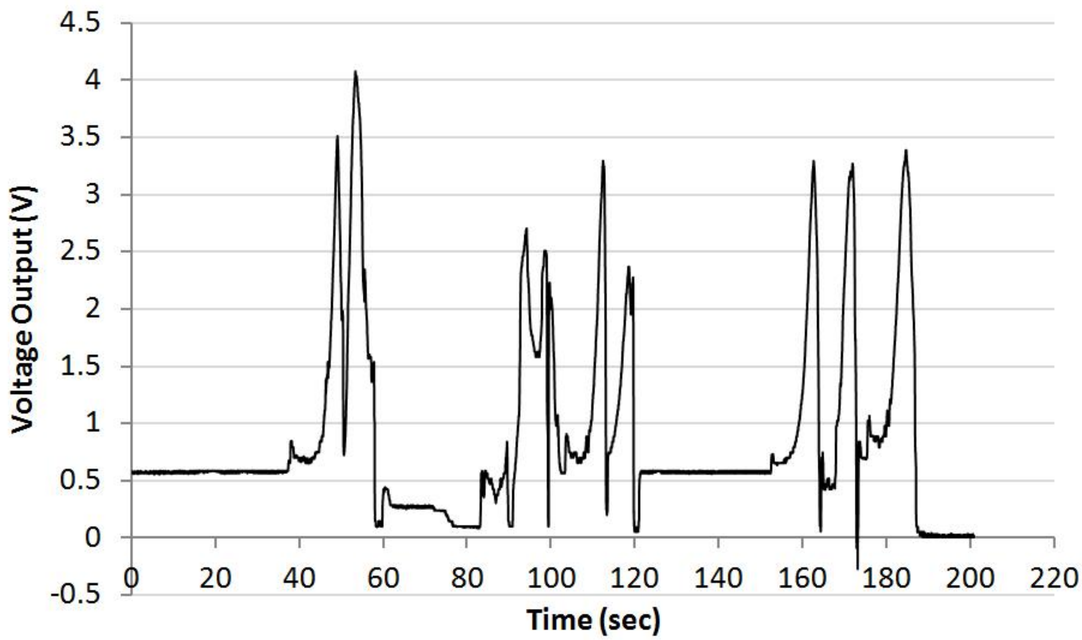

Figure 4.13: Light sensor output from mid-lane position - 3rd run

Chapter 5

Conclusions and Recommendations

No doubt, the experiment setup was able to detect the presence of vehicles through their headlight beams. It was also observed that the width of the pulses corresponded to the speeds of the vehicles. In situations where the sensor output was relatively constant, it can be concluded with much certainty that the vehicle was not moving.

An intelligent prototype needs to be further developed, incorporating the decision element that determines if the detected vehicle is either stopped or moving too slowly for the particular roadway, and also the required action to be taken. In the case of LED road studs, this action could take the form of flashing red or amber LEDs on the road studs. The prototype can be implemented using a microcontroller embedded in a road stud, with solar charging capabilities for power. Afterwards, a communication protocol could be designed to pass on the detection information to other road studs, perhaps a certain number of hops away or a particular distance, in order to provide advanced warning of the obstacle (vehicle) to oncoming vehicles. A model of the overall system is as shown in Figure 5.1. From Figure 5.1, the car traveling from the left direction could easily run into the one on the right as the hill blocks its view. With the intelligent road studs, the traveling car would be alerted early enough to know there could be an obstruction ahead and thus avoid a collision.

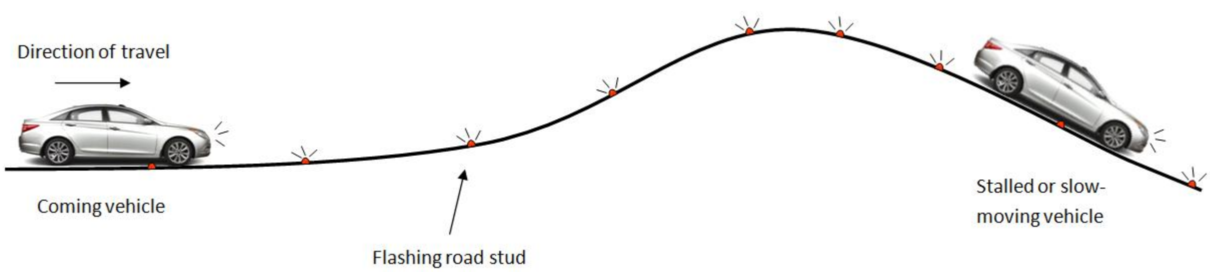

Figure 5.1: Model of proposed intelligent road stud

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Appendices

Appendix A

PDV-9008 Light Dependent Resistor (LDR) Specifications [12]

PDV-P9008 or PDV-9008 is a Cadmium-Sulphide (CdS), photoconductive photocell designed to detect light in wavelength range 400 to 700 nm. It is packaged in a 2-leaded plastic-coated ceramic header. This is as shown in Figure A.1. It responds to visible light and is of low cost. It is typically used in cameras and night light controls. Table A.1 shows its absolute maximum ratings while Table A.2 shows its electro-optical characteristics.

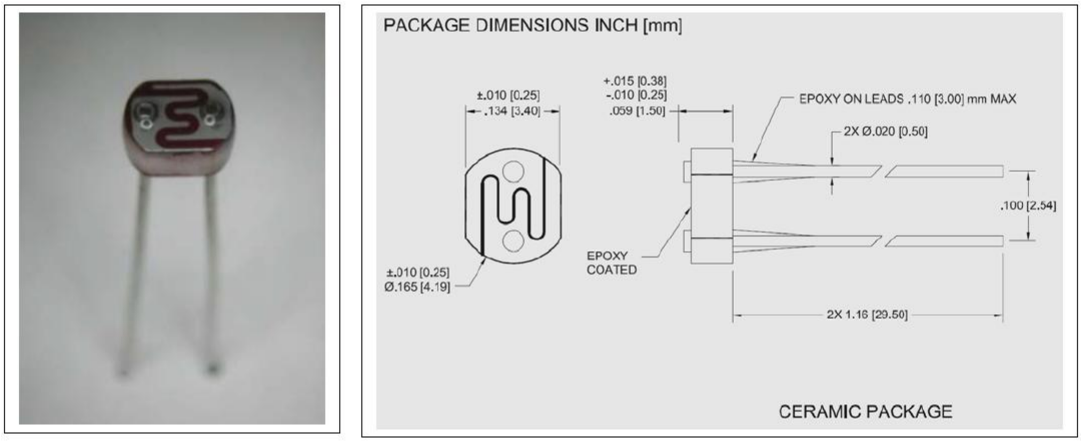

Figure A.1: PDV-9008 package

Table A.1: PDV-9008 Absolute Maximum Rating (23^0C)

SYMBOL	PARAMETER	MIN	MAX	UNITS
V_{pk}	Applied Voltage		150	V
$P_{d\Delta po/\Delta t}$	Continuous Power Dissipation		125	mW/^{0}C
T_O	Operating and Storage Temperature	-25	+75	^{0}C
T_S	Soldering Temperature		+260	^{0}C

Table A.2: Electro-Optical Characteristics Rating (23^0C)

CHARACTERISTIC	TEST CONDITIONS	MIN	TYP	MAX	UNITS
Dark Resistance	After 10 sec. @ 10 Lux @ 2856 ^{0}K	20			MΩ
Illuminated Resistance	10 Lux @ 2856 ^{0}K	10		200	KΩ
Sensitivity	$\frac{LOG(R100)-LOG(R10)}{LOG(E100)-LOG(E10)}$		0.85		Ω/Lux
Spectral Range	Flooded	400		700	nm
Spectral Range	Flooded		570		nm
Rise Time	10 Lux @ 2856 ^{0}K		60		ms
Fall Time	After 10 Lux @ 2856 ^{0}K		25		ms

Appendix B

ADC-200 PC Oscilloscope/Datalogger [24]

The ADC-200 PC Oscilloscope belongs to a family of high-speed analogue-to-digital converters (ADCs). It has 4 signal connectors and a 12V DC power socket. The 4 signal connectors are composed of 2 input channels (female BNC connectors), a parallel port and an external trigger (female BNC connector). It can be used as a PC-based oscilloscope / spectrum analyzer with appropriate software or as a datalogger with the *Picolog* software. Also, its driver software can be used to develop programs to collect and analyze data from the unit. Its specifications are shown in Table B.1. A picture of the ADC-200 is as shown in Figure B.1.

Table B.1: ADC-200 PC Oscilloscope/Datalogger Specifications

	ADC-200/20	**ADC-200/50**	**ADC-200/100**
Resolution (bits)	8		
Input Channels	2 x BNC connectors 1 Mohm impedance AC/DC coupling		
External Trigger	Ext BNC Input: TTL Level Trigger Output: Square Wave Signal Generator		
Voltage Ranges	±50 mV to ±20V in 1,2,5 steps (in 9 Ranges)		
Accuracy (%)	±3		
Overload Protection (V)	±100		
Sampling Rate (Samples/s)			
1 Channel	20M	50M	100M
2 Channel	10M	50M	50M
Buffer Size (kSamples)	8	16	32
Signal Generator	<250 kHz TTL square wave		
Power Supply	12V DC nominal at 500 mA max DC 1.3mm connector (center positive)		
Dimensions (mm)	140 x 190 x 45		

Figure B.1: ADC-200 PC Oscilloscope / Datalogger

Appendix C

Tektronix P2200 Passive Probe Electrical Characteristics [13]

The Tektronix P2200 passive probe has a male BNC plug on one end, a probe attenuation switch for selecting either 10X or 1X attenuation factor, a hook tip and ground lead. Its electrical characteristics are shown in Table C.1. Figures C.1 and C.2 show its operating curves. Figure C.3 shows a sample Tektronix P2200 probe.

Table C.1: Electrical Characteristics

System	**10X Position**	**1X Position**
Bandwidth	DC to 200 MHz	DC to 6 MHz
Attenuation Accuracy	10:1 ± 2%	1:1 ± 2%
Compensation Range	15 pF - 25 pF	—
Input Resistance	10 MΩ±3% at DC	1 MΩ±3% at DC
Input Capacitance	13.0 pF - 17.0 pF	80 pF - 110 pF
Risetime (typical)	<2.2 ns	<50 ns
Max. input voltage	300V (RMS, DC) CAT I 300V (RMS, DC) CAT II 100V (RMS, DC) CAT III 420V peak, <50% DF, <1s PW 670V peak, <20% DF, <1s PW	150V (RMS, DC) CAT I 150V (RMS, DC) CAT II 100V (RMS, DC) CAT III 210V peak, <50% DF, <1s PW 330V peak, <20% DF, <1s PW

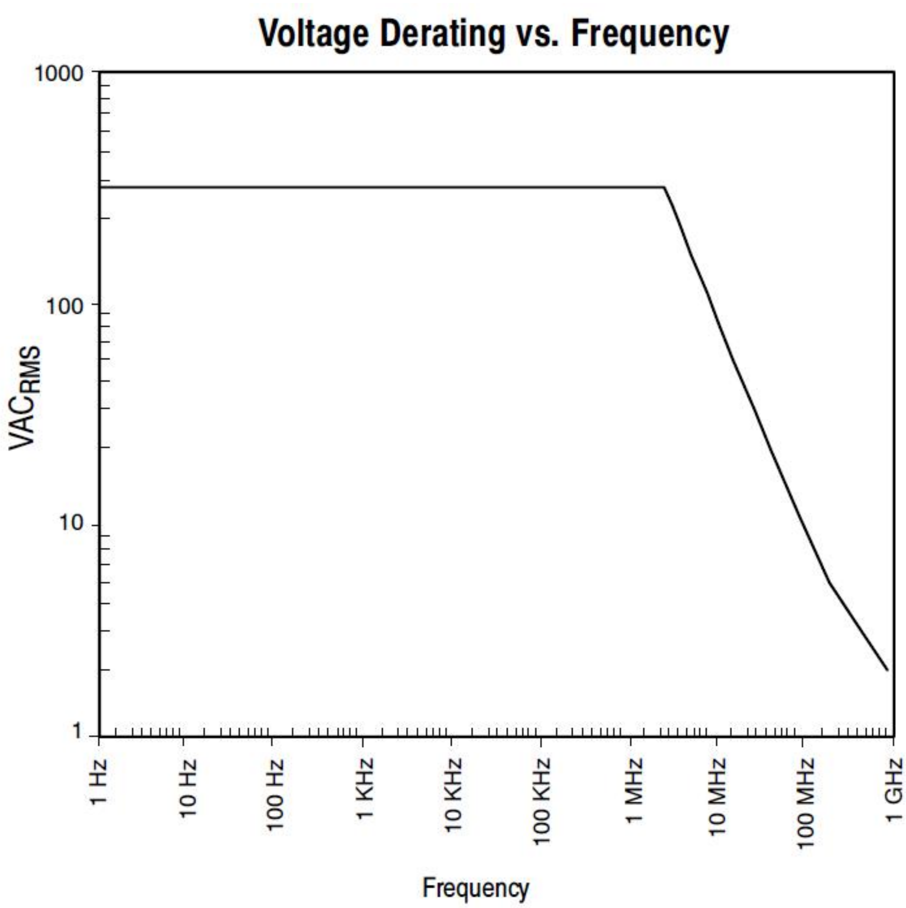

Figure C.1: Derating curve for determining maximum input voltage

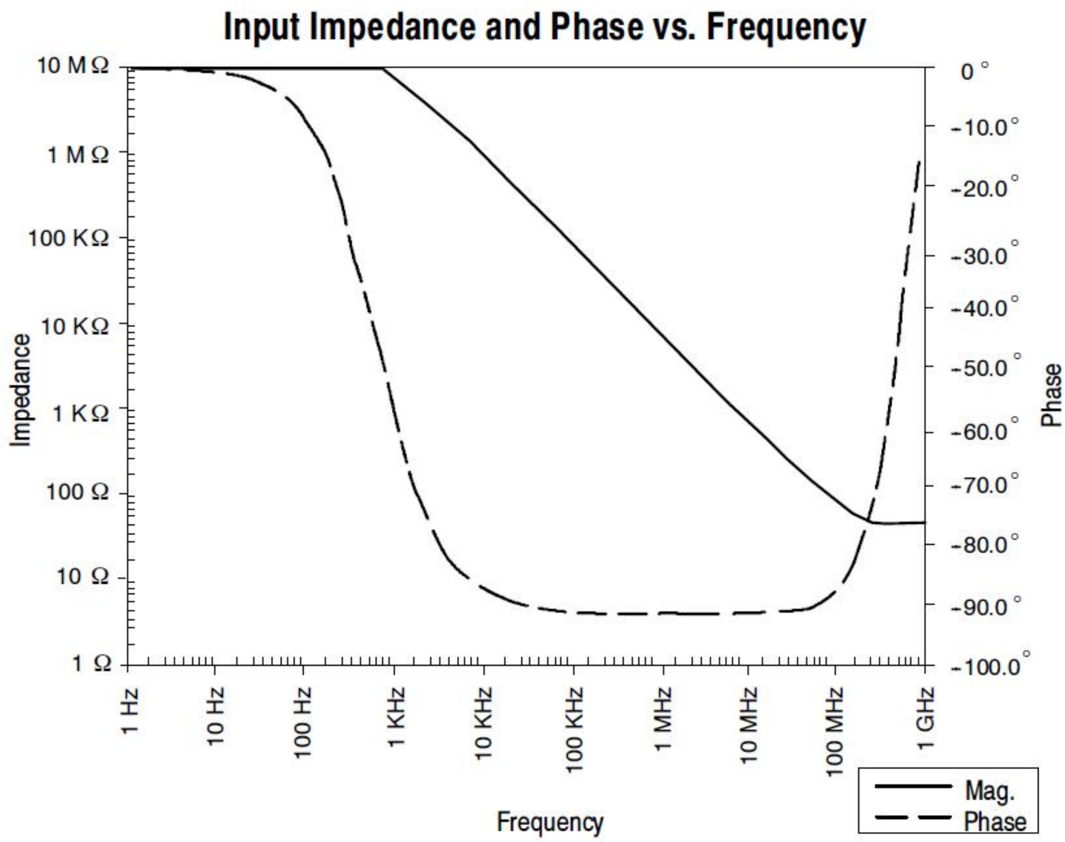

Figure C.2: P2200 probe input impedance and phase vs. frequency graph

Figure C.3: The Tektronix P2200 probe