DEVELOPMENT OF COLLISION AVOIDANCE WARNING SYSTEM FOR HEAVY VEHICLES FEATURING ADAPTIVE MINIMUM SAFE DISTANCE

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ABSTRACT

The great effort is being recently spent to develop better Collision Avoidance Warning Systems (CAWS) to reduce the total number of accidents. Improvements in crash avoidance have proven far more difficult to attain, mainly because the probability of a crash is affected by an array of complex and interacting factors involving the drivers, vehicles, and the road environment. One of the important criteria in CAWS is the criteria for system activation. Proper activation algorithm of the system will reduce the number of false alarms and collision by not presenting the warning too early or too late, but at the right time.

The determination of a minimum safe distance is a very fundamental and pivotal step for CAWS system activation. Hence, the success of CAWS system relies very much on whether the activation algorithm or model used is able to indicate a minimum safe distance precisely and timely. Limitations of existing methods in determining the minimum safe distance is restricted to only the kinematic variables such as speed and deceleration. Other important independent parameters for heavy vehicle such as vehicle classification (VC), Gross Vehicle Weight (GVW) and tire-road coefficient of friction (CoF), which may have a direct impact on vehicle braking performance, have not been explicitly considered. The characteristics of these important heavy vehicle parameters are assumed to be same for all types of vehicle.

The minimum safe distance is very much related on vehicle braking performance. The important parameters in vehicle braking performance are the deceleration and braking distance (BD). Thus, this study offers a detailed analysis in understanding the factors which influence the deceleration and BD for heavy vehicle. To do this, deceleration data for various heavy vehicle classes under various loads, speeds and road surface conditions was generated employing a commercial multi-body dynamic simulation package. Through statistical analysis, results shown that these four

parameters have significant effect on heavy vehicle's deceleration and braking distance. The results shows that changes in the vehicle dynamics' characteristics will affect a heavy vehicle's braking performance and its ability to stop safely in emergency situations. Therefore these parameters are important and must be considered in determining the minimum safe distance. This result is the first major contribution of this dissertation. To represent the adaptive minimum safe distance which will be used in activation algorithm for CAWS, the new distance-based CAWS model, namely Minimum Safe Distance Gap (MSDG) is introduced. By applying non-linear regression analysis to the simulation results, a mathematical model of MSDG has been established. This MSDG model is the second major contribution of this dissertation. In addition, a graphical user interface (GUI) based calculator was developed based on the proposed regression model. It is envisaged that this calculator would provide a more realistic depiction of the real situation for safety analysis involving heavy vehicles. Finally, the development of prototype microcontroller-based CAWS featuring MSDG activation algorithm has been developed. The accuracy and the functionality of the system has been tested and validated. It is envisaged that this CAWS featuring MSDG algorithm would provide a more realistic depiction of the real traffic situation for safety purposes.

ABSTRAK

Kajian yang lebih mendalam sedang di jalankan bagi membangunkan Sistem Amaran Pencegahan Pelanggaran (CAWS) yang lebih baik untuk mengurangkan jumlah kemalangan. Pembangunan sistem ini adalah sesuatu yang mencabar disebabkan kebarangkalian punca kemalangan yang sukar diduga dan dipengaruhi oleh pelbagai kriteria yang kompleks yang melibatkan pemandu, kenderaan dan persekitaran jalan. Salah satu kriteria yang utama dalam CAWS adalah algorithm ang digunapakai untuk pengaktifan system. Algorithm yang baik dapat menghindarkan berlaku ketidaktepatan dalam memberi amaran pelanggaran.

Penentuan jarak selamat minima adalah langkah asas dan penting untuk pengaktifan system CAWS. Oleh itu, kejayaan system ini banyak dipengaruhi samada algorithm yang digunapakai dapat mengira jarak selamat minima dengan tepat atau tidak. Algorithm yang sedia ada dalam menentukan jarak yang selamat minima pada masa kini adalah terhad kepada hanya pembolehubah kinematik seperti kelajuan dan nyahpecutan. Parameter lain seperti kelas kenderaan, Berat Kenderaan dan geseran tayar, yang mungkin mempunyai kesan langsung kepada prestasi kenderaan, tidak dipertimbangkan dan dianggap sama bagi semua jenis kenderaan.

Jarak selamat kenderaan saling berkait dengan prestasi brek kenderaan dan antara parameter pentingnya adalah nyahpecutan dan jarak brek (BD). Oleh itu, kajian ini menawarkan analisis terperinci dalam memahami faktor-faktor yang mempengaruhi nyahpecutan dan BD untuk kenderaan berat. Untuk melakukan ini, perisian simulasi "Mult-body Dynamic" digunakan untuk menjana data nyahpecutan untuk pelbagai kelas kenderaan berat di bawah pelbagai beban, kelajuan dan keadaan permukaan jalan. Melalui analisis statistik, keputusan menunjukkan bahawa keempat-empat parameter ini mempunyai kesan yang besar ke atas nyahpecutan dan BD kenderaan berat.

Hasil kajian menunjukkan bahawa perubahan dalam ciri-ciri dinamik kenderaan akan memberi kesan kepada keupayaan untuk berhenti dengan selamat dalam situasi kecemasan. Oleh itu parameter-parameter ini adalah penting dan perlu diambil kira dalam menentukan jarak selamat kritikal. Keputusan ini adalah sumbangan utama yang pertama bagi disertasi ini.

Untuk mewakili jarak yang selamat minima penyesuaian yang akan digunakan dalam pengaktifan algoritma untuk CAWS, model CAWS yang baru iaitu "Minimum Safe Distance Gap (MSDG)" telah diperkenalkan. Dengan menggunakan analisis regresi bukan linear kepada keputusan simulasi, model matematik MSDG telah dihasilkan. Model MSDG ini adalah sumbangan utama kedua disertasi ini. Di samping itu, kalkulator berasaskan antara muka pengguna grafik (GUI) telah dibangunkan berdasarkan model regresi yang dicadangkan. Adalah diharapkan kalkulator ini akan memberikan gambaran yang lebih realistik keadaan sebenar untuk analisis keselamatan yang melibatkan kenderaan berat. Akhir sekali, pembangunan prototaip system CAWS yang menggunakan algoritma pengaktifan MSDG telah dibangunkan. Ketepatan dan fungsi sistem itu telah diuji dan disahkan. Adalah diharapkan bahawa penggunaa system CAWS menggunakan algoritma MSDG akan memberikan gambaran yang lebih realistik keadaan trafik sebenar untuk tujuan keselamatan pemanduaan kenderaan berat.

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LIST OF SYMBOLS AND ABBREVIATIONS

For example:

BD	:	Braking Distance
CAWS	:	Collision Avoidance Warning Systems
CoF	:	Coefficient of Friction
FV	:	Following Vehicle
GUI	:	Graphical User Interface
GPS	:	Global Positioning Unit
GVW	:	Gross Vehicle Weight
ITS	:	Intelligent Transportation System
LV	:	Leading Vehicle
MSDG	:	Minimum Safe Distance Gap
PICUD	:	Potential Index for Collision with Urgent Deceleration
PRD	:	Proportional Reaction Distance
PRT	:	Proportional Reaction Time
SD	:	Stopping Distance
TTC	:	Time To Collision
VC	:	Vehicle Class

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CHAPTER 1 - INTRODUCTION

1.1 Road Accident Scenarios in Malaysia

In the last two decades, Malaysia has experienced a remarkable period of economic expansion and growth in population, economy, industrialisation and motorisation. The total number of vehicles on the road has increased considerably, from 17 million vehicles in 2008, to over 22 million in 2012, as shown in Table 1.1 (MOT 2013a). The increase in the level of motorisation and the continued reliance and dependence on private vehicles by the majority of the population looks set to continue well into the future. This is due to the relatively poor public transport system in the country. From the 22 million vehicles on the road in 2012, 4.7% is made up heavy vehicles such as busses and goods vehicles, as shown in Figure 1.1(MOT 2013b).

Table 1.1: Number of Vehicles on the Road by State, Malaysia, 2008 – 2012
Source: Road Transport Department

NEGERI *State*	2008		2009		2010		2011		2012	
	AKTIF *Active*	TIDAK AKTIF *Non-Active*	AKTIF *Active*	TIDAK AKTIF *Non-Active*	AKTIF *Active*	TIDAK AKTIF *Non-Active*	AKTIF *Active*	TIDAK AKTIF *Non-Active*	AKTIF *Active*	TIDAK AKTIF *Non-Active*
PERLIS	56,557	15,171	59,831	16,492	63,743	18,045	66,618	19,373	68,853	22,593
KEDAH	605,125	290,892	635,959	309,587	671,989	330,155	717,393	347,955	745,237	385,710
PULAU PINANG	1,478,826	418,812	1,540,529	453,974	1,614,307	492,924	1,686,521	527,226	1,735,367	590,849
PERAK	1,207,765	439,055	1,255,105	470,867	1,305,640	505,529	1,361,606	537,163	1,390,851	601,404
SELANGOR	1,482,326	582,648	1,527,221	628,523	1,582,587	679,296	1,636,011	727,322	1,663,026	803,089
WILAYAH PERSEKUTUAN	3,331,539	709,747	3,546,433	774,901	3,785,566	849,646	4,041,587	922,059	4,290,989	1,029,573
NEGERI SEMBILAN	490,407	220,585	507,097	235,400	525,097	251,757	544,534	266,055	553,716	292,089
MELAKA	445,282	161,471	465,696	172,778	487,240	185,188	509,414	196,547	524,690	217,297
JOHOR	1,831,776	654,559	1,912,894	707,096	2,003,475	764,791	2,105,420	818,478	2,185,121	909,835
PAHANG	516,322	204,230	542,982	219,763	570,653	237,155	603,906	252,373	619,965	285,966
TERENGGANU	303,785	99,317	326,866	106,844	351,839	115,242	376,449	122,952	394,851	139,758
KELANTAN	409,294	166,776	440,088	177,637	473,470	190,382	505,713	203,021	526,996	232,451
SABAH	553,765	180,184	598,291	195,463	649,911	213,270	712,093	230,344	770,272	256,595
SARAWAK	865,688	248,393	912,578	274,193	968,255	301,413	1,039,390	323,746	1,100,360	364,718
MALAYSIA	**13,578,457**	**4,391,840**	**14,271,570**	**4,743,518**	**15,053,772**	**5,134,793**	**15,906,655**	**5,494,614**	**16,570,294**	**6,131,927**

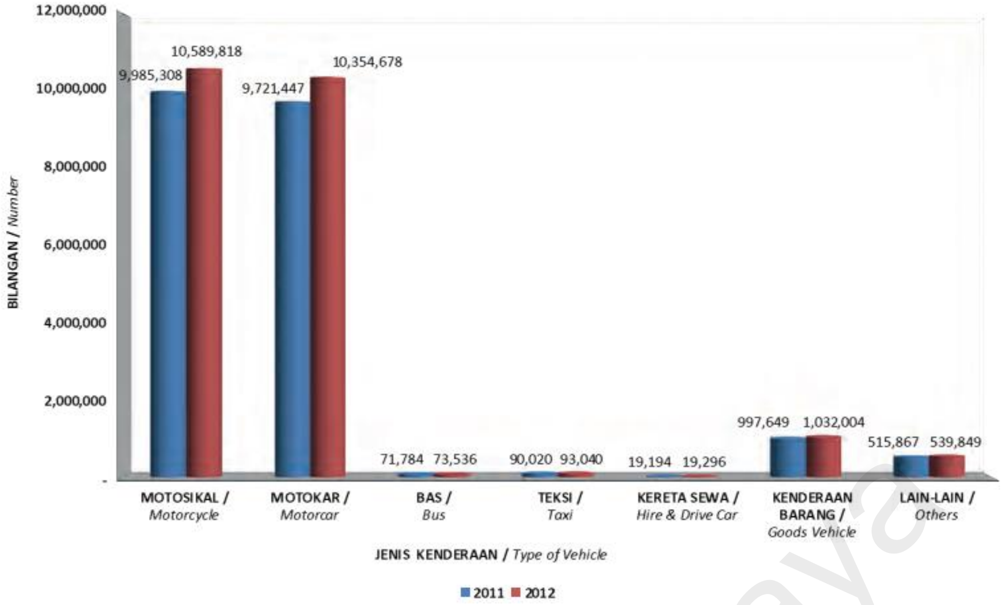


Figure 1.1: Total Motor Vehicles by Type in Malaysia, 2011-2012
Source: Road Transport Department

The increase in population and motorisation has led to a consequent increase in the number of road traffic accidents. From the 298,651 cases in 2003, the number of accidents in Malaysia has increased by 54% to a total number of 462,423 cases in 2012, as shown in Figure 1.2 (MOT 2013c). From this figure, 11.4% (52,775) of the accidents occurred involved heavy vehicles such as busses and lorries, as shown in Table 1.2 (MOT, 2013d).

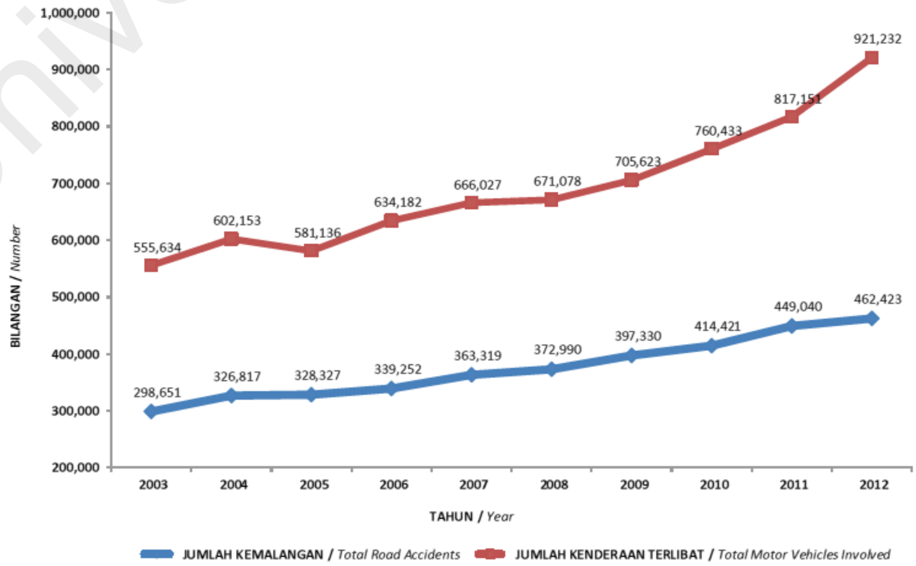


Figure 1.2: Total Number of Road accidents and Motor Vehicles Involved in Malaysia from 2003-2012

Table 1.2: Number of Vehicles on the Road by State, Malaysia, 2008 - 2012

TAHUN *Year*	MOTOSIKAL *Motorcycle*	MOTOKAR *Motocar*	VAN	BAS *Bus*	LORI *Lorry*	PEMACU 4 RODA *Four Wheel Drive*	TEKSI *Taxi*	BASIKAL *Bicycle*	LAIN-LAIN *Others*	JUMLAH *Total*
2003	95,545	351,832	20,277	9,673	42,753	16,429	6,632	2,993	9,500	**555,634**
2004	99,227	388,589	20,086	9,265	45,420	18,306	7,111	2,963	11,186	**602,153**
2005	97,072	376,061	19,085	8,594	42,062	19,106	7,043	2,751	9,362	**581,136**
2006	104,107	411,444	20,428	9,700	44,767	20,885	7,751	2,834	12,266	**634,182**
2007	111,765	426,941	21,109	10,285	47,696	21,823	8,809	2,690	14,909	**666,027**
2008	111,819	435,665	20,392	9,356	48,250	22,793	8,769	2,463	11,571	**671,078**
2009	113,962	472,307	19,220	9,380	46,724	23,581	8,669	2,486	9,294	**705,623**
2010	120,156	511,861	18,788	9,580	50,438	25,777	9,899	2,178	11,756	**760,433**
2011	129,017	546,702	17,916	9,986	53,078	30,828	11,197	2,033	16,394	**817,151**
2012	130,080	655,813	15,143	10,617	42,158	32,891	11,680	1,310	21,540	**921,232**

1.2 Collision Avoidance Warning System Concept

Car following begins when a following vehicle approaches the leading vehicle to a certain distance gap. The car following threshold is the critical gap between the leading vehicle and the following vehicle. A Collision Avoidance Warning Systems (CAWS) operates generally in the following manner as shown in Figure 1.3. A distance sensor is installed at the front-end of following vehicle (FV) and constantly scans the road ahead for leading vehicles (LV) or obstacles. When found, the system determines whether the vehicle is in imminent danger of crashing, and if so, warning systems or automatic brakes should be applied. There are several indicators that are currently used by a processor/controller to process the collected data before any appropriate action should be made. Generally, this kind of indicator can be classified into four groups that are time-based, distance-based and deceleration-based, as well as other composite measures. The algorithm of the indicator will be elaborated more in the next chapter.

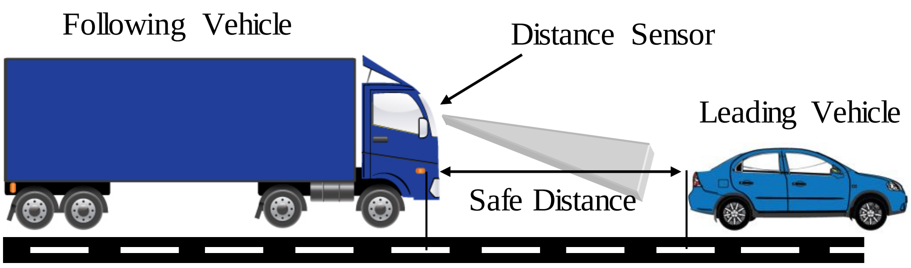


Figure 1.3: Overall Concept of Collision Avoidance Warning System

1.3 Stopping Distance (SD) and Braking Distance (BD)

The consciousness of the safe distance gap is very crucial for heavy vehicle drivers to prevent collision with the vehicle in front. Many different aspects need to be considered when attempting to determine the best critical safe distance for implementation into CAWS. The critical safe distance is very much related on the vehicle braking performance. One of the important parameters in vehicle braking performance is Stopping Distance (SD). SD is the distance it takes for a vehicle to stop from a specific speed with the consideration of the driver's reaction time as shown in Figure 1.4. According to Wong (2008), it is based on the sum of two important components: (1) the distance travelled from the time the object is sighted, to the instant the brakes are applied, where it is called the perception - reaction distance (PRD) and (2) the distance required for stopping the vehicle after the brakes are applied, which is called the braking distance (BD) as illustrated in Figure 1.4. The ability of a vehicle to achieve short braking distance under variable speed and loading is an essential aspect of heavy vehicle safety. Theoretically, a higher travelling speed requires a longer stopping distance as shown in Figure 1.5.

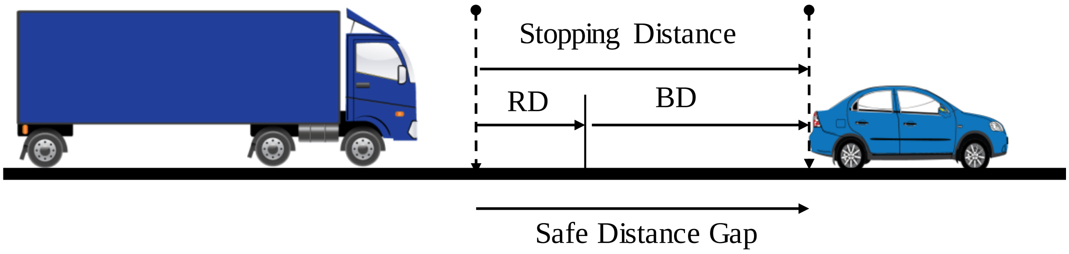


Figure 1.4: Concept of Braking Distance and Stopping Distance

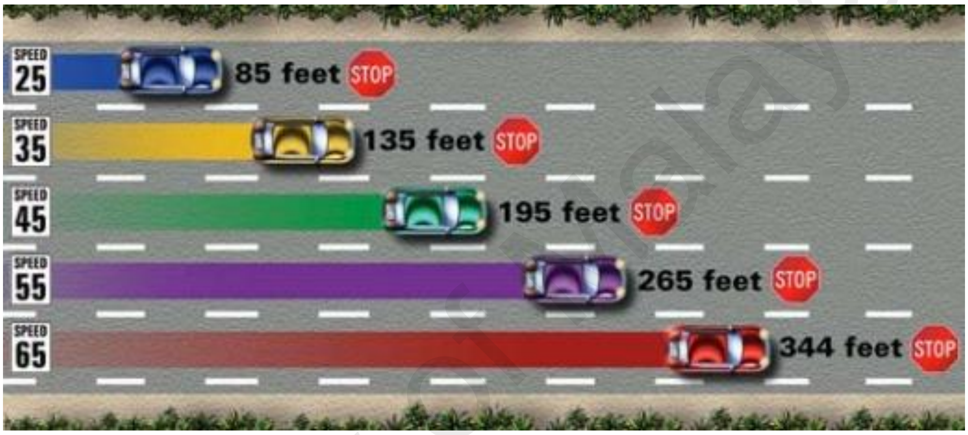


Figure 1.5: Average Stopping Distance on Dry, Level Pavement (VTRC, 2001)

Universally established traffic regulations stipulate that, at a speed of 60 km/hr, a car must maintain a distance of six car lengths from the front car, and at a speed of 90 km/hr, a distance of nine car lengths (Chi, 1992; Shyu, 1992). Admittedly, it is difficult for the driver to judge how many car lengths there are between his own car and the car in front. If the distance between the two cars is too short, when the front car brakes abruptly, the car behind may not be able to stop in time, causing a rear-end collision. Furthermore, if the distance between the two cars is too great, then the car following the second car will keep on pressing the horn or flashing the headlights to urge the front car to move faster (Chi, 1992). Other cars can also intrude at random, thus endangering the safety distance.

1.4 Problem Statement

Technology has been used increasingly to improve road safety. The CAWS is one of the tools designed to help drivers improve their detection and quickly respond to impending collisions. Such countermeasures may include advanced technologies to alert drivers of impending collisions, as well as enhancements to conventional systems, such as brakes, mirrors and lights. One of the recent efforts is to develop a better CAWS to reduce the total number of accidents. Improvements in crash avoidance have been proven to be far more difficult to attain. This is mainly due to the probability of a crash being affected by an array of complex and interacting factors involving the drivers, vehicles, and the road environment.

One of the important criteria in CAWS is the criteria for system activation. The algorithm used by CAWS is usually based on objective assumptions of a driver's response when required to brake, along with the physical characteristics of the vehicle in its stopping ability. For example, a CAWS developed at Honda calculates the braking distance based on velocity, relative velocity and deceleration of the two vehicles (Seller, Song and Hedrick, 1998). Whenever the real distance between the following and the leading vehicle is less than the "braking critical distance" calculated by the algorithm, the system triggers its warning. Other systems employed time to collision (TTC) as a type of "worst-case scenario", such that the systems provide its warnings when the TTC dips below a threshold value (Janssen and Thomas, 1997).

A proper activation algorithm of the system will reduce the number of false alarms and collision by not presenting the warning too early or too late, but at the optimal time. Late warnings that allow insufficient time for a driver to react to an unfolding scenario will result in more likelyhood of collision. Furthermore, the earlier the presentation of a warning, the less likely a collision is to occur (McGehee et al.,1998). However, a driver's trust in the system and hence their propensity to adhere to its alarms has also been found to depend on the timeliness of the warnings; the earlier a warning occurs, the more likely it is to be interpreted as a false alarm, which in turn leads to a reduction in drivers' future system use (Seller, Song and Hedrick, 1998). Abe and Richardson (2006) demonstrated that if drivers have already made an individual decision to brake prior to a CAWS alarm, their trust in subsequent alarms is reduced. Drivers then become more inclined to ignore the system, relying on their own individual judgements of impending danger and thus nullifying the potential benefits of the CAWS.

Therefore, the determination of an accurate minimum safe distance gap is the fundamental and pivotal step in developing a practical and reliable CAWS. Hence, the success of system design relies on whether the activation algorithm or model used is able to indicate a potential accident precisely and timely. In developing CAWS, there are some important criteria involving driver capabilities, environment or road surface and vehicle capabilities that must be considered to calculate the accurate safe distance gap. Limitations of existing methods in determining the minimum safe distance is restricted to only the kinematic variables such as speed and constant acceleration. Other important independent parameters for heavy vehicles such as Vehicle Classification (VC), Gross Vehicle Weight (GVW) and tire-road Coefficient of Friction (CoF), which may have a direct impact on the vehicle braking performance, have not been explicitly considered. The characteristics of these important heavy vehicle parameters are assumed to be the same for all types of vehicles. The impetus for this study arises from the intrinsic interest in understanding the factors which influence the stopping distance (SD) for heavy vehicle as there was previously no detailed investigation which relates the SD as a function of Gross Vehicle Weight (GVW), Vehicle Classification (VC) and Coefficient of Friction (CoF).

1.5 Aims of the research

The aim of this research is to develop a prototype Collision Avoidance Warning System (CAWS) for heavy vehicle to give a pertinent assistance to the driver by suggesting the minimum distance gap required to avoid rear-end collision. The suggested minimum distance gap is calculated using an improved frontal collision algorithm by considering the driver information (age and gender), vehicle conditions (speed, Gross Vehicle Weight (GVW) and Vehicle Classification (VC)) and also road surface condition (CoF).

1.6 Objectives

The main objective of this study is to develop an accurate, reliable method and a measuring apparatus that is capable of detecting a critical safe distance in a heavy vehicle following situation. This will be achieved by taking into account factors associated with vehicle characteristics, driver capabilities, and road conditions in providing a warning system to the driver.

The main objectives can be divided into four sub objectives:

(a) To determine the relationship between the deceleration of heavy vehicle with the GVW, VC, CoF and speed through simulation.

(b) To develop a comprehensive new mathematical model of adaptive CAWS as a function of speed, GVW, VC, CoF and also driver information (age and gender).

(c) To develop a user friendly GUI-based MSDG calculator for heavy vehicle.

(d) To design, develop and test a physical prototype of a microcontroller-based CAWS featuring the MSDG activation algorithm.

1.7 Scope of Work

The minimum safe distance is very much related to the vehicle braking performance. One of the important parameters in vehicle braking performance is the braking distance. Thus, this study offers a detailed analysis in understanding the factors which influence the braking distance for heavy vehicles as there is previously no detailed investigation which relates the braking distance as a function of Gross Vehicle Weight, Vehicle Classification, Condition of Friction and speed. To do this, commercial multi-body dynamics simulation software was used to generate the braking distance data for various heavy vehicle classes under various loads, speeds and road surface conditions.

To represent the adaptive critical safe distance which will be used in activation algorithm for CAWS, the new distance-based CAWS model, the Minimum Safe Distance Gap (MSDG) is introduced. This introduced model is considering the braking capability of various leader-follower compositions in vehicle following situations. The introduced model is a combination of the analytical and regression model, based on the established equation of motion and simulation data.

This research was divided into two main categories that is to develop an algorithm through simulation technique and to develop prototype system for CAWS. In developing the algorithm, the parameters have been restricted to the some important parameters to prevent the study from being overly broad. There are many parameters that affect a reaction time of driver. In this study, only two important parameters are consider that is age and gender. For heavy vehicle dynamics parameter, three important parameters are consider that is GVW, VC and CoF. The simulation has done in straight road condition without gradient. For prototype system development, the system was concentrate on objects in front of the vehicle in straight road condition only.

1.8 Thesis Outline

This thesis is composed of six chapters. The remaining content of this thesis is organized as follows. Chapter 2 will review the available technologies for CAWS and the activation algorithm or safety index currently used in CAWS. Chapter 3 will narrate the steps taken to obtain the deceleration and braking distance data using commercial multi-body dynamic software. This data will then be used in the development of a new CAWS algorithm which is also described in this chapter. Chapter 4 provides a detailed description on the design and development of the prototype microcontroller based CAWS featuring a new algorithm. A detailed hardware description is presented in this chapter. All the results from simulation and hardware tests will be explained in Chapter 5. Finally the conclusion and future work chapter summarizes the overall results of this thesis and provides recommendations for future efforts.

CHAPTER 2 - LITERATURE REVIEW

This section gives a brief overview and some of the milestones of the development of active safety functions that have become available in the market during the last few decades. This chapter begins with the overview of trends in automotive active safety and continues with the background of CAWS. The next two sections will review several algorithms that were developed for safety performance measures and CAWS.

2.1 Trends in Automotive Active Safety System

The importance of the road traffic has been rapidly growing in the last decades. Although this development is demanded and promoted by the needs of the society, it slowly becomes unsustainable. As the traffic density increases, the traffic situations become more complex and difficult to handle by the human driver, which eventually leads to road accidents. All communities of the world are looking for solutions to increase road safety.

Based on these issues, extensive studies have been conducted to provide proper solutions from different various perspectives. One of them is the introduction of the Intelligent Transportation System (ITS) which covers every feature of the transportation system which will enable it to function more efficiently and in an organized manner. ITSs are becoming increasingly technically feasible and economically affordable (Lee, 1997; Walker, Stanton, &Young, 2001).

There are generally two kinds of safety systems in automobiles; passive and active. A passive safety system is anything in a vehicle that sits idle and operates only when necessary. A good example of this is the common seat belt. An active safety system is very different from a passive system as these systems operate based on signal or information gathered. These systems actively seek out information in regards to the vehicle's current state. One example of this system is a pre-collision system. Unlike in-vehicle safety systems such as air bags and safety belts which focus on injury reduction, many new in-vehicle systems now focus on accident prevention by providing assistance to the driver during driving.

The trend in the automotive active safety system begins with the Anti-lock Braking System (ABS), first introduced in 1978. This system can be claimed to be the first electronic active safety system, where its goal is to help the driver to avoid accidents. The ABS prevents the wheels from locking and will maintain the steering ability of the vehicle during hard braking. During bad road conditions, the ABS will also reduce the stopping distance. The system measures the velocity of all four wheels, and if one of the sensors reports an abnormal deceleration (higher than a physically reasonable value), it concludes that the wheel is about to lock, and the pressure in the braking system is reduced. German automotive supplier Bosch in fact has a patent from 1936 for a "mechanism to prevent locking of the wheels of a motor vehicle". The first ABS prototype was tested in 1970, but reliability of the electronics was too low and it was not before 1978 that the first system was put into production, manufactured by Bosch (Bosch, 2014).

The first traction control system was launched in 1985. The functioning of the traction control system is very similar to that of the ABS. The system prevents the wheels from slipping during acceleration by using the same velocity sensors as the ABS. If a vehicle starts to slip, the engine power is reduced in order to maintain lateral control of the vehicle.

Stability control was introduced in 1995. Bosch was the first with their stability control system, ESP (Electronic Stability Program) developed in 1995. While slightly different configurations exist, the stability control system basically measures the yaw rate of the vehicle, i.e., the rotation in the ground plane, and compares it with the desired trajectory. If the deviation is greater than a certain threshold, the system will activate the brakes on one side of the vehicle to correct this situation.

Another active safety system introduced in the market was the Adaptive Cruise Control. While sources differ on this active safety system, Jones (2001) claims that in May 1998, Toyota became the first to introduce an Adaptive Cruise Control (ACC). ACC uses a forward looking sensor, usually radar or laser, to monitor the distance to the leading vehicles. If the cruise control is active and the time gap to the leading vehicle falls below a certain threshold, the vehicle's ACC system will automatically brake in order to maintain the distance. ACC is often not considered a safety system in isolation as it usually comes bundled with a forward collision warning. In Europe, government restrictions typically limit the permitted braking rate to 3.0 or 3.5 m/s^2. If the vehicle detects that a higher deceleration is required to avoid colliding with the leading vehicle, an audible warning is given to the driver.

The next active safety system is the Frontal Collision Warning / Collision Avoidance (FCW/CA) systems. These active safety systems are a natural extension of the Adaptive Cruise Control (ACC) systems due to their similarities in hardware requirements. Therefore, the FCW/CA systems are expected to take off quickly, in a fashion similar to the success of vehicle stability control systems. A FCW is an on-board electronic safety device that has the potential to warn the driver of the host vehicle of impending collision with preceding traffic. The system uses forward-looking sensors that continuously monitor traffic obstacles in front of the host vehicle and warns the driver when a risk of collision is imminent.

The Lane Guidance System (LGS) refers to systems that attempt to assist the driver to stay in the lane. These systems typically use an audible warning or a steering wheel torque to alert the driver if the vehicle is approaching the lane markings. The steering-wheel torque used by some of the proposed systems will automatically steer the vehicle back into the centre of the lane, thus working almost like an autopilot. In Japan, Honda has been selling their Honda Intelligent Driver Support (HIDS), which includes the Lane Keeping Assist System (LKAS), since 2003. The system combines an audible warning and steering-wheel torque. However, Honda's idea is that the driver should be kept in the loop at all times. Therefore, the system only supplies 80% of the required torques, the remaining 20% has to be provided by the driver (Ishida and Gayko, 2004).

A new concept is to try to mimic the sounds and vibrations that are generated by rumble strips, i.e., the grooved lane markings that are sometimes used on motorways to indicate lane departure. A lane guidance system like this has recently been put into production by Citroën (Citroën, 2005). This system differs from the lane guidance system discussed earlier which uses a camera mounted in the windscreen. The system from Citroën uses dedicated infrared sensors mounted in front of the front wheels, looking straight down. This construction makes the system very robust, but at the same time it cannot measure the distance to the line, nor can it distinguish between lane markers and, for example zebra crossings.

The blind-spot warning system was introduced to lower the risk of lane change accidents by warning the driver about vehicles in the blind spot. There are different techniques for achieving this but usually ocular vision or radar is used. Blind-spot warning systems have been announced several times in the past by different car manufacturers, but it was not until 2005 that Volvo released their Blind Spot Information System (BLIS) and became the first to actually put the system on the market.

2.2 Importance of Heavy Vehicle Safety

One of the primary functions of road transport infrastructure is to safely and efficiently transport goods and people. When heavy vehicle accidents occur, the mobility of the road user is impeded and significant user delay costs may be incurred. Due to their large size and weight, the operation of heavy vehicles has been a major concern of road safety. Heavy vehicle accidents are perceived to be a major highway or road safety problem with serious consequences for the drivers, companies and the travelling public.

Commercial trucks and busses have major economic importance in Malaysia and in most of the developed countries. In the United States, commercial trucking has annual revenues of more than $500 billion and employs nearly 10 million people. In 2002, 2.6 million Class 8 trucks and 3.5 million Class 3–7 trucks were used for business purposes in the United States (American Trucking Associations (ATA), 2004). In 2003, 9.1 billion tons of freight was transported by intercity and local trucks, representing 69% of the total domestic tonnage shipped (ATA, 2004). In the United States there are about 11 million commercial drivers license (CDL) holders, of whom 3.0 to 3.3 million are active truck drivers (FMCSA, 2007).

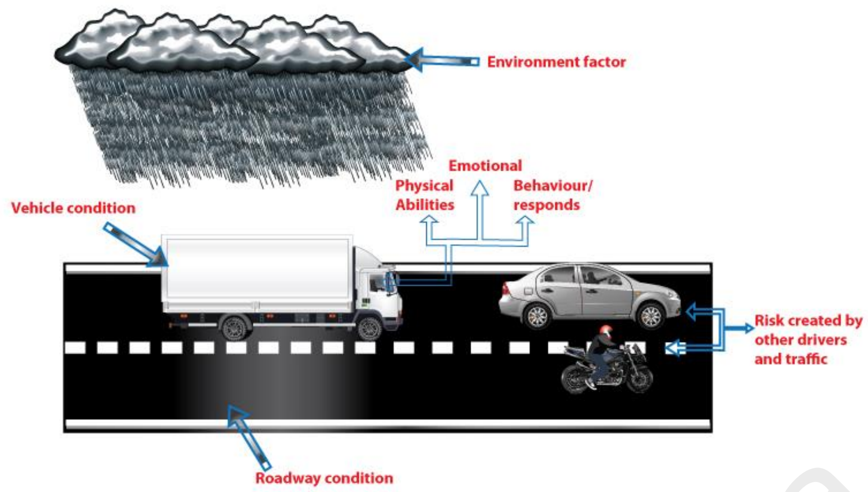
The economic impact of large trucks and bus crashes is significant. Zaloshnja and Miller (2002) determined that police-reported crashes involving large trucks (greater than 10,000 lb) had an average cost of $59,153 in year 2000. These costs included medical and emergency services, property damage, lost productivity, and a monetary valuation of pain, suffering, and quality-of-life loses associated with these crashes. The average cost of crashes involving transit or intercity buses was $32,548. For crashes with injuries, these costs rose to $164,730 for large trucks and $77,043 for buses. Annual total U.S. costs for large truck crashes averaged more than $19.6 billion for

1997–1999, whereas bus crashes averaged far less at $0.7 billion. Wang, Knipling, and Blincoe (1999) estimated that the average annual and lifetime crash costs (including all damages and injuries to all involved parties) for individual combination-unit trucks are approximately five times greater than those for individual passenger cars or light trucks and vans. Single-unit truck annual and lifetime crash costs are only slightly greater than those of light vehicles. Mileage exposure differences are a predominant factor in these vehicle type differences. On a per-Vehicle-Mile-Travelled (VMT) basis, crash costs are in fact about the same for combination-unit trucks, single-unit trucks, and light vehicles.

2.3 Factors Involved in Heavy Vehicle Crashes

Motor vehicle crashes are complex events, and they usually involve two or more vehicles. Elements that influence the occurrence of a crash may take place hours, days, or months before the crash. They include driver training and experience, vehicle design and manufacture, highway condition and traffic signaling, and weather conditions. Other elements may take place immediately before a crash, such as a decision to turn in traffic, a tire blowout, or snow. Accident reconstruction experts rarely conclude that crashes are the result of a single factor.

Just as heavy vehicle safety is multidisciplinary, understanding large-truck crashes requires a conceptualization of multiple interacting factors. Figure 2.1 is a conceptualization of major crash risk factors. Human behaviour, the roadway environment and vehicle failures are three major factors found in heavy vehicle crashes (Roger and Knipling, 2007). This is true for traffic crashes in general and for large-truck crashes. In Malaysia, the Road Safety Department (JKJR) has revealed that human error, carelessness and reckless driving caused 80% of the road fatalities (MIROS, 2015).



Vehicle Condition - Vehicle type, Brake technology, tires, Speed, GVW and etc

Road Condition - Pavement surface (coefficient of friction), Road geometric

Figure 2.1: Interacting Factors Affecting Heavy Vehicle Driver Crash Involvement

The Federal Motor Carrier Safety Administration (FMCSA) and the National Highway Traffic Safety Administration (NHTSA) conducted the Large Truck Crash Causation Study (LTCCS) to examine the reasons for serious crashes involving large trucks. From the 120,000 large truck crashes that occurred between April 2001 and December 2003, a national representative sample was selected. The FMCSA–NHTSA LTCCS (FMCSA. 2007) has identified a profile of contributing factors for crashes involving large trucks. Of serious large-truck crashes in the LTCCS (including both single- and multivehicle crashes), 87% had assigned to the driver of the large truck. Truck vehicle failure and environmental reasons related to the truck accounted for 10% and 3% of the crashes respectively, as shown in Table 2.1. Of the 87% of LTCCS crashes with assigned to large-truck drivers, the error type classifications were as follow: physical failure (12%), recognition failure (28%), decision errors (38%), and performance errors (9%). A principal goal of human factors studies of commercial drivers and their crashes is to understand the types of human errors resulting in crashes and the human risk factors that make these errors and crash outcomes more likely.

Table 2.1: Factors Affecting Heavy Vehicle Crashes (FMCSA, 2007)

Crash Reason	Example	Percentage (%)
Truck driver physical failure	•Asleep-at-the-wheel •Heart attack •Other physical impairment	12
Truck driver recognition failure	•Inattention •Distraction (internal or external) •Inadequate surveillance ("LBDNS")	28
Truck driver decision error	• Too fast for conditions • Following too closely •Misjudgment/false assumption	38
Truck driver performance error	Truck driver panicked, overcompensated, or exercised poor directional control.	9
Truck/Vehicle failure	• Brake failure • Tire failure • Cargo shift	10
Roadway/Environment affecting truck	• Road signs/signals missing • Road design • Weather and/or slick roads	3
Total		100

The most common critical errors made by drivers, whether they are truck drivers or other involved drivers, appear to be following too closely or distance gap misjudgements. This is when a driver follows too closely and is over confident in their ability to stop the truck before the crash. The consciousness of the critical safe distance gap is very crucial for heavy vehicle drivers to prevent collision with the vehicle in front. Providing an early warning notification can increase the driver's reaction time to stop the vehicle without the occurrence of a crash.

2.4 Collision Avoidance Warning System

CAWS is likely to become increasingly important in new vehicles in the future. Research carried out by Transportation Research Institute (TRI) has indicated that there have been a significant amount of casualties saved by equipping vehicles with these systems. The TRI research indicates that the highest benefits to cost ratios are likely to be achieved through fitting these systems to heavy vehicles due to increased severity of front to rear collision involving this type of vehicle. In 2009, the U.S. National Highway Traffic Safety Administration (NHTSA) began studying on whether to make frontal collision warning systems mandatory. The mandatory fitting of Advanced Emergency Braking Systems in commercial vehicles will be implemented on 1 November 2013 for new vehicle types, and on 1 November 2015 for all new vehicles in the European Union. This could, according to the impact assessment, ultimately prevent around 5,000 fatalities and 50,000 serious injuries per year across the EU (Regulation (EC), 2009).

A CAWS is a system that alerts or warns a driver of a probable collision situation (Lerner et al., 1993). CAWS began to be researched in the mid-80s. Originally, they were designed to support the concept of Automated Highway Systems (AHS). By automating highway driving, researchers hoped to increase freeway capacity by decreasing the spacing between adjacent vehicles (Wang and Rajamani, 2004). The CAWS uses a combination of object detection sensors and existing electronic systems to determine if a collision is probable. The use of laser and radar technologies for collision avoidance is popular for the application of CAWS (Sanmartin et al.,1999). A CAWS typically will contain three subsystems, recognition, processing, and presentation (Wilson et al., 1996). The activities of these subsystems include recognizing data involving potential collisions, processing this data into a usable format for the driver, and presenting the data to the driver in a usable structure.

Since the early 1990s, many CAWS algorithms and systems have been proposed, mostly by industrial researchers. Doi et al. (1994) studied the effectiveness of a rear-end collision avoidance system, capable of working on both straight and curved sections of a highway. They identified four key elements; forward looking sensor (laser radar), path estimation, collision prediction and automatic brake control. Fujita et al. (1995) proposed a radar-based automatic braking system to prevent the vehicle from a rear-end collision, or to reduce the impact speed without adverse effects on normal driving. Araki et al. (1997) developed a rear end collision avoidance system by integrating CCD cameras, a laser radar and a fuzzy learning algorithm from the driver's brake timing. Barber et al. (1998) presented two collision warning algorithms based on time-to-collision, range, range rate and relative acceleration. Seiler et al. (1998) derived a collision warning algorithm using parameters estimated from a tire–road friction estimation scheme.

Existing literatures reveal two major technical challenges for the CAWS systems; the development of a reliable all-weather target detection system, and the trade-off between false/nuisance alarms (false-positive) and missed detections (false-negative). The second challenge is related to the first, and is more complicated because it depends on human perceptions and has to encompass widely varying driving situations and human characteristics. Thus, for any fixed (non-adaptive) CAWS system, disagreement between the human drivers and system response always exists. How to minimize the rate of false/nuisance alarms without significantly raising the rate of missed detection is a question that has been feverishly pursued. However, since the evaluation of CAWS systems has been largely done in a subjective manner, few impartial comparisons of multiple algorithms have been reported.

2.5 Kinematics of Particles

2.5.1 Rectilinear Motion

Rectilinear motion is another name for straight-line motion. This type of motion describes the movement of a particle or a body. A body is said to experience rectilinear motion if any two particles of the body travel the same distance along two parallel straight lines. Position means the location of the particle with respect to a fixed reference point say origin O. Displacement is a change in the position of the particle. It is difference between final position and initial position. It is a vector quantity connecting the initial position to the final position. Displacement depends only on initial and final position of the particle and its value may be positive or negative.

The rate of change of displacement with respect to time is called velocity. It is a vector quantity. If *s* is the displacement in time t, then the average velocity is

$$v = \frac{s}{t} \quad \text{(Eq. 2.1)}$$

The S.I unit of velocity is m/s. The rate of change of distance with respect to time is called speed. It is scalar quantity. The magnitude of velocity is also known as speed.

2.5.2 Equation of Motion

2.5.2.1 First Equation of Motion

Consider a body initially moving with velocity V_i. After a certain interval of time "t", its final velocity becomes V_f. Therefore, the change in velocity, ΔV is $V_f - V_i$. The rate at which an object's velocity changes is called the acceleration of the object. Deceleration is the term used for acceleration that causes an object to slow down. The constant acceleration formula is given by;

$$a = \frac{\Delta V}{t} \quad \text{(Eq. 2.2)}$$

Substituting the value of "ΔV" with $V_f - V_i$ yields

$$a = (V_f - V_i)/t$$

$$at = (V_f - V_i)$$

$$V_f = V_i + at \qquad \text{(Eq. 2.3)}$$

2.5.2.2 Second Equation of Motion

Consider a car moving on a straight road with an initial velocity equal to V_i. After an interval of time, t, its velocity becomes 'V_f'. First, we will determine the average velocity of the body.

Average velocity = (Initial velocity + final velocity) / 2

or

$$V_{av} = (V_i + V_f)/2 \qquad \text{(Eq. 2.4)}$$

But $V_f = V_i + at$. Putting the value of V_f

$$V_{av} = (V_i + V_i + at)/2$$

$$V_{av} = (2V_i + at)/2$$

$$V_{av} = V_i + at/2 \qquad \text{(Eq. 2.5)}$$

we know that, distance S

$$S = V_{av}\, x\, t$$

Putting the value of 'V_{av}'

$$S = \left[V_i + \left[\frac{1}{2}\right] at\right] t$$

$$S = V_i t + \left[\frac{1}{2}\right] at^2 \qquad \text{(Eq. 2.6)}$$

In this thesis, distance *S* represents the braking distance, *BD*.

2.5.2.3 Third Equation of Motion

Initial velocity, final velocity, acceleration, and distance are related in the third equation of motion. Let the body travel a distance of 's' meters. According to the first and second equation of motion:

$$t = \frac{V_f - V_i}{a} \qquad \text{(Eq. 2.7)}$$

Putting the value from Equation 2.6 (where *S* is replaced by *BD*) in Equation 2.7

$$BD = V_i t + \left[\frac{1}{2}\right] at^2$$

$$BD = V_i \left[\frac{V_f - V_i}{a}\right] + \frac{1}{2}\,[a]\left[\frac{V_f - V_i}{a}\right]^2$$

$$BD = \frac{1}{2a}\left[V_f^2 - V_i^2\right]$$

$$2aBD = V_f^2 - V_i^2 \qquad \text{(Eq. 2.8)}$$

2.6 Kinetics of Particles

2.6.1 Force and Momentum

Force is an external agent which tends to change the state of rest or of uniform motion of a system. A force is applied whenever the system needs to be accelerated or decelerated. Force is a vector quantity specified completely by its magnitude, point of application, line of action and direction. The relationship between motion and force is provided by laws of dynamics; the most prominent being the Newton's second law. Newton's second law of motion state that force is proportional to rate of change of momentum. That is

$$Force \propto rate\ of\ change\ of\ momentum$$

Momentum is the product of mass and velocity of a body and represents the energy of motion stored in a moving body.

$$Force \propto rate\ of\ change\ of\ (mass\ x\ velocity)$$

$$Force \propto mass\ x\ rate\ of\ change\ of\ velocity$$

$$Force \propto mass\ x\ acceleration$$

$$Force \propto ma$$

$$F = ma \qquad \text{(Eq. 2.9)}$$

Where m is the mass, a is acceleration

Replacing the acceleration a by the derivative dv/dt in equation xxx, the equation can be write as

$$\Sigma F = m\frac{dv}{dt} \qquad \text{(Eq. 2.10)}$$

Or, since the mass of the particle is constant,

$$\Sigma F = \frac{d}{dt}(mv) \qquad \text{(Eq. 2.10)}$$

The vector mv is called the linear momentum, or simply the momentum of the particle.

2.6.2 Kinetics Energy

Kinetic energy is the energy of motion. An object that has motion, whatever it is vertical or horizontal motion has kinetic energy. There are many forms of kinetic energy - vibrational (the energy due to vibrational motion), rotational (the energy due to rotational motion), and translational (the energy due to motion from one location to another). The amount of translational kinetic energy (from here on, the phrase kinetic energy will refer to translational kinetic energy) that an object has depends upon two variables: the mass (m) of the object and the speed (v) of the object. The following equation is used to represent the kinetic energy (KE) of an object.

$$\text{KE} = 0.5\ x\ m\ x\ v^2 \qquad \text{(Eq. 2.11)}$$

where m = mass of object, v = speed of object

This equation reveals that the kinetic energy of an object is directly proportional to the square of its speed. That means that for a twofold increase in speed, the kinetic energy will increase by a factor of four. For a threefold increase in speed, the kinetic energy will increase by a factor of nine. The kinetic energy is dependent upon the square of the speed.

2.7 Review of Safety Performance Measures

Safety performance measures, also known as proximal safety indicators or surrogate safety measures (Jeffery Archer (2005), Douglas Gettman and Larry Head (2003)), are defined to reflect high risk events in relation to a projected point of collision. These measures are usually based on pair-wise vehicular velocity and spacing attributes. A review of the literature reveals that several algorithms were developed for safety performance measures. These can be classified into four groups; time-based, distance-based, deceleration-based as well as other composite measures.

2.7.1 Time-Based Measures

One of the most frequently used time-based measures is Time-To-Collision (TTC). TTC, which is defined as the time that remains until a collision between two vehicles would have occurred. TTC has been one of the most well-recognized safety indicators in transportation safety (Chin and Quek (2009), Sharriat et al. (2011) and Matsui et al. (2013)). For vehicles travelling in the same direction, the TTC can be continuously measured over time using the following expression:

$$TTC_{i,t} = \frac{(X_{i-1} - X_{i,t}) - L_{i-1,t}}{V_{i,t} - V_{i-1,t}}$$

(Eq. 2.9)

Where t = time interval, X = positions of the vehicles, L = vehicle length, V = velocity

Several studies have benefited from TTC to evaluate traffic safety. Minderhoud and Bovy (2011) found several values for critical time to collision, which are 4 or 5 seconds, or 3 or 3.5 seconds. For determining TTC values, they used trajectories of vehicles in a certain time period on a specific road length. They concluded that the minimum TTCs, which may happen during the continuous measurement time, can be calculated. They also introduced two new safety indicators which are the TET (Time Exposed Time-to-collision) and TIT (Time Integrated Time-to collision). TET represents the time that the TTC value remains below the demanded TTC threshold. The other indicator is TIT is an integral value of the TTC profile once the TTC is below the threshold. TIT can present an index of severity when the TET fails to detect.

2.7.2 Distance-Based Measures

There are four important distance-based safety indices such as the (i) Proportion of Stopping Distance (PSD), (ii) Stopping Distance Algorithm, (iii) Potential Index for Collision with Urgent Deceleration (PICUD) and (iv) Predicted Minimum Distance (PMD) as stated in Table 2.2. Proportion of Stopping Distance (PSD) was defined by Allen et al. (1978) as the ratio between the remaining distances to the point of collision expressed over its minimum acceptable stopping distance.

Another commonly used algorithm in distance-based safety indicator could be the Stopping Distance Algorithm (SDA) (Wilson et al., 1997). The Eq. 2.12 in Table 2.2 shows the formula to calculate Stopping Distance Algorithm. The CAWS based on a stopping distance algorithm gives the collision warning when the calculated inter-vehicular distance d, called the Stopping Distance (SD), becomes smaller than the safety distance d_s. The velocities v_f, v_p are not preset, but are updated constantly, while the driver reaction time T and the decelerations a_f, a_p are set by predefined parameters. Consequently, the warning provision timing can be changed by adjusting these parameters.

PICUD was introduced by Uno et al. (2005). They believe that PICUD can solve a TTC weak point. The TTC can be used in a situation where the leading vehicle with the higher speed cannot be identified, while PICUD can indicate the safety risk in that situation. PICUD is an index to evaluate the possibility that two consecutive vehicles might collide, assuming that the leading vehicle applies its emergency brake. PICUD is defined as the distance between the two vehicles considered when they completely stop (Uno et al., 2005). The two parameters required to predict PICUD are the Reaction Time and the Maximum Deceleration Rate. They assume 1 second for the reaction time and 3.3 seconds for emergency braking in their study on a weaving section. Eq. 2.13 in Table 2.2 shows the equation to calculate PICUD.

The Predicted Minimum Distance (PMD) was introduced by Ploychronopoulos et. al (2004). PMD can be defined as the minimum distance between a vehicle and a potential obstacle predicted in real time (if PMD=O then the impact is forecasted, if PMD > threshold, then the obstacle is not to be considered dangerous). Eq. 2.14 in Table 2.2 shows the formula to calculate PMD.

Table 2.2 summarizes the main distance-based safety indicator that can currently be applied to highway safety analysis.

Table 2.2: Summary of Distance-Based Safety Indices Formula

Indicator	Description
Proportion of Stopping Distance (PSD)(Allen et al. 1978) $PSD = \frac{\mathrm{RD}}{\mathrm{MSD}}$ (Eq. 2.10)	RD = remaining distance to the potential point of collision (m). MSD = minimum acceptable stopping distance (m), which is defined as $MSD = \frac{V^2}{2\mathrm{d}}$ (Eq. 2.11) Where *V*= approaching velocity (m/s); d = maximum acceptable deceleration rate (m/s^2)
Stopping Distance Algorithm (SDA)(Wilson 1997) $D_w = -x_r - v_f.RT + \left(\frac{V_f^2}{2\mathrm{a_f}} - \frac{\mathrm{V_L^2}}{2\mathrm{a_L}}\right)$ (Eq. 2.12)	*D_w : warning distance (m)* V_f: velocity of following vehicle (m/s) V_L: Velocity of leading vehicle (m/s) RT = Reaction Time = 1.0s a_f = Acceleration for following vehicle (m/s^2) a_L = Acceleration for leading vehicle (m/s^2)

Potential Index for Collision with Urgent Deceleration (PICUD) [Yang, H. et al. 2010] $PICUD = \left(\frac{V_1^2 - V_2^2}{2\propto}\right) + S_0 - V_2\Delta t$ (Eq. 2.13)	V_1, V_2 : velocity of leading car 1 and 2, respectively S_0 : distance between car 1 and 2 Δt : driver's reaction time $\propto$: deceleration rate to stop
PMD (predicted minimum distance) (Polychronopoulos, A. et al. 2004) $pd(k+i) = d[X_{svf}(k+i), X_{0f}(k+i)$ $PMD = \min_{i=1\ldots\max point} pd(k+i)$ (Eq. 2.14)	pd = predicted distance d = distance(m) $X_{svf}(k+i)$ = minimum unbiased Estimator $X_{0f}(k+i)$ = fused estimator

2.7.3 Deceleration-Based Measures

Deceleration Rate to Avoid Crash (DRAC) and Crash Potential Index (CPI) (Saccomanno and Cunto, (2006)) are typical deceleration-based indicators. DRAC was defined by Almquist et al. (1991) as the differential speed between a following vehicle (FV) and its corresponding lead vehicle (LV) divided by their closing time. He explained DRAC in terms of differential speed between the following vehicle and the leading vehicle divided by their closing time. The lead vehicle is responsible for the initial action (braking, changing lanes, accepting gap), while the following vehicle reacts to this action by braking.

Several researchers have argued that the conventional DRAC measure fails to accurately reflect traffic conflicts because it does not explicitly consider the vehicle's braking capability for prevailing road and traffic conditions. Intuitively, one would expect a higher collision risk for wet pavement conditions than for dry pavements.

The braking capability of a given vehicle (i.e., the FV) can be reduced appreciably when the pavement is wet, making it difficult for the tires to generate enough friction to exceed the DRAC requirements for collision or crash avoidance. To address this concern, Cunto and Saccomanno (2006) introduced the CPI, expressed for an individual FV as the probability that the DRAC exceeds the vehicle braking capability or the maximum available deceleration rate (MADR). Both DRAC and MADR are estimated for each FV in 0.1s increment as the vehicle progresses along its path.

2.7.4 Others Measures

Besides these time-based, distance-based and deceleration-based measures, several other studies also proposed specific indicators such as Unsafe Density (UD) (Barcelo et al., 2003 and Torday et al., 2003), J-value (Pham et al. 2007) and Crash Potential Index (CPI) (Barceló et al., 2003; Minderhoud and Bovy, 2011; Cunto, 2008), etc, in support of safety evaluation. In recent years, such indicators were more frequently used. This is possibly due to the development of the technology such as video image analysis, sensors, advanced computer simulation software, etc, to collect more detailed information of vehicle trajectories for indicator derivation.

2.8 Review of CAWS Algorithm

There have been many papers published on CAWS algorithms over the last decade. The following paragraph shows the related work done in the past from researchers at Mazda, Honda, JHU, Jaguar, Berkeley Algorithm, NHTSA Alert Algorithm, CRISS Driving Simulator and CAMP Alert Algorithm. These algorithms all calculate the threshold distance based on vehicle motion (range rate and velocity) and human characteristics variables (human delay). When the measured range is smaller than this threshold distance, a warning or avoidance signal is triggered.

2.8.1 Mazda Algorithm

Mazda's algorithm uses the following braking critical distance definition (Doi. et al., 1994):

$$R_{braking} = f(\dot{R}, V_F) = \frac{1}{2}\left(\frac{V_F^2}{\alpha_1} - \frac{V_L^2}{\alpha_2}\right) + V_F\,\tau_1 - \dot{R}\tau_{2+} + R_{min} \qquad \text{(Eq.2.15)}$$

where V_F is the following vehicle velocity, V_L is the leading vehicle velocity, α_1 is the maximum deceleration of the following vehicle, α_2 is the maximum deceleration of the leading vehicle and τ_1 and τ_2 are delay times. A plot of this critical distance as a function of velocity and relative velocity is shown in Figure 2.2. The following parameter values were used: α_1 = 6 m/s^2, α_2 = 8 m/s^2, τ_1 = 0.1 s, τ_2 = 0.6 s, and R_{min} = 5 m. Note that this is an imagined worst case scenario. Here, x(y) axis indicates time τ (vehicle velocities). The measurements (V_F, V_L) are used as initial conditions at τ = 0. The scenario assumes that the lead (host) vehicle maintains the current velocity V_L (V_F) during the time τ_2 (τ_1 + τ_2) and then engages the emergency brake where the slope is at $-\alpha_2$ ($-\alpha_1$). The colored area between the two velocity profiles (of each lead vehicle and host vehicle) is the required safety range minus the minimum range. This scenario continues until both vehicles come to a full stop. Note that, R_{min} is the minimum distance needed to prevent a collision if both vehicles begin braking with their respective maximum decelerations.

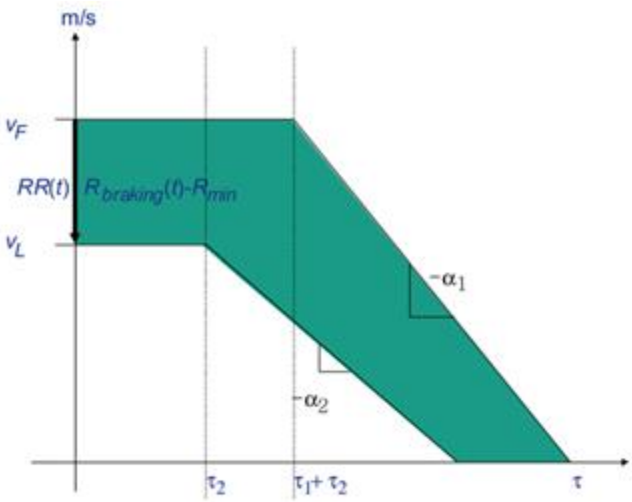


Figure 2.2: An Interpretation to Mazda's Logic (Doi. et al., 1994)

2.8.2 Honda Algorithm

The Honda logic consists of a warning algorithm and an avoidance algorithm (Fujita, Akuzawa, and Sato, 1995). The avoidance logic has two parts and the switching between them depends on whether the estimated lead vehicle's time to stop is shorter than the reaction time of the host vehicle driver. Honda's algorithm in mathematical form is shows in Eq 2.16.

$$\begin{cases} R_{warning} = f(\dot{R}) = -2.2\dot{R} + 6.2 \\ R_{braking} = f(\dot{R}, V_F) = \begin{cases} -\tau_2.\dot{R} + \tau_1\tau_2\alpha_1 - 0.5\alpha_1{\tau_1}^2 & \frac{v_2}{\alpha_2} \geq \tau_2 \\ \tau_2.V_F - 0.5\alpha_1(\tau_2 - \tau_1)^2 - \frac{V_L^2}{2\alpha_2} & \frac{v_2}{\alpha_2} \geq \tau_2 \end{cases} \end{cases}$$

(Eq. 2.16)

where. $\dot{R}$ is the relative velocity between vehicles.

A plot of this braking critical distance as a function of velocity and relative velocity is shown in Figure 2.3. The following parameter values were used: α_1=7.8 m/sec^2, α_2=7.8 m/sec^2, τ_1=0.5 sec and τ_2=1.5 sec. The Honda's warning algorithm is a straight line in the range rate-range plane, indicating a time-to-impact consideration. Their braking logic has two parts selected by the estimated shortest time-to-lead-vehicle-stop. If the lead vehicle is not expected to stop within τ_2, the first part is selected; otherwise, the second part is used. Both of the scenarios assume that the lead vehicle is engaging the emergency braking and the host vehicle engages in emergency braking after reaction time τ_1 and in the estimated safety range until τ_2.

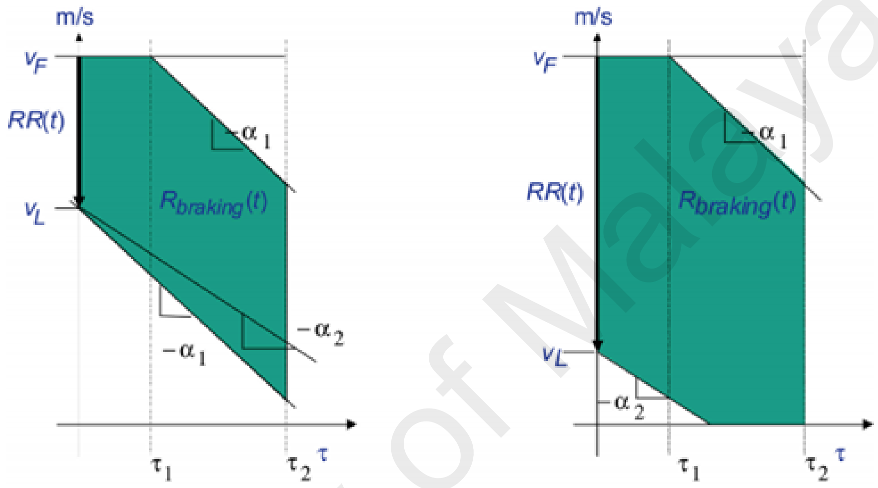


Figure 2.3: Interpretation to Honda's Logic (Lee and Peng, 2007).

2.8.3 Jaguar Algorithm

The Jaguar algorithm also contains two parts: warning algorithm and braking algorithm [Barber and Clarke, 1998].

$$\begin{cases} R_{warning} = f(R, \dot{R}, \ddot{R}) = \begin{cases} -4.\dot{R} & V_L = 0 \\ -4.\left[\dfrac{\dot{R} \pm \sqrt{\dot{R}^2 - 4R\left(-\frac{1}{2}\ddot{R}\right)}}{2R}\right]^{-1} & if\ V_L > 0 \end{cases} \\ R_{braking} = \dfrac{1}{2} a\dot{R}^2 \end{cases} \qquad \text{(Eq.2.17)}$$

The warning logic consists of two parts. For fixed objects, the warning criterion is simply a 4-second time-to-impact. For moving vehicles, the warning criterion calculates the time to collision, assuming the instantaneous relative acceleration is maintained into the future, which is depicted in Figure 2.4. For the braking logic, the suggested value for parameter 'a' is 0.2.

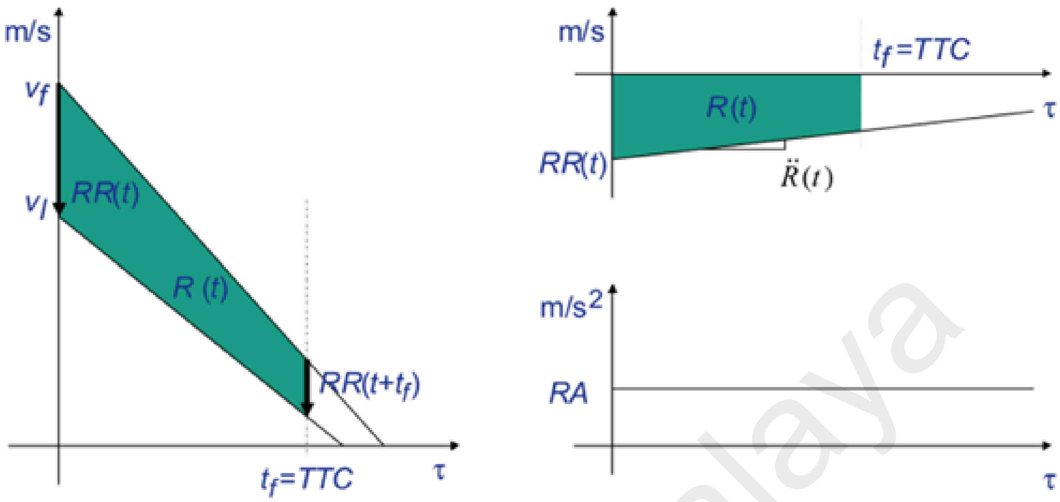


Figure 2.4: Concept of Jaguar's Collision Warning Logic for Moving Targets (Lee and Peng, 2007).

2.8.4 JHU-APL Algorithm

In the collision warning logic developed by NHTSA and the Applied Physics Laboratory of the Johns Hopkins University – (JHU APL) (Brunson et al., 2002), the variable 'Time to Lead Vehicle Stop' is an important criterion used in their logic. The algorithm is presented in Eq 2.18

$$D_{thresharnin} = 2[m] + V_H.0.1(s)$$

$$D_{miss} = \begin{cases} R + \Delta R_1 + \Delta R_2 + \Delta R_3 & T_{LS} \geq T_R \\ R + \Delta R_1 + \Delta R_4 & T_{LS} < T_R \end{cases}$$

$$\Delta R_1 = \dot{R}T_R + \frac{1}{2}(a_L - a_F)T_R^2$$

$$\Delta R_2 = [\dot{R} + (a_L - \dot{a}_F)T_R](T_{LS} + T_R) + \frac{1}{2}(a_L - a_{F\,max})(T_{LS} + T_R)^2$$

$$\Delta R_3 = \left[\dot{R} + (a_L - a_F)T_R\right] + (a_L - a_{F\,max})(T_{LS} - T_R)(T_{HS} - T_{LS}) + \frac{1}{2}(0 - a_{F\,max})(T_{HS} + T_{LS})^2$$

$$\Delta R_4 = \left[\dot{R} + (a_L - a_F)T_R\right](T_M - T_R) + \frac{1}{2}(a_L - a_{F\,max})(T_M + T_R)^2$$

$$T_{LS}\left(V_L, \dot{R}, a_L\right) = \frac{V_F + \dot{R}}{-a_L} \quad a_L < 0$$

$$T_{HS}(V_F, a_F) = \begin{cases} T_R + \dfrac{V_F + a_F T_R}{-a_{F\,max}} & V_F + a_F T_R \geq 0 \\ \dfrac{V_F}{-a_F} & V_F + a_F T_R < 0 \end{cases}$$

$$T_M = \frac{\dot{R} + (a_L - a_F)T_R}{a_{F\,max} - a_L} + T_R \qquad \text{(Eq. 2.18)}$$

The suggested parameter values are: $a_{Fmax} = -0.5$g and T_R=1.5 sec. When the time to lead vehicle stop (T_{LS}) is longer than the human reaction time (T_R), this logic divides the time-to-stop into three segments: 0 to T_R (ΔR_1), T_R to T_{LS} (ΔR_2) and T_{LS} to T_{HS} (time to host vehicle stop) (ΔR_3) as shown in Figure 2.5.

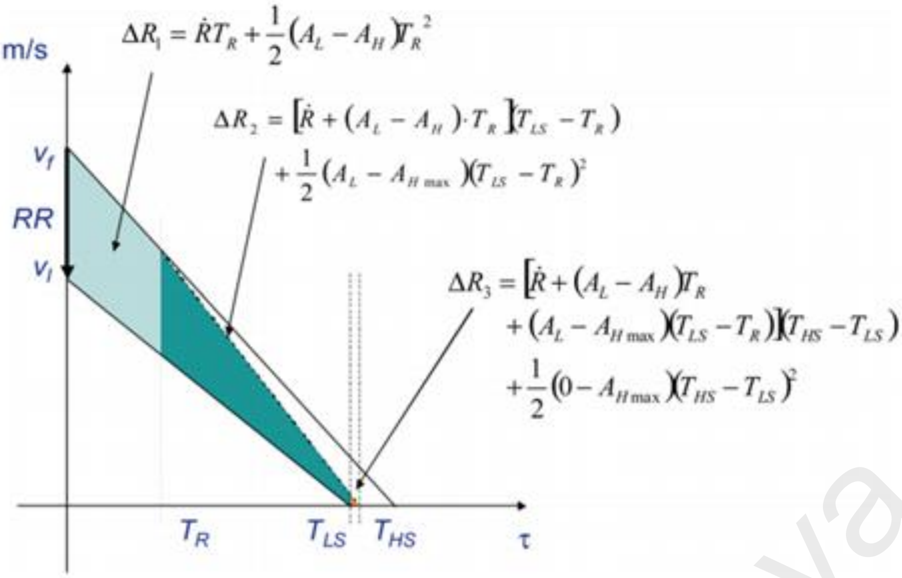


Figure 2.5: JHU-APL Algorithm for $T_{LS} \geq T_R$ (Brunson et al., 2002)

The logic calculates the range consumed within each segment from the final relative velocity of the previous segment and the duration of the segment. When T_{LS} is shorter than T_R, the logic only considers two segments: 0 to T_R (ΔR_1) and T_R to T_M (ΔR_4) (Figure 2.6). Within the first segment (0 to T_R), the range calculation is the same for both cases. In figure 2.6, the area below the x-axis should have been subtracted from the overall range calculation because the vehicle speed should not become negative. We assume that this compensation is not included in the original JHU-APL algorithm because its calculation is somewhat complicated. The proposed threshold range calculation is simpler and offers an extra safety margin by neglecting this area. The JHU-APL algorithm also includes an additional rule to improve implementation robustness: the warning signal will be triggered only if D_{miss} is smaller than D_{thresh} for two out of the last three detections.

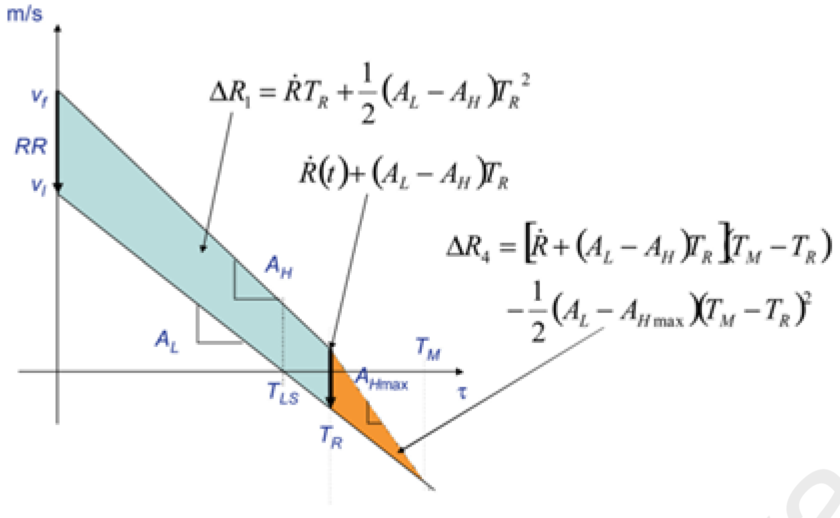


Figure 2.6: JHU-APL Algorithm for $T_{LS} < T_R$ (Brunson et al., 2002)

2.8.5 Berkeley Algorithm

The Berkeley algorithm (Seiler, Song, and Hedrick, 1998) proposes a conservative warning range (R_w) to provide a wide range of visual feedbacks to the driver, and a non-conservative overriding range (R_o) to reduce undesirable effects of overriding to normal driving operations. It is assumed that the lead vehicle brakes at the maximum constant deceleration level $-\alpha$, while the host vehicle starts to brake after reaction time τ at the same deceleration level. Note that the reaction time τ here accounts for both, the driver reaction time and the system delay time. The warning range (R_w) is estimated as the minimum range buffer needed to avoid collisions until both vehicles come to a full stop in the above scenario, while the overriding range (R_o) only considers the range buffer needed from time 0 to τ as:

$$R_W = \frac{(V_H^2 \dot{-} V_L^2)}{2_\alpha} + V_H\tau + R_{min}$$

$$R_0 = -RR.\tau + \tfrac{1}{2}\alpha\tau^2 \qquad \text{(Eq. 2.19)}$$

2.9 Literature Review Summary

It is clear that active safety technology in vehicles is becoming more and more advanced and is utilizing more and more information from the vehicle itself and its surroundings. One proposed solution in active safety is the implementation of CAWS. There are many aspects in designing CAWS in a more proper manner. The type of alarm to be used in the system must be determined. CAWS will be of greatest value when it is used to warn a distracted driver. Therefore, the alarm must be able to be perceived by the driver when his/her attention is diverted from the roadway. When to activate the system must also be determined. The activating algorithm of the CAWS must activate the alarm at the optimal time, where the alarm must be sounded early enough to allow for proper evasive maneuvers, but not too early, which might cause the alarm to become a nuisance to the driver. One observation made regarding the parameters considered in most of the safety indicators or algorithm that have been proposed is that certain parameters which may have a direct impact on vehicle braking performance have not been explicitly considered

Although there are researchers working to develop the safety performance or the CAWS algorithm as explained earlier in this chapter, there were no detailed investigations related to a heavy vehicle's GVW, CoF and vehicle classification. These three parameters are assumed to be the same for all types of vehicles. Thus, it is important to extend the study on the influence of GVW, CoF and its class on safety indicators in a vehicle following situation to further understand the subject not only from the driver's visual input perspective, but also from vehicle's dynamics capability perspective.

CHAPTER 3 - COLLISION AVOIDANCE WARNING SYSTEM MODEL DEVELOPMENT

In view of the problems encountered as described in the problem statement, the principal objective of the development of the CAWS is to provide an accurate and reliable method, as well as a measuring apparatus capable of detecting a potentially unsafe following distance in a vehicle following situation. This will be achieved by taking into account factors associated with the vehicle, road and driver capability that will eventually provide a warning system to the driver.

In order to accomplish the objectives of this study, the methodology of this research is separated into two parts: the Mathematical Model Development (Chapter 3) to cover objectives one and two, and the Hardware Development (Chapter 4) to cover objectives three and four. This chapter will present and explain the work performed to develop a new CAWS model. In order to develop a new model, an extensive study of the effect of Gross Vehicle Weight, Vehicle Class and Coefficient of Friction towards the heavy vehicle's deceleration and Braking Distance was undertaken.

The second part of this chapter will cover the statistical method to develop the new algorithm for CAWS. This algorithm, the Minimum Safe Distance Gap (MSDG), incorporates the components of vehicle-driver-environment factors such as vehicle braking capability, the driver perception reaction time (PRT) and the road surface condition.

3.1 The Study of the Effect of Vehicle Capability, GVW and Road Surface Condition towards Heavy Vehicle's Deceleration and Braking Distance

The brake performance of vehicles can be analyzed in several different ways. This can be done through a real experimental work or through computer simulation. Evidently, the process of building and constructing the prototype for actual experimental tests involves significant engineering time and cost. Furthermore, at times, tests involving two vehicles following closely at high speeds are quite dangerous and difficult to implement. Additionally, it is also difficult to ascertain the safe following gap distance in a close vehicle-following situation.

With the evolution of computer science, a computer simulation offers a better advantage in understanding physical problems such as those considered in this study. This simulation technique is often used as an alternative for very costly and risky experimental methods. In this study, an industrial standard multi-body dynamics modeling software package, the IPG TruckMaker®, was used to generate deceleration and braking distance (BD) data for 2 to 4-axle single unit trucks (SUT) under various GVW, CoF, VC and speed. The TruckMaker® is a software used to analyze the multi-body system. This software is well suited for the global vehicle dynamics simulation of heavy commercial vehicles, articulated lorries and buses, as well as concrete mixers, construction vehicles, heavy tractor-trailers and heavy special vehicles.

There are three main steps involved in obtaining the deceleration and BD data from the TruckMaker® software, which are (a) Virtual Vehicle Modeling, (b) Simulation and (c) Data Acquisition and Interpretation.

3.1.1 Virtual Vehicle Modeling

3.1.1.1 Model Validation

To validate the vehicle modelling from TruckMaker® simulation results, a comparison between simulation result and experimental data has been done. In this case experimental data from the National Highway Traffic Safety Administration (NHTSA) has been chosen to compare with simulation data from TruckMaker®.

In 2009, National Highway Traffic Safety Administration (NHTSA) has conducted experiments to obtain data on the stopping performance of one truck tractor-semitrailer combination vehicle from a range of initial speeds. The truck tractor tested was a 1991 Volvo 6x4 tractor towing a 28 foot long, unbraked control trailer. Vehicle testing was performed in accordance with the office of Vehicle Safety Compliance Laboratory Test Procedure No. TP-121V-04. Figure 3.1 shows an overall picture of this truck tractor-semi-trailer rig and Table 3.1 shows the specifications.

Figure 3.1: 1991 Volvo 6x4 Tractor with TRC's 28 foot long, unbraked control trailer (NHTSA 2011)

Table 3.1: Volvo 6x4 Truck Tractor Data (1991) (NHTSA 2011)

Product Model		Volvo N 12 (1991) / White GMC
Year/Make/Model/Body Type		1991 White GMC (Made by Volvo)
VIN		4VIWDBJH5NN645138
TRC/NHTSA NO.		TRC162
Engine Data type		Cummins, model #CUM91 N14-460E 460
Transmission		18(manual)
Axle/Drive Configuration		6x4
WheelBase (inch)		189.5
Suspension	Front	Leaf spring
	Rear	Leaf spring
Rear Axle Spread (inch)		96
Fifth wheel Height Relative to ground (Inch)		45
Fifth wheel Position relative to rear centerline (Inch)		24.5

Table 3.2 shows the results of braking distance obtained from the experiment done by NHTSA

Table 3.2: Braking Distance Result from NHTSA experiment (NHTSA 2011)

Target Speed (mph)	Average Braking Distance (ft)	Steady State Deceleration (ft/sec2)
20	31.2	20.00
25	44.2	21.40
30	61.4	20.70
35	78.8	21.00
40	104.4	19.80
45	135.9	19.10
50	167.5	18.70
55	200.5	18.50
60	250.7	17.30

Using the same truck and specification as shown in Table 3.3, with assumption road coefficient is equal to 0.7, pedal force is 285N and duration step is 0.45, the simulation has been conduct using TruckMaker® software to validate the data.

Table 3.3: Data based on the Experiment setup carried by NHSTP

Model Type		Volvo 6x4 tractor with trailer
Loaded Condition	Rear axle weight distribution	10,990 pounds
	Front axle weight distribution	27,360 pounds
	Trailer weight distribution	4,490 pounds
	Total GVW	42,840 pounds

Braking distance comparison between experimental result done by NHTSA and simulation data using TruckMaker® has been done as described. Table 3.4 shows the braking distance data for experimental and simulation. Figure 3.2 shows the comparison graph for experimental and simulation data using TruckMaker® software. From this result, it is shows that the simulation prediction is quite close to the experimental result. Taking into account that the estimated error for between simulation and experimental below than 10%, it can be concluded that both results are compatible.

Table 3.4: Average braking distance comparison

Velocity (mph)	Experimental Data (m)	TruckMaker®(m)	Percentage Error (%)
0	9.51	9.12	4.1
25	13.47	13.64	1.3
30	18.71	18.97	1.4
35	24.02	25.33	5.5
40	31.82	32.39	1.8
45	41.42	40.28	2.8
50	51.05	49.72	2.6
55	61.11	58.38	4.5
60	76.41	71.84	5.9

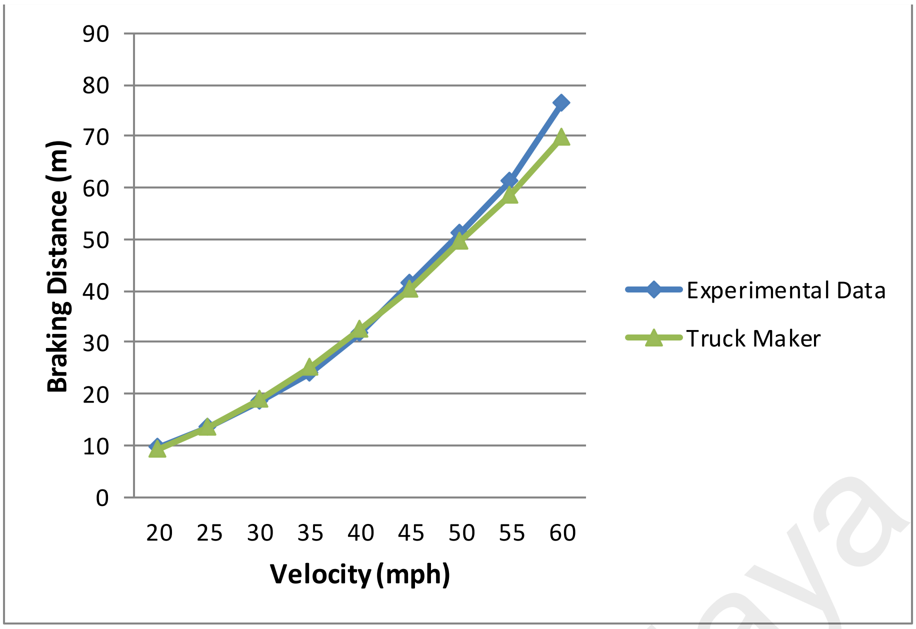


Figure 3.2: Braking distance data comparison between experimental and simulation.

3.1.1.2 Virtual Vehicle Development

Since the aim of the study is to develop a model that can reflect an actual two to four axle brake distance situation, it is important to develop realistically simulated SUT models. Thus, in this study, the vehicle models and the SUT specifications of the 2-axle, 3-axle and 4-axle trucks have been developed in accordance to the type of vehicle that is available on the road. Studies and the understanding of the method were done in the first stage of the research. From the statistics and information obtained, the road type with the most frequent accident rates had been determined and carried out further study on the factors that lead to the road accident itself. The type of trucks operating in Malaysia was also studied in this stage where it is important for the future simulation settings. This is to obtain the results of the deceleration and braking distance of the vehicles. The common used truck with several of axles has been shown in Appendix A. Table 3.5 shows the data required for the braking simulation in the software.

Table 3.5: Vehicle Modeling Parameters and Simulation Setup

Items	Details
Simulation Type	Braking
Road Type	Straight road
Starting Weight	Curb weight, 10 tons to 45 tons with 5 tons interval
Starting Velocity	40km/h to 100km/h (2 axles) and 110km/h (3 and 4 axles) with 10km.h interval
Time Start to Brake	At 5 second
Brake Force	285N
Reaction Time	2.5 second
Road Surface Coefficient of Friction	0.30 to 0.70 with 0.10 interval

One of the benefits of the IPG TruckMaker® when compared to other similar simulation software is that the IPG Automotive provides a wide variety of truck models with the trucks' actual data. An example of this would be the Volve Actros heavy vehicles. This entire model is programmed with the actual system specifications such as the ones in production. Figure 3.3 shows the browser of the truck's data in the IPG TruckMaker®.

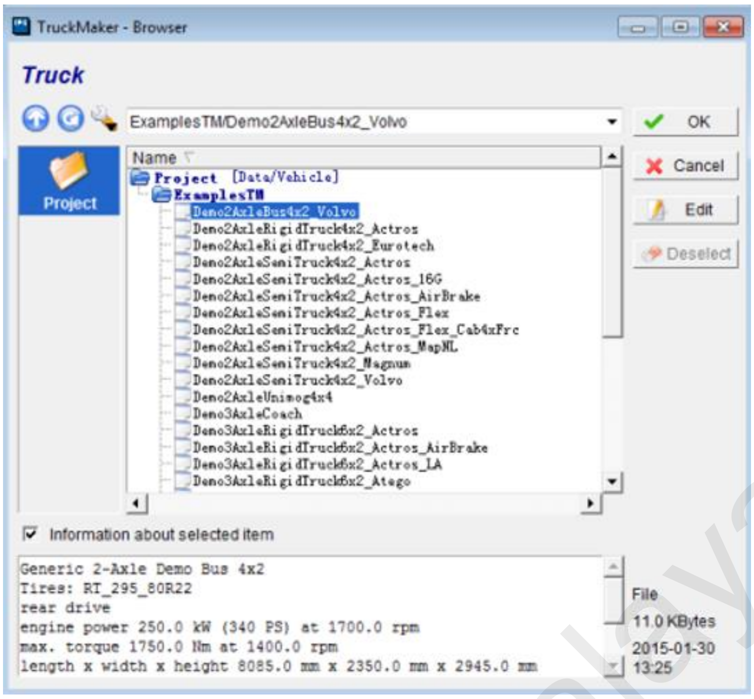


Figure 3.3: IPG TruckMaker® Truck Data Browser

Road and maneuver settings are very important parameters in a simulation run for this research. In an IPG TruckMaker®, the road settings are divided into three categories, which are the global settings, segments and the IPG Movie interface. For example, the track width and coefficient of friction can be set in the global settings, while the track length, turning angle and radius are set in the segments. Many types of track segments can be added and joined as one for the simulation which will be based on the time frame. The road can also be improved visually in the IPG Movie interface settings. Figures C-1.1, C-1.2 and C-1.3 in Appendix C show the road settings interface in the software. The maneuver setting is similar to the road segments where different types of maneuver segments can be added and joined together as one. Figure C-1.4 shows the maneuver interface.

3.1.2 Simulation

In this stage, the truck model selected undergoes a straight road braking simulation. During the simulation, all the required parameters including the road surface coefficient of friction, traveling speed and weight load of the truck were varied based on the interval set. To start the simulation, the user needs to specify the required parameters and settings for the braking test. The braking simulation and brief elaboration are detailed in the following subsections.

3.1.2.1 Truck Data Selection

In this research, three different types of axles of truck are tested, which are the two axles, three axles and the four axles. Figures C-2.1, C-2.2 and C-2.3 in appendix C show the truck axles' class selected in any increasing order. The Gross Vehicles Weight (GVW) of the three different axle trucks in the software is obtained and matched as close as possible to the truck models available in the current Malaysian market. Table 3.6 shows the truck model match. Details of the truck models are shown in Appendix B.

Table 3.6: Truck Models with GVW and Curb Weight

Number of Axles	Gross Vehicles Weight in Software (GVW)	Truck Model	Gross Vehicles Weight (GVW)	Curb Weight
2	18200kg	ISUZU FVR285	18000kg	5600kg
3	25200kg	Mitsubishi Fuso FJY1WN1R	25000kg	7180kg
4	32000kg	Volvo FM84RB1HR	37000kg	9775kg

When the truck model required was selected, information of the braking system was set in the vehicles data set in the brake section, such as the brake force and reaction time. Besides that, the load of the truck was set in the truck/trailer load section. Figure C-3.1 and C3.2 in appendix C show the parameters settings.

3.1.2.2 Road and Maneuver Settings

For the road settings, two road segments were added into the system. The first segment was a 100m long straight track and the second segment was an 8000m long straight track with the friction strips according to the Coefficient of Friction. The second segment changes for the different conditions of the truck model. Table 3.7 shows the second segments' settings. Figure C-1.2 in appendix C shows the road segment interface with the required parameters to set.

Table 3.7: Road Second Segment Settings

Truck Model	Road Length (m)
Two axles and three axles	5000
Three axles (25 tons load and above)	8000
Four axles	9000

For the maneuver section, there were also two segment maneuvers. The first maneuver was for the acceleration of the truck to the desired speed, while the second segment was for the braking to start until the vehicles reach a complete halt on the tracks. Figure C-4.1 and C-4.2 show the settings for both of the maneuver segments.

3.1.2.3 Task Manager

In the IPG TruckMaker software, there is a Task Manager feature as shown in Figure 3.4 which enables the user to run a large quantity of simulation runs in just one click. In other words, for this research, the speed, load and surface coefficient can be pre-set in this window for one type of truck axle. For example, the simulation will start with the curb weight model at a speed of 40km/h and a 0.3 in surface road roughness. Then the system will continue to run the pre-set parameters for the next simulation run. This will save a lot of time which can avoid the changing of parameters from time to time.

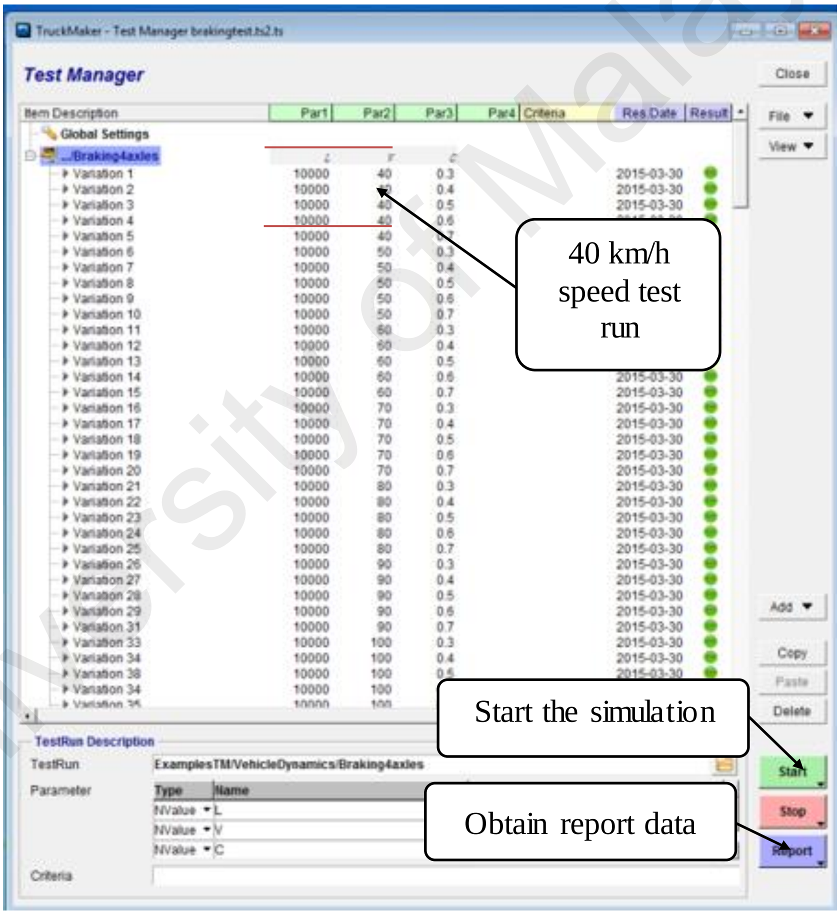


Figure 3.4: Task Manager

The user will be able to add in the variations of different parameters in the list of the simulation runs. After all the simulations had been done, the results or data were obtained by pressing the “report” button. A report data was generated in a pdf file where the user can link back the file into the IPG Control window for data interpretation.

The simulation was carried out to emulate the vehicle traversing a flat and dry road at a constant forward velocity before the brake is applied. The vehicle will then decelerate until it stops and the deceleration and BD data was recorded. The brake force of 285N was applied as suggested by Mazzae et al.,(1999) which represents the average maximum brake pedal force during an emergency brake for dry pavements (Mazzae et al., 1999). An additional simulation was conducted to study the effect of a heavy vehicle's braking force on braking distance above and below 285N at various constant forward velocities. The results from this simulation suggested that the variations in brake pedal force above 100N showed minimal effect on the BD as shown in Figure 3.5 (Sharizli 2015). The brake forces applied between 100N and 500N emulated the emergency braking situation in which the brake mechanism in all wheels was fully engaged. Below 100N, the brake mechanism was not fully engaged, thus resulting in a longer braking distance. The findings from these simulations showed a similar outcome when compared to a research conducted by Gregory (2010). His experimental study revealed that the braking forces have little effect on the braking distance when the brake mechanism was fully engaged, as shown in Figure 3.6.

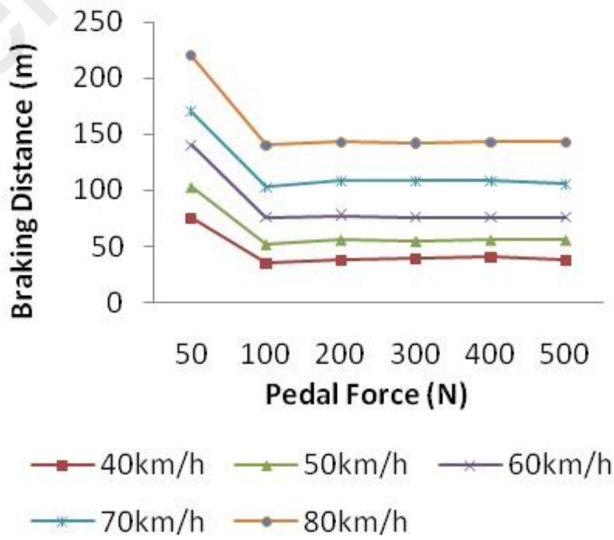


Figure 3.5: Braking Distance for Difference in Braking Force (Sharizli 2015)

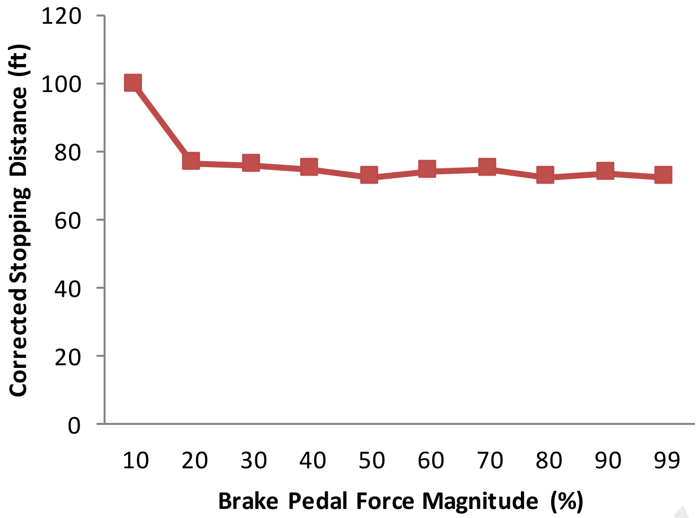


Figure 3.6: Corrected Stopping Distance by Brake Pedal Force Magnitude for Tests Performed at 45 mph (72 km/h) (re-plotted from Gregory et al. 2010)

3.1.3 Data Generation and Interpretation

As stated in the objectives for this study, the GVW is a crucial element for this simulation. The lumped mass added in the storage compartment was assigned with different masses (5000kg interval) for each simulation done. After a heavy vehicle was loaded, its GVW was calculated. The whole event was then conducted under constant velocity starting from 30km/h with 10km/h intervals, until 100km/h. After each speed interval was tested out, the next GVW with a 5000kg interval was tested. Once the respective heavy vehicle has gone through all the simulation steps, the procedures were repeated for the rest of the heavy vehicles that have been constructed.

The data for the results obtained were exported into a spreadsheet program (Microsoft Excel) in the IPG Control. The results were then imported into a MATLAB software to be analyzed and summarized, and discussed.

3.1.3.1 Data Generation

In this section, the simulation results (braking distance vs. time) were shown in the IPG Control truck and presented in a graph as shown in Figure 3.7.

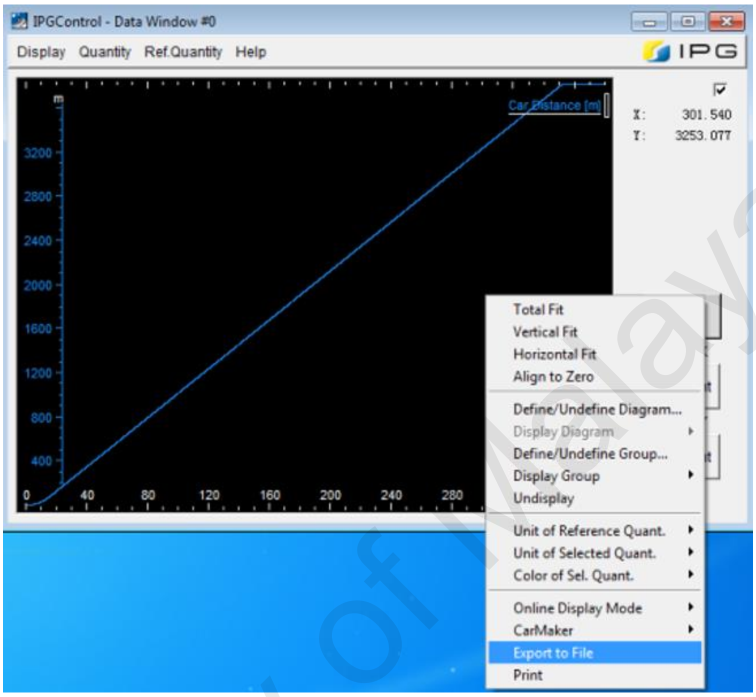


Figure 3.7: IPG Control Graph Data

3.1.3.2 Data Interpretation

The data from the IPG TruckMaker was imported into the MATLAB workspace for as shown in Figure 3.8 and 3.9 graph plotting which is based on the variables time (s), and distance (m).

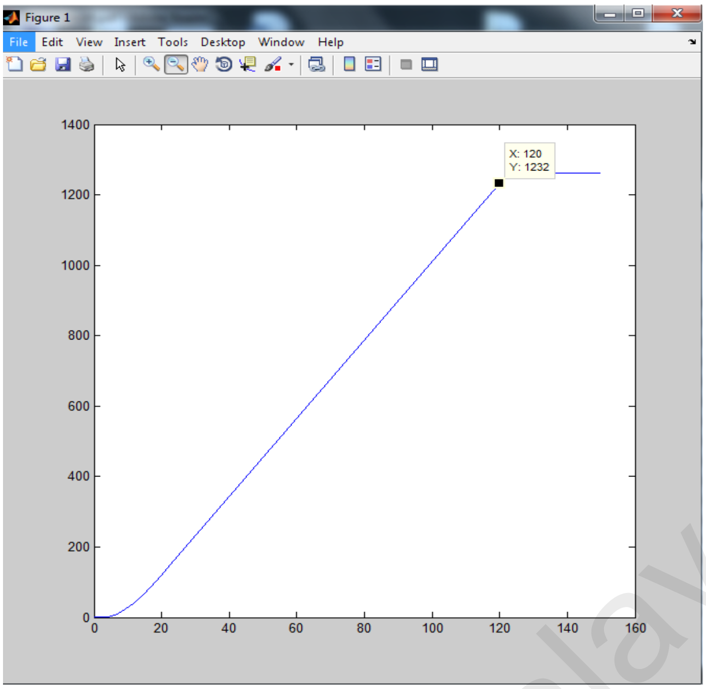


Figure 3.8: Result in MATLAB (Start Brake Distance)

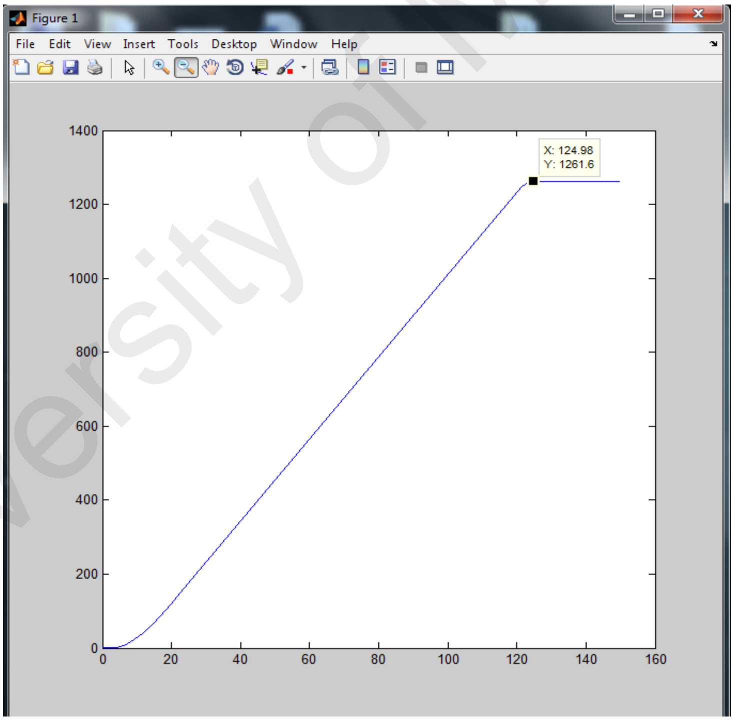


Figure 3.9: Result in MATLAB (Stop Distance)

From the graph, we were able to use the data cursor to determine the data along the graph line. In this research, the braking characteristics were analyzed based on the braking time and braking distance. In order to obtain the braking distance, the final distance (m) traveled by the truck before a complete stop. Therefore, from Figure 3.8

we know that the truck stopped at the distance of 1261.6m (Y_2), while from Figure 3.9, we know that the truck started to apply the brake at a distance of 1232m (Y_1). Hence,

Braking distance $= Y_2 - Y_1$

$= 1261.6 - 1232$

$= 29.6m$

This calculation method was repeated for all the remaining simulation data. The deceleration and distance values were tabulated using Microsoft Excel. The details of the data will be discussed in the Chapter 5.

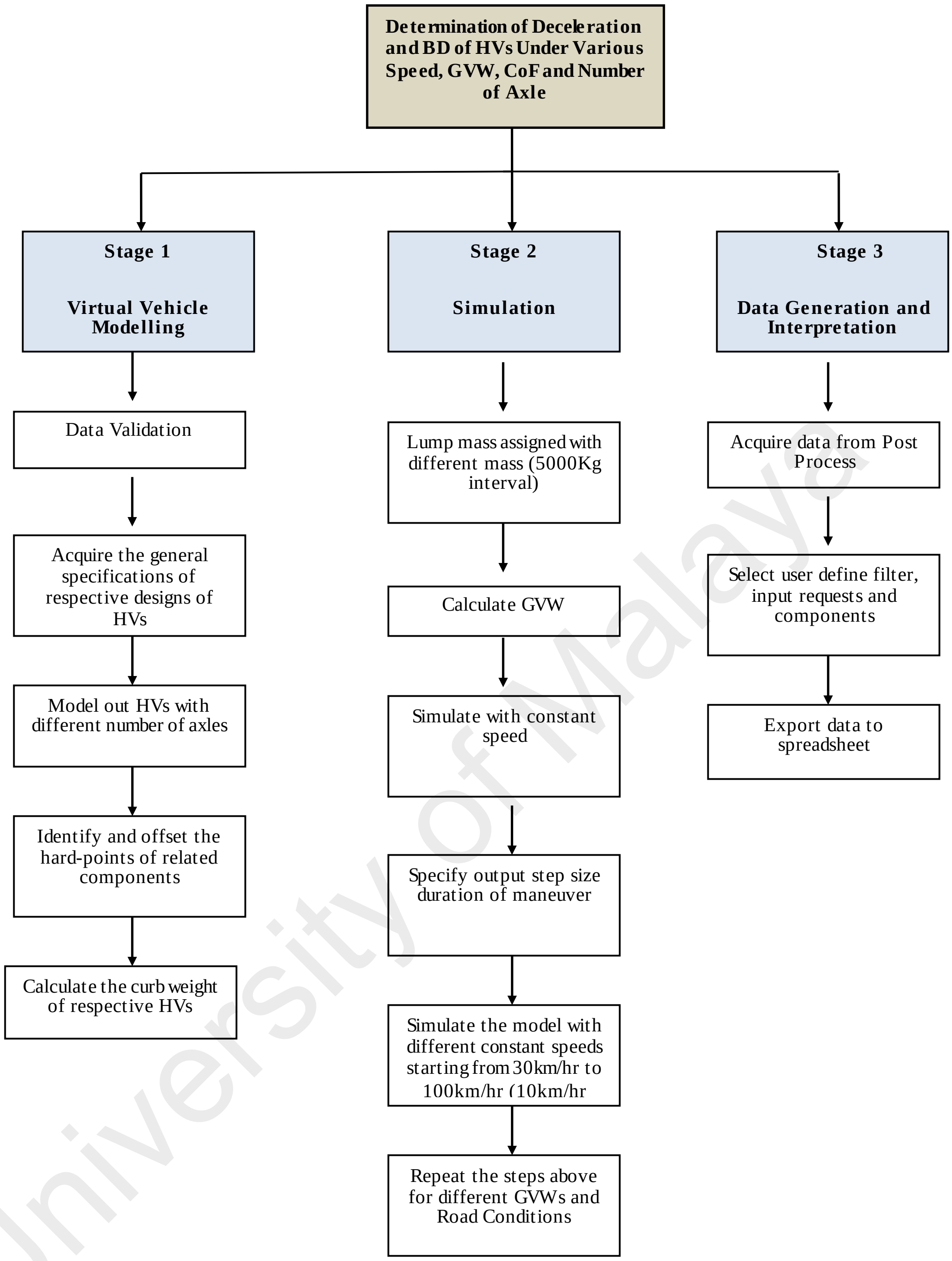


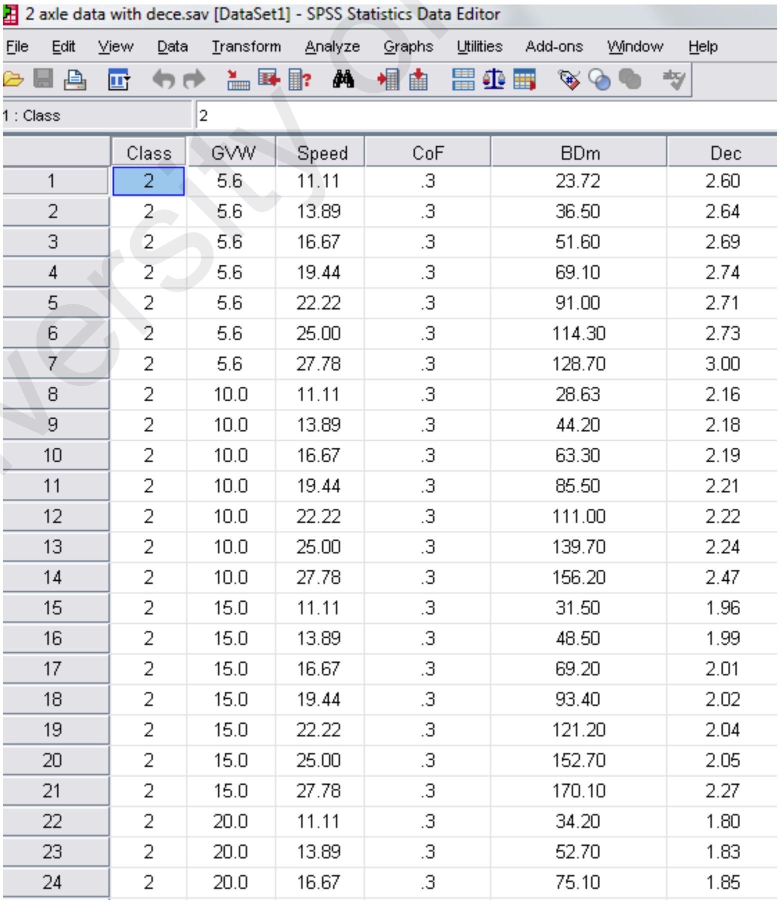
Figure 3.10: Workflow Summary

3.2 Data Analysis

In this study, the Statistical Package for the Social Science (SPSS) version 17.1 has been used for data analysis.

3.2.1 Data Setup and Scatter Plot

A total of 1059 sets of data were generated from the previous steps. The first step to carry out before the analysis is to properly set up the collected data from the previous section. It begins by selecting and filtering out missing data and the outlier data in the data set. Then, the data is split according to the VC, CoF, GVW and speed to make it easier to analyze as shown in Figure 3.11. The next step is to plot the graph between the deceleration and GVW, VC and CoF to study the relationship that exists between the variables.



	Class	GVW	Speed	CoF	BDm	Dec
1	2	5.6	11.11	.3	23.72	2.60
2	2	5.6	13.89	.3	36.50	2.64
3	2	5.6	16.67	.3	51.60	2.69
4	2	5.6	19.44	.3	69.10	2.74
5	2	5.6	22.22	.3	91.00	2.71
6	2	5.6	25.00	.3	114.30	2.73
7	2	5.6	27.78	.3	128.70	3.00
8	2	10.0	11.11	.3	28.63	2.16
9	2	10.0	13.89	.3	44.20	2.18
10	2	10.0	16.67	.3	63.30	2.19
11	2	10.0	19.44	.3	85.50	2.21
12	2	10.0	22.22	.3	111.00	2.22
13	2	10.0	25.00	.3	139.70	2.24
14	2	10.0	27.78	.3	156.20	2.47
15	2	15.0	11.11	.3	31.50	1.96
16	2	15.0	13.89	.3	48.50	1.99
17	2	15.0	16.67	.3	69.20	2.01
18	2	15.0	19.44	.3	93.40	2.02
19	2	15.0	22.22	.3	121.20	2.04
20	2	15.0	25.00	.3	152.70	2.05
21	2	15.0	27.78	.3	170.10	2.27
22	2	20.0	11.11	.3	34.20	1.80
23	2	20.0	13.89	.3	52.70	1.83
24	2	20.0	16.67	.3	75.10	1.85

Figure 3.11: Data Set after Data Setup Procedure in SPSS

3.2.2 New Model Development – MSDG

3.2.2.1 MSDG Concept

Keeping a safe following distance from the leading vehicle (LV) is critical for reducing rear-end crashes in vehicle following situations since it allows the following vehicle (FV) a sufficient distance to stop, as well as to stop gradually. Thus, in this thesis, the concept of the Minimum Safe Distance Gap (MSDG) is introduced. MSDG is defined as the minimum distance required by the FV to decelerate and stop safely without colliding into the LV when both LV and FV apply the emergency brakes due to unforeseen circumstances. It is important to note that the vehicle following distance is different from the vehicle stopping distance in the sense that the leading vehicle is assumed to be completely stopped, which could be considered as a special scenario of the following distance.

The value of MSDG (as illustrated in Figure 3.12) is obtained by considering the braking distance of the following vehicle (BD_{FV}) and the leading vehicle (BD_{LV}), as well as the perception-reaction distance (RD) of the following vehicle driver. The overall concept of the system is shown in Figure 3.12.

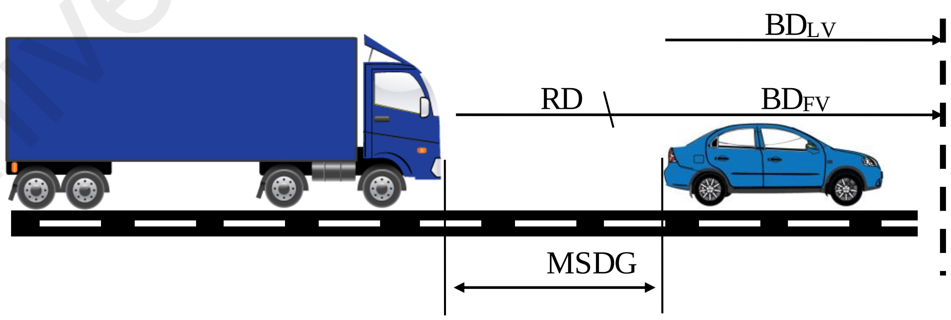


Figure 3.12: Concept of MSDG Algorithm

The FV is considered to be in an unsafe condition when the gap distance calculated between FV and LV is lower than the MSDG value. Different compositions of leader-follower pairs, for example in the case of a heavy vehicle following a car, will affect the

MSDG value due to the difference in braking performance and braking capability of the vehicles. Similarly, the FV's driver's physical and psychological conditions will also affect the perception-reaction distance (PRD) which will ultimately affect the MSDG. In this study, for the purpose of maximum safety, only the passenger car with GVW equal to 2 tonne has been chosen as the LV since it has maximum braking capability compared to the heavy vehicle. GVW is equal 2 tonne based on the maximum curb weight of sedan car (Kate Miller, 2014).Also the PRD for LV ignored for maximum safety. Also for maximum safety, the algorithm already consider for the worst case scenario by not counting the reaction time of leading vehicle. This causes the value of MSDG to be less than it should be.

3.2.2.2 MSDG Algorithm

The general equation of MSDG incorporating braking distance (BD) and perception-reaction distance (PRD) can be expressed as Eq. (3.1):

$$MSDG = BD_{FV} - BD_{LV} + PRD \quad \text{(Eq. 3.1)}$$

where the MSDG is the Minimum Safe Distance Gap (m), *PRD* is the FV's driver's perception-reaction distance (m), and BD_{FV} and BD_{LV} are the braking distance (m) of the FV and LV, respectively. The Derivation of BD and PRD will be given in the following paragraph.

The PRD is proportional to the driver's reaction time (RT) and the vehicle speed, as shown in Eq. (3.2):

$$PRD = V \times RT \quad \text{(Eq. 3.2)}$$

whereby *PRD* is the FV's driver's perception-reaction distance (m), V is the speed of the FV (m/s) and RT is the reaction time (s). Studies by Atif Mehmood and Said M.Esa

(2009) revealed that age and gender were significant factors that affect RT in all scenarios, as shown in the developed model in Eq. (3.3).

$$RT = 0.025Age + 0.401\ Gender \qquad \text{(Eq. 3.3)}$$

whereby RT is reaction time (s), Age is age (years) of driver of the FV and Gender is gender of the FV's driver (0 for males and 1 for females). Referring to Eq. 3.1, the BD can be derived from Equation of Motion as in Eq. 2.8

$$BD = (V_f^2 - V_i^2)/2a \qquad \text{(Eq. 3.4)}$$

From Eq. 3.4, V_f is the final velocity. When the vehicle completely stops, the $V_f = 0$, The BD as a function of deceleration, a is as Eq. 3.5

$$BD = \frac{V_i^2}{2a} \qquad \text{(Eq. 3.5)}$$

Replace Eq. 3.3 and Eq. 3.5 to Eq 3.1

$$MSDG = \frac{U_{FV}^2}{2a_{FV}} - \frac{U_{LV}^2}{2a_{LV}} + 0.025V(Age) + 0.401V(Gender) \qquad \text{(Eq. 3.6)}$$

Where $a_{FV}, a_{LV} = f(w, u, VT)$; w is GVW, VT is vehicle class and u is CoF.

Eq. 3.6 is the MSDG algorithm general formula as a function of deceleration. From the data collected, the deceleration, a as a function of GVW, CoF and speed was calculated using the regression method. Linear regression is the next step after the scatter plot. It is used when we want to predict the value of a variable based on the value of another variable. The variable we want to predict is called the dependent variable (in this case, deceleration, a). The variable we are using to predict the other variable's value is called the independent variable (in this case, GVW, CoF and Speed). The result of deceleration will be discussed in Chapter 5.

CHAPTER 4 - PROTOTYPE SYSTEM DEVELOPMENT

This chapter starts with the development of the MSDG calculator software to cover objective three, and then continues with the development of the CAWS prototype system to cover objective four. The prototype system has two major parts, the hardware development and the software development. The details of the CAWS hardware and software are presented as follow.

4.1 Development of Graphical User Interface MSDG Calculator Software

A GUI makes an application easier to use, especially for non-technical users. A graphical user interface (GUI) is a computer program designed to allow a computer user to interact easily with the computer typically by making choices from menus or groups of icons. With the combination of an input device and the visual representations of the workspace and tasks, the user is able to interact with the computer or laptop in a manner similar to physical manipulations available in the real world. In a robotic or automation field, the GUI is often used to interface with other external devices to communicate with computers. This is so that the user can ease the use of a GUI to control specified hardware operations and produce data.

Using an algorithm that have been developed in the last section, a graphical user interface (GUI) MSDG calculator software has been developed using the Microsoft Visual Basic 2010 (VB2010) programming language. The aims of this calculator is to simplify the driver to calculate the MSDG value based on their own vehicle parameters, road condition as well as the driver's own information. The development of this software has been divided into two parts, where the first part is to gather related information from the user, and the second part is to calculate the MSDG value using the MSDG algorithm. Use of this software will indirectly educate users to be more conscious about safe distance difference for each vehicle category and conditions.

The development of the CAWS calculator starts with the GUI design. Designing is an important part of software development as it mainly concerns the decomposition of a system into its constituent parts (Hans, 2008). A good design is necessary for a successful implementation of the system. This calculator has two main frames, which are the input and the output frame. In the input frame, the input parameters are categorized into 3 main groups: the FV parameters, road surface and driver information. The output frame will show the result when the user presses the “calculate” button. The overall sketch of the design is shown in Figure 4.1.

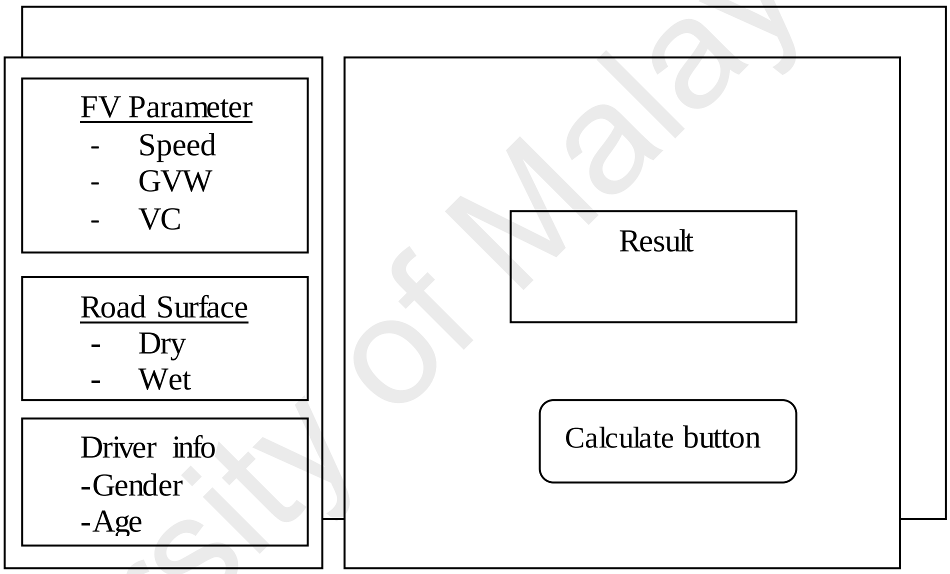


Figure 4.1: Overall Sketch Design of CAWS Calculator

The Visual Basic .NET (VB.NET) is a multi-paradigm, high level programming language, implemented on the .NET Framework. Microsoft launched the VB.NET in 2002 as the successor to its original Visual Basic language. The VB2010 is an object oriented and event driven programming language. In fact, all windows are event driven. Event driven means that the user will decide what to do with the program, and only required to ‘double click’ the component on the GUI platform.

Figure 4.2 is a screen shot of a new VB2010 project. The object in the center is called a form. On the left is the toolbox, and on the right is a box which contains all the properties of the form. Coding for the calculator is written in the code window as shown in Figure 4.3.

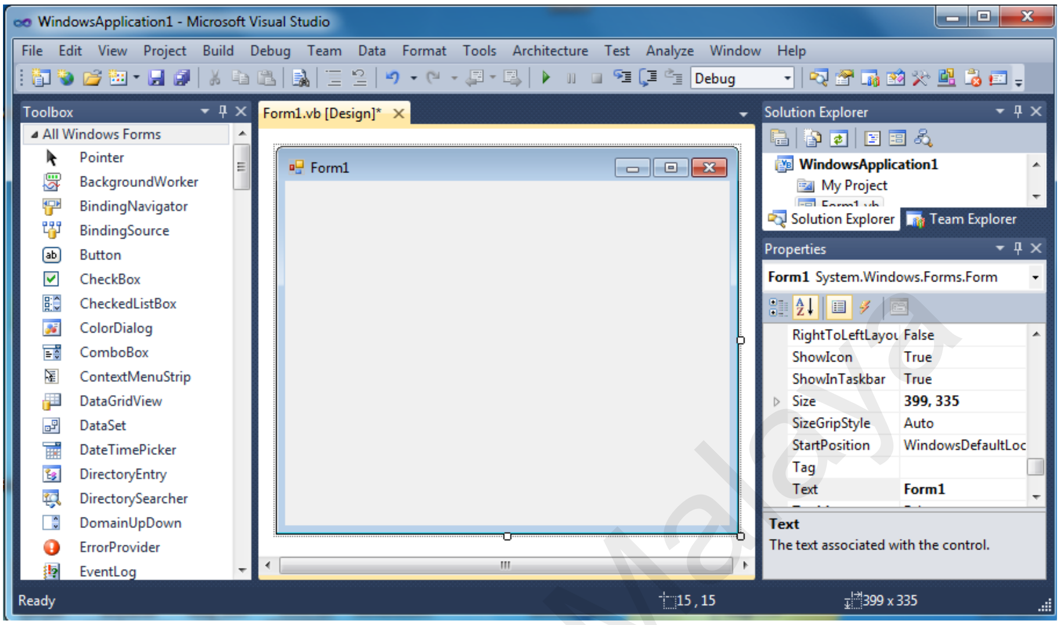


Figure 4.2: Screen Shot of a New VB2010 Project

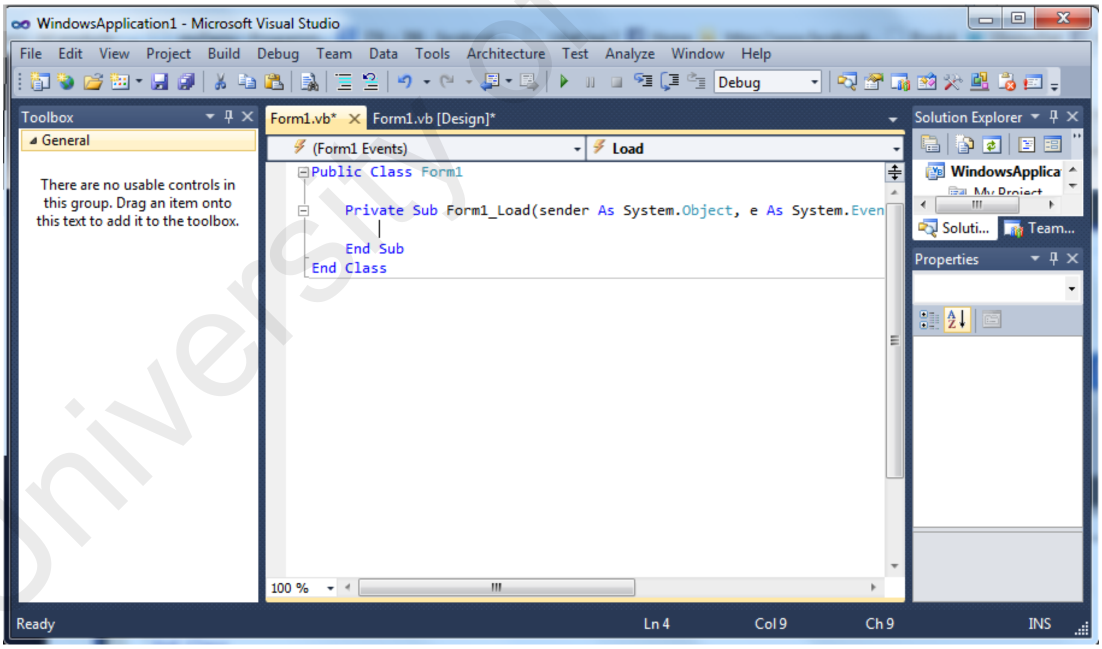


Figure 4.3: VB2010 Code Window

4.2 Prototype CAWS - Hardware Development

The overall block diagram of the hardware is shown in Figure 4.4. The design consists of a microcontroller (MCU) and several peripherals connected, such as sensors, an SD card and a display unit. Each major component of the design is briefly described below.

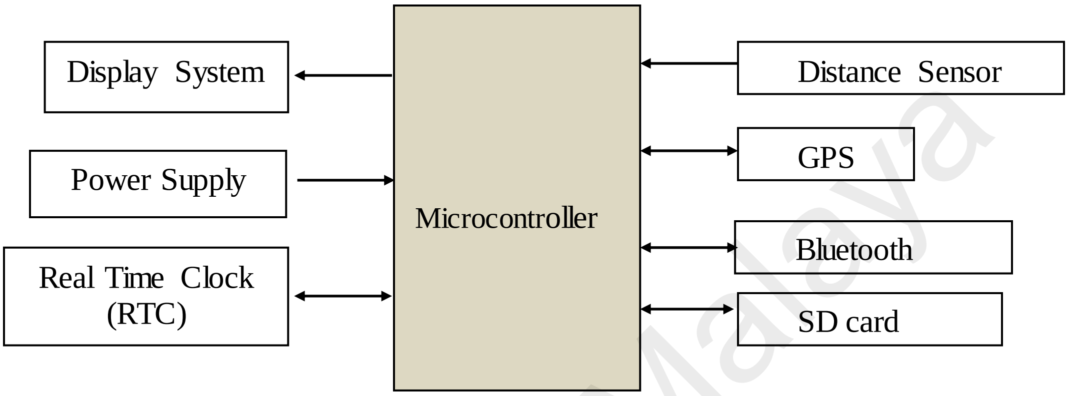


Figure 4.4: Hardware Framework of System

4.2.1 Microcontroller

To increase the data sample rate and writing speed in the storage device, a high speed Arduino Mega 2560 MCU such as the one shown in Figure 4.5 was chosen. Moreover, several peripherals were connected with the MCU using the SPI and UART protocol. The Arduino Mega is a microcontroller board based on the ATmega2560. It has 54 digital input/output pins, 16 analog inputs, 4 UART, a 16 MHz crystal oscillator, a USB connection, a power jack and an ICSP header. The chosen MCU also has a 256kB flash for program storage, 8kB SRAM to store user defined variables temporarily and a 4kB EEPROM to store variables permanently. Table 4.1 shows the summary of the Arduino Mega Specifications.

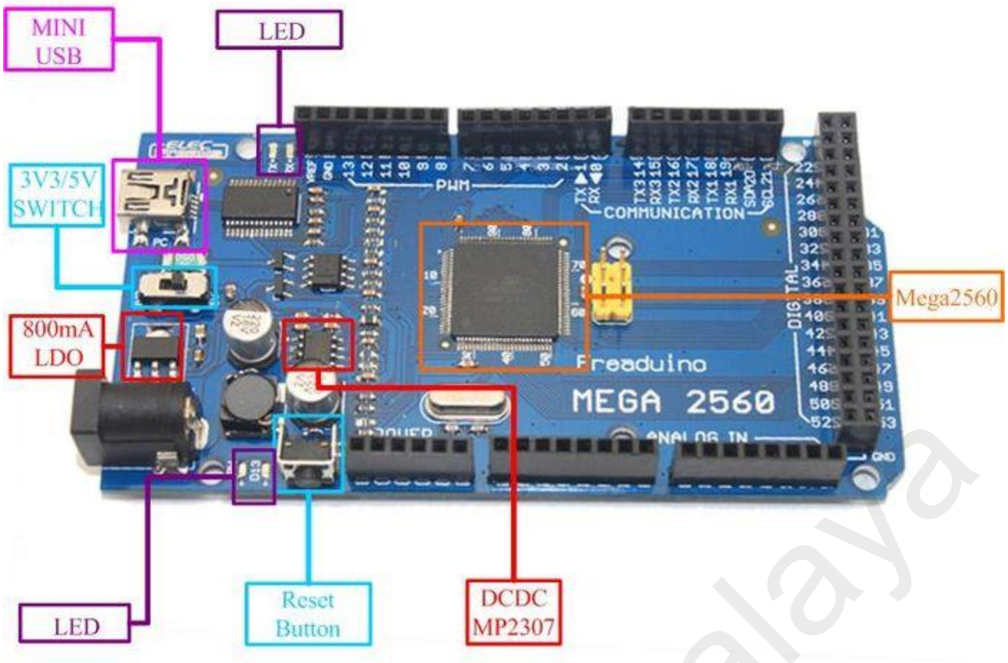


Figure 4.5: Arduino Mega 2560

Table 4.1: Arduino Mega 2560 Specifications

Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	128 KB of which 4 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

The Arduino Mega has a number of facilities for communicating with a computer, another Arduino, or other microcontrollers. The ATmega1280 also provides four hardware UARTs for TTL (5V) serial communication. An FTDI FT232RL on the board and the FTDI drivers (included with the Arduino software) provide a virtual com port to software on the computer. The Arduino software includes a serial monitor which allows simple textual data to be sent to and from the Arduino board. The RX and TX LEDs on the board will flash when data is being transmitted via the FTDI chip and USB connection to the computer (but not for serial communication on pins 0 and 1). The ATmega1280 also supports I2C (TWI) and SPI communication. The Arduino software includes a Wire library to simplify the use of the I2C bus.

4.2.2 Distance Sensor

To detect the distance gap between the leading vehicle (LV) and the following vehicle (FV), the optoNCDT ILR 1191 (Figure 4.6) was used as a distance sensor. The optoNCDT ILR 1191 is a laser-based distance sensor for non contact, precise distance and speed measurement for industrial use. This sensor was chosen because of its ability to measure very large measuring ranges, from 0.5m up to 3000m with and without reflectors. Due to the very high measuring rate of the sensor, moving objects can be measured easily and precisely. The sensor operates according to the laser pulse runtime principle and is therefore particularly well suited to applications with large distances. The sensor is connected to the MCU using the hardware UART. The full specifications of the ILR 1191 Distance sensor are shown in Table 4.2.

Figure 4.6: OptoNCDT ILR 1191Laser Distance Sensor

Table 4.2: Full Specifications of ILR 1191 Distance Sensor

Model		ILR1191-300
Measuring Range	Black	1….150m
	Grey	0.5….200m
	White	0.5….300m
	Reflector	300…3000m
Speed		$0ms^{-1}…100ms^{-1}$
Linearity		±20mm (at measurement output 100Hz) ±60mm (at measurement output 2kHz)
Resolution		1mm
Repeatability		≤20mm
Response Time	Distance Measurement	0.5ms
	Speed Measurement	12ms
Laser Class	Measuring Laser	905 nm, laser class 1
	Sighting laser	635 nm laser class 2
Operation Temperature		-40ºC…+60ºC
Storage Temperature		-40ºC…+70ºC
Limit Outputs		QA / QB (max. 200mA)
Switching Points		Free adjustable
Switching hysteresis		Free adjustable
Trigger input		Trigger edge and trigger delay programmable, trigger pulse max 30V
Serial Interface		RS232 and RS422 with 1.2kBaud…460.8kBaud
		SSI interace (RS422), 24bit, Gray-encoder 50kHz…1MHz
Profibus		RS485,9.6kBaud…12MBaud
Operation mode		Single/continuous measurement, external triggering, speed measurement
Analogue output		4…20mA (16bit DA)
Temperature stability		≤50ppm/ºC
Supply		10…30V DC
Max. Consumption		<5W without heating, 11.5W with heating
Connection		1x12-pin M16, 2x5-pin M12 B-coded
Protection class		IP67
Material housing		Aluminium strangeness profile, powder-coated
Weight		800g
Vibration/shock		10g,6ms,1000 shocks /axis (DIN ISO 9022-3-31-01-1)
EMV		EN 61000-6-2, EN55011

4.2.3 Data Storage Device

Having a removable storage option is essential, especially when a lot of data storage is involved. Most microcontrollers have extremely limited built-in storage. For example, even the Arduino Mega chip (the Atmega2560) has a mere 4Kbytes of EEPROM storage. The system uses an SD card module as shown in Figure 4.7 for storing all important information such as the GPS location, vehicle information, gap distance etc. The Micro SD card is chosen as it has a high memory capacity and needs only a few I/O lines to interface with the microcontroller. Moreover, its defect and error management unit promises reliable data read/write. The SD card was connected to the MCU using an SPI hardware at 16MHz clock speed. Note that the storage capacity can be increased significantly by increasing the SD card memory.

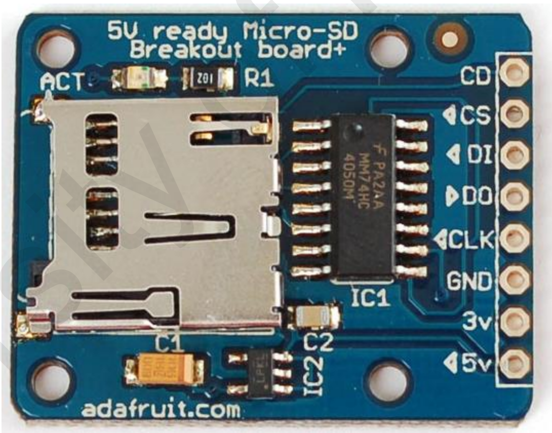


Figure 4.7: SD Card Module

Features:

- Onboard 5v->3v regulator provides 150mA for power-hungry cards
- 3v level shifting means you can use this with ease on either 3v or 5v systems
- Uses a proper level shifting chip, not resistors: less problems, and faster read/write access
- Uses 3 or 4 digital pins to read and write 2Gb+ of storage
- Activity LED lights up when the SD card is being read or written

4.2.4 Display Unit

The display unit provides real-time monitoring responses to the driver. The ACER Iconia W3 tablet, the first 8.1" tablet with Windows 8 was chosen as shown in Figure 4.8. This tablet possesses a touch screen interface which enables a driver to enter important parameters such as vehicle class and GVW. The tablet was connected to the MCU using the UART hardware. The details of the display unit GUI will be discussed in the next section (section 4.3).

Figure 4.8: ACER Iconia W3 Tablet

Table 4.3: ACER Iconia W3 Specifications

Design	
Device Type	Tablet
OS	Windows (8 Pro)
Dimension	8.58 x 5.31 x 0.39 inches (218 x 135 x 10mm)
Weight	17.6 oz (499 g)
Display	
Resolution	8.1 inches
Physical size	1280 x 800 pixels
Pixel density	186 ppi
Technology	LCD
Screen-to-body ratio	64.72 %
Colors	16 777 216
Touchscreen	Multi-touch
Hardware	
System chip	Intel Atom Z2760
Processor	Dual core, 1800 MHz, Saltwell
Graphics processor	Intel Graphics Media Accelerator 3650
System memory	2048 MB RAM
Built-in storage	64 GB
Storage expansion	microSD, microSDHC

4.2.5 Global Positioning Unit (GPS)

The SKM53 GPS module Starter Kit (SKGPS-53) shown in Figure 4.9 was used in this system to continuously track the vehicle's position and keeps record of accurate time. This GPS is a specially designed starter kit which offers a convenient yet safer GPS module for users. Power for SKGPS -53 is supplied from the 5V of UART pin. UART communication is provided for user interface this GPS to microcontroller. The SKM53 Series with an embedded GPS antenna enables high performance navigation in the most stringent applications and a solid fix even in harsh GPS visibility environments. It is based on the high performance features of the MediaTek 3329 single-chip composition. Its -165dBm tracking sensitivity extends positioning coverage into places like urban canyons and dense foliage environments where the GPS was not possible before.

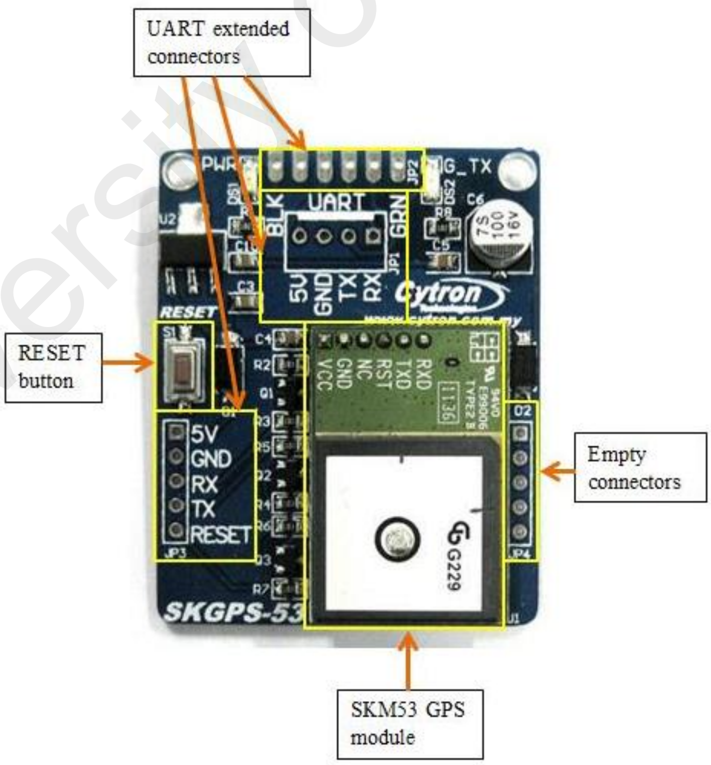


Figure 4.9: SKGPS-53 GPS Module

Basically, SKGPS-53 will send the data continuously either indoors or outdoors as long as it is powered up, but we can only read the correct data when the SKGPS-53 is exposed to the sky. Normally, we can check the two main data from the GPS module, i.e. the current date and time based on the Coordinated Universal Time (UTC) and our current position coordinates in terms of latitude and longitude.

SKGPS-53 Module Features:

- Ultra high sensitivity: -165dBm
- 22 tracking/66 acquisition-channel receiver
- WAAS/EGNOS/MSAS/GAGAN support
- NMEA protocols (default speed: 9600bps)
- Internal back-up battery
- One serial port
- Embedded patch antenna 18.2 x 18.2 x 4.0 mm

4.2.6 Bluetooth Module

This BlueBee wireless module shown in Figure 4.10 is a new product from Cytron Technologies. Utilizing the XBee form factor, BlueBee is compatible with XBee adapters such as the SKXBee (without module), the XBee breakout board and the Arduino-XBee shield. Though the form factor (pin out) is compatible with the XBee module, the BlueBee uses Bluetooth Technology. It is compact in size, the pinout is compatible with XBee which is suitable for all kinds of microcontroller systems that have a 3.3V power out, and the module utilizes the AT commands to set the baud rate and other parameters. The BlueBee module comes with an on-board antenna where the antenna provides a better signal. It acts like a transparent serial port, which works with a variety of Bluetooth adapters and Bluetooth phones. The BlueBee module's baudrate can be modified using the XBEE adapter.

Figure 4.10: BlueBee Bluetooth Module

Specifications:

- Bluetooth Chip: CSR BC04 Chipset
- Bluetooth Protocol: Bluetooth Specification v2.0 + EDR
- Operating Frequency: 2.4 ~ 2.48GHz unlicensed ISM band
- Modulation: GFSK (Gaussian Frequency Shift Keying)
- Transmit Power: ≤ 4dBm, Class 2
- Transmission Distance: 20 ~ 30m in free space
- Sensitivity: ≤-84dBm at 0.1% BER
- Transfer Rate: Asynchronous: 2.1Mbps (Max) / 160 kbps; Synchronous: 1Mbps/1Mbps
- Safety Features: Authentication and encryption
- Can be Configured as Master or Slave node. Default is slave mode.
- Support Profiles: Bluetooth serial port
- Serial Port Settings: 1200 ~ 1382400 / N / 8 / 1
- Baud Rate Default: 9600 bps(Serial Port Profile, transparent mode)
- Baud Rate Default: 38400 bps in AT mode.
- Pair Number/ID: 1234
- Input Voltage: +3.3 DC/50mA
- Operating Temperature: -20 ℃ ~ +55 ℃
- Module Size: 32 × 24 × 9mm

4.2.7 Real Time Clock (RTC)

A real-time clock (RTC) IC module is a small timekeeping device that opens all kinds of possibilities for real time projects. In this project, we used the RTC v0.9b DS1307 Real Time Clock Module for Arduino as shown in Figure 4.11. The module is based on the DS1307 high precision real time clock module. The module can also interface with the microcontroller through the I2C interface. It can read the year, month, day, week, time, minute and second. Table 4.4 shows the specifications for this RTC module.

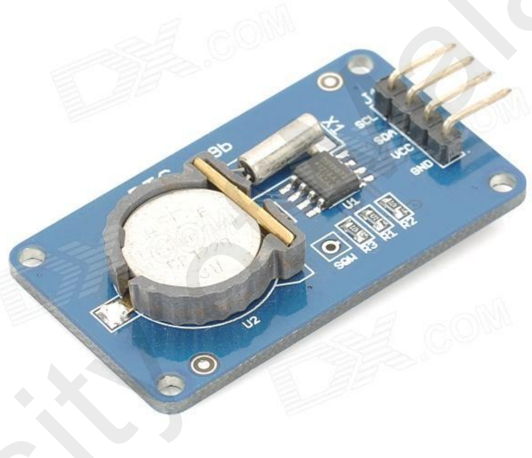


Figure 4.11: RTC Module

Table 4.4: RTC v0.9b DS1307 Real Time Clock Module Specifications

Power Voltage	4.5~5.5V
Battery voltage:	2.0~3.5V
High level input:	2.1~VCC + 0.3V
Low level input	-0.3~+0.8V
Control interface	4-pin (GND, VCC, SDA, SCL), GND for ground wire, VCC for power source, SDA for I2C interface data cable, SCL for I2C interface clock cable;
Real time IC	DS1307Z;
Independent timing:	Through I2C interface communicate with MCU
Battery	CR1220
Installed hole	4-M2 screw hole
Diameter hole	2.2mm

4.3 Prototype CAWS - Controller Driver

A software driver of an embedded system is important in order to have a real product and in enhancing the competitiveness of the embedded system development. The driver layer consists of low level program routines for accessing different hardware peripherals such as MicroSD card, sensors etc. The Arduino Mega can be programmed with the Arduino software. The program is designed in Adriano Sketch software using C language.

The main function of the program is to read the distance gap and speed from the sensors, the GPS coordinates from the GPS module, and the vehicle parameters such as GVW and vehicle class entered by the user using the GUI display. All these parameters will be processed to calculate the minimum safe distance gap based on the MSDG algorithm. If the gap distance is below the MSDG value, the program will activate the alarm system to warn the driver. Also, the calculated MSDG and others important parameters will be displayed in a display unit for real time monitoring, as well as to the MicroSD card for future analysis. The overall concept of the program is shown in a flowchart in Figure 4.12.

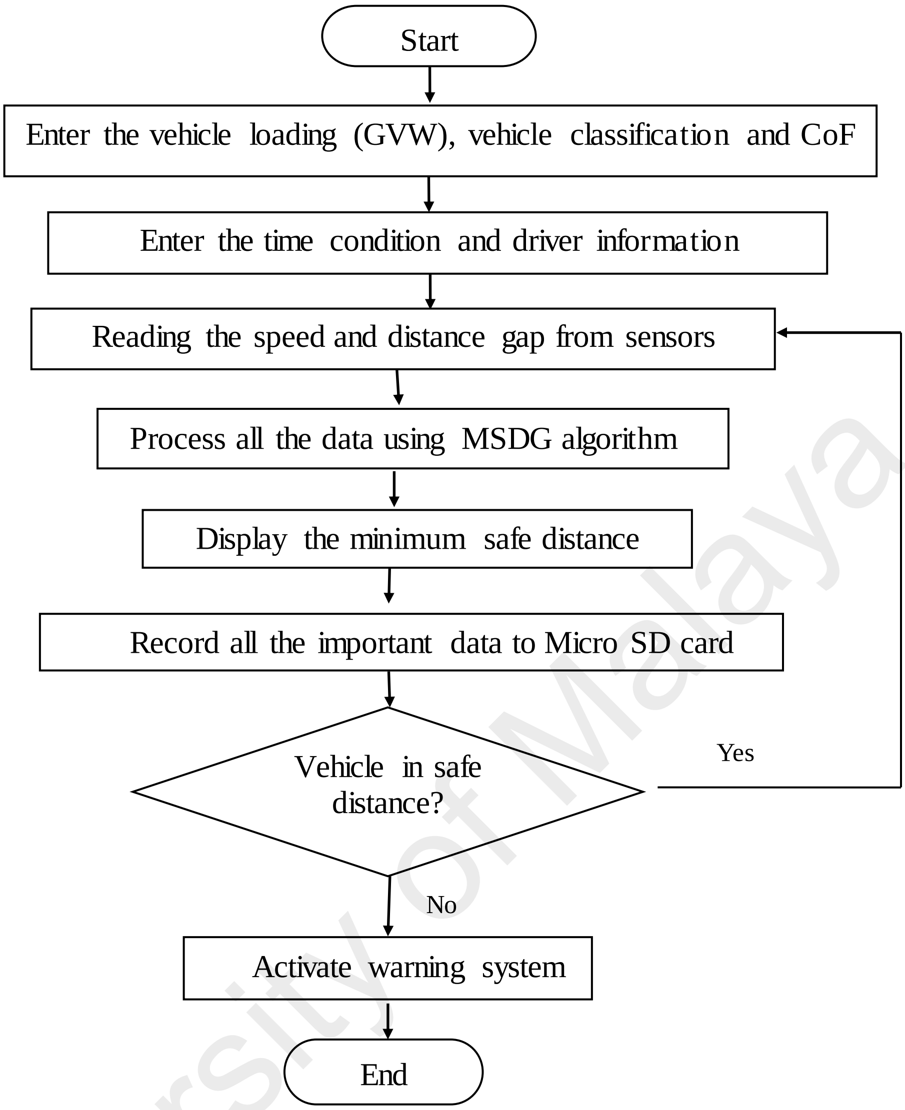


Figure 4.12: Flow Chart of the System Program

4.4 Prototype CAWS - Graphical User Interface (GUI) Software Development

The second part is to develop the software, which would provide a user-friendly interface for the user so that easy operations can be performed by the vehicle's driver. The visual graphical interface was carried out using the Visual Basic 2010 language. This GUI is the perfect companion for drivers as driving heavy vehicles can become increasingly complicated and technology reliant. There are three functions of this interface, with the first being to set different vehicle parameters such as the GVW and VC. In order to calculate the MSDG value, the driver needs to enter some parameters to the system by keying in the appropriate values. The second function is to display important information such as vehicle speed, gap distance and MSDG status. This function is very important to help the driver know the safe distance to follow the leading vehicle. The third function is to record all the important data such as speed, distance gap, GPS coordinates etc. in the Excel file format.

When designing the interface, the VB2010 form was divided to two main tabs. The first and second function are displayed in the first tab, which is the main page, while the third function is displayed in the second tab named as the data collection page. The GUI's main page is responsible for interfacing with the user and the process system. It takes user inputs and uses the input data from the sensor, and processes both data using the MSDG algorithm. The result will then display the MSDG value and status regardless whether the FV is in safe situation or not. The Data Collection page will display the important values into the table according to the predetermined time interval set in microcontroller. The overall sketch of the interface design for the main page tab and data collection tab is shown in Figure 4.13 and Figure 4.14. Appendix D2 shows the complete programming code for CAWS featuring the MSDG GUI interface.

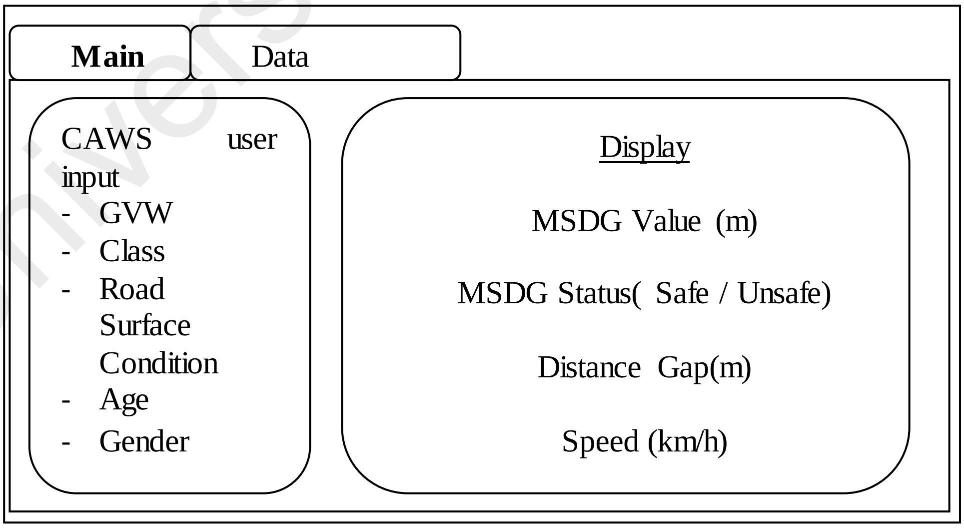


Figure 4.13: Overall Sketch Design of Main Page of CAWS GUI

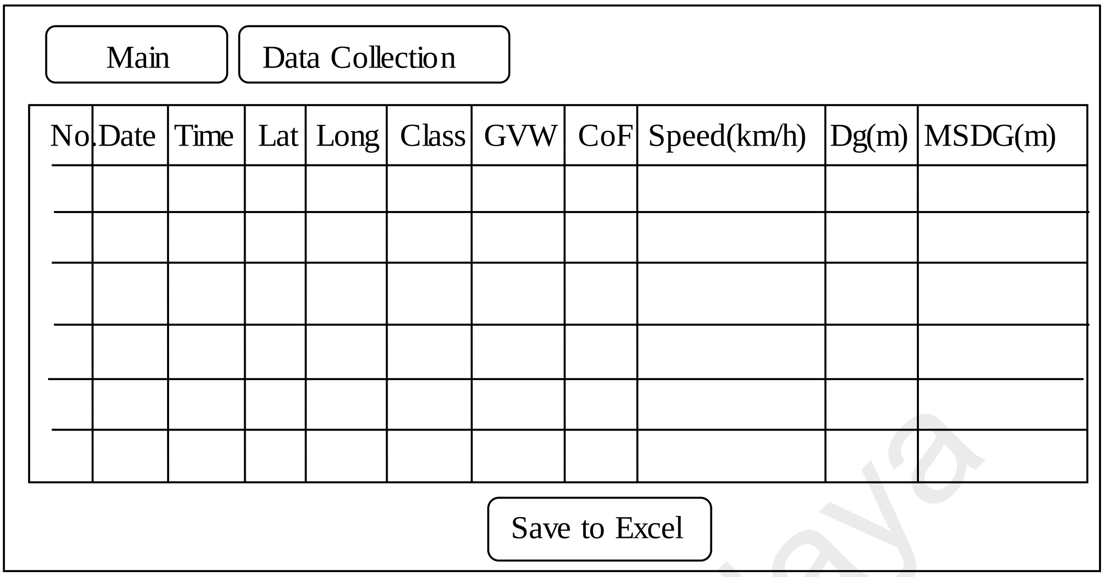


Figure 4.14: Overall Sketch Design of Data Collection Page of CAWS GUI

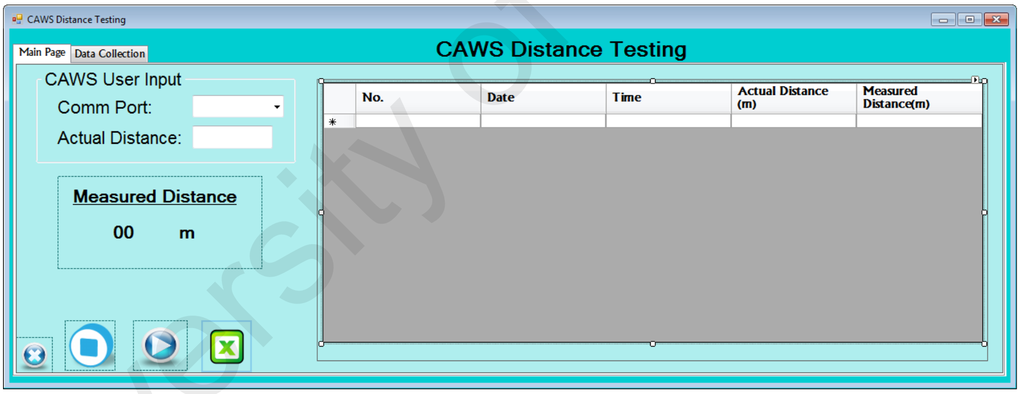
4.5 Prototype System Testing

In order to test the performance of the developed system, two tests were conducted, which are the accuracy test and the functionality test.

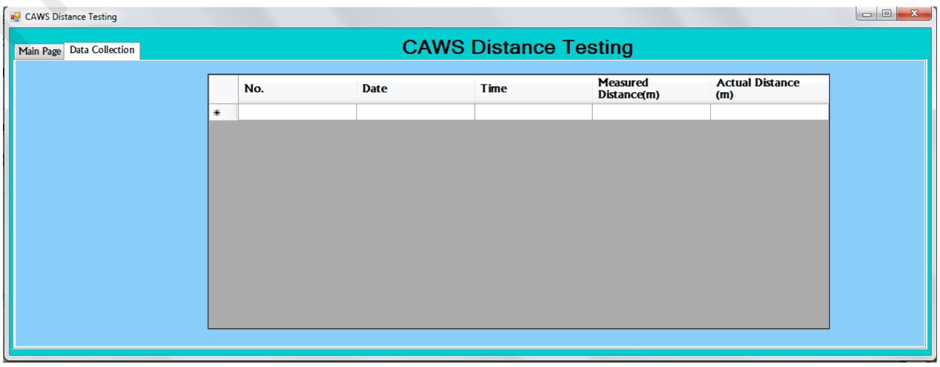
4.5.1 Accuracy Testing

The accuracy and repeatability of the distance gap measurement are essential aspects in the CAWS system. Tests were carried out to study the accuracy and repeatability of the laser distance sensor measurement in real situations. This test has been done in a still situation, where one leading vehicle had been parked in front of the lorry (in which the prototype system was installed) from the distance gap ranging from 2m to 25.8m as shown in Figure 4.15. The manual distance gap reading had been done using the Trumeter road measuring wheel. The distance gap measurement from the laser distance sensor has been collected and recorded 50 times for each distance gap using the developed GUI as shown in Figure 4.16.

Figure 4.15: Testing the Distance Sensor Accuracy



(a)



(b)

Figure 4.16: Software for Accuracy Test. (a) Main Page, (b) Data Collection Page

4.5.2 System Functionality Testing

After the installation of the sensors, the data logger and other instruments, the CAWS system was needed to do field testing to ensure that all the instruments and sensors are functioning and working well. By doing so, any faults or problems that may arise can be identified where troubleshooting can be done to solve the problems. Tests were also conducted for evaluating the functionality and performances of the system. The prototype system was installed in front of the three ton lorry as shown in Figure 4.17. The system was tested on dry road conditions along the 29km experimental routes as shown in Figure 4.18. The system performed well during real time experiments. The alarm system was activated to warn the driver when the distance gap is less than the MSDG value. All results have been recorded and saved to the personal computer through the developed software.

Figure 4.17: Snap Shot System Installation In Front of Lorry

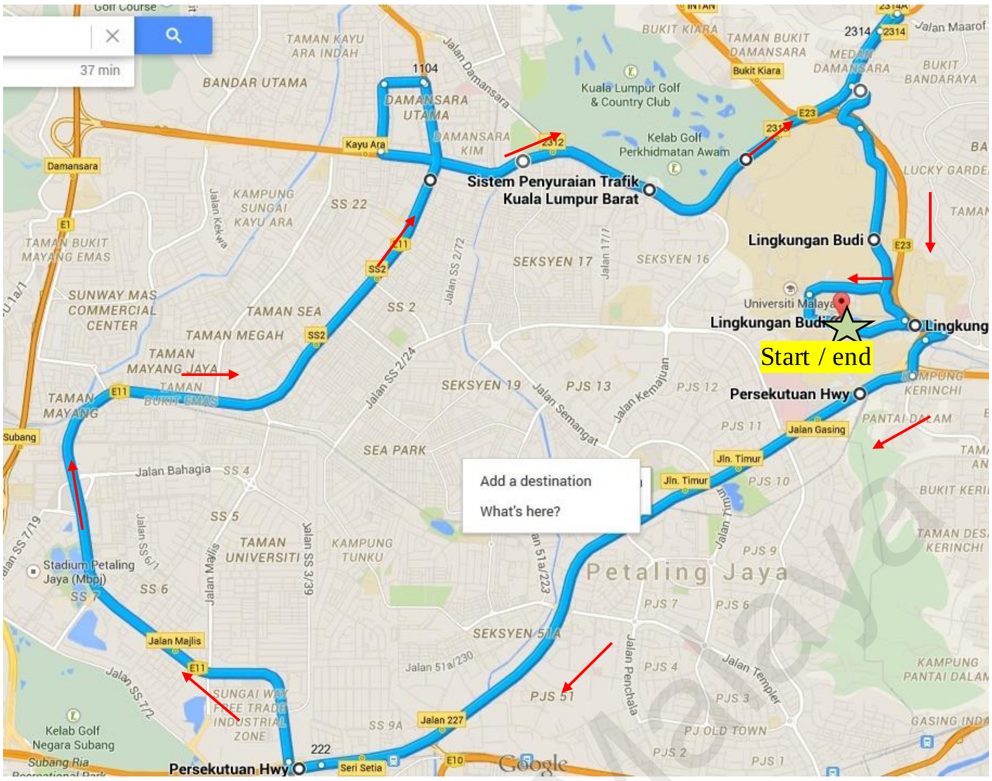


Figure 4.18: Experimental Routes for System Functionality Testing

CHAPTER 5 - RESULTS AND DISCUSSION

This research has been conducted accordingly to accomplish all the four objectives as stated in chapter 1. This chapter will explain the results obtained through the steps that have been undertaken as explained in chapter 3. In this research, data was generated through simulations as detailed in chapter 3. A total of 1059 data was generated throughout the simulations. The data was then grouped according to class, GVW, CoF and speed for the analysis of the effect of the parameter towards deceleration. This result is the first major contribution for this thesis.

By applying non-linear regression analysis to the simulation results, a mathematical expression of the deceleration model was established. The results show that the model is dynamically changed according to the GVW, VC, CoF and speed. From the deceleration model, a new mathematical model for the critical safe distance has been developed, known as MSDG. This MSDG model is the second major contribution of this dissertation.

The Graphical User Interface (GUI) calculator software was developed using the Visual Basic 2010. The software is user friendly and is able to calculate the MSDG based on the model that has been established. The design and development of CAWS using the adaptive minimum safe distance is presented and discussed in this chapter. The complete system is portable with real time monitoring and a state-of-the-art touch screen technology. The potentially unsafe following distance was calculated using a special algorithm which incorporates the vehicle braking capability, driver perception-reaction capability and road surface condition called the Minimum Safe Distance Gap (MSDG) algorithm. The display and warning system can guide the driver to keep an optimal and safe following distance. All the important data are logged into micro SD cards which can be transferred to the PC using a card reader, a USB interface or a

Bluetooth wireless link. The MSDG calculator software and the prototypes are the third and fourth major contribution of this dissertation.

5.1 Table Results

In this section, the data from the simulation is converted into a table using Microsoft Excel. Figure 5.1 shows an example of the results. There were a total of 1059 tables tabulated based on the simulation results. These full results tables can be referred to Appendix D of the report.

2 axle data with dece.sav [DataSet1] - SPSS Statistics Data Editor

File Edit View Data Transform Analyze Graphs Utilities Add-ons Window Help

1 : Class 2

	Class	GVW	Speed	CoF	BDm	Dec
1	2	5.6	11.11	.3	23.72	2.60
2	2	5.6	13.89	.3	36.50	2.64
3	2	5.6	16.67	.3	51.60	2.69
4	2	5.6	19.44	.3	69.10	2.74
5	2	5.6	22.22	.3	91.00	2.71
6	2	5.6	25.00	.3	114.30	2.73
7	2	5.6	27.78	.3	128.70	3.00
8	2	10.0	11.11	.3	28.63	2.16
9	2	10.0	13.89	.3	44.20	2.18
10	2	10.0	16.67	.3	63.30	2.19
11	2	10.0	19.44	.3	85.50	2.21
12	2	10.0	22.22	.3	111.00	2.22
13	2	10.0	25.00	.3	139.70	2.24
14	2	10.0	27.78	.3	156.20	2.47
15	2	15.0	11.11	.3	31.50	1.96
16	2	15.0	13.89	.3	48.50	1.99
17	2	15.0	16.67	.3	69.20	2.01
18	2	15.0	19.44	.3	93.40	2.02
19	2	15.0	22.22	.3	121.20	2.04
20	2	15.0	25.00	.3	152.70	2.05
21	2	15.0	27.78	.3	170.10	2.27
22	2	20.0	11.11	.3	34.20	1.80
23	2	20.0	13.89	.3	52.70	1.83
24	2	20.0	16.67	.3	75.10	1.85

Figure 5.1: Part of Two Axles SUT, CoF =0.3 Simulation Result

5.2 Effect of GVW, CoF, VC and Speed towards Heavy Vehicle Deceleration

As stated in Eq. 2.8, braking distance BD is inversely proportional to deceleration. Thus in this study, the data obtained was reviewed and analyzed to determine the correlation between deceleration and GVW, CoF, VC and speed.

5.2.1 Deceleration vs. GVW

The graphs plots in Figure 5.2 until Figure 5.8 clearly show the relationship between the deceleration of the two axle truck with the GVW and CoF. For the same speed and CoF, the GVW has a significant effect towards deceleration. Hence, we can conclude that the deceleration of the truck decreases as the GVW increases. This result also shows that two axle trucks with higher GVW will take a longer distance to stop at the same speed and CoF. Thus, in an emergency situation, the overloaded truck will not be able to stop in the same distance as a non-overloaded truck, no matter how hard the driver presses the pedal brake.

Furthermore, for the same speed and GVW, the CoF has a significant effect towards deceleration. As the CoF increases, the deceleration will increase. This is due to the road surface texture becoming rougher as the coefficient of friction increases. Thus, a rougher road surface will provide more grip power between the truck tires and the road surface, resulting in a reduced braking distance. This shows that under the wet road surface (with a lower coefficient of surface) the truck requires further braking distance before stopping.

The same simulation and data are done on three and four axle trucks and the result of the relationship was found to be the same as the two axle truck braking simulations. These results graph can be referred to Appendix E of the report.

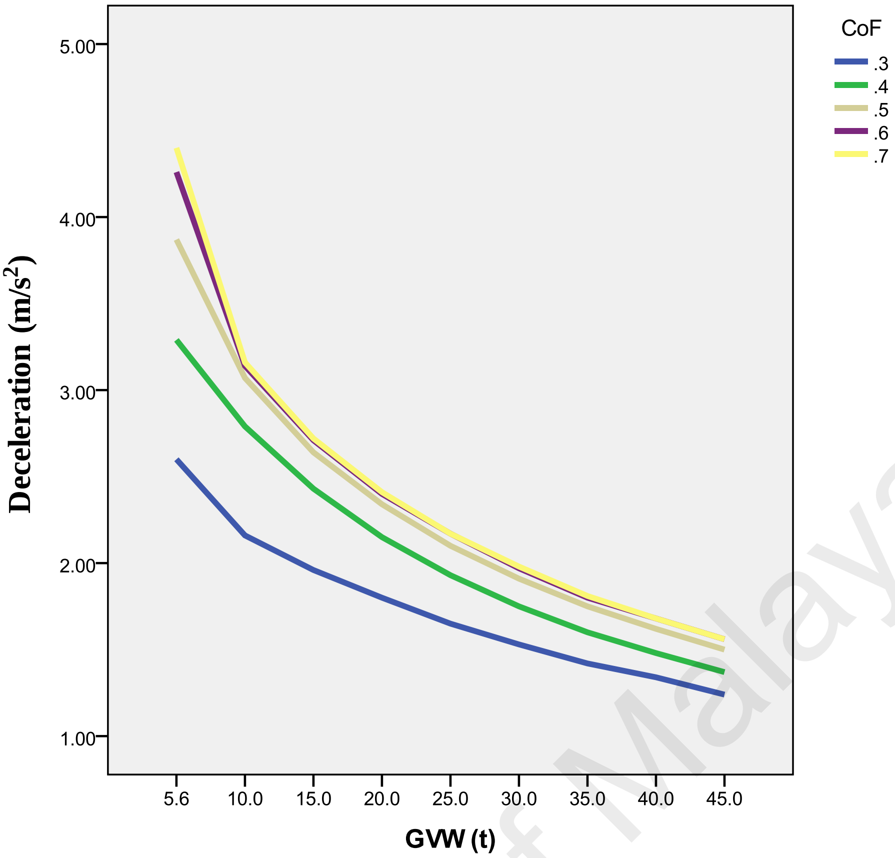


Figure 5.2: Two Axles, Deceleration vs. GVW for Speed = 11.11m/s (40km/h)

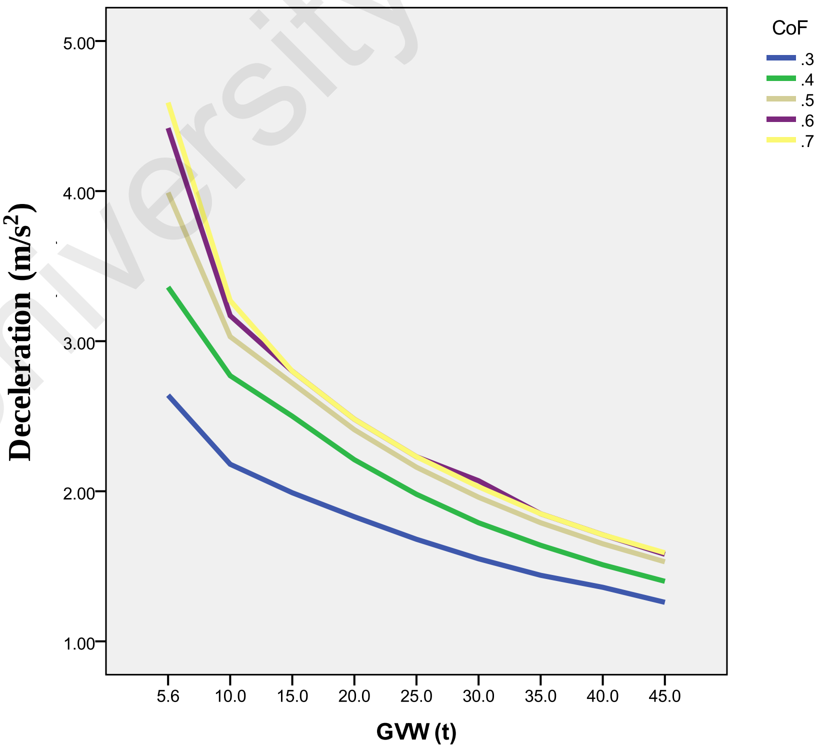


Figure 5.3: Two Axles, Deceleration vs. GVW for Speed = 13.89m/s (50km/h)

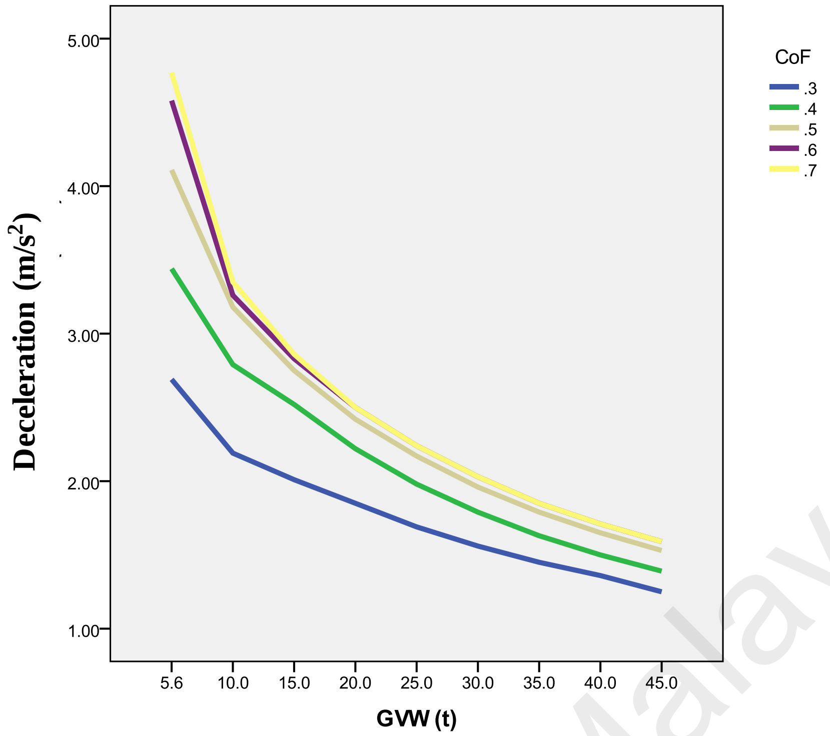


Figure 5.4: Two Axles, Deceleration vs. GVW for Speed = 16.67m/s (60km/h)

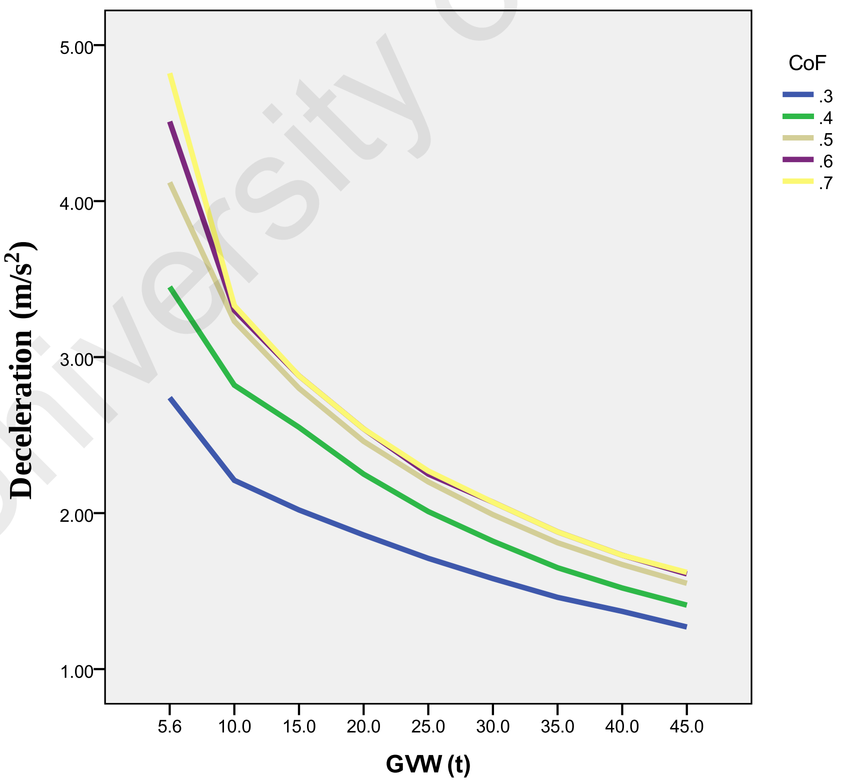


Figure 5.5: Two Axles, Deceleration vs. GVW for Speed = 19.44m/s (70km/h)

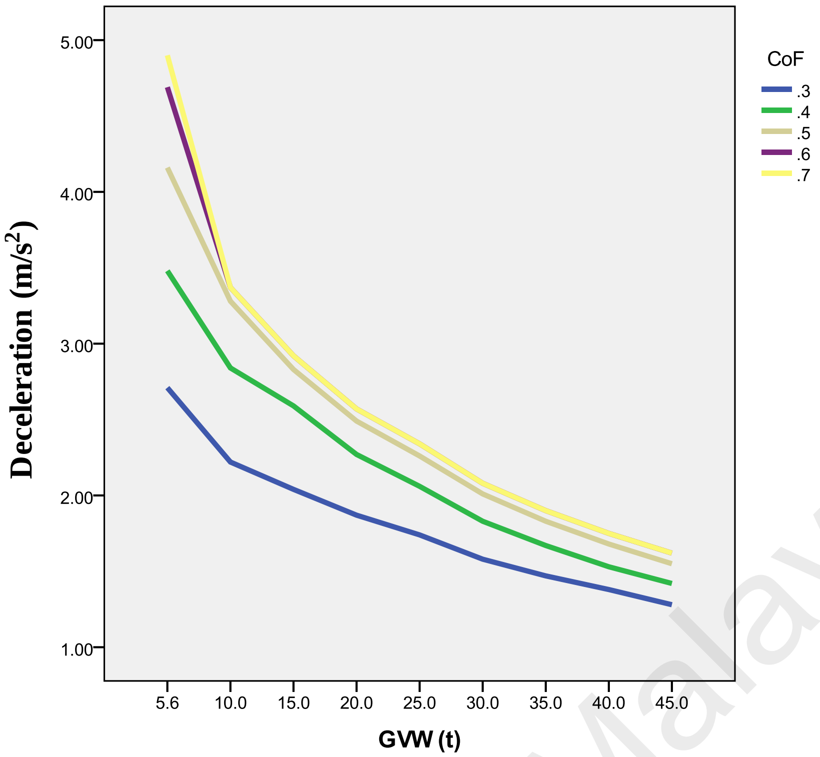


Figure 5.6: Two Axles, Deceleration vs. GVW for Speed = 22.22m/s (80km/h)

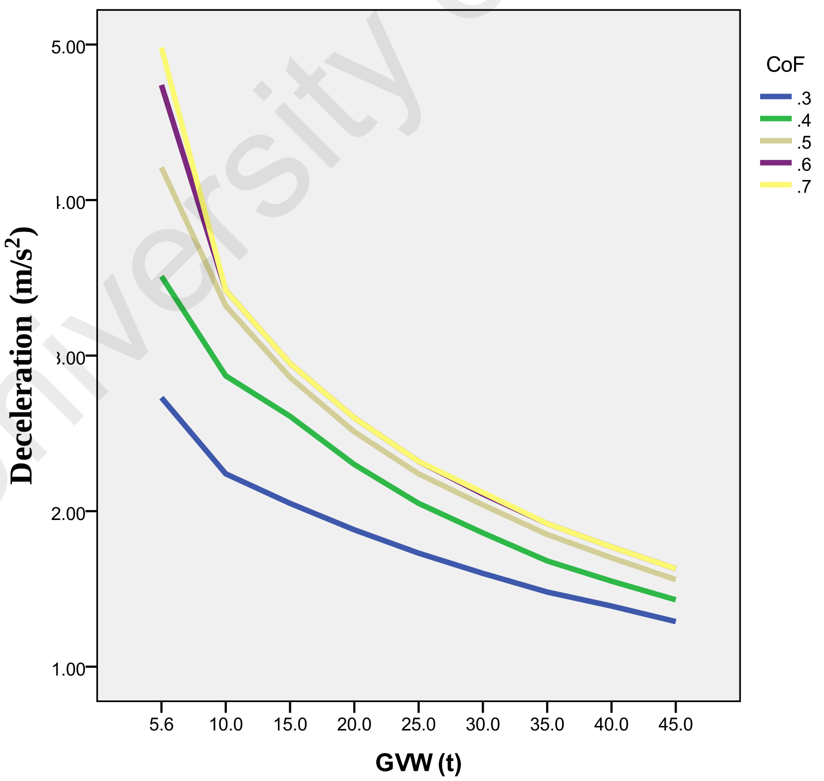


Figure 5.7: Two Axles, Deceleration vs. GVW for Speed = 25.00m/s (90km/h)

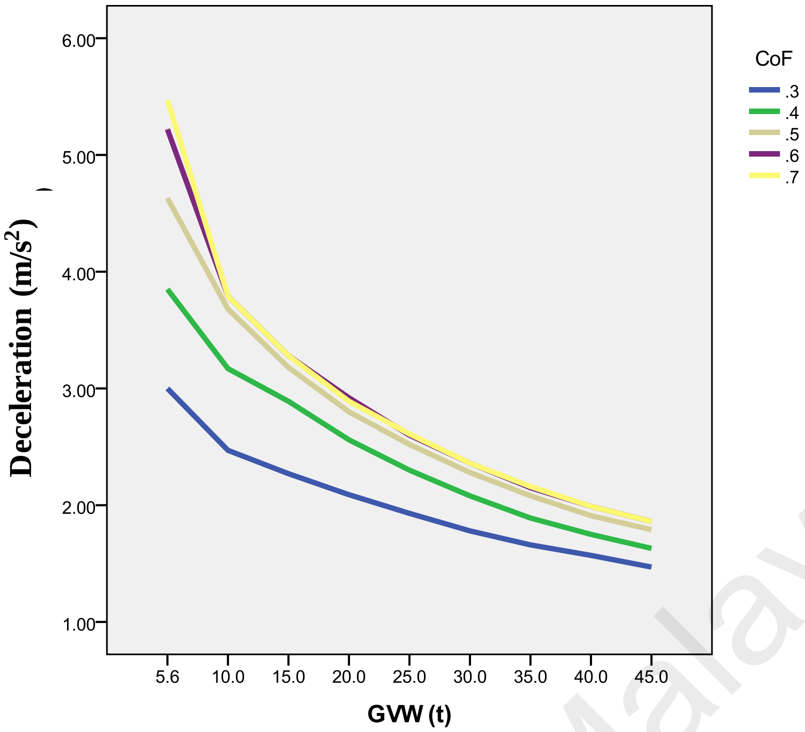


Figure 5.8: Two Axles, Deceleration vs. GVW for Speed = 27.78m/s (100km/h)

5.2.2 Deceleration vs. Class

The plots in Figure 5.9 until Figure 5.16 show the relationship between deceleration and vehicle class. From these figures, it can be clearly seen that for the same GVW, the deceleration time will increase with the increase in truck axle since the different vehicle classes have different dynamic capabilities. Due to the superior vehicle dynamics and braking performance characteristics, the heavy vehicles with higher number of axles will have a lower braking distance and vice-versa. For example, a two-axle truck overloaded with GVW of 35 tonnes travelling at a speed of 50 km/h will need around 20m to stop, while a three-axle truck with the same GVW and speed will only need around 18m to stop because of its superior vehicle dynamics and braking performance. It should also be mentioned that the simulation of the BD is based on the ideal condition of the truck and road surface. If the truck condition is less than ideal (for e.g. poor brake condition, bad tires etc) and the road surface is wet/slippery, the outcome of an emergency situation may be fatal.

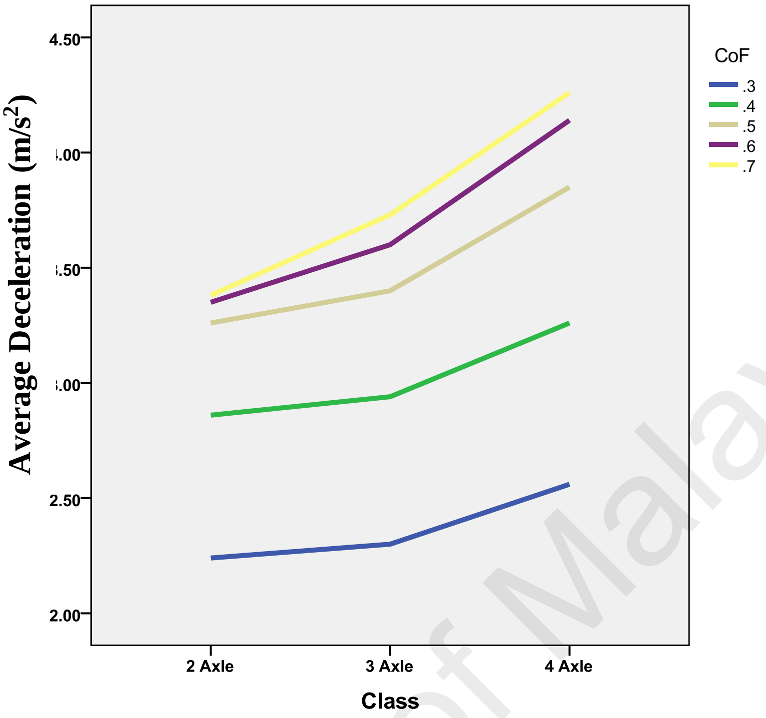


Figure 5.9: Deceleration vs. VC for GVW = 10t

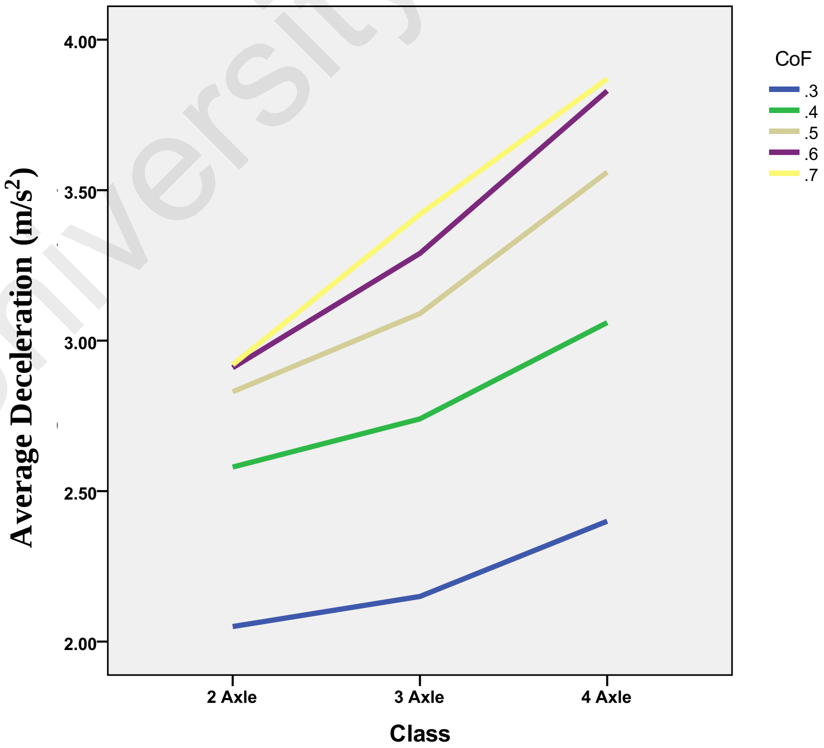


Figure 5.10: Deceleration vs. VC for GVW = 15t

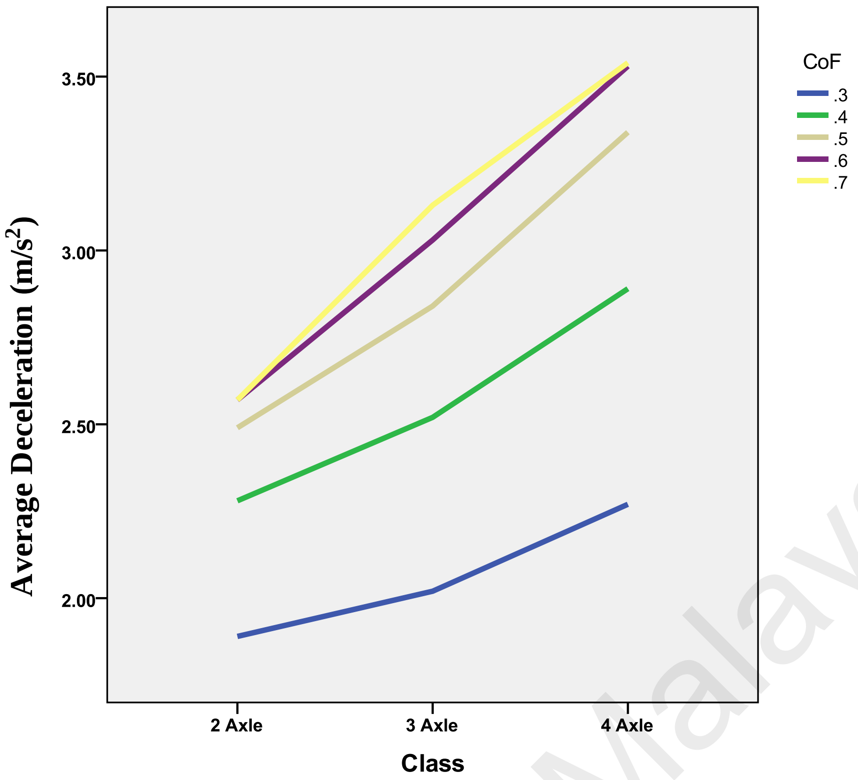


Figure 5.11: Deceleration vs. VC for GVW = 20t

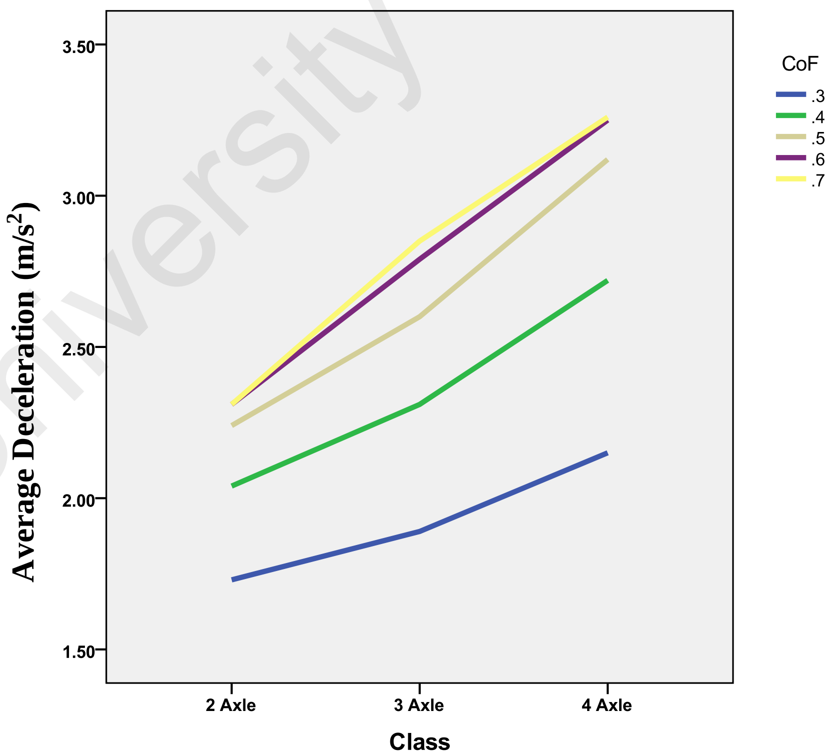


Figure 5.12: Deceleration vs. VC for GVW = 25t

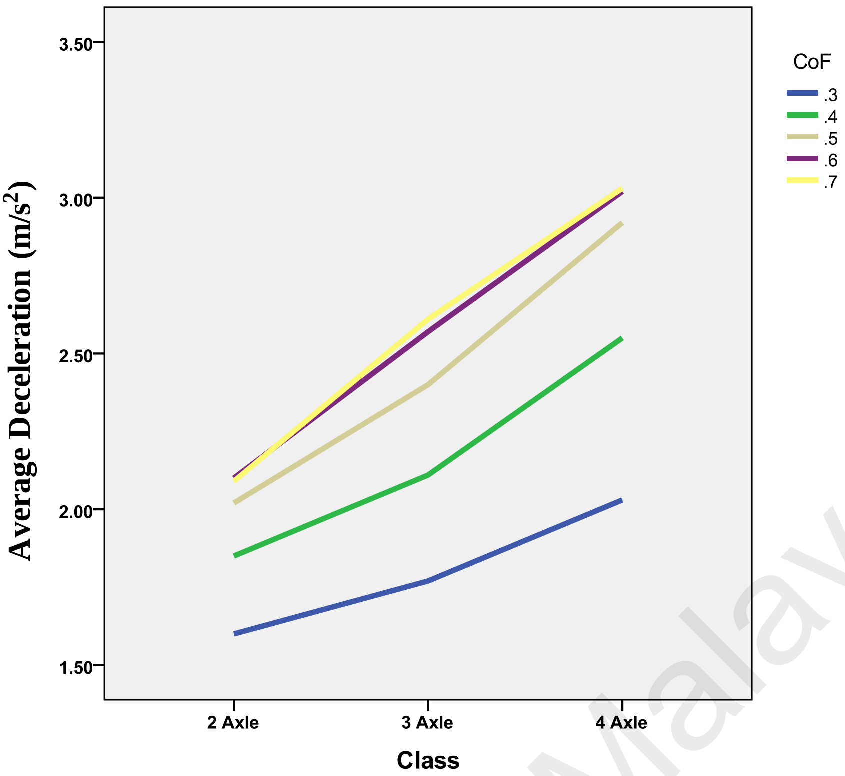


Figure 5.13: Deceleration vs. VC for GVW = 30t

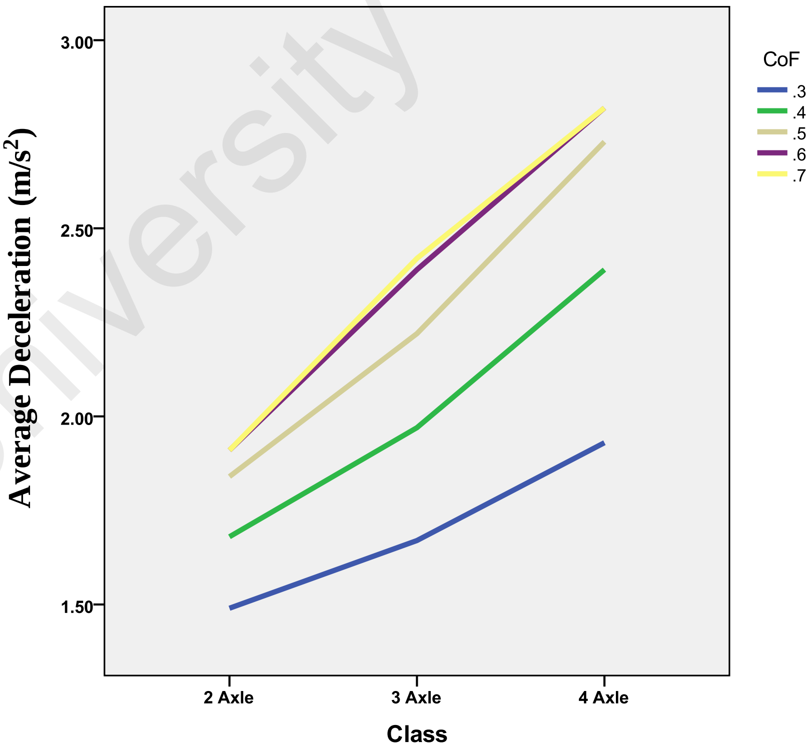


Figure 5.14: Deceleration vs. VC for GVW = 35t

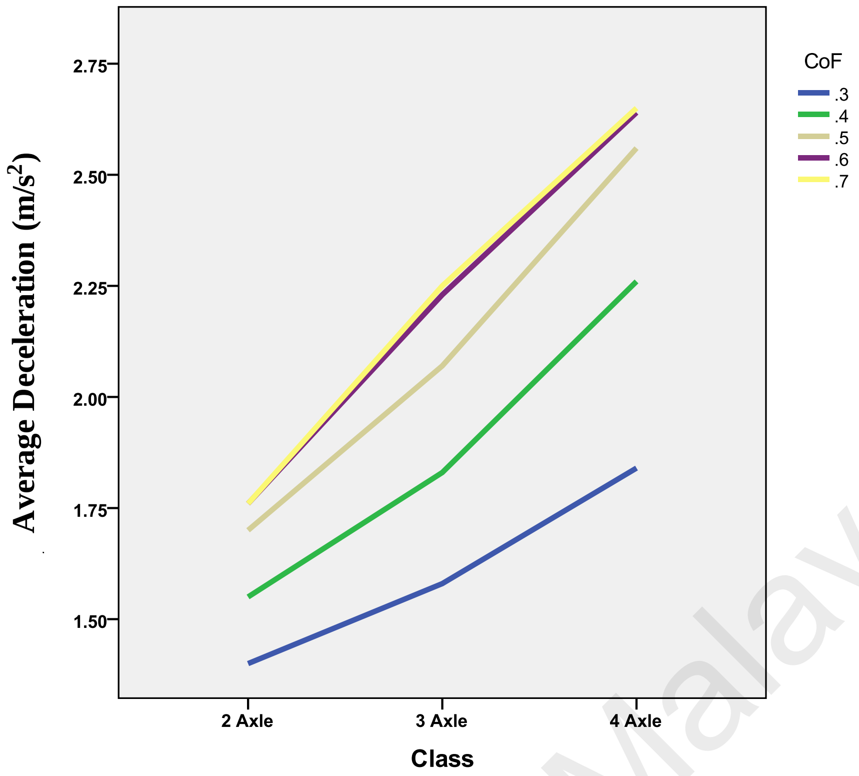


Figure 5.15: Deceleration vs. VC for GVW = 40t

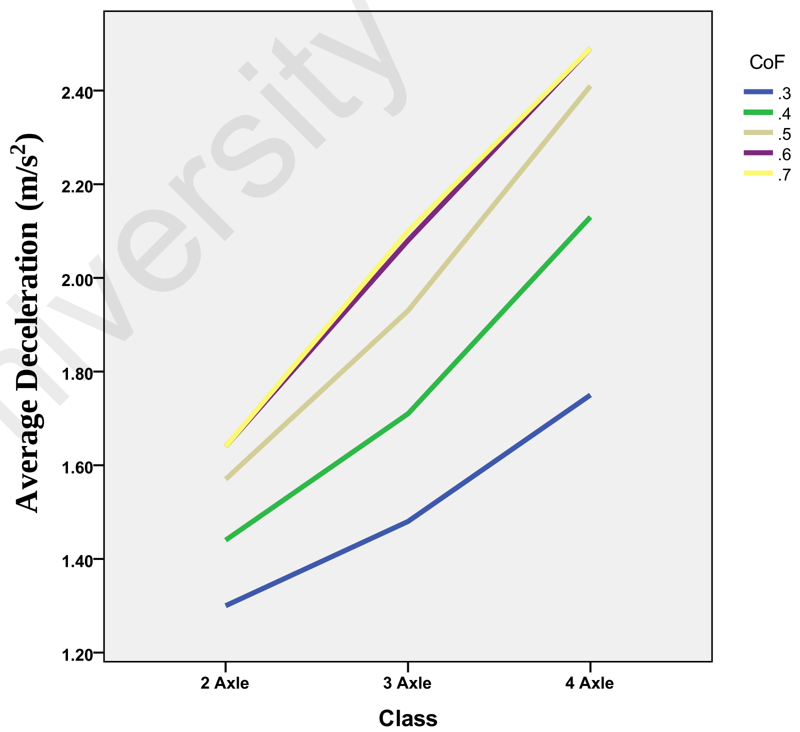


Figure 5.16: Deceleration vs. VC for GVW = 45t

5.3 Deceleration Model

Based on the deceleration vs GVW graph plots in the last section, a deceleration model for each class of heavy vehicle is proposed. The graph shows that the heavy vehicle deceleration is logarithmically proportional to GVW, while the deceleration is exponentially proportional to CoF. Based on this, the proposed deceleration model can be expressed as follows:

$$a_t = p + q\log(w) \qquad \text{Eq. (5.1)}$$

where $p = C_1 + C_2 / \mu$

$q = C_3 + C_4 / \mu$

where a_t is deceleration for truck in ms^{-2}, w is GVW and μ is CoF.

In this research, statistical regression analysis has been used to develop a model. Regression analysis is a form of predictive modelling technique which investigates the relationship between a dependent (target) and independent variable (s) (predictor). Regression analysis indicates the significant relationships between dependent variable and independent variable.

The first regression was carried out to determine the coefficients of the regression lines, p and q in Equation (5.1). The value of these coefficients and coefficients of determination, R^2 for all cases are described in Table 5.1.

Table 5.1: Regression Coefficients with p-Value of Coefficient *p* and *q*

Class	CoF	*p* (constant)	p-value (*p*)	*q*	p-value (q)	R^2	N
2	0.3	3.834	.000	-.660	.000	.995	9
2	0.4	5.162	.000	-.974	.000	.998	9
2	0.5	6.141	.000	-1.210	.000	.996	9
2	0.6	6.709	.000	-1.358	.000	.978	9
2	0.7	6.991	.000	-1.441	.000	.967	9
3	0.3	3.627	.000	-.551	.000	.992	9
3	0.4	4.931	.000	-.831	.000	.991	9
3	0.5	5.864	.000	-1.025	.000	.996	9
3	0.6	6.280	.000	-1.097	.000	.992	9
3	0.7	6.540	.000	-1.159	.000	.994	9
4	0.3	3.818	.000	-.531	.000	.992	9
4	0.4	4.984	.000	-.726	.000	.985	9
4	0.5	6.057	.000	-.935	.000	.991	9
4	0.6	6.818	.000	-1.123	.000	.995	9
4	0.7	7.169	.000	-1.223	.000	.998	9

The p-values for both coefficients that are both lower than 0.05 indicates that the coefficient of *p* and *q* are statistically significant. The high R^2 indicates that the regressions are approximately the real data point.

From this table, another regression was done to determine the coefficients of the regression lines, C_i (i =1, 2, 3, 4 as in Equation 5.1). The result from this second regression is described as shown in Table 5.2.

Table 5.2: Regression Coefficients with p-Value and R^2 for C_i

Class	C1	p-v (C1)	C2	p-v (C2)	C3	p-v (C3)	C4	p-v (C4)	R^2 (p)	R^2 (q)	N (a)	N (b)
2	9.479	0.000	-1.698	0.000	-2.041	0.000	0.417	0.000	0.998	0.998	5	5
3	8.869	0.000	-1.565	0.000	-1.642	0.000	0.324	0.000	0.995	0.994	5	5
4	9.719	0.000	-1.807	0.000	-1.713	0.000	0.369	0.002	0.990	0.969	5	5

The p-values for all C_i coefficients that are lower than 0.05 indicate that the coefficient of C_1, C_2, C_3 and C_4 are statistically significant. A high R^2 indicates that the regression is approximating the real data point. By replacing all the *Ci* coefficients in Eq. 5.1 with the values as in Table 5.2, the respective values of deceleration can be determined as shown in Table 5.3.

Table 5.3: Proposed Model for Deceleration

Vehicle Type	Deceleration Model (a)
2 Axle	$9.479 - 1.698/u - 2.041\log(w) + [0.417/u]\log(w)$
3 Axle	$8.869 - 1.565/u - 1.642\log(w) + [0.324/u]\log(w)$
4 Axle	$9.719 - 1.807/u - 1.713\log(w) + [0.369/u]\log(w)$

As stated in chapter 3, for maximum safety, the leading vehicle (LV) is fixed to sedan car with GVW is 2 tonne. Using Equation 3.6 and proposed deceleration model form Table 5.3, the respective values of MSDG can be determined for the different composition of the follower-leader pair as shown in Table 5.4.

Table 5.4: Proposed Model for Minimum Safe Distance Gap (MSDG)

2 axle
$\left[\frac{U_{FV}^2}{18.958 - \frac{3.396}{u} - 4.081 log(w) + [0.834/u]\ log(w)}\right] - \left[\frac{U_{LV}^2}{18.836 - \frac{3.145}{u}}\right] + 0.025V * Age + 0.401V * Gender$
3 axle
$\left[\frac{U_{FV}^2}{17.738 - \frac{3.130}{u} - 3.284 log(w) + [0.648/u]\ log(w)}\right] - \left[\frac{U_{LV}^2}{17.244 - \frac{3.033}{u}}\right] + 0.025V * Age + 0.401V * Gender$
4 axle
$\left[\frac{U_{FV}^2}{19.438 - \frac{3.614}{u} - 3.426 log(w) + [0.738/u]\ log(w)}\right] - \left[\frac{U_{LV}^2}{18.407 - \frac{3.392}{u}}\right] + 0.025V * Age + 0.401V * Gender$

The MSDG varies for the different combinations of type, GVW and travel speed of the following vehicle. In general, it is worth noting that for a particular following vehicle type, say the 4-axle following vehicle, when travelling at a particular speed, say 80 km/h, the following vehicle braking distance (BD_{FV}) will increase as the GVW increases. This means that as the GVW of the following vehicle increases, it needs a longer distance to stop safely after the brakes are applied. Consequently, the MSDG also increases as the GVW increases, implying that for a truck following a car, the minimum safe distance gap will be longer than usual if the following vehicle is carrying a higher payload than usual. The truck driver would need to understand this in order to avoid a forward collision accident in emergency situations.

5.4 MSDG GUI Calculator Software

This software has 2 parts; the user input parameter and the MSDG calculation results, as shown in Figure 5.17. Firstly, the user needs to enter the vehicle parameters, road surface condition and driver information. Once the “calculate MSDG” button is pressed, the software will calculate the MSDG value and shows it in the MSDG box.

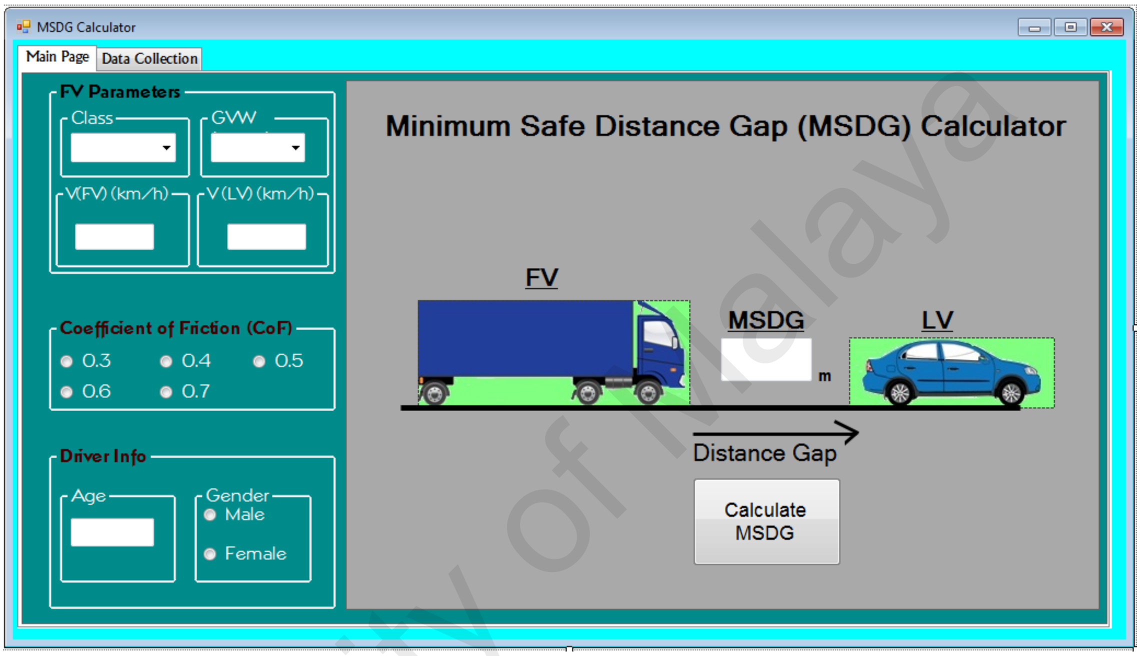


Figure 5.17: MSDG Calculator Software

5.5 Prototype CAWS featuring MSDG algorithm

5.5.1 Overall Concept of the System

Figure 5.18 is a schematic block diagram showing the collision avoidance warning system using the MSDG algorithm. This system comprises of a control unit as a main component, including a microcontroller with an I/O interface, and various drives and detecting circuits. The control unit receives various measured signals detected by a distance sensor, a vehicle speed sensor and also the input entered by the driver from the vehicle dynamics' parameter input means. From all this input, the controller will process the data using the MSDG algorithm to obtain the minimum safe gap distance.

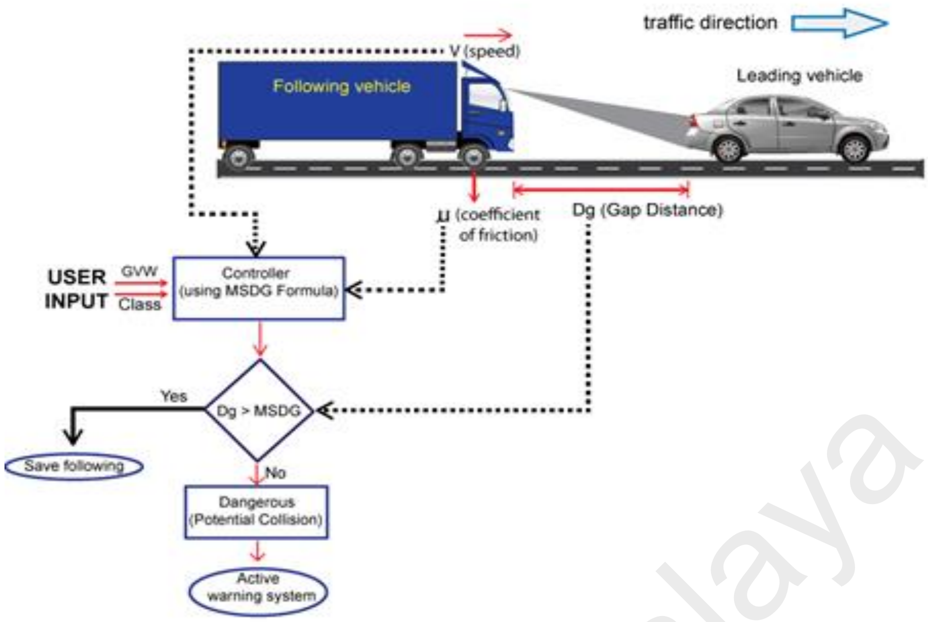


Figure 5.18: CAWS System Block Diagram

5.5.2 Complete System

Figure 5.19 shows the schematic of the CAWS system, which is a combination of a microcontroller, distance sensor, GPS, SD Card, RTC and Bluetooth module. The complete prototype CAWS system featuring the MSDG algorithm was successfully developed as shown in Figure 5.20. The size of the controller was small enough to be placed in a small space by using a battery or car cigarette to operate.

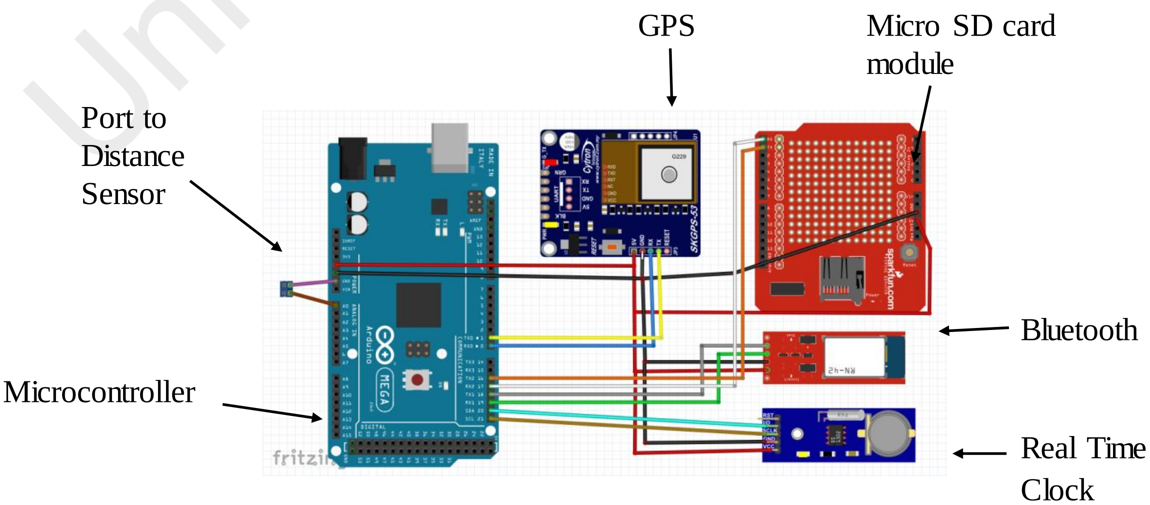


Figure 5.19: CAWS Data Logger Circuits

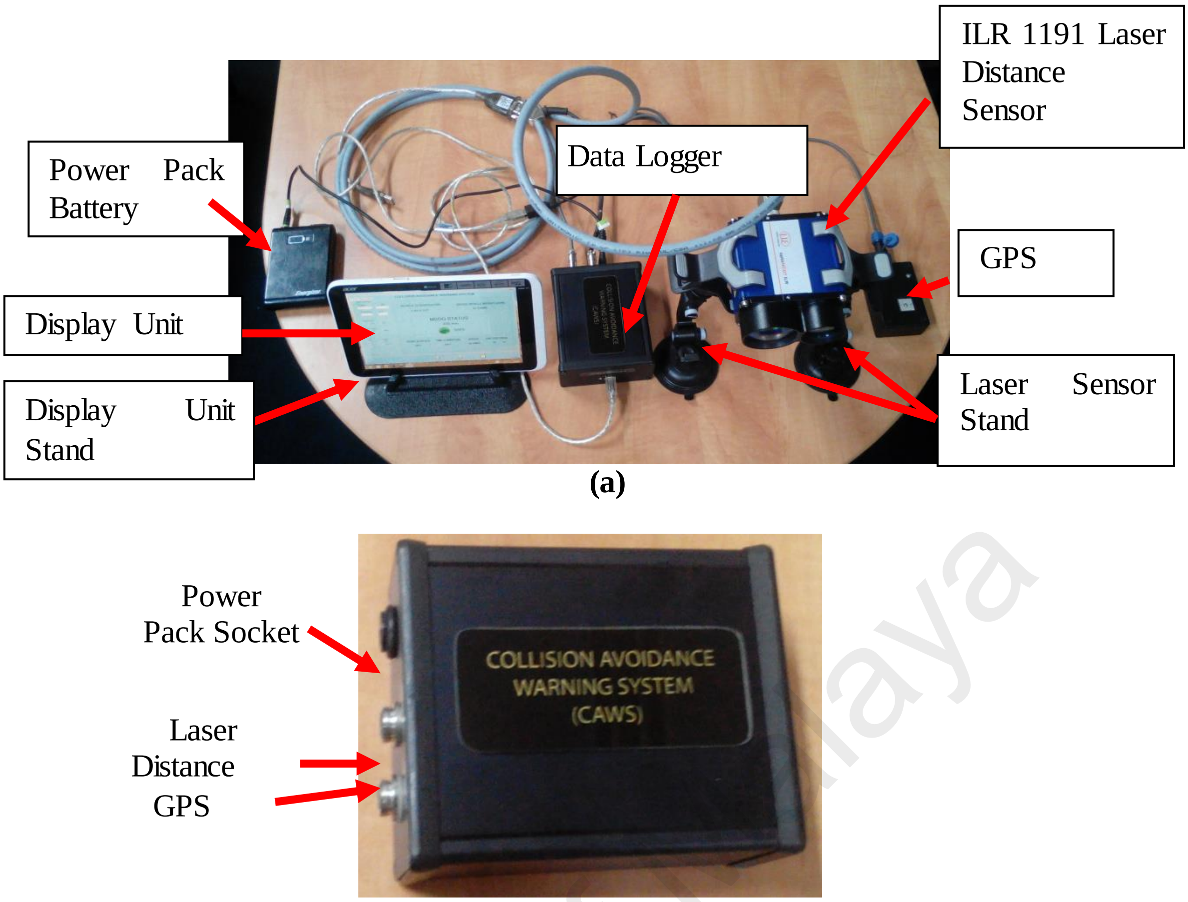


Figure 5.20: Final Prototype System (a) Complete System (b) Data Logger

Figure 5.21 shows the system installation in a lorry for test purposes. The distance sensor was mounted on the windscreen and connected to the logger via a wire or Bluetooth. The GPS and display tablet were mounted on the dashboard towards driver.

Figure 5.21: System Installed in 3 Ton Lorries

5.6 System Testing

5.6.1 Distance Accuracy Testing

Figure 5.22 shows the reading from the laser distance for the difference in the distance gap. An analysis was done to study the accuracy of the sensor as shown in Table 5.4. Based on Table 5.5, it can be found that the ILR laser distance performed well with the total mean error rate from its reference value 2.66%.

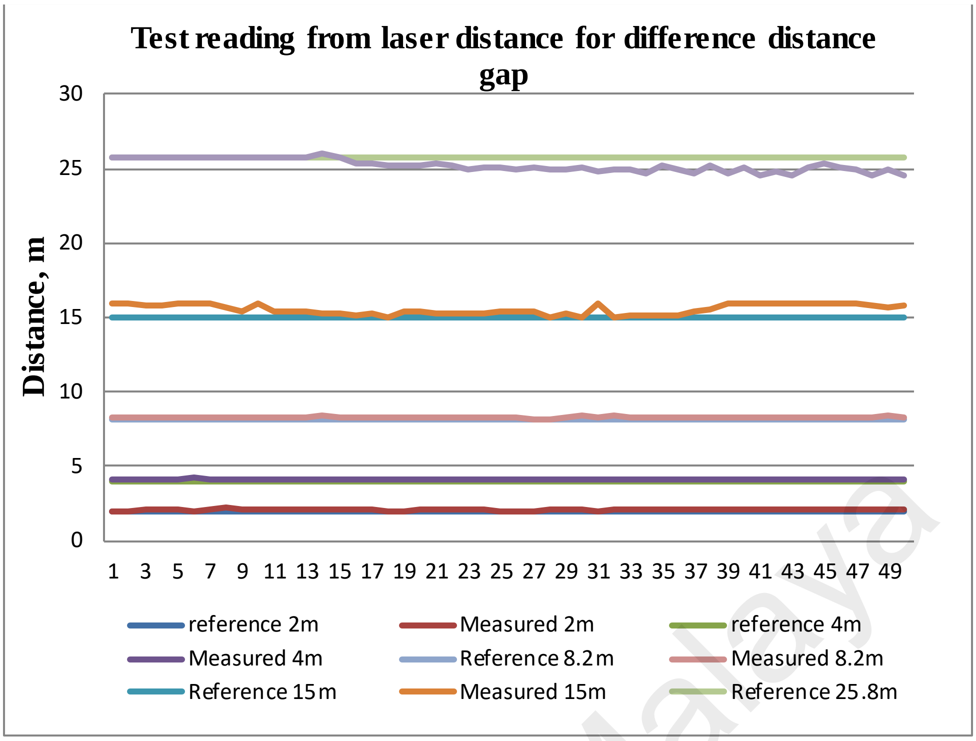


Figure 5.22: Distance Gap Measurement Using Manual and Laser Sensor

Table 5.5: Distance Gap Analysis

No.	Actual Distance (m)	Measured Distance Mean (m)	Std. Deviation	Variance	Mean Error (m)	Mean Error Rate(%)	N
1	2	2.063	0.046	0.002	0.0635	3.175	50
2	4	4.128	0.018	0.00036	0.1288	3.220	50
3	8.2	8.293	0.037	0.001	0.0937	1.143	50
4	15	15.536	0.337	0.114	0.5361	3.574	50
5	25.8	25.231	0.417	0.174	0.5688	2.205	50
Average			0.1716		0.2782	2.663	

5.6.2 System Functionality Testing

System functionality was carried out to test the functioning of the complete system as described in the methodology section. Data was recorded every half a second. The results were satisfactory and the software did not crash during the traveling experiments. All the results were recorded and saved to the personal computer through a developed GUI. The graph in Figure 5.39 shows the Dg and MSDG recorded during the real time experiments.

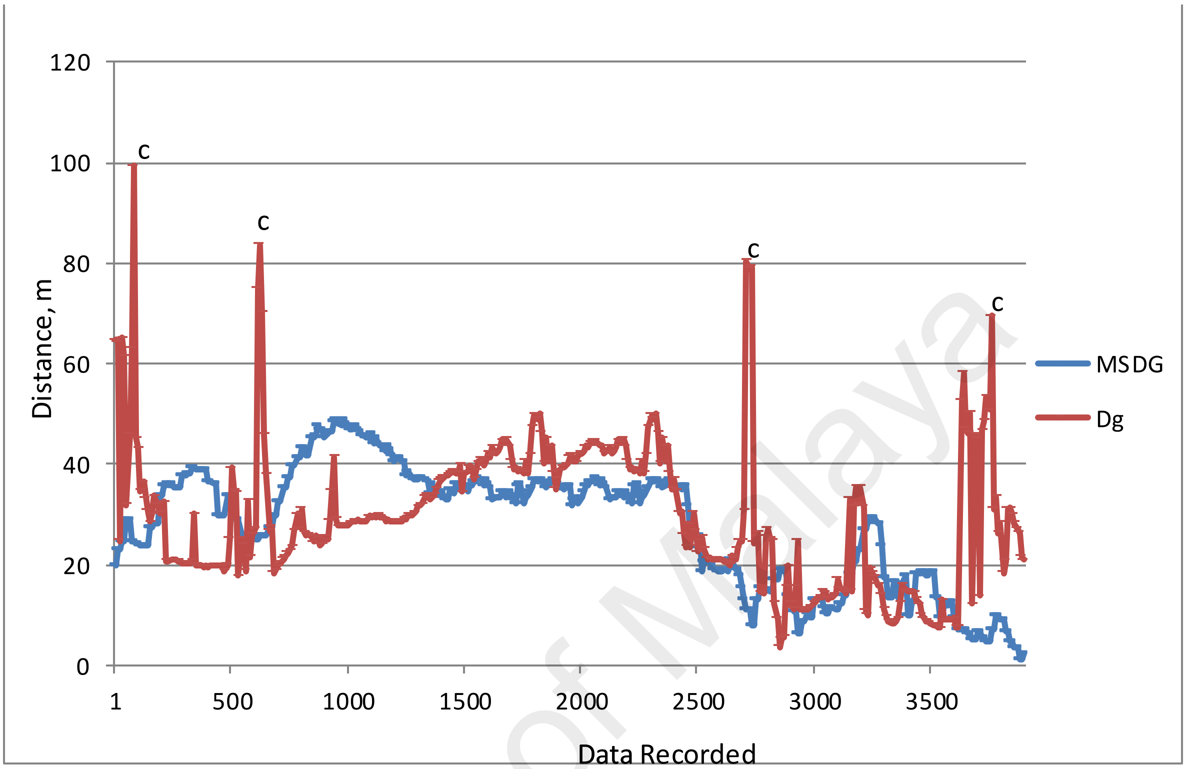


Figure 5.23: System Functionality Test

This system was designed for forward collision avoidance. This means it is designed for following vehicles on straight road conditions at medium to high speed. At this condition, the system performed as expected and was capable in detecting the unsafe conditions. However, when travelling at corner roads at certain angles, the sensor could not detect the leading vehicle and produce the incorrect reading for distance gap measurement as shown in Figure 5.23 (labeled with c).

CHAPTER 6 - CONCLUSION

This chapter presents a summary of the study, draw a number of conclusions based on the outcomes of this research, as well as highlighting a few recommendations for future research.

6.1 Conclusion

This research was carried out to study the four main objectives; to study the impact of GVW, CoF, VC and speed towards the heavy vehicle's deceleration and braking distance, to develop a new CAWS algorithm in the form of MSDG, to develop GUI MSDG calculator software and lastly, to develop a prototype CAWS featuring this new algorithm. It has been established that a vehicle's braking performance is of utmost importance in relation to the vehicle's deceleration and braking distance. Hence, it has to be incorporated into the safety indicator.

This research studies the effect of the GVW, CoF, speed and VC towards a deceleration and braking distance of a heavy vehicle using a multi-body dynamics simulation software. The deceleration data was generated using multi-body dynamics simulation software to analyze the influence of GVW, VC, CoF and speed on the deceleration. After analysis of the simulation results, the results show that speed is not the only important factor that affects the deceleration. GVW, CoF and VC also give significant effects on the deceleration of the heavy vehicles. The results also suggest that GVW, CoF, speed and VC are four important vehicle factors that are crucial for consideration in a CAWS algorithm. Drivers of heavy vehicles must be aware of their vehicles' braking capability. This is because heavy vehicles have considerably poorer braking capability than passenger cars, and take a minimum 60% more distance during emergency stops on dry roads. This would increase the possibility of higher rear-end-collision for heavy vehicles compared to other road vehicles.

This study could bring an impact to the efforts of improving the collision avoidance system. From the results, the new algorithm for CAWS has been proposed, which is the MSDG. The proposed MSDG algorithm in this study may overcome the limitations of the traditional/conventional analytical methods, in which the present method simplified the complexity of heavy vehicle's deceleration. Based on this algorithm, the GUI software to calculate the MSDG of the heavy vehicle has been developed. This calculator provided driver a way on the prediction of the safe distance that changes regarding with the change of speed, GVW, CoF, VC and PRD. Therefore, a more suitable and safer distance can be chosen in order to reduce the number of accidents.

The prototype of CAWS featuring the MSDG algorithm has been developed to test the overall functionality of the system. This microcontroller–based system used an advance laser distance sensor and other electronic components that were able to measure the current distance gap, calculate the MSDG value and display the current distance gap and MSDG value to the driver using a tablet device. This system is also equipped with a data storage system which can record all the important data and retrieve them back when necessary. Even though there are a number of limitations regarding this prototype, generally the results from this study should provide vital knowledge for researchers and engineers. This is for them to understand further on the parameters' effects on the CAWS algorithm, especially for heavy vehicles.

6.2 Novelty of the Research

- It was previously established that vehicle speed has a significant impact towards braking distance of heavy vehicle. However, other factors of the dynamics of heavy vehicle had not been studied. Our study has shown and proof that the GVW, VC and CoF has significant effect towards heavy vehicle's braking distance.

- Previous CAWS has used algorithm which mainly based on the speed as the parameter. There is no detailed studies that relates CAWS algorithm as a function of vehicle dynamics (GVW, VC), road surface condition (CoF) and driver info (age, gender). This research provides a CAWS algorithm as a function of all above mention parameters. This algorithm named as Minimum Safe Distance Gap which is also known as MSDG.

6.3. Potential Application of the Research

Road accidents are perceived to be a major highway or road safety problem, with serious consequences for the drivers, companies and the traveling public. When accidents occur, the mobility of the road user is impeded and causing significant delay. Road accidents are complex events, often resulting from multiple contributing factors. Road accidents statistics consistently have shown that driver error i.e. mistakes and misbehavior are the principal contributing factor to traffic crashes. The most common critical errors made by drivers, whether they are heavy vehicle drivers or passenger vehicle drivers, appear to be following too closely or distance gap misjudgments, and over confidence in their ability to stop the vehicle before collision. The consciousness of the critical minimum safe distance gap is therefore very crucial especially for heavy vehicle drivers to prevent collision with the leading vehicle.

Presently, passive safety systems such as air bags and seat belts have been employed in most vehicles. However, active and intelligent systems that can achieve accident prevention are still uncommon, particularly for heavy vehicles. Crash or collision avoidance system is one of the intelligent solutions designed to help drivers better detect and quickly respond to impending collisions. In the current situation, without such system in vehicles, the safe following of a vehicle is completely dependent on the driver's own judgment which can be erroneous or inaccurate. This research serves as a solution to this problem by developing a system known as the Collision Avoidance

Warning System (CAWS) which will warn and alert the heavy vehicle's driver when a potential unsafe following distance is detected at any instant during vehicle following situation. With CAWS as driver aid, the likelihood of forward collision in the event of close vehicle following will be significantly reduced. Also with this proposed solution it will indirectly educate the heavy vehicle driver to be more conscious about minimum safe distance difference for each heavy vehicle category and conditions. In addition, a graphical user interface (GUI) based calculator was developed based on the proposed regression model. It is envisaged that this calculator would provide a more realistic depiction of the real situation for safety analysis involving heavy vehicles.

This proposed prototype solution relates to a system and method of automatically alerting heavy vehicle's driver of minimum distance gap to another leading vehicle as shown in Figure 6.1. The system is a combination of microcontroller and various electronics devices and sensors. The microcontroller receive various measured signals detected by a distance sensor, vehicle speed sensor and also input entered by driver from by designed graphical interface panels. From all this input, the microcontroller will process the data using the novel MSDG algorithm to obtain the minimum safe gap distance. The processed data will be displayed in the interface panel in display device and activate the alarm system if the following vehicle in unsafe following condition. All of the hardware system is intended to be employed as a third party system i.e not embedded to the vehicle's electronic control unit (ECU) due to complexity, safety and vehicle warranty and insurance.

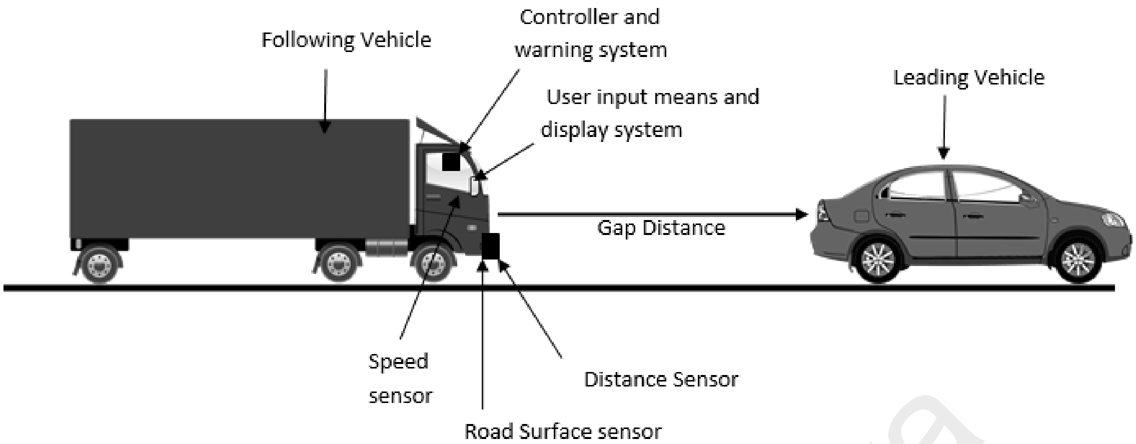


Figure 6.1: The Application of the CAWS featuring MSDG algorithm

6.4 Recommendations for Future Work

The CAWS featuring the MSDG algorithm presented in this thesis is able to be implemented together with today's technology. However, more work is still needed to solve the remaining technical issues and ensure high reliability and low cost. The determination of the accurate safe gap distance algorithm for a close following situation is a very important part in developing a better and reliable CAWS system. It would provide many important readings which can help traffic engineers and policy makers in their efforts to improve traffic safety. Numerous improvements and suggestions can be done to obtain a better and reliable result from the same study field. It is recommended that further research should be undertaken in several study areas. For instance, more simulation data can be collected using various the multi-body software and they can be compared with existing results. Further investigation into the different parameters that can influence the deceleration and braking distance is strongly recommended. Furthermore, it should also be suggested for modifications of the program so that it can also resolve problems involving curved sections of the roads.

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Patent

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Award

Gold Medal, Seoul International Invention Fair (SIIF) 2013, Seoul, South Korea. "*Collision Avoidance Warning System Featuring MSDG Technology*".