Development of Integrated Weigh-in-motion System and Analysis of Traffic Flow Characteristics considering Vehicle Weight

By

AHMAD SAIFIZUL ABDULLAH

A thesis submitted in accordance with the requirements for the degree of
Doctor of Engineering

The University of Tokushima
Japan

November 2011

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others

Acknowledgement

I am forever indebted to Professor Hideo Yamanaka and Professor Mohamed Rehan Karim, my main supervisor and home advisor, for their excellent ideas, guidance and continuous support helped me to stay focused on the objectives of this dissertation. The knowledge and experience, I received by doing this research under them makes me possible to apply my background in instrumentation and control engineering to develop a new idea and application in an intelligent transportation system field.

I would also like to express my sincere gratitude to the evaluation committee in-charge, chaired by Professor Akio Kondo and other members Professor Yoshihiro Deguchi and Dr. Masashi Okushima for their assistance in completing this work.

An acknowledgement is also made to my financial support, Japan Society for the Promotion of Science (JSPS) for providing me an opportunity to complete this work through a JSPS Ronpaku (Dissertation PhD) Program.

Finally, I would like to extend my sincere appreciation to my lovely wife and children, parents, parents in law and brothers for their invaluable support, prayers and continuous encouragement. They were always with me during the difficult times.

Abstract

This study attempts to explore empirically how gross vehicle weight (GVW) will affect traffic flow characteristics in both free-flow and vehicle following situations. The success of the study is highly dependent on the empirical data provided by the traffic data-collection system.

Currently, many kinds of systems or devices are available which measure or monitor or enforce traffic dedicatedly. The use of these dedicated or nonintegrated systems or devices in traffic data-collection or monitoring and traffic enforcement is useful in certain application, especially when only dedicated parameter is considered.

However, these devices may have limited measurement capabilities and unsuitable for this study, where the devices are incapable of simultaneously measuring all essential traffic and vehicle parameters such as speed, headway as well as weight in real-time. The use of these dedicated devices for this study will result in data inconsistency and incomprehensive measurable traffic parameters.

Thus, a comprehensive and continuous traffic data-collection system based on weigh-in-motion technology has been developed and installed at one of the federal roads in Malaysia for study purposes. The developed system is capable of simultaneously and continuously measuring large sample and all essential traffic and vehicle parameters in real-time. It also uses the minimum number of sensors necessary to provide the maximum number of various traffic and vehicle parameters.

Statistical analysis was then performed to the collected data to quantify that the gross vehicle weight can have a significant effect in traffic flow characteristics in both free flow and following situations. The results lead to explore the driver behavior in controlling the vehicle from two different perspective: driver's visual input and vehicle dynamics capability.

The first empirical analysis results showed that statistically for each type of heavy vehicle, there was a significant relationship between free flow speed of a heavy vehicle and its GVW. Specifically, the results suggest that the mean and variance of free flow speed decrease with an increase GVW by the amount unrelated to size and shape for all GVW range. Then, based on the 85th percentile principle, this study proposed a new concept for setting differential speed limit for heavy vehicle by incorporating GVW where a different speed limit is imposed to the heavy vehicle according to its GVW.

The second empirical analysis results showed that how GVW of following vehicle and size of leading vehicle will affect the driver behavior in controlling their speed under different compositions of leader-follower pairs in a car-following situation. The main findings of this study are when we incorporate the vehicle dynamic's capability in a car-following situation, the GVW of following vehicle and the size of leading vehicle were significant sources of variation in following vehicle speed and relative speed, and their interaction influence the driver behavior in controlling the speed.

The third study investigated empirically how different composition of leader-follower pairs will affect time headway with the focus on following vehicle (FV) GVW and leading vehicle (LV) size. The results from statistical analysis were quite revealing in terms of quantifying that the GVW of FV and the class of LV were a significant source of variation in time headway. Based on these empirical results, the study suggests a preferred minimum headway model from driver perspective incorporating heavy vehicle size and GVW. The proposed model also suggests the selection of the optimum value of preferred minimum headway based on percentile value if human reaction time, public support and traffic flow interference are to be considered.

Based on these empirical analyses, it can be concluded that, the main findings of this study are when we incorporate the vehicle dynamics capability in a traffic flow study, the gross vehicle weight should be considered as one of the variable of interests to obtain more rational results.

Committee in Charge:

Professor Akio Kondo, Chair
Professor Hideo Yamanaka
Professor Yoshihiro Deguchi
Associate Professor Masashi Okushima

Table of Contents

CHAPTER 1

GENERAL INTRODUCTION

1.1 Research Motivation

One of the primary functions of the road transport infrastructure is to safely and efficiently transport goods and people. When commercial 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 highway safety. Accident involving heavy vehicle is perceived to be a major highway safety problem, with serious consequences for the drivers, companies and the traveling public.

Since the last two decade, Malaysia has experienced a remarkable period of economic expansion and growth in population, economy, industrialization and motorization. The population increased from 19.5 to 25.6 million at an average growth rate of about 3% per year. During the same period, the total length of paved roads and registered vehicles increase considerably. The increase in population and motorization led to a consequent increase in the number of road traffic accidents.

Based on accident data obtained from the Malaysian Institute of Road Safety Research (MIROS), the ratio of fatal accident involving heavy vehicle (FAIHV) to total road fatalities is relatively significant as in 2008 the ratio is 25.1% as given in Table 1.1. This means that at least 25.1% of all road fatalities are due to fatal accidents involving heavy vehicles (because by definition a fatal accident is when at least one death occurs in that accident). An analysis of the accident fatality data further reveal that at least 41% of fatal accidents involving heavy vehicles occurred between the heavy vehicle (HV) and motorcycle as shown in Figure 1.1.

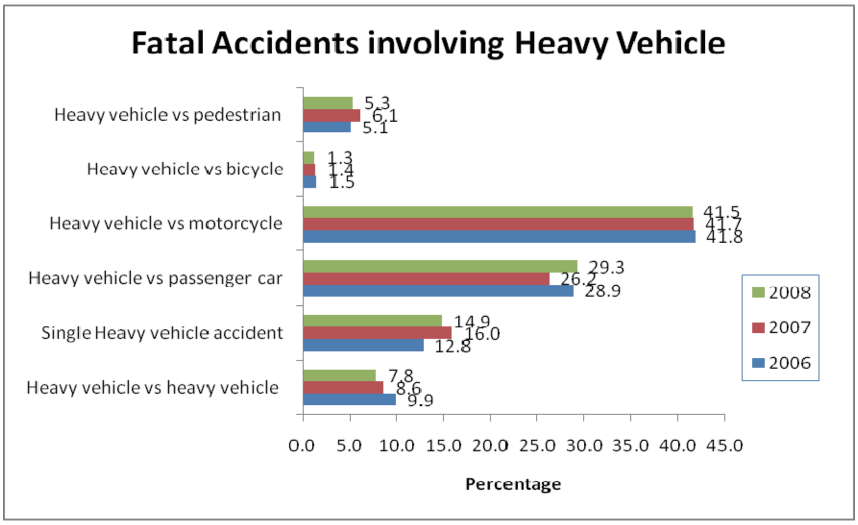


Figure 1.1 Fatal accidents involving HV by vehicle types

Table 1.1 Total fatal accidents involving heavy vehicles

	2006	2007	2008
Fatalities	6287	6282	6527
Fatal accidents involving HVs	1846	1730	1641
Ratio FAIHV to fatalities (%)	29.4	27.5	25.1

In this study, among other factors that can affect the vehicle dynamics, this study attempts to explore and to provide a valid empirical evidence that the vehicle weight is one of the essential parameters in vehicle design study that can affect traffic flow characteristics. The effect of weight on commercial vehicle performance is more considerable compared to a non-commercial vehicle.

1.2 Traffic Flow Models

Traffic is defined as movement, which occurs on a particular transport mode (Lay, 1986). Ever since, vast number of results, both analytically and empirically, have emerged in traffic discipline (Lay, 1986; Smith et. al., 2002; Garber and Hoel, 2001; Zhang and Kim, 2005; Gartner et. al., 1992; Tiwari, Fazio and Pavitravas, 2000). The basic question which arises is: How vehicle dynamics capability has been considered to produce these results?

Vehicle as one of the important element in a traffic stream is completely a dynamics system. Equation of motions of vehicle dynamics can be found in Wong (1993) which is derived analytically from Newton's fundamental law. The vehicle weight is one of the essential parameters in vehicle design study that can affect vehicle driving, braking and handling performance characteristics (Bixel et al, 1998). The effect of weight on commercial vehicle performance is more considerable compared to a non-commercial vehicle.

However, the previous researches only address the traffic flow models in both microscopic and macroscopic approach arising from driver behavior perspective. The characteristics of the vehicle such as performance, braking and acceleration capability is assumed to be same for all type vehicles and for different compositions of a follower-leader pair in the model development. The main reason is in the past it is difficult to obtain the weight, speed, acceleration and classification data simultaneously and continuously over the period of time without disrupting the natural way of traffic flow.

To date, the relationship among vehicle speed, acceleration and weight in a contribution to the road safety, planning, management, enforcement and environmental issue remained unanswered. Hence, another important variable of interest that should be introduced to the model development in both macroscopic and microscopic approach is vehicle weight. In discussing on the development of the relationships or empirical models, the link with data-collection device or system measurement capability is very important in order to have a practical and realistic model.

1.3 Traffic Data Collection and Monitoring Technology

The emerging technology in measurement field recently is undoubtedly changing the way some traffic measurements are obtained and will likely provide the opportunity for acquiring more and better data to further advance understanding of the fundamental issues and enforcement strategies. At present, the known system for traffic data collection, monitoring and enforcement use various types of sensors. The sensor technologies used for the system can be divided into three major categories: intrusive sensors (in-roadway), non-intrusive sensors (above roadway or roadside), and off-roadway sensors. Each sensor offers strengths and limitations; the successful application of the sensors depends on proper device selection to meet specific system requirements.

The major limitations of non-intrusive and off-roadway sensors, such as camera, infrared, microwave radar, ultrasonic, probe vehicles, and remote sensing, are as follows:

- Most of them are only capable of measuring dedicated traffic parameter;
- Using them to measure vehicle parameters, such as gross vehicle weight (GVW), axle weight and wheelbase, is impossible; and
- These sensors are not robust to precipitation and climate changes.

The measurement from an intrusive sensor is generally more robust and used in continual and permanent measurement procedure of obtaining traffic data. The most prominent intrusive sensor is weigh-in-motion (WIM) sensors and its main advantage as compared to other intrusive sensors is their ability to measure vehicle weight (Stoneman and Moore, 1989; Stewart, 1989).

1.4 Weigh-in-motion Technology

One of the most difficult tasks related to measurement capability is to obtain weight data of moving vehicle. The only prominent technology used to obtain weight data is WIM technology.

In ASTM Standard E 2300-06 (2007), traffic monitoring device (TMD) is defined as *'A Traffic Monitoring Device (TMD) is equipment that counts and classifies vehicles and measures vehicle flow characteristics such as vehicle speed, lane occupancy, turning movements, inter-vehicle gaps, and other parameters typically used to portray traffic movement'*.

On the other hand, ASTM Standard E 1318-02 (2002) defines WIM System as '*A set of sensors and supporting instruments that measure the presence of a moving vehicle and the related dynamic tire forces at specified locations with respect to time; estimate tire loads; calculate speed, axle spacing, vehicle class according to axle arrangement, and other parameters concerning the vehicle; and process, display, store, and transmit this information'*.

From these two definitions of terms, theoretically it can be said that WIM system is capable to be TMD. Nevertheless, in practical, measuring capability of TMD, which is not based on WIM technology is limited by weight data and WIM system is limited by vehicle-type and road-type. Figure 1.2 shows the position of WIM technology in a measurement procedure of obtaining traffic data.

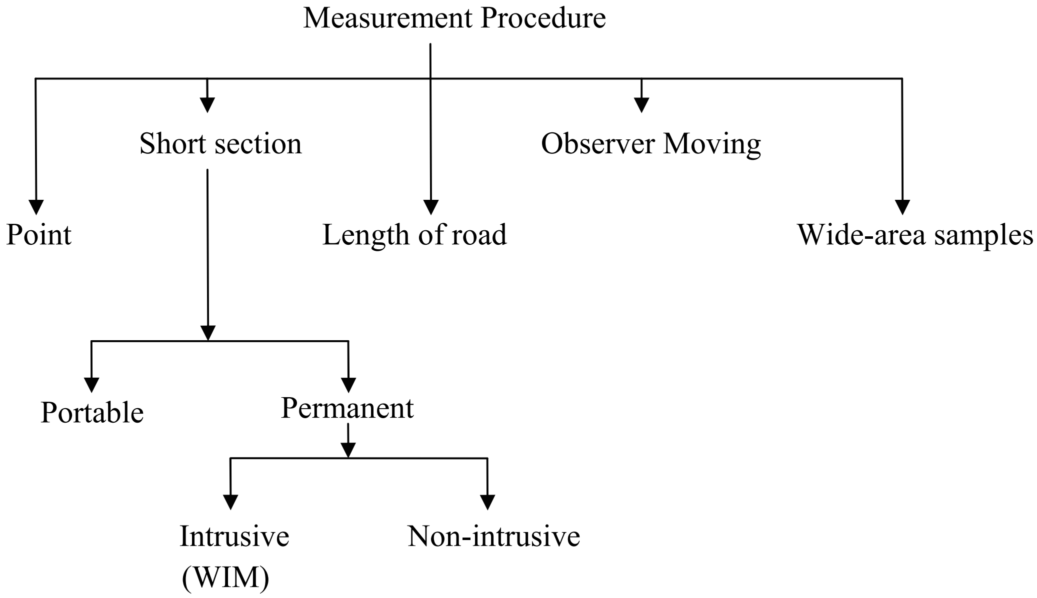


Figure 1.2 Position of WIM technology in measurement procedure

Four major types of WIM sensors are available on the market (Wang and Wu, 2004), and they are basically based on two different sensor technologies, i.e., strain gauge and piezoelectric. Bending plate and load cell WIM sensors use strain gauge technology and are dedicated to measuring vehicle weight. If this type of sensor is used to measure other traffic parameters, such as speed and axle spacing, the number of sensor arrays must be increased, or it must be integrated with another hardware. This will make the installation work tedious and will definitely increase the cost. Other types of WIM sensors use piezoelectric technology, and the quartz sensor has been introduced to overcome the limitations of ordinary piezoelectric WIM sensors. At present, WIM system is only used for an enforcement aid of an overloaded heavy vehicle and collecting related traffic data of commercial motor vehicle (Seegmiller, 2006; Nichols and Bullock, 2004; Wang and Wu, 2004).

1.5 Problem Statement

This study attempts to explore empirically how GVW will affect traffic flow characteristics in both free-flow and vehicle following situations. The success of the study is highly dependent on the empirical data provided by the traffic data-collection system.

Currently, many kinds of systems or devices are available which measure or monitor or enforce traffic dedicatedly. The use of these dedicated or nonintegrated systems or devices in traffic data-collection or monitoring and traffic enforcement is useful in certain application, especially when only dedicated parameter is considered.

However, these devices may have limited measurement capabilities and unsuitable for this study, where the devices are incapable of simultaneously measuring all essential traffic and vehicle parameters such as speed, headway as well as weight in real-time. The use of these dedicated devices for this study will result in data inconsistency and incomprehensive measurable traffic parameters.

Thus, a comprehensive and continuous traffic data-collection system based on weigh-in-motion technology need to be developed and installed at one of the federal roads in Malaysia. The developed system must be also capable of simultaneously and continuously measuring large sample and all essential traffic and vehicle parameters in real-time. It also uses the minimum number of sensors necessary to provide the maximum number of various traffic and vehicle parameters.

Statistical analysis will then be applied to the collected data to explore the driver behavior in controlling the vehicle from two different perspective: driver's visual input and vehicle dynamics capability to quantify that the gross vehicle weight can have a significant effect in traffic flow models in both free flow and following situations.

1.6 Research Approach

The research includes two parts, the design and development of integrated WIM system, and performing statistical analysis to quantify the effect of GVW on traffic flow characteristics in both free-flow and vehicle following situations.

1.7 Thesis Layout

Following the introduction in Chapter One, Chapter Two introduces the system development methodology including software development of integrated WIM system and then reports the performance testing results and improvements. Chapter Three provides a study about the prospect of using WIM system for enhancing vehicle weight enforcement. Chapter Four to Chapter Six provide empirical investigations about a new relationship among variables of interest in traffic flow characteristics when vehicle weight is taken into consideration. Chapter Four investigates the relationship between GVW and free flow speed and consideration on its relation with a differential speed limit. Chapter Five investigates the effect of GVW and vehicle size on speed in a vehicle following situation. Chapter Six investigates the effect of GVW and vehicle size on headway characteristics in a vehicle following situation. Finally, a conclusion and recommended future work is anticipated in Chapter Seven.

CHAPTER 2

SYSTEM DEVELOPMENT METHODOLOGY

2.1 Main Function

To produce the cost-effective system, the proposed system is developed using only a quartz sensor as a primary sensor for acquiring traffic and vehicle parameters. The main advantage for choosing a quartz sensor is its ability to measure various traffic and vehicle parameters without any additional hardware, ease of installation and robust to precipitation and weather changes. There are three main functions of the system: traffic data collection and monitoring, variable speed limit violation detection system and customized weight violation sorting system as shown in Figure 2.1.

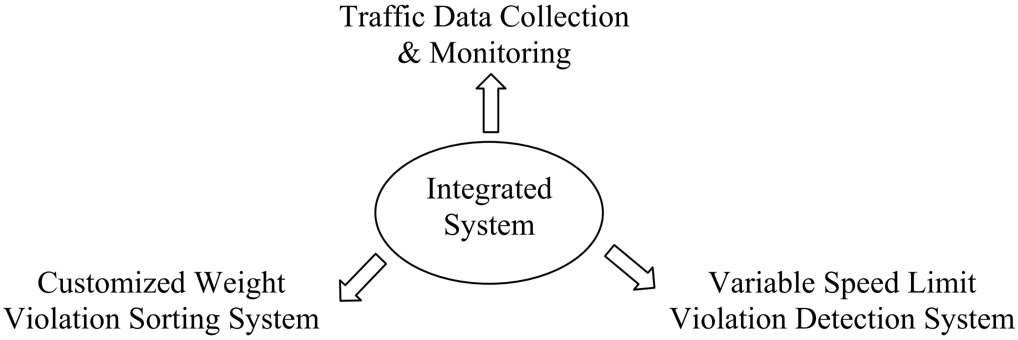


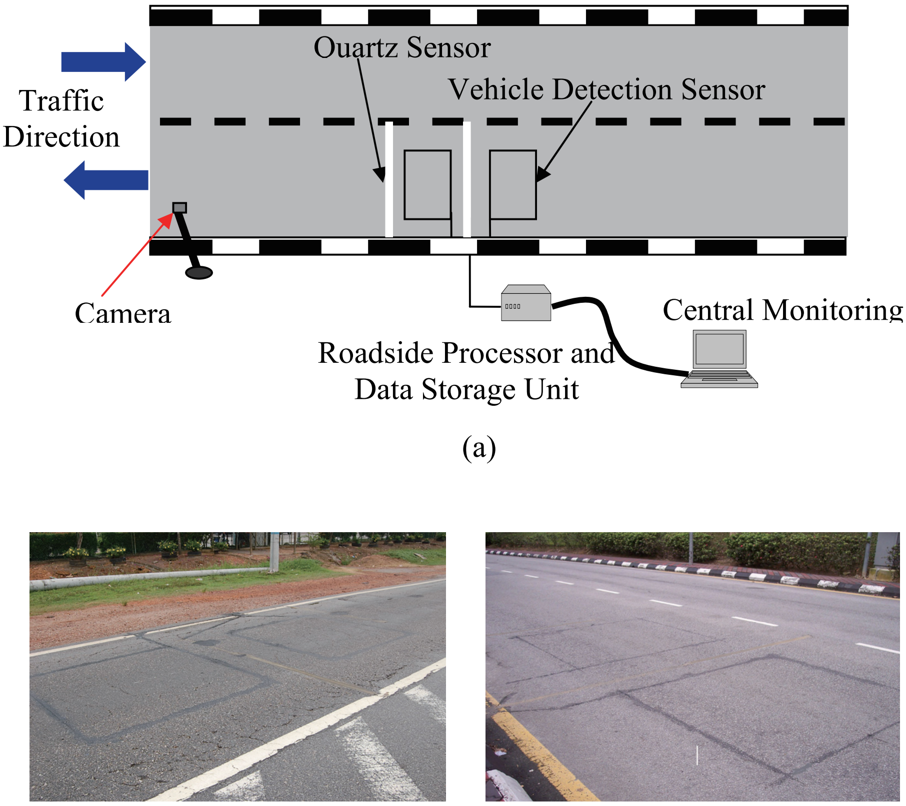
Figure 2.1 The main function of the proposed integrated system

2.2 Development Methodology

The development of WIM system for this study was executed according to the following process:

2.2.1 Project site selection

The development was started in June 2006 where the first installation site was chosen to be inside campus for ease and accelerate the development process. After the successful development and verification test, the second installation was carried out on Federal Road 54 to obtain actual traffic data. The new site is selected to be in front of Road Transport Department (RTD) static weigh enforcement station, which is 30km from the city centre. The traffic direction move from city to a rural area and the road type is a rural single carriageway road with standard width and layout. Furthermore, the area also was chosen with a flat road geometry and high proportion of vehicle class and gross vehicle weight (GVW). The schematic diagram of system layout and installation sites are shown in Figure 2.2.



(a)

(b) (c)

Figure 2.2 (a) Schematic diagram of system layout (a) Federal Road 54 site
(b) Universiti Malaya campus site

2.2.2 Hardware Selection and Configuration

The proposed system comprises a set of sensors for providing signals in response to vehicle travel across the sensors, a license plate camera, a signal conditioning component and a data-acquisition component to digitize the signal, and a processor unit, a license plate recognition software and a software for processing and computing the digitized signals to determine related vehicle parameters for enforcement purposes.

In terms of hardware cost, the most expensive item in the proposed system is the WIM sensor. Hence, proper selection of WIM sensor to obtain multi parameters traffic and vehicular data with reasonable cost is crucial. The quartz WIM sensor used for this research is the Lineas 9195E from the Kistler Instrumente ~~Corporation~~AG. A Lineas Quartz sensor is made up of a quartz-sensing element placed in a high-strength aluminum alloy extrusion and surrounded with elastic material. A load pad of epoxy-silica sand compound is attached to the top of the load the aluminum housing during the manufacturing process. The sides of the load pad are wrapped with closed-cell foam padding to isolate any side forces caused by a volume change in the pavement. A one meter length sensor has twenty quartz-disks, under a pre-load, distributed evenly throughout. When a force is applied to the sensor surface, i.e., the load pad, the quartz disks yield an electric charge proportional to the applied force as a result of the piezoelectric effect. The electric charge is converted by a charge amplifier into a proportional voltage. This signal is utilized through appropriate electronic interfaces to determine axle or wheel load. The sensor cross-cut is shown in Figure 2.3.

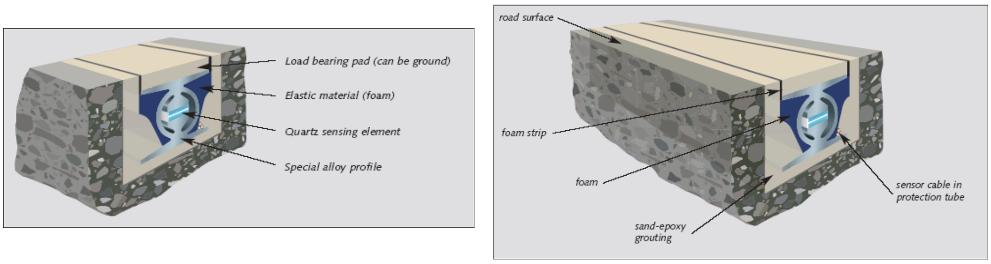


Figure 2.3 Lineas sensor cross-cut view (adapted from Kistler Lineas user manual)

Other related hardware items such as vehicle detector, data signal conditioning and acquisition and stand-alone processor have been selected with considering the basic requirements of the system, for instance, climate condition, accuracy and robustness are still fulfilled. In this research, staggered layout which requires four sensors (i.e. bar length is 0.75 m) per lane was chosen for both installation sites. The high-speed traffic camera was chosen to capture the vehicle image while passing through the sensor for data validation and record purposes. The camera as shown in Figure 2.4 was equipped with strong IR strobe for capturing the image in daytime as well as night time.

Figure 2.4 High Speed camera with strong IR probe

2.2.3 System installation and setup

The installation was done based on sensor installation guide and under the guidance of Kistler officer. The main steps for an installation are given as follows:

Road Marking

Using pavement crayons, tape measure and other marking tools, carefully mark the layout of the sensor installation as shown in Figure 2.5. Ensure sensors are emplaced exactly perpendicular to the flow of traffic and that all lines are straight.

Figure 2.5. Road marking

Cutting the pavement

As shown in Figure 2.6, using a 10mm Diamond Blade, dry cut slot for sensor. Slot must be 72 mm wide by 55 mm minimum deep. This can be applied for both bitumen or concrete pavement.

Figure 2.6. Dry cut pavement slot

Cleaning the slot

The pavement between the cuts must be removed to create a slot of 55 mm by 72 mm. The slot must be dry and free of loose material before grouting is carried out as shown in Figure 2.7.

Figure 2.7. Clean slot

Mounting and grouting the sensors

WIM sensors must be assembled into a row in a clean and dry environment. This is usually done in a workshop, warehouse or other building. As shown in Figure 2.8, the grout should be thoroughly mixed and then quickly poured into a slot that is dry, clean and straight.

Figure 2.8. Grouting the sensor

Grinding the surface

After the grout has completely cured, the sensor surface and grout require grinding in order to leave a finish that is completely flush with the surrounding pavement as shown in Figure 2.9

Figure 2.9. Grinding excessive grout

After installation and hardware configuration had been done, the process of development has started with software development and end with a system performance test. This process is repeated until the measurement readings are within the Type III ASTM E1318-02 functional performance requirements (ASTM E1318-02).

2.2.4 Software development

When the vehicle tire passes on the quartz sensor, an electrical charge proportional to the applied vertical force is produced due to piezoelectric effect. The electric charge as is then converted by a charge amplifier into a proportional voltage which is then further processed by the software to obtain various parameters as required.

The software was designed and programmed from scratch in each and every aspect that can accommodate the study requirements and can be further enhanced to accommodate any special characteristics of local Road Transport Act and the peculiarities of traffic and road system. A detailed description of software development will be given in Section 2.3.

2.2.5 Trials run and performance testing

A total of 90 test runs were conducted using four different vehicle classes that were not just specific to a heavy truck or trailer. To analyze the repeatability and stability of the measurements, each vehicle was tested fifteen times at five different speeds (range from 20 km/h to 100 km/h) and under various prevailing conditions, such as normal, dry, wet, and hot road surface conditions. In this situation, normal and hot conditions indicate an environment where the ambient temperature is between 20 to 30°C and more than 30°C, respectively. The reference data were collected prior to the experimental trials, and their descriptions are as follows:

- manual speed calculation was conducted by measuring the traveling time for a known distance for each test run,
- the actual vehicle wheelbase was measured manually for each vehicle, and
- the static GVW was obtained using a certified, portable weigh scale.

The aim of the performance test is to show that the developed system complies to the performance requirements set by local and international standard.

2.2.6 System optimization and standardization

Optimization involves a method for processing the signal, improving reliability of related hardware component, stability of data transfer and communication, alert system for remote system power failure and system malfunction, enhancing data storage and human-machine interface capability. This significantly will provide a more robust and accurate system for collecting a large amount of data.

2.3 Software Development

When a force is applied to the sensor surface, the quartz disks yield an electric charge that is proportional to the applied force through a piezoelectric effect as shown in Figure 2.10. Then, the electric charge is converted by a charge amplifier into a proportional voltage, which then must be further processed as required. The sensor must be integrated into the road surface and is, thus, only viable for permanent installation applications. As a vehicle starts to drive over the sensor, the software begins gathering data. Data is gathered until the vehicle's entire axle has passed completely over the sensor. When this is complete, the software analyzes the data that was captured to determine the desired parameters, such as axle weight, GVW, average speed, number of axles, and other parameters.

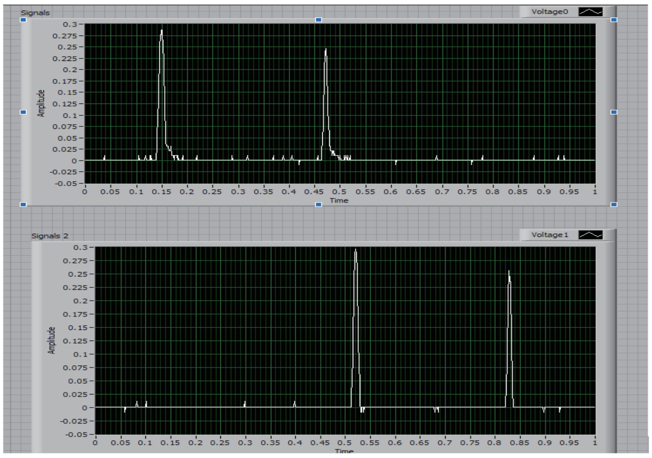


Figure 2.10 Typical analog output signal of a 2-axle vehicle from quartz WIM sensors

2.3.1 Signal processing and Calibration

A typical truck tire force signal as sensed by WIM quartz sensor is shown in Figure 2.11.

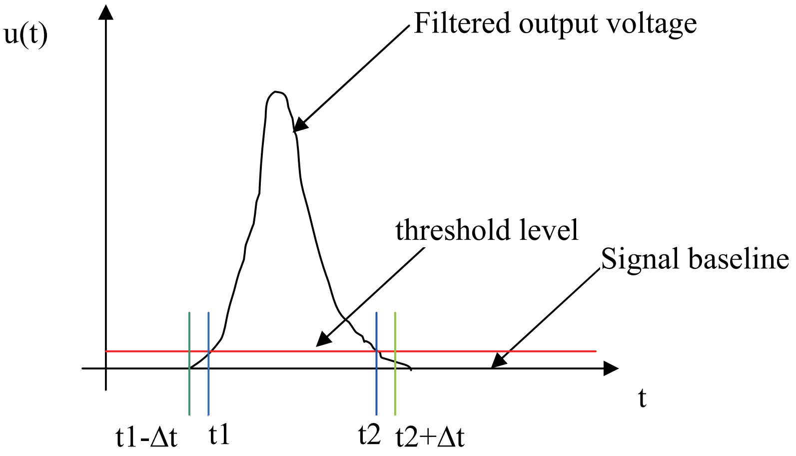


Figure 2.11. Typical truck tire force signal for signal processing

The procedure to process the signal for obtaining the various traffic and vehicle data is given as follows:

1. A threshold level to avoid false detection and miscalculation due to signal noise is defined so as to trigger at points t1 and t2.
2. Introduce a Δt such that the starting point and ending point to calculate an area under the curve will represent almost exactly an area between output voltage and signal baseline.

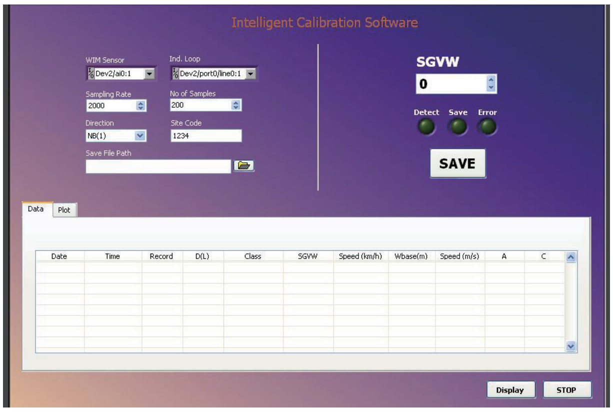
3. Compute an area under the curve between the start and end points.

4. Calculation of wheel load can be expressed as follows:

   $$WL = (V/d) \times A \times C$$

   where WL is wheel load, V is vehicle velocity, d is sensor width, A is signal area under the curve and C is calibration constant.

5. Calibration is used to ensure that the estimation of the dynamic weight produced by the WIM system is as close to the static weight as possible. Calibration constant can be determined by test with known-weight vehicle and software to calculate it has been developed as shown in Figure 2.12.



WIM Sensor: Dev2/ai0:1
Ind. Loop: Dev2/port0/line0:1
Sampling Rate: 2000
No of Samples: 200
Direction: NB(1)
Site Code: 1234
Save File Path:
SGVW: 0

Date	Time	Record	D(L)	Class	SGVW	Speed (km/h)	Wbase(m)	Speed (m/s)	A	C

Figure 2.12 Calibration software

6. The quartz sensor is insensitive to temperature effects, velocity effects and aging effects. Hence, no compensation algorithms are required in this case.

The algorithm to process the signal for obtaining the various traffic and vehicle data specific to each function is given in the following sections.

2.3.2 Traffic data collection and monitoring algorithm

Throughout the development, the method for processing the signal has been improved the system is capable of measuring various traffic and vehicle parameters for various vehicle types including lighter-weight vehicle such as a subcompact car. A data item that can be measured by the system is given in Table 2.1.

Table 2.1 Measurable data items by the developed system

1.	Date of Vehicle Passing
2.	Time of Vehicle Passing
3.	Record Number
4.	Traffic Direction
5.	Lane Number

6.	Vehicle Classification
7.	Spot Speed
8.	Acceleration
9.	Time Headway
10.	Space Gap
11.	Center-to-Center Spacing Between Axles
12.	Wheelbase (front-most to rear-most axle)
13.	Wheel Weight
14.	Axle Weight
15.	Axle-Group Weight
16.	Gross Vehicle Weight

This significant development provides more and quality data for traffic data-collection and monitoring, which eventually can be used for planning and design purposes as well as for enforcement of speed limits and vehicle weight limits. The overall sequence of signal operations for measuring various traffic and vehicular data by the quartz sensor is shown in Figure 2.13.

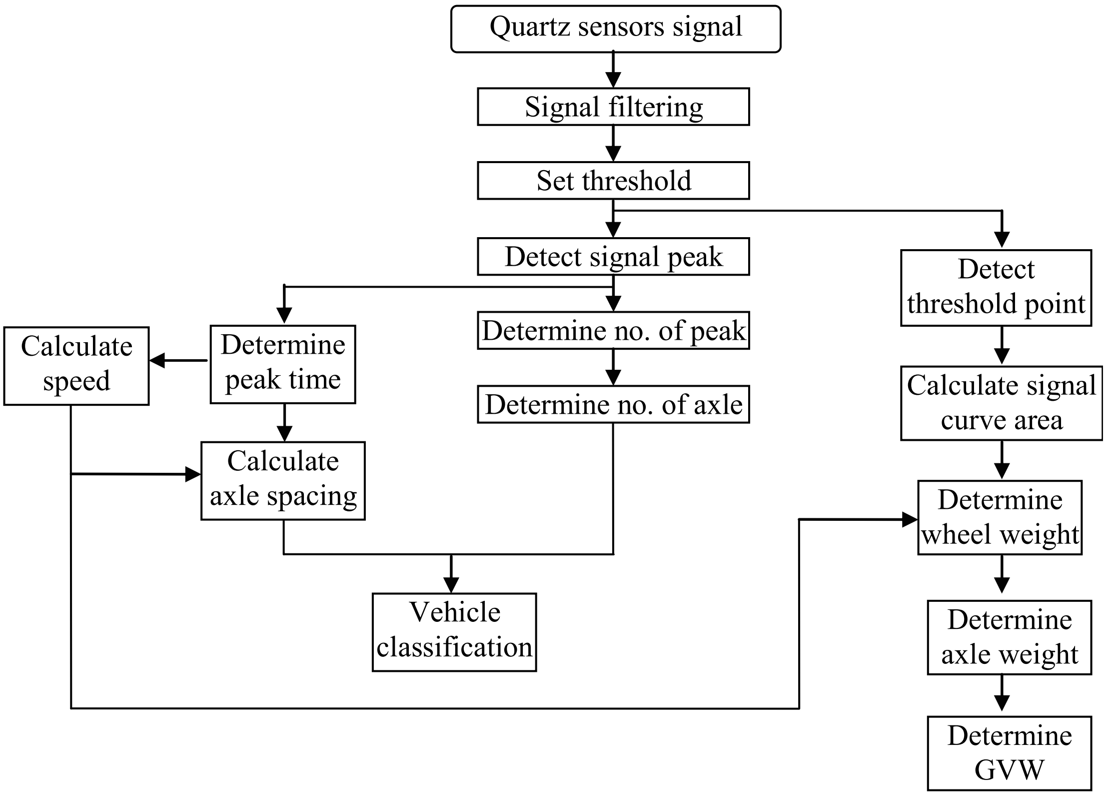


Figure 2.13 Flowchart of sequence of operation for measuring basic traffic data

2.3.3 Variable speed limit violation detection system algorithm

Using the new developed system, it is possible to measure vehicle speed, wheelbase and weight simultaneously in real-time over any section of the road continuously. The most relevant application which can be carried out using this empirical relationship data is variable speed limit violation detection system. The current practice does not consider vehicle class or weight in speed limit enforcement due to the limitation of non-intrusive speed measuring devices such as speed laser gun even though it is stated in the regulation that speed limits for light-weight vehicle and heavy-duty vehicle are different.

The sequence of data analysis operation for variable speed limit violation detection system is shown by flowchart in Figure 2.14. In this figure, the processor determines whether or not vehicle weight is greater than a user-defined weight limit. If the vehicle weight is greater than the user-defined weight limit, the speed limit is equal to HW (i.e. Heavy-weight) speed limit. If it has not, the speed limit is equal to LW (i.e. Light-weight) speed limit. Furthermore, the processor determines whether or not vehicle speed is greater than a specified speed limit. If it is greater, then the vehicle is classified and recorded under the category of speed violation and all related processed data are overlaid to the snap image. All violation data and snap images will be recorded separately. If it has not, the processor takes no further action.

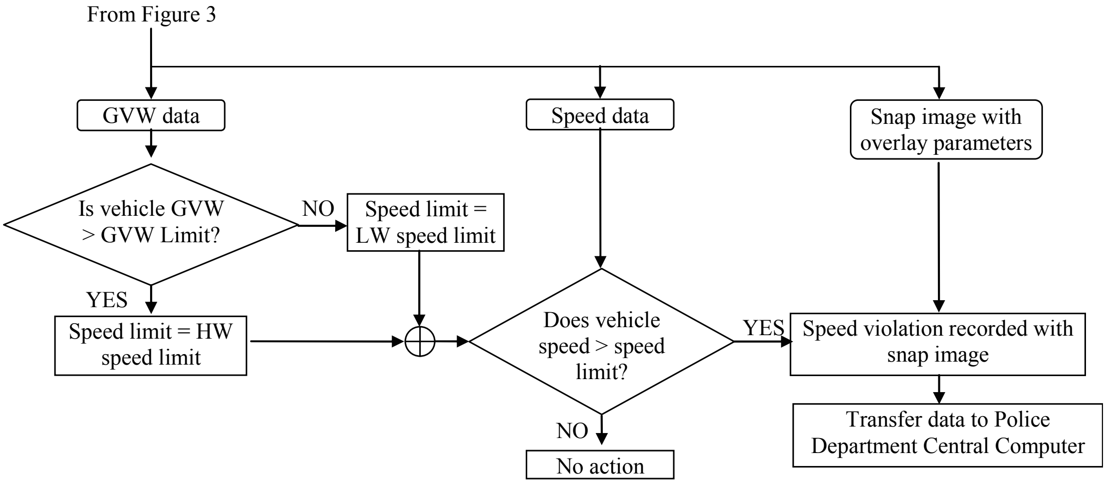


Figure 2.14 Flowchart of sequence of operation for variable speed limit violation detection system

2.3.4 Customized weight violation sorting system

The limitations of enforcement based on existing static weighing scale such as long-queue, time consuming and limited operation is the root cause of inefficient implementation of weight limit enforcement. As one of the main functions, the developed integrated system can also be used to weigh vehicles while they are in motion or as weight violation sorting system.

For this reason, it will overcome limitations of static weigh scale and improve implementation of weight limit enforcement. For sequence of data analysis operation of WIM based weight violation sorting system as shown by flowchart in Figure 2.15, the processor first identifies the permissible GVW limit based on vehicle classification. Then, the processor determines whether or not a GVW and axle weight are greater than the GVW limit axle weight and user-defined axle weight limit, respectively. If it is greater, then the vehicle is classified and recorded under the category of weight violation and all related processed data are overlaid to the snap image.

All violation data and snap images will be recorded separately and transfer to the road transport department local station computer or any other related agencies. If it has not (i.e. no violation), the processor takes no further action.

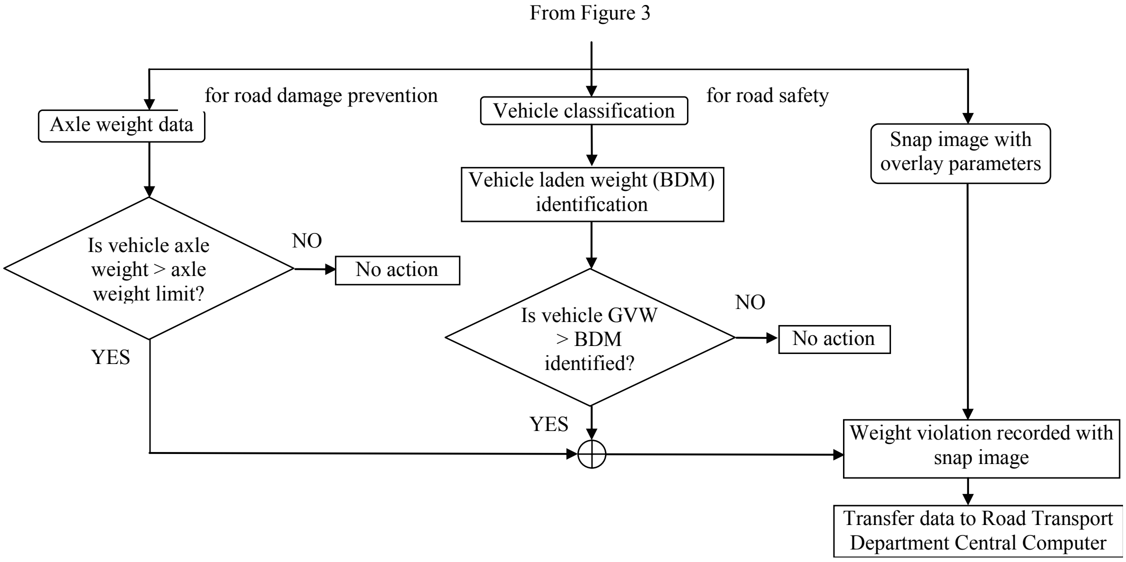


Figure 2.15 Flowchart of sequence of operation for WIM based weight violation sorting system

2.4 Results

Many tests were conducted for evaluating the performance of the system from passenger car to the heavy-duty vehicle with speed range 15 km/h to 100 km/h .The reference value of basic traffic data in Table 2.2, 2.3 and 2.4 were collected prior to the experimental trials, and their descriptions are as follows:

- The actual vehicle wheelbase was measured manually for each vehicle, and
- The static wheel weight and GVW were measured using a Road Transport Department static weigh scale, and
- Reference speed values are obtained through manual measurement

The performance test showed that the developed system complies with the performance requirement for all types of vehicle as shown in Table 2.2.

Table 2.2 Results of GVW performance test

Vehicle Type	Reference GVW (tonne)	GVW	
		GVW (tonne)	% Error
Class 02 (Passenger Vehicle)	1.8450	1.7826	3.3825
		1.7800	3.5206
		1.8117	1.8061
		1.7991	2.4898
Class 05 (2 Axle Single Unit Truck)	7.4200	7.1711	3.3541
		7.3578	0.8379
		7.5061	1.1599
		7.6533	3.1443
Class 04 (Bus)	12.1450	12.5735	3.5283
		12.6664	4.2933
		12.6663	4.2922
		12.5868	3.6381
Class 07 (4 Axle Single Unit Truck)	47.9550	49.0132	2.2067
		48.3049	0.7297
		49.0201	2.2210
		47.1218	1.7374

For measurement of speed and wheelbase, results in Table 2.3 and 2.4 show that the systems comply with the performance requirements for a wide range of wheelbase and speed.

Table 2.3 Results of wheelbase performance test

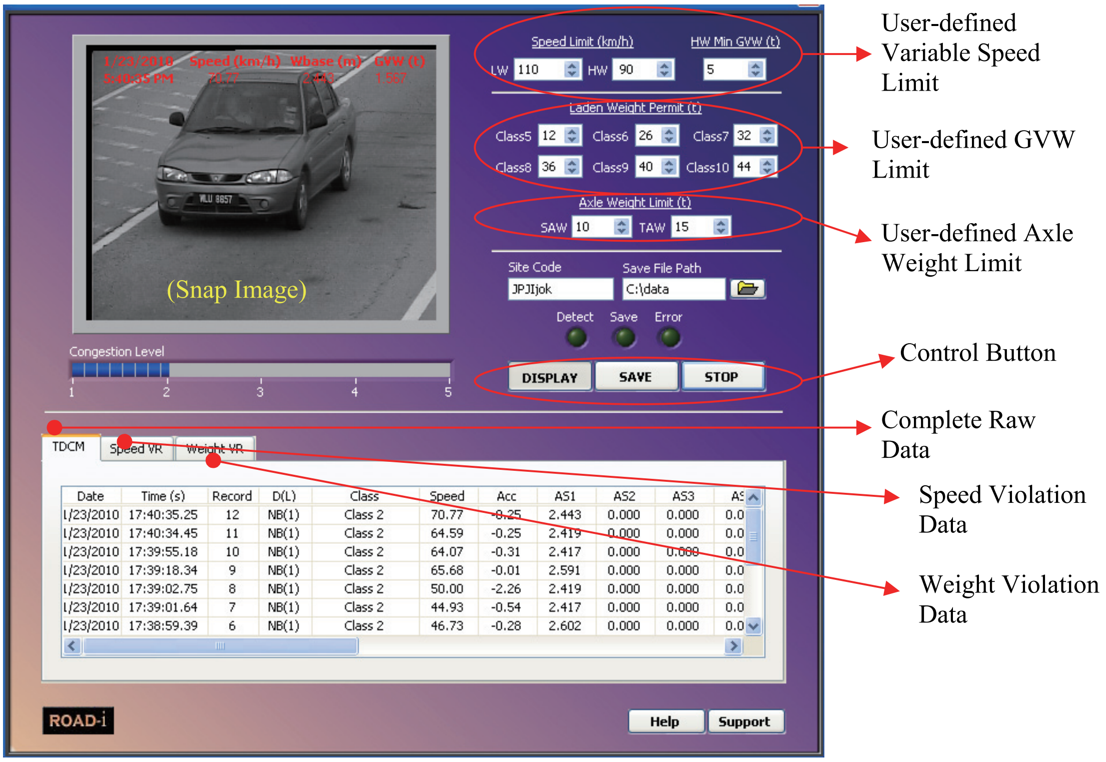
Vehicle Type	Reference Wheelbase (m)	Wheelbase	
		Wheelbase (m)	Error (m)
Class 02 (Passenger Vehicle)	2.86	2.82	0.04
		2.84	0.02
		2.84	0.02
		2.84	0.02
Class 05 (2 Axle Single Unit Truck)	5.00	5.01	0.01
		4.98	0.02
		5.01	0.01
		4.99	0.01
Class 04 (Bus)	6.00	6.09	0.09
		6.09	0.09
		6.04	0.04
		6.07	0.07
Class 07 (4 Axle Single Unit Truck)	6.66	6.59	0.07
		6.61	0.05
		6.57	0.09
		6.60	0.06

Table 2.4 Results of speed performance test

Reference Speed (km/h)	Speed Speed (km/h)	Speed Error (km/h)
95.35	96.91	1.56
90.12	91.98	1.86
63.22	61.95	1.27
60.41	61.82	1.41
37.33	37.34	0.01
35.92	36.24	0.32
27.00	28.48	1.48
27.50	28.37	0.87
18.22	18.69	0.47
20.81	20.07	0.74

The software to process, analyze and store data has been developed from scratch in every single aspect to incorporate the three main functions and other features that can suit the specific needs of relevant agencies. Thus, it is possible to accommodate virtually any changing requirements of Road Transport Act and the peculiarities of traffic and road system before and after implementation of the system. It is flexible and can be easily customized accordingly.

The current version has been designed to be user-friendly, interactive with user-define input as well as for integrated application as shown in Figure 2.16.



Speed Limit (km/h): LW 110 HW 90

HW Min GVW (t): 5

Laden Weight Permit (t): Class5 12 Class6 26 Class7 32 Class8 36 Class9 40 Class10 44

Axle Weight Limit (t): SAW 10 TAW 15

Site Code: JPJIjok

Save File Path: C:\data

Date	Time (s)	Record	D(L)	Class	Speed	Acc	AS1	AS2	AS3	AS
1/23/2010	17:40:35.25	12	NB(1)	Class 2	70.77	-0.25	2.443	0.000	0.000	0.0
1/23/2010	17:40:34.45	11	NB(1)	Class 2	64.59	-0.25	2.419	0.000	0.000	0.0
1/23/2010	17:39:55.18	10	NB(1)	Class 2	64.07	-0.31	2.417	0.000	0.000	0.0
1/23/2010	17:39:18.34	9	NB(1)	Class 2	65.68	-0.01	2.591	0.000	0.000	0.0
1/23/2010	17:39:02.75	8	NB(1)	Class 2	50.00	-2.26	2.419	0.000	0.000	0.0
1/23/2010	17:39:01.64	7	NB(1)	Class 2	44.93	-0.54	2.417	0.000	0.000	0.0
1/23/2010	17:38:59.39	6	NB(1)	Class 2	46.73	-0.28	2.602	0.000	0.000	0.0

Figure 2.16 Front panel of custom software developed for integrated application

The software front panel contains three groups of user-defined input tabs, one group of controls, data set table indicator and one image display indicator. The user-defined input tabs can be categorized into two sections: user-defined input for variable speed limit violation detection system, and user-defined input for weight limit sorting system (both axle weight and GVW).

When the vehicle pass through the sensor, the software will snap the vehicle image and overlay related processed data to the snap image as shown in Figure 2.17.

Figure 2.17 Example of snap image from the software

Moreover, all measurable data items will be captured and displayed by the table indicator. All data, including violated vehicle snap image will be recorded separately and transfer to database station for enforcement and statistics purposes.

2.5 Discussion

One of the nine major areas through the Intelligent Transport System (ITS) promotion is to increase efficiency in road management policy and program. This obviously will be related to data collection and enforcement issues. The proposed system incorporated a number of innovative measures makes it ideal basis for achieving ITS goals. The key benefits of applying the proposed system are as follows:

- Cost savings: The concept of an integrated system can optimize government spending on providing better information and more quality data to all related agencies by using only one integrated system and not separate dedicated system. It will also help government to increase revenue generated through an efficient and effective enforcement system.
- Data consistency: Integrated systems will reduce data discrepancies by eliminating inconsistencies and conflict among database, and increase data reliability.
- Share Data: In Malaysia, as shown in Figure 2.18, the integrated system makes it easier to share data across various related agencies. Sharing data will definitely reduce duplication of effort, improve interdepartmental cooperation and improve communication.
- Efficient and effective enforcement: The proposed integrated system will assist the enforcement agency to implement the actual regulation related to specific speed limit enforcement of heavy vehicles. It will be also plausible to implement enforcement related to both over speed and overload vehicles.

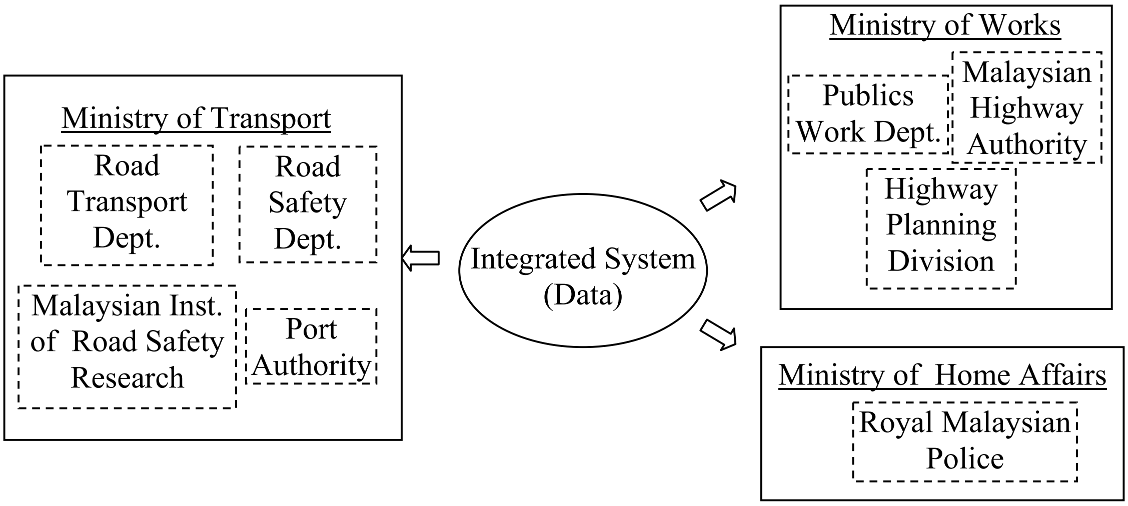


Figure 2.18 Integrated system improve share data and interdepartmental cooperation

CHAPTER 3

PROSPECT OF USING WEIGH-IN-MOTION BASED SYSTEM FOR ENHANCING VEHICLE WEIGHT ENFORCEMENT

3.1 Background

The need to monitor and enforce vehicle weight limits is important to road authorities and those responsible for the maintenance of roads and highways. Overloading of the road and highway pavement by overloaded trucks would accelerate the deterioration of the pavement leading to rutting, cracking, fatigue and possibly structural failure. This is explained by the fact that the relation between vehicle axle load and the damage factor is to the fourth power. This chapter discusses the results obtained from a developed integrated WIM system installed near a RTD static weigh station along a Federal Route 54 road in Malaysia. The WIM system enables the capturing of several traffic and vehicular data which were validated on-site. Vehicle classification, especially different truck categories, as well as gross vehicle weight and each axle weight for each truck were analyzed. The findings were quite revealing in terms of explaining the possible reasons as to why roads in Malaysia experience failures long before the design life span. Based on the results of this study, it is proposed that the weigh-in-motion system should be used in conjunction with the existing static weighing stations to improve vehicle weight enforcement in the country and help prevent the premature road pavement failures.

3.2 Introduction

It is of great importance to monitor and prevent truck overloading for those responsible for the maintenance and operation of highway infrastructures. The additional weight carried by overloaded trucks accelerates the deterioration of the roadway, leading to rutting, fatigue, and in some cases structural failure (Rob et al., 2003; Santero et al., 2005). In a TRB Report 225 (1990), illegally loaded trucks were estimated to cost United States taxpayers $160 to $670 million per year on the highway system. Sandy and John (2006) conducted a study to quantify state highway damage on the basis of the impacts of overweight vehicles. Each year, millions of dollars of damage associated with life span, design, and maintenance of state highways and structures are attributed to vehicles that exceed state weight limits. They found that for every dollar invested in motor carrier enforcement efforts, there would be $4.50 in pavement damage avoided. It is possible to develop a system that would increase the proportion of noncompliant vehicles subjected to inspection relative to compliant vehicles (Matthew, 1996). As such, the weigh-in-motion system may be used in conjunction with existing static weighing stations to improve vehicle weight enforcement.

Many reports and research papers have also shown benefits of using the WIM system as an essential tool for pavement management, highway monitoring, optimizing enforcement and minimizing impacts of overweight vehicles on infrastructure (Conway and Walton, 2004; Liu et al., 2005; Wang and Wu, 2004).

3.3 Purpose and Scope

The main purpose of this study serves as a pre-implementation research where it will provide feasibility studies and some guidelines about this new technology including its benefits in terms of weight enforcement efficiency and effectiveness when use in conjunction with existing static weigh station. The research effort investigated the issue by focusing on three subjects:-

1. Explore and deploy the most suitable WIM sensor technology and develop the WIM system that can be used according to Malaysian weight limit enforcement regulation and climate.
2. Measure the actual trucks violation rates to have firm and comprehensive understanding about the issue.
3. Explore the feasibility of using WIM system to enhance vehicle weight enforcement.

3.4 The WIM System

For the purpose of this study, an accurate and a reliable WIM system using quartz weigh-in-motion sensor has been developed for measuring the speed, class, GVW, and other traffic and vehicular data simultaneously and continuously 24 hours a day and 7 days a week throughout the year. Further elaboration of the developed system has been presented in Chapter Two.

3.5 Data Analysis

In Malaysia, there are several legislative laws to regulate the operation of commercial vehicles. The government agency which is responsible for vehicle weight enforcement is the Road Transport Department (RTD) under the Ministry of Transport (MOT). Automotive Engineering Division under the Road Transport Department is responsible for deciding the maximum permissible laden weight (GVW) for each class of commercial vehicle. On the other hand, the government agency which is responsible to issue the permit is the Commercial Vehicle Licensing Board (CVLB). Under this regulation, all commercial vehicles must apply GVW permit through CVLB in order to be on the road so that severe road damage can be reduced and problems related to road safety can be minimized. Basically, the GVW permit is categorized based on vehicle class and the summary is shown in Table 3.1.

Table 3.1 Maximum permissible laden weight (GVW) by vehicle class

	Class			
	2 Axle	3 Axle	4 Axle	5 Axle
GVW (t)	16.8 t	27.3 t	33.6 t	39.9 t

For the purpose of this study, a total of more than 100,000 commercial vehicle data was analyzed in four months from the system. Fig. 3.1 shows the number of GVW violations (based on maximum permissible GVW given in Table 3.1) for each month from October 2009 to January 2010. On the whole, the rate of GVW violation is found to range between 24% and 29% of the total commercial vehicles for each month and it is expected that the violation rate will hover within this range every month if no drastic action such as regular enforcement exercise is undertaken.

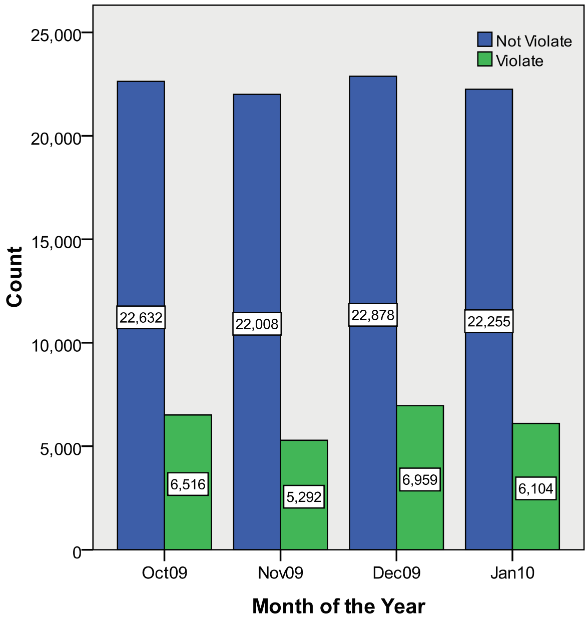


Figure 3.1 No. of GVW violation cases by month of the year (Oct 2009 - Jan 2010)

Although this violation rate may be considered rather high, what is more alarming is the range of GVW values and degree of overloading beyond the allowable GVW for each category of heavy commercial vehicles (see Fig. 3.2). It can be observed that there are cases that the actual GVW measured by the WIM system is almost double the permissible GVW allowed by law for the particular commercial vehicle category. The significantly high GVW beyond the permissible level for each commercial vehicle category would be a cause of major concern especially in terms of the capability of handling the extra heavy commercial vehicle in emergency situations. As such, the extra heavy commercial vehicle may be hazardous and could compromise the safety of other road users should such situations arise. In addition, the fuel consumption of the extra heavy commercial vehicle will increase significantly and the final carbon footprint attributed to this extra heavy commercial vehicle will be higher than what it should be if the permissible GVW was abided to.

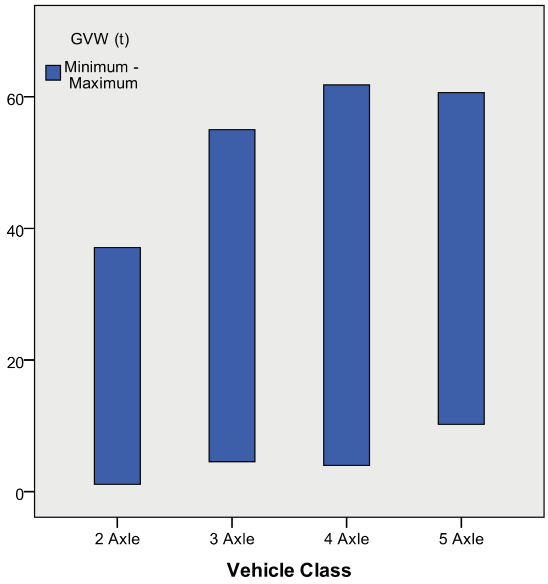


Figure 3.2 GVW variation by vehicle class (Jan 2010)

The extra heavy commercial vehicle would also have significantly higher axle loads beyond the permissible axle load (which is usually used in pavement design) which would increase the pavement deterioration significantly and shorten the pavement life well below what it was designed for. This is because the damage factor of the pavement surface is to the fourth power of the axle load.

Fig. 3.3 shows an example of the distribution of GVW violations by hour of the day for each day of the week in the third week of January 2010. There appear to be two major distinct patterns in GVW violations, namely, between day and night as well as between weekdays and the weekend (especially Sunday). The lower GVW violations is obviously related to the lower percentage of heavy commercial vehicles in the traffic stream during night time and in the weekend, especially on Sunday at this location. Data obtained within the four months revealed that about 24% to 29% of the commercial vehicles exceed the permissible GVW limits. Knowing the GVW violation pattern according to hour of the day and day of the week would definitely assist in planning for effective weight enforcement strategies by the authorities.

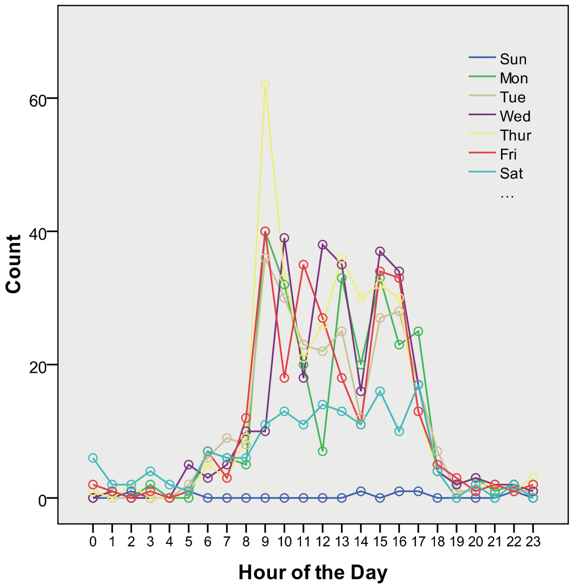


Figure 3.3 No. of GVW violation cases (exceed maximum permissible GVW) by hour of the day (Monday to Sunday), Jan 2010, week 3

The variation of GVW violations by each day of the month for the months of October 2009 to January 2010 is shown in Fig. 3.4. There appear to be a general pattern where more GVW violations are observed during the weekdays as compared to the weekends, especially Sunday. The variation in GVW violations during weekdays does not appear to be very significant except for certain Fridays of the week (in December 2009).

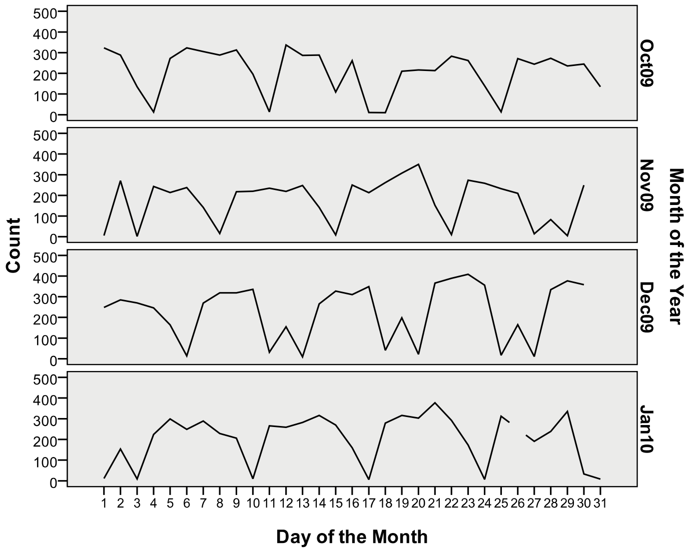


Figure 3.4 No. of GVW violation cases (exceed maximum permissible laden weight) by day of the month (Oct 2009 – Jan 2010).

The two-axle trucks form the majority (about 60%) of the commercial vehicles population in the traffic stream (see Fig. 3.5). At least more than 10% of this truck category exceeds the permitted GVW while about 50% of the 3-axle trucks and about 40% of the 4-axle trucks also exceed the permitted GVW for their respective categories.

Although the GVW violation rate of the 2-axle truck is small as compared to that of the other categories, its actual number is still quite significant, and the risks involved as mentioned earlier in this paper are therefore quite significant. It is also very worrying to know that for the larger commercial vehicles (3-axles and 4-axles) the GVW violation rates are extremely high (although their population is smaller than the 2-axles).

Excessive GVW of these trucks beyond the permitted GVW would almost certainly make them more difficult to handle in critical situations, thus making them hazardous to other road users while contributing significantly to premature pavement damage.

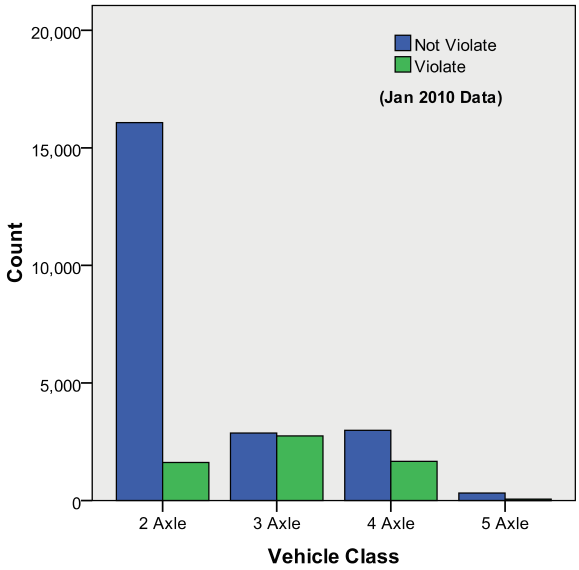


Figure 3.5 No. of GVW violation cases by vehicle class (Jan 2010)

A similar pattern of GVW violation by the different categories of commercial vehicles has also been observed for each of the four months from October 2009 to January 2010 (see Fig. 3.6).

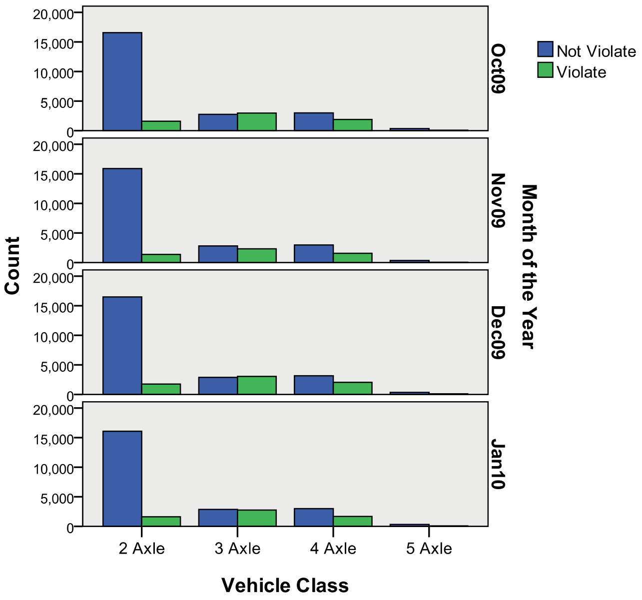


Figure 3.6 No. of GVW violation cases by vehicle class (Oct 2009 - Jan 2010)

A closer look at the WIM data which has been processed to obtain the degree of overloading revealed that there are cases the actual GVW are very much larger than the permitted GVW for the particular commercial vehicle category (see Fig. 3.7). There are even cases that the actual GVW is twice that of the allowable GVW.

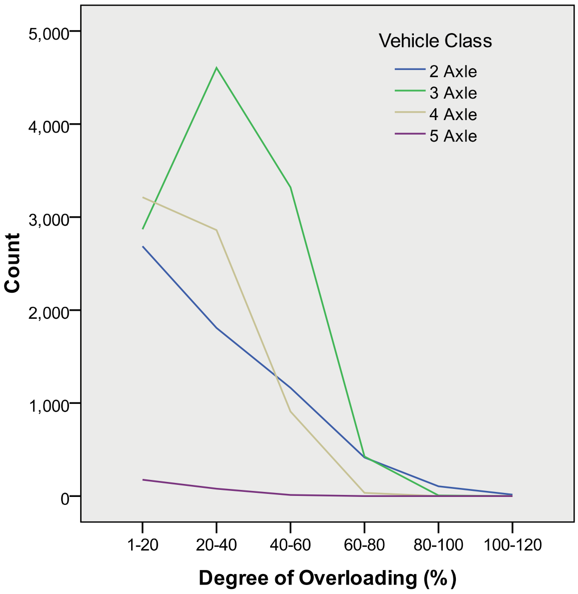


Figure 3.7 No. of GVW violations by degree of overloading (Oct 2009 - Jan2010)

The 3-axle trucks appear to have the largest number of overloading cases for each percentage degree of overloading up to 80% overloading. A similar pattern of degree of overloading is observed for each of the four months, i.e. October 2009 to January 2010 (see Fig. 3.8).

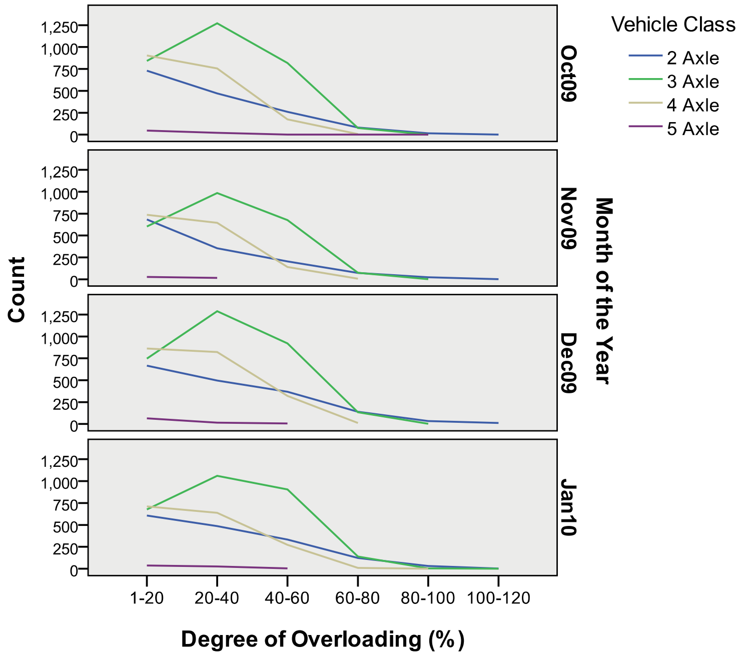


Figure 3.8 No. of GVW violations by degree of overloading (Oct 2009 - Jan2010)

3.6 Discussion

All aforementioned figures are examples to show how a WIM system can provide invaluable data for planning and enforcement purposes. Without a WIM system in place, it is almost impossible to predict detail information related to commercial vehicle characteristics on the road.

There are about 1.0 million registered commercial vehicles on the road in year 2008 throughout Malaysia. According to the results from this study, using four months data, it can be estimated that the average number of illegal overweight commercial vehicles was about 27% which will come out to 270,000 illegal overweight commercial vehicles. If each of these commercial vehicles makes one trip a day, there will already be that huge number of overweight commercial vehicles plying our roads daily.

One pertinent question to ask would be why is the overloading rate very high? There could be many reasons for this and probably the main reasons are as follows:

1. The payment scheme in road freight business in Malaysia is based on the number of trips. More trips to deliver goods would mean higher operating cost to truck operators. In order to reduce the number of trips, the truck operator would overload the truck so that the same amount of goods could be delivered in less number of trips. Thus, in this way the total operating cost to the truck operator would be reduced.

2. The limitations in enforcement capability (limitations from visual inspection and static weigh scale) make the intentional violators more likely to be habitual violators that overload their trucks frequently.

The Malaysian government has spent a large portion of the yearly infrastructure budget on road network and bridge maintenance. A significant amount of the total allocated budget for road maintenance could be saved if road damage caused by overweight vehicles can be avoided or at least minimized. The damage on road pavements would be accelerated as the volume of overweight vehicles increases.

For these reasons, it is proposed that the government to adopt new and innovative technologies such as the WIM system to facilitate the monitoring of commercial motor vehicles in conformance with regulations governing vehicle size and weight.

Successful development and deployment of WIM system involve many key factors such as physical requirements for WIM facility location, standard specification of system components, data performance requirements, operational and maintenance issues, cost and budget, institutional and legal issues, and awareness of freight transportation companies. All these factors are different in each country.

In Malaysia, based on authors' observation and discussion, these key factors need to be carried out through a public-private partnership between the government and the private sector companies. It could be suggested that there are four important organizations which may work closely with one another to develop and deploy the WIM system and the flowchart of implementation process is given in Fig. 3.9.

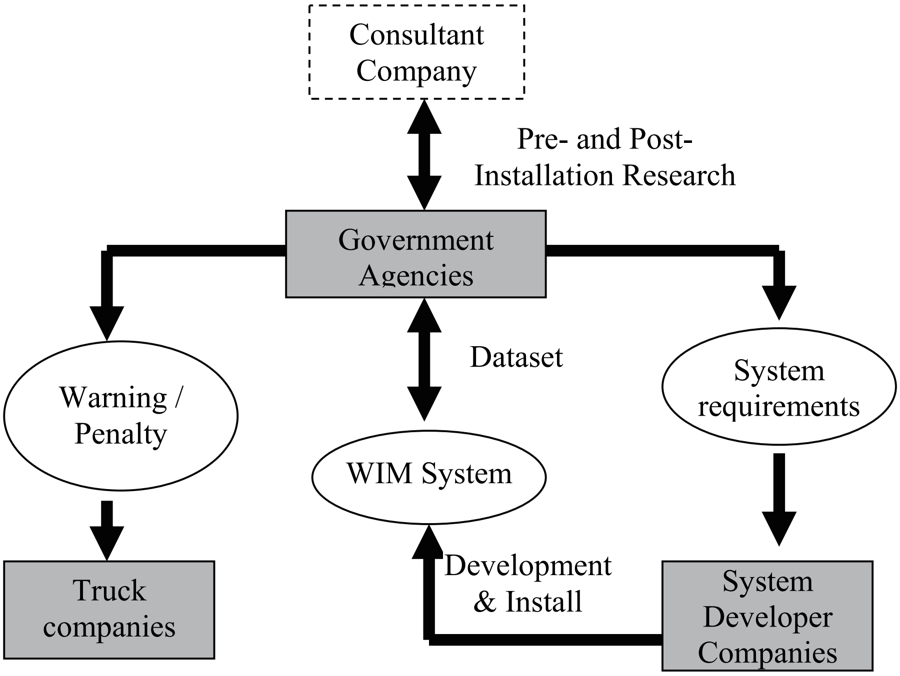


Figure 3.9 Suggested implementation process of WIM System

The main purpose of pre-installation research is to provide feasibility studies and some guidelines about this new technology including its benefits in terms of financial, safety, data and environmental improvement in comparison with existing static weigh scale system. In addition, the research outcome must also provide some guidelines about proper site selection, comparisons among available WIM system and their costs, and system performance specifications which have to be complied with by system developer companies.

Then, through post-installation research, various important information can be obtained by performing empirical analysis using the collected data. Research also involve identifying problems that occur after the installation in terms of system performance and legislative enforcement, and provide a variety of solutions to overcome those problems as well as some necessary information to system developer companies to improve the existing system.

In addition, the system developer companies may also play the role to provide the WIM system with reasonable price so that a moderate number of WIM systems can be installed throughout the nation to alleviate as much as possible the truck drivers bypassing the system. The hypothesis that truck drivers will bypass the system is not always necessarily true. As given in Nichols and Bullock (2004), one of the case studies showed that the weight violation ticket had appeared to be constant after weigh stations were open throughout the day.

Increase of awareness, involvement and support from truck companies may also create a successful implementation of overweight enforcement using WIM system.

In summary, successful implementation of these systems would likely require proper legislative system, close co-operation among related organizations and also require a new level of trust and cooperation among companies and authorities.

CHAPTER 4

EMPIRICAL ANALYSIS OF GROSS VEHICLE WEIGHT AND FREE FLOW SPEED AND CONSIDERATION ON ITS RELATION WITH DIFFERENTIAL SPEED LIMIT

4.1 Introduction

Each year the number road accident fatalities and casualties are increasing and this cause a heavy burden on the health services and national economy. In Malaysia, for instance, the number of road accidents and fatalities are increasing every year and for the year 2008 the total accident increase by 2.7% and road fatality increase by 3.9% from the year before (according to Royal Malaysian Police). Based on accident data obtained from the Malaysian Institute of Road Safety Research (MIROS), the ratio of fatal accident involving heavy vehicle (FAIHV) to total road fatalities is relatively significant as in 2008 the ratio is 25.1% as given in Chapter One. Speed has been identified as one of the most important contributors to road traffic injuries. There are significant numbers of researches that have reported a strong statistical relationship between speed and road safety (GRSP, 2008; OECD/ECMT Report, 2006). In addition, Farmer et al., (1999); Clarke et al., (2010); Dee and Sela, (2003) observed that speed not only makes a large contribution to all injuries but also the most important contributor to fatalities.

Among other risk factors, the need for regulating speed as a risk factor by introducing a speed limit is necessary in all highly motorized countries. Speed limits do influence the mean speed. However, the proportion of violations also changes with respect to the change in speed limit (Elvik et al., 2004). In addition to Uniform Speed Limit (USL), where the same speed limit is applied for both passenger cars and heavy vehicle, Differential Speed Limit (DSL) was introduced in many countries. Differential speed limits are speed limits that restrict all heavy vehicles, or at least heavy vehicles of a specific size, weight, or axle configuration, to traveling at lower speeds than the rest of the traffic stream (Harwood et al., 2003).

Analysis from first principles suggests that speed may be an even more critical factor for heavy vehicle safety than for vehicles in general (Brooks, 2002). This is because, in contrast to passenger cars, heavy vehicles have more complicated systems with a variety of possible failure modes and performance characteristics including locked-wheel braking, trailer swing-out, rollover, poor acceleration characteristics and longer braking distance. Furthermore, as mentioned by Fancher and Campbell, (1995) the heavy vehicle weight shows the strongest association with fatal accident rates among all other vehicle characteristics such as wheelbase, configuration and number of axle. The finding is also consistent with physical principles that the energy to be dissipated in a collision is proportionate to weight. The kinetic energy to be absorbed equals one half mass multiplied by the square of velocity involved – expressing that during a crash, the amount of mechanical (kinetic) energy that must be absorbed by the impact is greater at a higher speed and mass. Further details about the energy loss in damage due to vehicles in road accidents can be found in Vangi (2009), Wood and Simms (2002) and Wood (1997).

In addition to the issue of accident potential, there are also other reasons for limiting the speed of vehicles with high GVWs, particularly the potential adverse effect high speeds of GVWs can have on road infrastructure and road maintenance costs. Road damage attributed to the effect of heavy commercial vehicles has been widely studied and documented (Cebon; 1989, 1993).

In Malaysia and some other countries, the speed limit for heavy vehicles are chosen to be lower than that of the passenger car and it is fixed for all types of heavy vehicles for simplicity and ease in regulation and enforcement .

Hence, although, there are many factors that can be associated with accident crashes, this study focuses on the speed of vehicles and attempts to explore empirically the relationship between the free flow speed and GVW especially heavy vehicle. Based on this analysis, a new concept of determining speed limit for heavy vehicle incorporating GVW is proposed.

4.2. Approach

4.2.1 Data collection

Data were collected from continuously operated weigh-in-motion (WIM) station that works in all weather conditions, 24 hours a day and 7 days a week throughout the year. The system is located on a rural single carriage-way two-lane road with straight and flat road geometry, named Federal Route 54. The basic configuration of the developed WIM system installed at the study location has been discussed in Chapter Two.

For the purpose of this study, in order to remove the influence of the surroundings and the behavior of other drivers, data were selected based on following conditions:

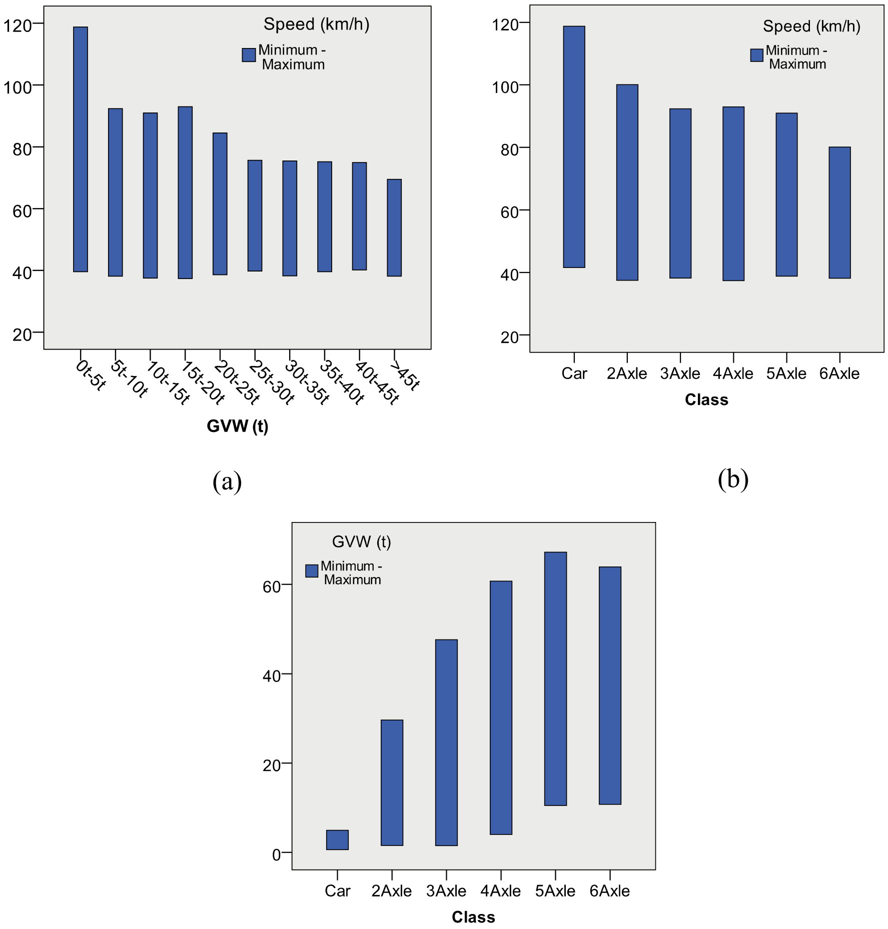
- Dry weather condition
- No change in the infrastructure and surrounding
- Vehicle speed more than 40 km/h
- Time headway more than 5 s

4.2.2 Data Analysis

The statistical analysis is categorized into two parts: (1) two-way ANOVA analysis to explore how both vehicle class and GVW effect on speed and their interaction effect, and (2) 85th percentile speed distribution analysis for finding the most appropriate speed limit when GVW is incorporated. For both cases, the speed data are grouped according to vehicle class and GVW range. In this study, according to Malaysian Road Transport Department, the heavy vehicle is classified based on their number of axle configuration.

4.3. Results

To explore the relationship among speed, class and GVW, the matrix scatter plot is plotted as shown in Figure 4.1. It can be clearly seen that the variation of speed data for every vehicle class and GVW range is considerable and the variation is decreasing as the number of axle or GVW increases. The figure also shows that the relationship between class and GVW where the same type of vehicle can have variation of GVW especially for 3-axle until 6-axle truck. To investigate whether the effect is statistically significant, two-way ANOVA analysis was carried out.



(a) (b)

(c)

Fig. 4.1. Matrix scatter plot of selected variables

Table 4.1 shows that overall there was significant effect of both class and GVW on speed, F (9, 7608)= 16.16, $p < 0.01$ and F (5, 7608)= 29.16, $p < 0.01$.

Table 4.1 Two way ANOVA test

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	376850.63[a]	42	8972.63	124.35	.000
Intercept	9762398.30	1	9762398.30	135293.34	.000
ClassNum	10519.77	5	2103.95	29.16	.000
GVWNum	10494.73	9	1166.08	16.16	.000
ClassNum * GVWNum	14923.042	28	532.97	7.39	.000
Error	548972.532	7608	72.16		
Total	3.045E7	7651			
Corrected Total	925823.16	7650			

a. R Squared = .407 (Adjusted R Squared = .404), Dependent Variable: Speed (km/h)

Figure 4.2 shows that when GVW is ignored, the mean speed is very similar among 3-axle (M = 57.58, SD = 7.38), 4-axle (M = 58.09, SD = 7.14), 5-axle (M = 59.68, SD = 7.80), and 6-axle (M = 57.98, SD = 7.15) vehicle class. However, the significant main effect of class can be seen as the increase in the mean speed for passenger car (M = 75.06, SD = 12.14), and 2-axle truck (M = 63.58, SD = 10.64). This finding seems to indicate that the vehicle category did affect the speed but not among more than 3-axle heavy vehicles.

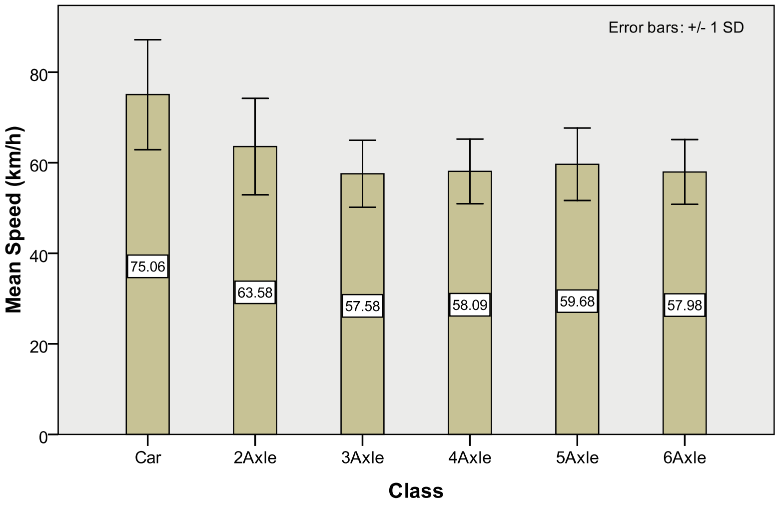


Fig. 4.2. Graph showing the main effect of vehicle class

Considering GVW, the results from the analysis also indicate that when vehicle class is ignored, the average speed of GVW range more than 20t was fairly similar while for GVW range less than 20t, the mean speed is significantly different. The meaning of this main effect can be seen in the error bar chart as shown in Figure 4.3 and the R-E-G-W-Q test as given in Table 4.2 confirms the earlier statement.

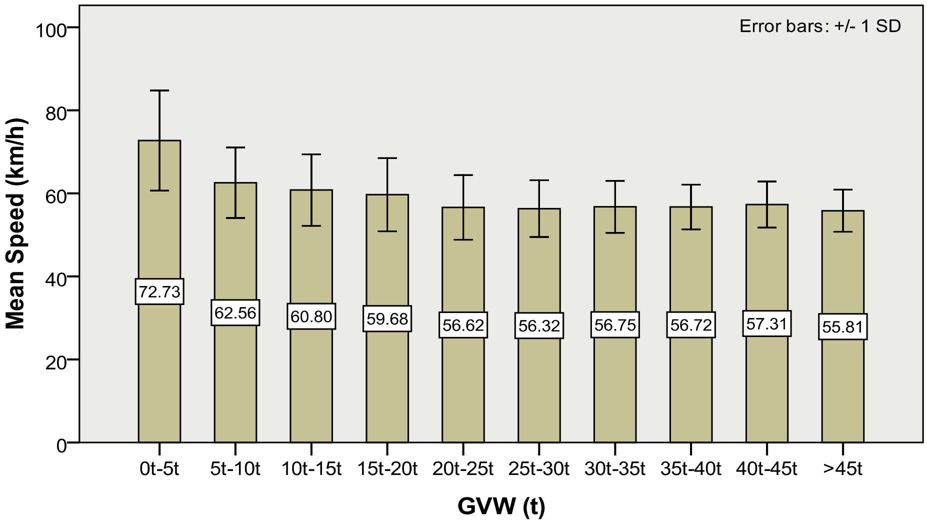


Figure 4.3 Graph showing the main effect of GVW

Table 4.2 Mean speed for groups in homogeneous subsets for GVW

	GVW (t)	N	Subset			
			1	2	3	4
Ryan-Einot-Gabriel-Welsch Range[a,,b]	>45t	373	55.8106			
	25t-30t	517	56.3237			
	20t-25t	537	56.6154			
	35t-40t	825	56.7195			
	30t-35t	632	56.7536			
	40t-45t	572	57.3061			
	15t-20t	767		59.6788		
	10t-15t	713		60.8006		
	5t-10t	693			62.5635	
	0t-5t	2022				72.7264
	Sig.		.244	.062	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square(Error) = 72.157.

a. Critical values are not monotonic for these data. Substitutions have been made to ensure monotonicity. Type I error is therefore smaller.

b. Alpha = .05.

The two-way ANOVA results in Table 4.2 also indicate that there was a significant interaction between the class and GVW, on travel speed, *F* (28, 7608) = 7.39, $p < 0.01$. The important point now is how the effect of GVW on speed is different for each category of vehicle since there is a large variation of GVW for each vehicle category as shown by the matrix scatter plot in Figure 4.1. This also reveals that the result demonstrated earlier for 3-axle to 6-axle truck (the class main effect) in which there was no significant difference in mean speed is misleading if this interaction or GVW is not taken into consideration.

Figure 4.4 shows that for each class of heavy vehicle, the mean speed varies across the GVW range. The mean speed rapidly declines with an increase in GVW until GVW is 20t and then stabilizes to a near-horizontal line.

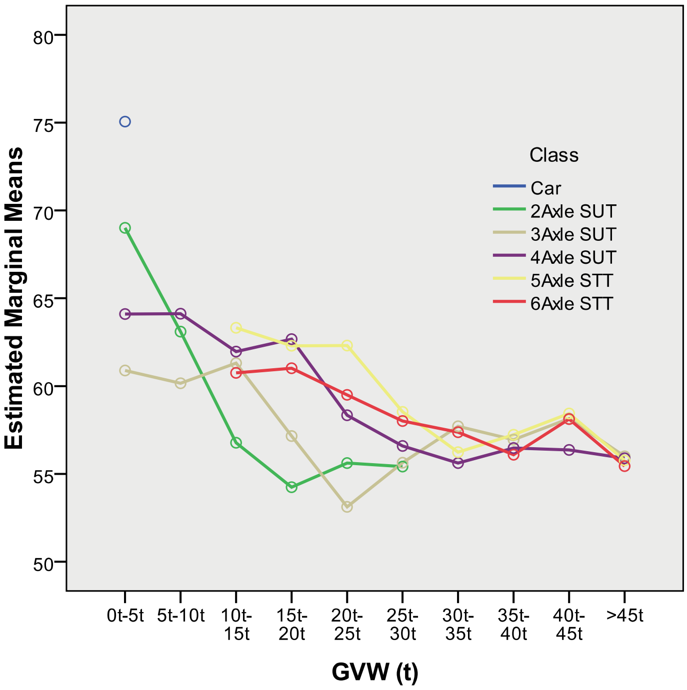


Fig. 4.4. Graph of the interaction effect

Taken together, these results suggest that the effect of GVW on speed is significant for all heavy vehicle categories and GVW can be a dominant factor that affects the mean speed regardless of heavy vehicle class.

4.4 Discussion

The results of statistical tests appear to indicate that the majority of drivers of heavy vehicles are traveling below the posted speed limit. It is also noted that the speed monotonically decreases with GVW only when a heavy vehicle has a lower GVW (i.e. in this case less than 20t) where as the speed seems to stabilize at a particular value for heavier trucks (more than 20t).

This situation would most probably be due to the driver's understanding and appreciation about heavy vehicle dynamics and stability. As such, trucks heavier than 20t in a particular heavy vehicle class are travelling at similar speeds.

Various countries have imposed different speed limit to different types of vehicles traveling on different types of road. In Malaysia, for instance, Federal and State Routes have the speed limits 90 km/h for non-commercial or light commercial vehicle and 70-80 km/h for heavy commercial vehicle. In the case of interurban expressway, the speed limits for non-commercial or light commercial vehicle and heavy commercial vehicles are 110 km/h and 90 km/h, respectively. There are also special speed limits within towns and cities.

Limiting heavy vehicle speed could reduce the severity and incidence of truck-related crashes. However, the current speed limit for heavy vehicle is fixed at certain value without considering the variation of GVW for each type of heavy vehicle. Previous research has shown that the safest group of vehicles is traveling below the 85th to 90th percentiles as the crash risk is the lowest. Figure 4.5 shows the bar graph representing the 85th percentile of speed data grouped into vehicle class and cluster by GVW. This figure indicates that the current speed limit allows the heavy vehicle with GVW more than 20t to drive above 85th percentile. This may increase accident risk and the role of having a speed limit to ensure safer driving environment is defeated. The situation becomes worse for the vehicles that are not designed for the loads they carry.

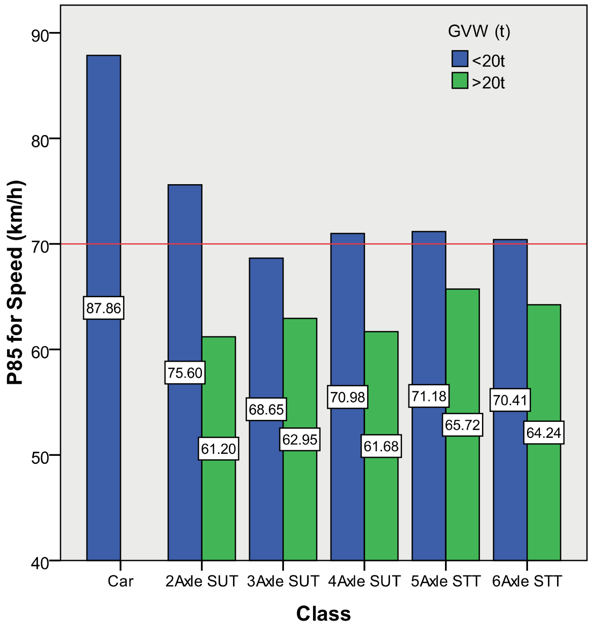


Figure 4.5 Graph shows 85th percentile for each vehicle class and cluster by GVW

Based on the results from statistical analysis above, this study proposes a new concept for setting the speed limit for heavy vehicle by incorporating GVW where a different speed limit is imposed to the heavy vehicle according to its GVW. There are various principles that have been used for setting speed limits. In this study the 85th percentile of speed distribution principle is adopted.

Figure 4.6 shows the proposed speed limit for heavy vehicle. The speed limit for heavy vehicle more than 20t is proposed to be 60 km/h in accordance to the 85th percentile principle, which is 7 km/h lower than the existing speed limit. The speed limit remains at 70 km/h for heavy vehicle having GVW of less than 20t.

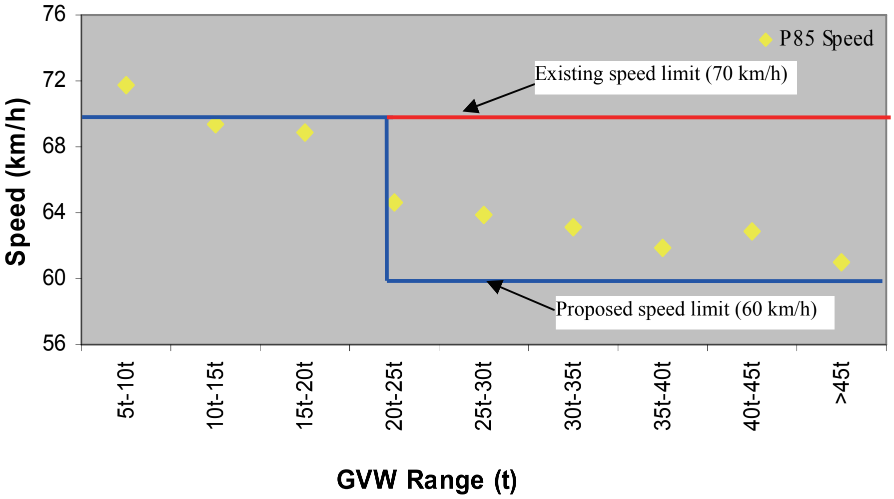


Fig. 4.6. The proposed speed limit for heavy vehicle incorporating GVW

As given by LTSA Online, (Year Unknown), the example shows that the overturning forces acting on a truck driven through the same corner in a 90 km/h and 30 km/h will be nine times higher and has a dramatic impact on vehicle stability and controllability. In addition, according to Fancher et al., (1986), for loaded single unit trucks, a speed increase from 35 miles/h (56.3 km/h) to 40 miles/h (64.4 km/h) will increase braking distance by about 23%. Thus, setting lower speed limits for a heavy vehicle over 20t at 60 km/h will have an impact on road safety considering such risks.

From the enforcement point of view, with the advancement in transport data measurement system and the introduction of weigh-in-motion technology, it is possible to implement weight based speed limit enforcement. The weigh-in-motion sensor, especially quartz piezoelectric weigh-in-motion sensor would be the most appropriate sensor for measuring the speed, class and weight simultaneously and accurately in real-time.

In addition, because this study investigated the relationship using empirical data on a location along one road category (Federal Route 54), other freeway systems need to be investigated so that a more generic and confident analysis on the relationship can be achieved.

CHAPTER 5

EMPIRICAL ANALYSIS ON THE EFFECT OF GROSS VEHICLE WEIGHT AND VEHICLE SIZE ON SPEED IN CAR FOLLOWING SITUATION

5. 1. Introduction

Vehicle as one of the important element in a traffic stream is completely a dynamic system. Equation of motions of vehicle dynamics can be found in many references related to fundamental of vehicle dynamics such as Wong (1993) and Jazar (2008), which are derived analytically from Newton's fundamental law. From macroscopic approaches, traffic stream models, either in two-variable or in three-variable models, is the relationship among speed, flow (vehicles/hour), and concentration (whether density or occupancy) (Gartner N. H. et. al., 1992). Values of these variables of interest are obtained as a function of many implicit factors including vehicle dynamics. Thus, it can be said that implicitly vehicle dynamics is considered in the model development.

On the other hand, microscopic traffic flow models focus on a single vehicle-driver unit. To date, one of the popular topics among the family of microscopic traffic models is a car-following model (Brackstone and McDonald, 1999). In deriving the models, the previous researches have made many assumptions to greatly simplified by merely describing the driving strategies of drivers in response to the leading vehicles.

As mentioned in Wang et. al., (2008), car following strategies can be divided into two classes: the driver is assumed to maintain a safe distance to the leading vehicle by controlling his own speed (Chandler et al., 1958), and the desired speed of the following vehicle depends on the gap distance with respect to the leading vehicle (Bando et al., 1995). In order to reach good agreement with the field data, many improvements have been done to both classes of the model among them are introducing sensitivity function (Chung. et al, 2005; Chang and Chon, 2005), considering the headway of the immediately preceding one (Sawada, 2002), considering the effect of environments on driver behavior in a car-following situation (Ni et al., 2010), considering the effect of curve or intersection (Suzuki et al., 2005) and considering the effect of driving style due to the different compositions of a leader-follower pair (Ossen and Hoogendoorn, 2011).

However, the previous researches only address the modeling of car-following situation arising from driver behavior perspective. The characteristics of the vehicle such as performance, braking and acceleration capability is assumed to be same for all type vehicles and for different compositions of a follower-leader pair in the model development. The main reason is in the past it is difficult to obtain the weight, speed, acceleration and classification data simultaneous and continuously over the period of time without disrupting the natural way of traffic flow.

As mentioned in Wong (1993), the behavior of a ground vehicle represents the results of the interactions among the driver, the vehicle, and the environment. Most of the time the vehicle dynamics influence drivers behavior in controlling their vehicles. Thus, the model can be improved to be more realistic if the vehicle dynamics is incorporated.

In this study, among other factors that can affect the vehicle dynamics, this study attempts to explore and to provide a valid empirical evidence that following vehicle (FV) GVW and leading vehicle (LV) size will affect the driver behavior in controlling their speed under different compositions of leader-follower pairs (different weight of followers follows different size of leaders) in a car-following situation.

The vehicle weight is one of the essential parameters in vehicle design study that can affect vehicle driving, braking and handling performance characteristics (Bixel et al, 1998). The effect of weight on commercial vehicle performance is more considerable compared to a non-commercial vehicle. In discussing on the development of the relationships or empirical models, the link with measurement capability of a transport data collection system is very important in order to have a practical and realistic model.

The emerging technology in a measurement field recently is undoubtedly changing the way some traffic measurements are obtained and will likely provide the opportunity for acquiring more and better data to further advance understanding of the fundamental issues. One of the most difficult tasks related to measurement capability is to obtain weight data of moving vehicle. The only prominent technology used to obtain weight data is weigh-in-motion (WIM) technology. For the purpose of this study, a comprehensive, accurate and reliable traffic and vehicular data collection system using quartz weigh-in-motion sensor has been developed for measuring the speed, class, GVW, time headway and other traffic and vehicular data simultaneously and continuously 24 hours and 7 days.

5.2. The Data Collection System

The quartz WIM sensor is used to measure related traffic and vehicular data and schematic diagram of the developed system has been presented in Chapter Two. The data-collection system was installed on Federal Route 54 which located 35 km from the city center and the traffic direction move from city to a rural area. Road type is rural single carriageway with standard width and layout and road geometry is a straight and flat road. The traffic composed of high proportion of a commercial and non-commercial vehicle.

5.3. Results

The following behavior of a driver can be affected by various internal factors and its surrounding such as driver’s condition and vehicle dynamic characteristics, and changes in roadside infrastructure, traffic condition, road geometry condition and sight distance due to weather and day or night condition. Because the objective of this study is to provide a valid empirical evidence that following vehicle (FV) GVW and leading vehicle (LV) size affect the following behavior, real data should be carefully selected to minimize the errors caused by changes in the surroundings. In addition, the collected real data is a mixture of restrained and unrestrained vehicles. The analysis should only consider the case of restrained vehicles where the follower and its leader have influence on each other.

A total of more than 500,000 data was collected in four months from the system. For the purpose of this study, in order to remove the influence of the surroundings and concentrate on the driver behavior in a car-following situation, data were filtered based on following conditions:

- Dry weather condition
- Daytime from 7am (after sunrise) and before 7 pm (before sunset)
- No change in the infrastructure and surrounding at the site

- Time headway less than 4 s (assuming the follower and its leader have influence on each other if the time headway is less than 4s)

After the filtered, total number of samples reduced to 61,381. The speed data (FV speed and relative speed) are then grouped according to FV GVW and LV wheelbase (19 FV GVW range and 3 LV wheelbase range, as wheelbase directly related to vehicle size). There are total 57 groups of data. Normal test has been performed for each group of data and all data can be considered having normal distribution with slightly different in Skewness and Kurtosis. Number of sample for each group is given in Table 5.1.

Table 5.1 Number of sample of each group

GVW Range (t)	<2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15	15-17.5	17.5-20	20-22.5	22.5-25	25-27.5	27.5-30	30-32.5	32.5-35	35-37.5	37.5-40	40-42.5	42.5-45	>45
Case1	10986	3913	3807	1512	1307	1461	1363	786	429	382	372	276	309	430	519	435	365	227	253
Case2	10921	2402	965	400	336	372	357	229	168	151	156	115	120	210	201	216	144	113	121
Case3	8998	1993	508	249	196	245	232	164	133	147	144	117	154	267	311	262	203	108	121

To simplify the results generation and analysis, the analysis is divided into three cases according to LV wheelbase range as mentioned earlier and is shown in Table 5.2.

Table 5.2 Three cases according to LV wheelbase range

	LV Wheelbase		
	<3m (Small size)	3-5m (Medium size)	>5m (Large size)
FV Speed (All FV GVW Range)	Case 1	Case 2	Case 3

5.3.1 Analysis on Speed of Following Vehicle

The line plots of mean and standard deviation of following vehicle speed as a function of GVW for all cases (following various sizes of leading vehicle) are shown in Figure 5.1 and 5.2.

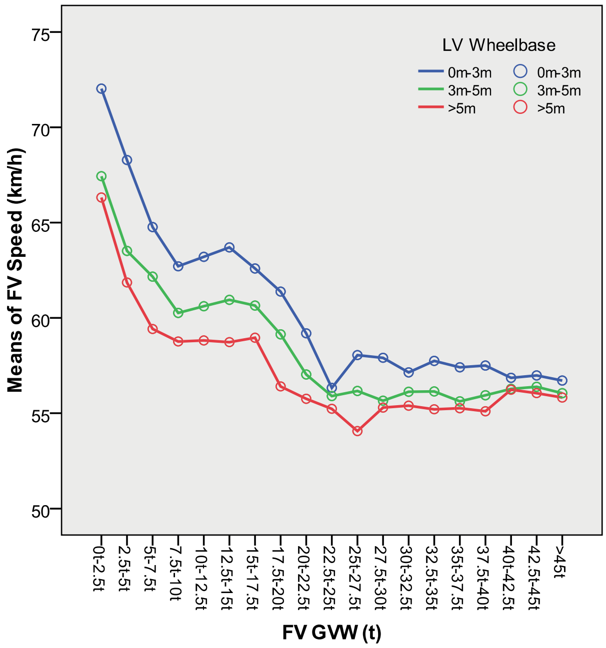


Figure 5.1 Means plot of FV speed for all cases

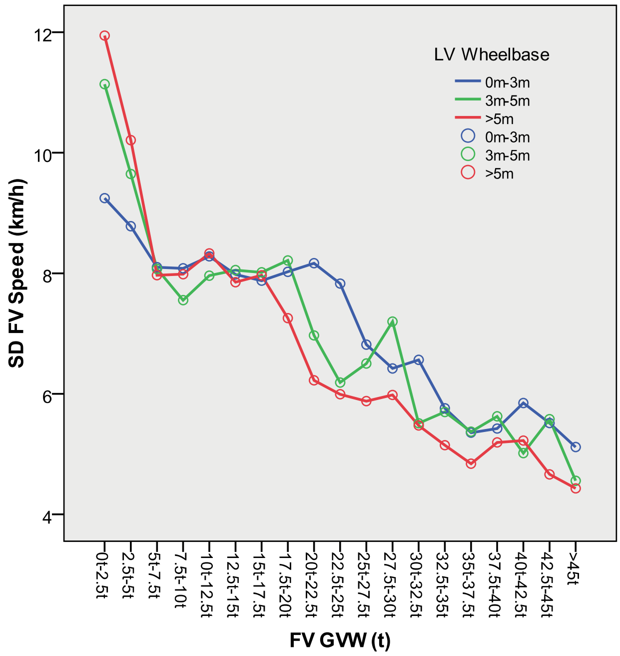


Figure 5.2 Standard Deviation plot of FV speed for all cases

The relationship is based on the assumption that a linear relationship exists between the mean of FV speed and the logarithm of the mean FV GVW, and between the standard deviation of FV speed and the mean of FV GVW as express in Equation (1).

$$\begin{aligned} \mu_{FV} &= C_1 \log w + C_2 \\ \sigma_{FV} &= C_3 w + C_4 \end{aligned} \qquad (1)$$

where μ_{FV} and σ_{FV} are means and standard deviation of FV speed and w is FV GVW. Coefficients of the regression lines, C_i where $i=1,2,3,4$ in Equation (1) and coefficients of determination, R^2 for all cases can be described as in Table 5.3:

Table 5.3 Regression coefficients with p-value and coefficients of determination of the FV mean and standard deviation speed

	C_1	C_2	C_3	C_4	R^2 (Means)	R^2 (SD)	N
Case 1	-10.355	73.505	-.089	9.223	.939	.907	19
(p-value)	<0.001	<0.001	<0.001	<0.001			
Case 2	-7.791	68.274	-.109	9.600	.922	.841	19
(p-value)	<0.001	<0.001	<0.001	<0.001			
Case 3	-6.792	65.797	-.130	9.859	.881	.847	19
(p-value)	<0.001	<0.001	<0.001	<0.001			

Regression coefficients in Table 5.3 indicate that an exponential relationship between mean of FV speed and FV GVW. In this case, mean of FV speed decreases very rapidly as mean of FV GVW first increases, but then decreases much less rapidly as mean of GVW increases further. The value of coefficients also indicates that the estimation of intercept and slope may change under different cases (Case 1 to Case 3), but the forms of the relations should remain valid.
In case of standard deviation, a negative straight-line or linear relationship between standard deviation of FV speed and FV GVW. However, there were some differences in the gradients of regression lines for all three cases. In the case where light vehicles follow small size vehicles, the speed variation is substantially lower than when they follow large size vehicles. This situation is different for a heavy vehicle. The speed variation is small when heavy vehicles follow large size vehicles compared to small size vehicles.

Table 5.3 also indicate that the estimate of the slope and intercept for Equation (1) is significantly different from zero and the model adequately described the data (for each case, $p < 0.001$).

5.3.2 Analysis on Relative Speed

In the previous subsection, the effect of LV speed on a car-following situation was not taken into consideration. By assuming that the leading vehicle was constantly speeding at the recorded speed after passing through the sensor until the following vehicle touches the sensor, the effect of FV GVW and LV size on relative speed in car following situation can be performed. The relative speed in this study is defined as follows:

$$\Delta V = V_{LV} - V_{FV} \qquad (2)$$

where V_{LV} and V_{FV} are speed of leading and following vehicle, respectively.

The line plots of mean and standard deviation of relative speed as a function of GVW for each case are shown in Figure 5.3 and 5.4.

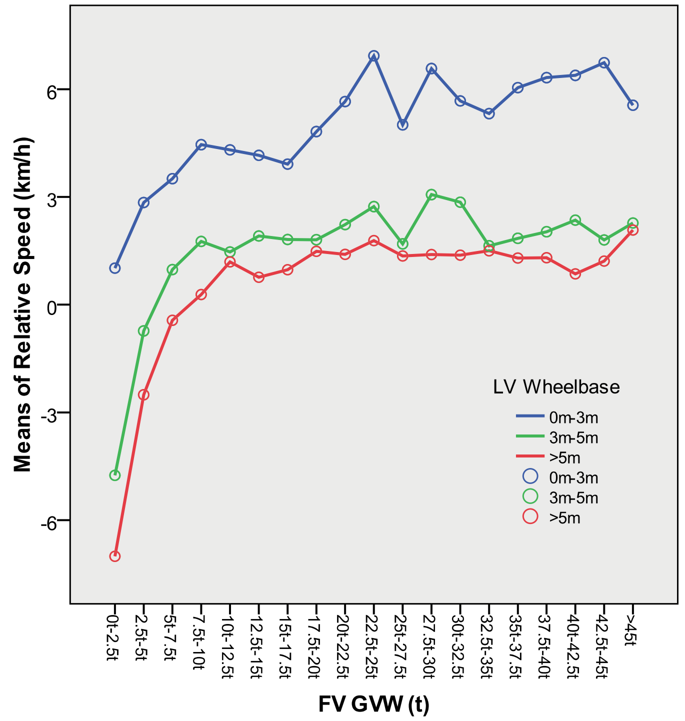


Figure 5.3 Means plot of Relative Speed for all cases

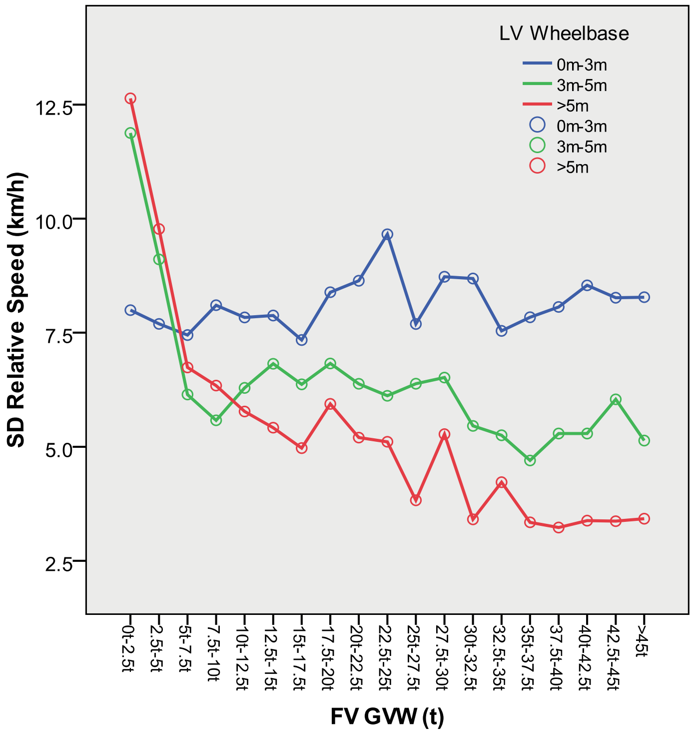


Figure 5.4 Standard deviation plot of Relative Speed for all cases

For the case of relative speed, the relationship is based on the assumption that a positive curvilinear relationship exists between both the mean of FV GVW and the relative speed, and the standard deviation of relative speed and the mean of FV GVW as express in Equation (3).

$$\begin{aligned} \mu_{\Delta V} &= D_1 \log w + D_2 \\ \sigma_{\Delta V} &= D_3 \log w + D_4 \end{aligned} \qquad (3)$$

where $\mu_{\Delta V}$ and $\sigma_{\Delta V}$ are means and standard deviation of relative speed and w is FV GVW. Coefficients of the regression lines, D_i where $i=1,2,3,4$ in Equation (3) and coefficients of determination R^2 for all cases can be described as in Table 5.4:

Table 5.4 Regression coefficients with p-value and coefficients of determination of mean and standard deviation of relative speed

	D_1	D_2	D_3	D_4	R^2 (Means)	R^2 (SD)	N
Case 1	3.355	.816	.426	7.604	.843	.099	19
(p-value)	<0.001	=0.094	=0.190	<0.001			
Case 2	3.546	-2.921	-3.391	10.640	.724	.733	19
(p-value)	<0.001	<0.001	<0.001	<0.001			
Case 3	4.484	-5.066	-5.621	12.367	.784	.929	19
(p-value)	<0.001	<0.001	<0.001	<0.001			

Regression coefficients in Table 4 indicate that the means of relative speed is increasing rapidly as the means of FV GVW increases, but this increase tapers off beyond certain values of mean FV GVW (i.e. in this case 10 tonne).

For the case of standard deviation, the coefficients of determination and the p-value of the slope coefficient for Case 1 indicate that the slope coefficient is not significantly different from zero and the relative speed is not affected by FV GVW. However, the situation is different for Case 2 and Case 3, where the variance of relative speed decreases very rapidly as mean of FV GVW first increases, but then decreases much less rapidly as mean of GVW increases further.

Table 5.4 also indicate that the estimate of the slope and intercept for Equation (3) is significantly different from zero and the model adequately described the data (for each case, $p < 0.001$ except for Case 1 standard deviation).

5.4. Discussion

The main findings of this study are when we incorporate the vehicle dynamic's capability in a car-following situation, the GVW of following vehicle and the size of leading vehicle were significant sources of variation in FV speed and relative speed, and their interaction influence the driver behavior in controlling the speed. More specific, indications are found that the driver's ability to achieve its desired speed is not only impeded by leading vehicle size and leading vehicle speed but also constrained by its vehicle weight.

In vehicle design study (as given in the aforementioned reference), the vehicle weight directly affects a variety of vehicle characteristics, including traction, braking and handling characteristics. Thus, most countries imposed additional requirements or training to heavy vehicle drivers. The following subsections provide more details discussion of the results of statistical tests.

5.4.1 Effects on Speed of Following Vehicle

The results indicate that average speed of FV is decreasing with an increase in its GVW would most probably due to the driver's understanding the heavy vehicle limitations and/or may also due to the heavier vehicle has fewer dynamic performance capabilities. In case where following vehicles follow various sizes of leading vehicles, the average speed of FV also decreases with an increase in LV size. This may due to the large size vehicle can obstruct the visibility of the driver beyond LV and/or FV being impeded by LV speed because vehicle size is inversely proportional to the speed. The same phenomena can be observed for heavy vehicle.

Results from linear regression also show that the variance of FV speed decreases with an increase in FV GVW, which may also due to vehicle dynamic's limitations. The speed variance of light FV is larger when follow large LV in comparison to follow small LV. However, the results show a reverse effect when heavy vehicles follows various sizes of LV as shown in Figure 5.2. The speed of heavy vehicles has less variance when follow large LV compared to small LV. One possible reason of the observed is that light or small vehicles have better performance capability, which may allow the driver to accelerate or decelerate faster. The following subsection further discusses the results when LV speed is taken into consideration.

5.4.2 Effects on Relative Speed

Regression plots of an average relative speed show that for Case 1 (following small size vehicle), the relative speed increase as mean of FV GVW increases. The results obviously show that light vehicles do not have difficulty achieving its desired speed or maintain closely with LV speed. However, for heavier vehicles, the drivers are constrained by its vehicle dynamic's capability and the positive values of the average mean relative speed show that most of the time they are unimpeded by the speed of their small size leading vehicles.

Furthermore, we can also observe that when light vehicles follow medium or large size vehicles, their average speed is slightly higher than the leader may because, with better dynamic's capability, they were trying to follow the leader speed (especially when the gap distance allows them to accelerate) or in a process of attempting to overtake the leading vehicle.

But why, then did heavy vehicles when follow small size vehicles have the same variation of relative speed as given in Figure 5.4? We postulate that result can be explained as light and small vehicles the drivers do not being constrained by its vehicle performance capability cause them to drive as they like. There are a situation where the follower keeps away from the leader (positive relative speed) or the follower accelerates to get close to the leader (negative relative speed). But in the case of heavy vehicles following small size vehicle, the relative speed variation mainly caused by the loading that they carried. If the loading is within the vehicle design specification, the heavy vehicle drivers are able to achieve their leader speed or impeded by them as long as the leader speed is within their maximum vehicle capability. However, most of the cases, as shown in Figure 3.2, in Malaysia, each vehicle class (according to the number of axle and wheelbase) can have large variation in GVW. For instance, there appear a difference in dynamic capability between 3 axle trucks and 5 axle trucks when both carry 50 tonne loads. Because of constraints in it dynamic's capability, obviously the driver of 3 axle trucks cannot drive at the same speed as 5 axle trucks. This cause a variation in relative speed when they follow a passenger car even though in both situations they are not always impeded by leader speed. The sketch of the proposed relationship among FV speed and GVW, and LV size, and among relative speed, FV GVW and LV size are given in Figure 5.5 and 5.6.

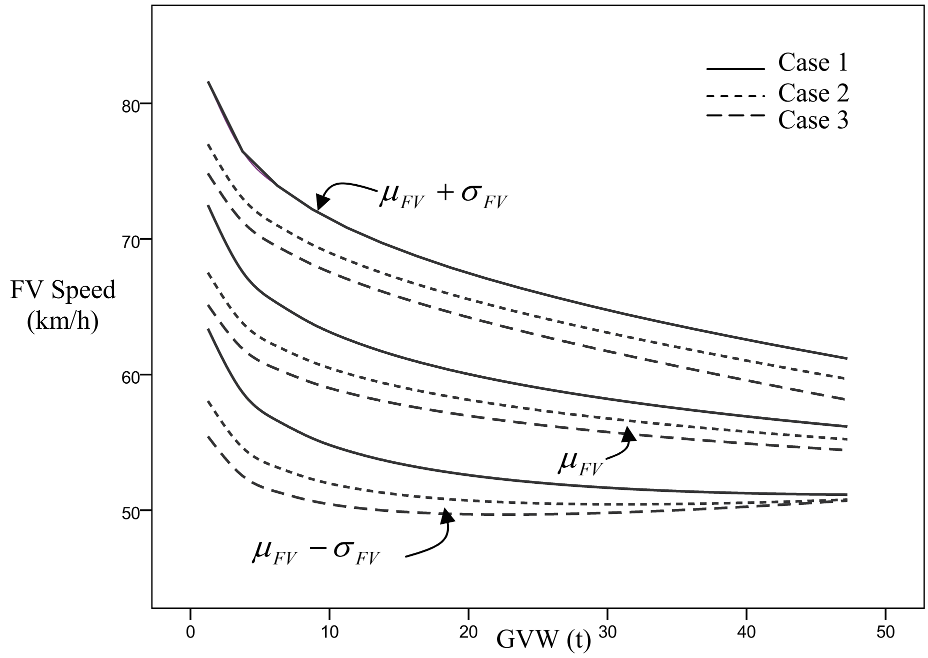


Figure 5.5 The proposed relationship among FV speed, FV GVW and LV size

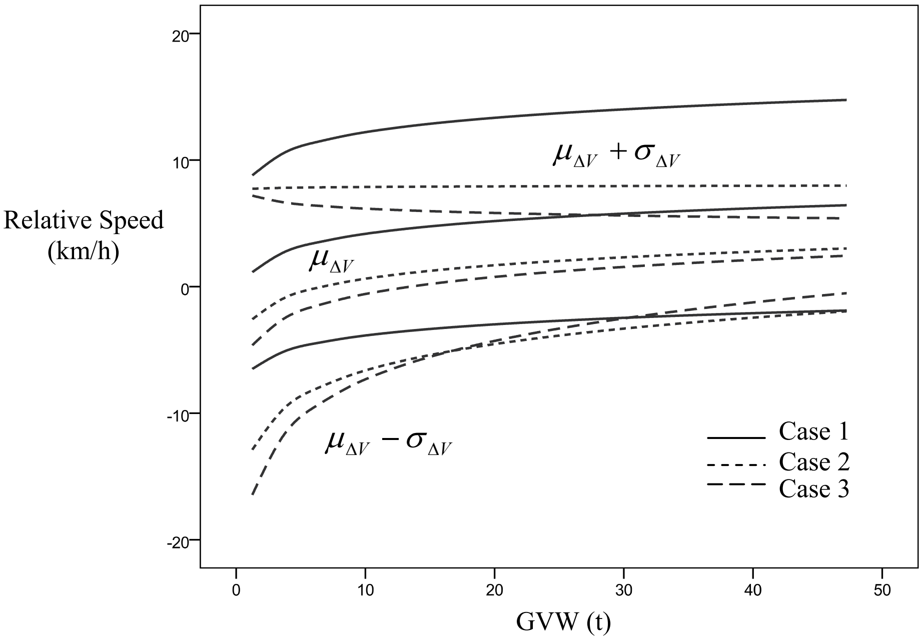


Figure 5.6 The proposed relationship among relative speed, FV GVW and LV size

CHAPTER 6

THE EFFECT OF GROSS VEHICLE WEIGHT AND VEHICLE SIZE ON HEADWAY CHARACTERISTICS IN VEHICLE FOLLOWING SITUATION

6.1. Introduction

Much research has been conducted to understand the headway characteristics in a vehicle following situation. Headway is defined as the time that elapses between consecutive vehicles and it is considered as one of the safety-related parameters in a traffic study. Short headways are always associated with a large number of rear-end crashes and also with some other types of crashes. Knipling et. al. (1993) stated that the main causal factors of rear-end collision are inattention and following too closely. Study by Micheal et. al. (2000) also stated that 28.3% of rear-collisions in Tennesse in 1997 were because of closed following. There are many other studies provide empirical evidence to support the connection between short headway and rear-end collisions (Evans and Wasielewski, 1982; Postans and Wilson, 1983; Fairclough et. al., 1997). With the increase of in-vehicle electronic gadget for information and entertainment, the risk of rear-end collisions may increase in the near future.

Many countries have imposed the rules and practices concerning the minimum safe distance between two vehicles on roads to prevent front-end and rear-end collision. In most countries in Europe, the general rule is that each driver must keep sufficient distance with leading vehicle and the 2-second rule is often used as a rule of thumb in Traffic Law and Rode Code, and taught at driving schools (CEDR Report, 2010). For instance, in Netherlands, fines can be imposed if the distance between the two vehicle is less than 1 second. In Norway, for vehicle weighing more than 3.5 tons, a distance of between 0.5 to 1 second leads to a suspension of the license for 3 to 6 months. In South Australia, the Driver's Handbook describes 2 seconds as reasonably safe distance (Hutchinson, 2008).

Most countries mentioned earlier have imposed different and specific rules for heavy vehicles (HV) which generally the headway distance is double. Since the characteristics of the HVs such as performance, braking and acceleration capability is different depending on its size and weight, their existence in a traffic stream will definitely cause a significant difference in the vehicle-following behavior. For instance, there are many studies about passenger car equivalent (PCE) factors using headway approach suggest PCE values greater than one when considering HV or introduce HV adjustment factor (Ahmed, 2010 and the reference therein; Kockelman, 2000).There are also studies conducted previously to investigate the effect of HV on driving following behavior (Sayer et al, 2000; Harb et al, 2007).

Although headway differences were identified in the previous research depending on whether a PC leads or lags a HV, there was no detail investigation related to HV gross vehicle weight (GVW), but, rather, on HV size or class only.

As mentioned by Bixel et. al. (1998), the vehicle weight is one of the essential parameters in vehicle design study that can affect vehicle driving, braking and handling performance characteristics. Furthermore, most of the time the vehicle dynamics influence driver behavior in controlling their vehicles (Wong , 1993). The study by Saifizul et. al. (In Press) and Saifizul et. al. (2011) has obviously shown that HV GVW has direct influence on speed, whether the vehicle travel in a vehicle following situation or in free flow condition. Thus, it is important to extend the study on the influence of both HV GVW and its class or size on headway in a vehicle following situation to further understand the subject not only from the driver visual input perspective but as well as vehicle dynamics capability perspective.

6.2. Data Collection and Preparation

Headway data together with all other traffic and vehicular data such as GVW, wheelbase and vehicle class were collected from the developed weigh-in-motion (WIM) system that operated continuously throughout the year. The system has been installed one of the federal roads where the road type is rural single carriageway with standard width, and layout, and geometry is a straight and flat road as shown in Fig. 6.1 and Fig. 6.2. Further elaboration of the developed system has been presented in Chapter Two.

In this study, a total of more than 500,000 data was collected in four months from the system. However, in order to remove the influence of the surroundings and focus on the driver behavior and vehicle performance capability in a vehicle following situation, data were filtered based on following conditions:-

- Dry weather condition
- Daytime from 7am (after sunrise) and before 7 pm (before sunset)
- No change in the infrastructure and surrounding at the site
- Time headway less than 4 s (assuming the follower and its leader have influence on each other if the time headway is less than 4s)

By limiting the number of sample consisting of small relative speed between leading and following vehicle, the data that passed the filtering stage of this study consisted of 49,725 observations. The headway data are then grouped according to leader-follower pair composition, GVW and vehicle class (in this study the heavy vehicle is classified based on their number of axles). To simplify the results generation and analysis, the analysis is divided into three cases of leader-follower pairs composition, and the specific hypotheses are then introduced in this paper for each case, and they are given as in Table 6.1.

Table 6.1 Hypotheses table

	Following Situation	Hypothesis
Case 1	PC-Truck pairs with leading PC	GVW of following vehicle (FV) may significantly affect the headway characteristics of PC-truck pairs with leading PC in car following situation.
Case 2	PC-Truck pairs with lagging PC	Vehicle class of leading vehicle (LV) may significantly affect the headway characteristics of PC-truck pairs with lagging PC in car following situation.
Case 3	Truck-Truck pairs	Both GVW and vehicle class of lagging and leading vehicle, respectively may significantly affect the headway characteristics of truck-truck pairs in car following situation.

6.3. Data Analysis

There are a total of 50 groups of data to investigate the three hypotheses and the number of samples for each group is given in Table 6.2.

Table 6.2. Number of sample for hypotheses analysis

	FV GVW (t)	FV Class					Total
		2Axle	3Axle	4Axle	5Axle	6Axle	
Case1	10-20	1113	1514	2017	196	74	17492
	20-30	462	543	360	63	31	
	>30t	17	1462	977	66	17	

	LV GVW (t)	LV Class					
		2Axle	3Axle	4Axle	5Axle	6Axle	
Case2	10-20	1776	1655	2039	193	85	21742
	20-30	927	1042	516	82	49	
	>30t	48	2378	1935	102	72	
	FV GVW (t)	LV Class					
		2Axle	3Axle	4Axle	5Axle	6Axle	
Case3	0-10	2607	1085	896	72	25	10491
	10-20	1206	491	398	26	6	
	20-30	521	363	218	22	5	
	>30t	925	1091	499	26	9	

At first, to show the general effect of different composition of leader-follower pairs on headway, the box plot for all cases is plotted as shown in Fig. 6.1.

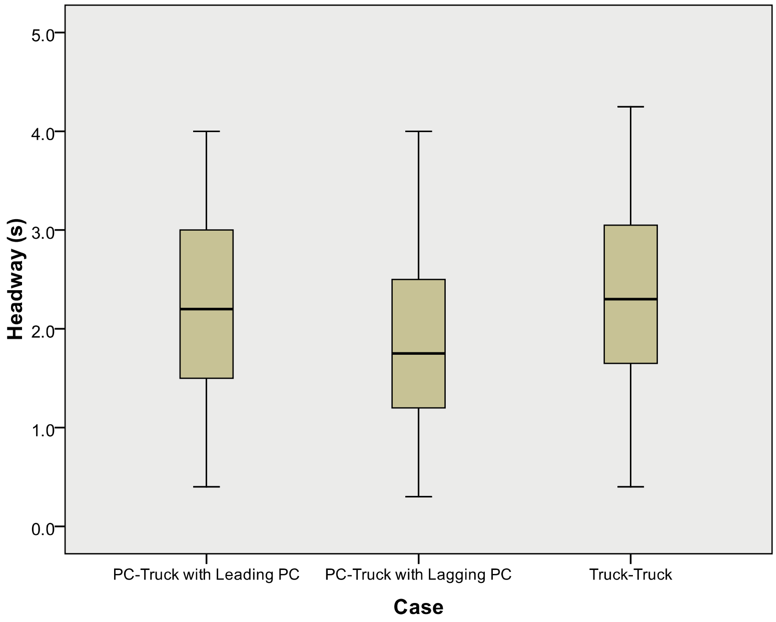


Fig. 6.1. Graph showing box plot of headway for all cases

To investigate whether the effect of LV class and FV GVW on headway for each case is statistically significant, data analysis was conducted using a parametric tests. Since the headway data for each group were distributed in a highly skewed pattern, the data were subjected to a square-root transformation. Then, using transformed data, the two-way ANOVA analysis was carried out as given in the following subsection.

6.3.1 Analysis on Case 1

This case investigates the effect of lagging truck GVW and class on headway in PC-truck pairs following composition. The two-way ANOVA results in Table 6.3 indicate that there was a dominant significant effect of FV GVW on headway, F (3, 17472)= 9.71, p < 0.001 and with less significant effect of FV class on headway, F (4, 17472)= 2.50, p = 0.040.

Table 6.3. Two-way ANOVA test for Case 1

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	75.179[a]	19	3.957	54.811	.000
Intercept	1362.144	1	1362.144	18869.122	.000
ClassNumFV	.722	4	.180	2.500	.040
GVWNumFV2	2.104	3	.701	9.714	.000
ClassNumFV * GVWNumFV2	3.320	12	.277	3.833	.000
Error	1261.287	17472	.072		
Total	51562.450	17492			
Corrected Total	1336.466	17491			

a. R Squared = .056 (Adjusted R Squared = .055)

b. Case = PC-Truck with Leading PC, Dependent Variable:Headway (s)

The line plots of mean headway in Case 1 as a function of FV class and in a cluster of FV GVW range is shown in Fig. 6.2.

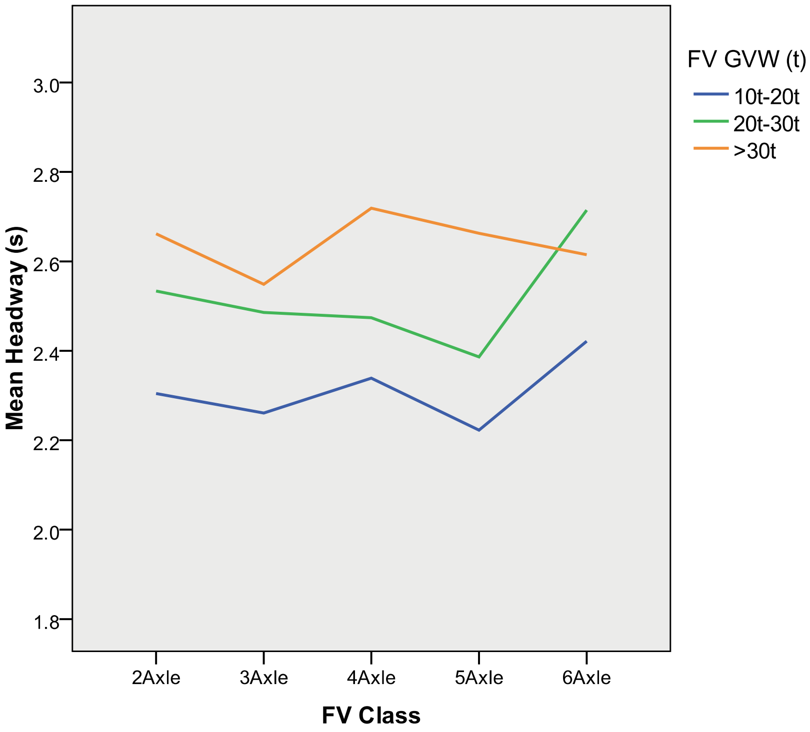


Fig. 6.2. PC-Truck pairs with leading PC

It can be clearly seen that for the same truck class, in the case where light trucks follow PCs, the mean headway is substantially lower compared to heavy trucks follow PCs. This indicates that the FV GVW is a dominant factor that affect the mean headway regardless of FV class in the Case 1 scenario.

6.3.2 Analysis on Case 2

For Case 2, the effect of leading truck class and GVW on headway in PC-truck pairs following composition is investigated. The two-way ANOVA results in Table 6.4 indicate that the GVW of leading truck has no significant effect on headway, *F* (3, 21722)= 0.84, *p* =

0.471. However, the effect of leading truck class is significant, F (4, 21722)= 4.81, $p = 0.001$ and as shown in Fig. 6.3, the mean headway for every vehicle class is increasing as the number of axle increases.

Table 6.4. Two-way ANOVA test for Case 2

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	15.885[a]	19	.836	11.899	.000
Intercept	1842.047	1	1842.047	26217.780	.000
ClassNumLV	1.351	4	.338	4.809	.001
GVWNumLV2	.177	3	.059	.841	.471
ClassNumLV * GVWNumLV2	1.612	12	.134	1.912	.028
Error	1526.176	21722	.070		
Total	56889.050	21742			
Corrected Total	1542.061	21741			

a. R Squared = .010 (Adjusted R Squared = .009)

b. Case = PC-Truck with Lagging PC, Dependent Variable:Headway (s)

The line plots of mean headway of following PC following various classes and ranges of GVW is shown in Fig. 6.3.

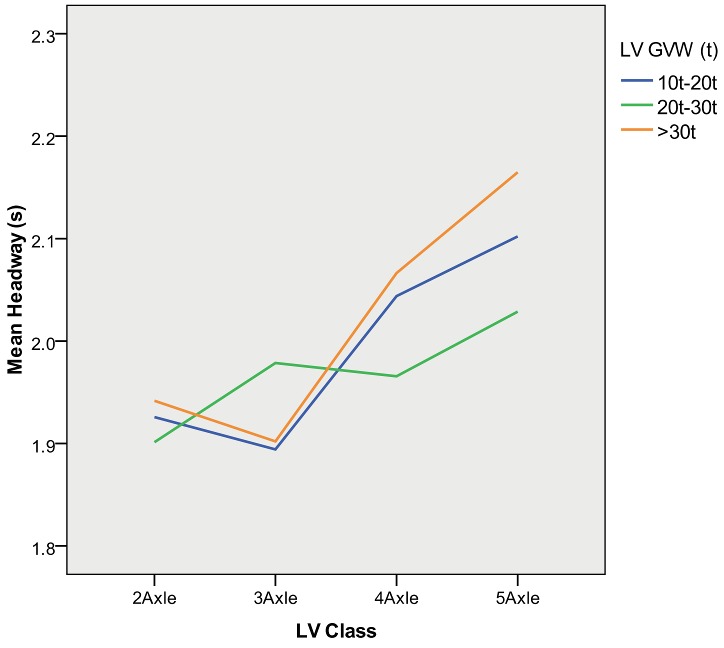


Fig. 6.3 PC-Truck pairs with lagging PC

6.3.3 Analysis on Case 3

In this case where trucks follow trucks, results from two-way ANOVA show that both LV size and FV GVW apparently have significant effect on the headway as shown in Table 6.5, F (4, 10471)= 13.61, $p < 0.001$ and F (3, 10471)= 23.64, $p < 0.001$.

Table 6.5. Two-way ANOVA test for Case 3

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	51.557[a]	19	2.714	45.205	.000
Intercept	1886.211	1	1886.211	31422.636	.000
ClassNumLV	3.267	4	.817	13.606	.000
GVWNumFV2	4.256	3	1.419	23.635	.000
ClassNumLV * GVWNumFV2	.197	12	.016	.274	.993
Error	628.544	10471	.060		
Total	31992.700	10491			
Corrected Total	680.101	10490			

a. R Squared = .076 (Adjusted R Squared = .074)

b. Case = Truck-Truck, Dependent Variable:Headway (s)

As shown in Fig. 6.4, headway of light weight follower trucks was apparently shorter than those of medium weight trucks, which in turn were shorter than heavy truck headway when following the same class of trucks. Also, mean headway of light weight trucks varies when following different class of trucks and differences in headway between two axle and six axle leading trucks are increasing for medium and heavy follower trucks.

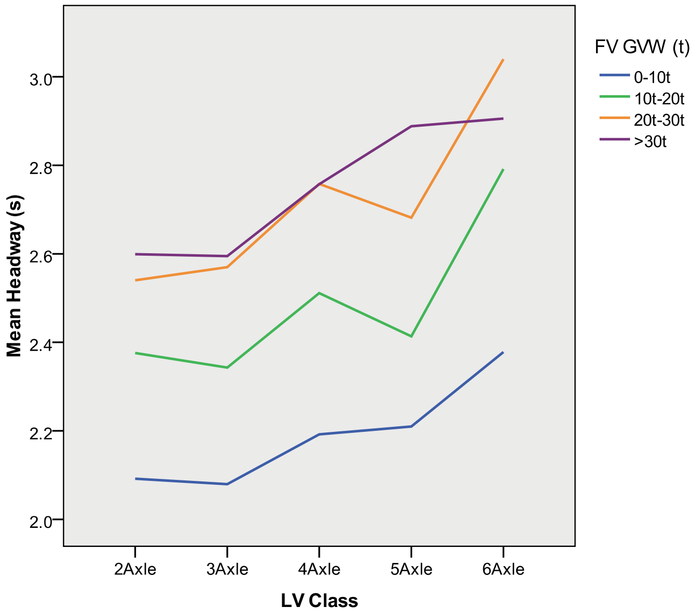


Fig. 6.4 Truck-Truck pairs

6.4. Discussion

Presence of HV in the traffic stream obviously has a significant impact on headway characteristics. This study aims to make a preliminary analysis of the influence of HV size and its GVW on headway characteristics in a vehicle following situation and then provide a preferred minimum headway model incorporating both factors. Empirical evidence from this study quantifies that under near optimal driver condition with small relative speed, both FV GVW and LV class has a direct impact on headway, and they can be used to confirm the following hypotheses as shown in Table 6.6.

Table 6.6 Hypotheses results

Hypothesis	Result
GVW of FV may significantly affect the headway characteristics of PC-truck pairs with leading PC in car following situation.	Confirmed
Vehicle class of LV may significantly affect the headway characteristics of PC-truck pairs with lagging PC in car following situation.	Confirmed
Both GVW and vehicle class of lagging and leading vehicle, respectively may significantly affect the headway characteristics of truck-truck pairs in car following situation.	Confirmed

The result from first hypotheses is consistent with the past research where HV has been identified to have operating capabilities that inferior to those of PC, thus requiring longer headways. However, the effect of FV GVW on headway of different composition of leader-follower pairs has not been addressed in past research. This may be due to limited measurement capabilities or lack of sufficient data. The empirical investigation in this study also leads to the observation that, it is FV GVW rather than FV class or size that affects HV headway and GVW should be considered as one of the variables of interest in a vehicle following study. The situation is mainly due to HV performance capability (acceleration/deceleration) especially considering drivers knowledge on stopping distance requirement. Most of the drivers notice that the heavier the load they carry, the longer the headway they need in order to have adequate stopping distance and to avoid rear-end collision.

The second hypothesis investigates the effect of LV class or size on FV headway. This study confirmed that, in the case of PC-tuck pairs with lagging PC following composition, the class of LV is a dominant factor that affects the headway as compared to LV GVW. As mentioned earlier, the size of leading truck may make it impossible for the following drivers in smaller vehicles to see the traffic ahead. Since the drivers' sight view is restricted by LV size (the following section will show that from observed data the truck number of axles is proportionate to its wheelbase which in turn proportionate to its size), the drivers need safe headway so that they have sufficient time to react appropriately when unintentional situation occurs. This is why many improvements have been introduced to improve the brake light function to avoid rear-end collision. Center High Mounted Stop Lamps (CHMSL) or also widely known as 'third brake light' can be considered as a successful effort to improve the brake light function and the study of the long-term effectiveness of the system can be found in Kahane and Hertz (1998).

From the third hypothesis, this study confirmed that in the case of a truck following truck, both FV GVW and LV class has a significant effect on headway. This shows that when the vehicle dynamic's capability is incorporated into a vehicle following situation with a small relative speed, the FV GVW and LV class were significant sources of variation in headway. Empirical evidence in this paper indicates that the driver's ability to achieve the minimum safe headway is not only impeded by LV size but also constrained by its vehicle weight. Light vehicles have better performance capability, which allow the driver to accelerate or decelerate faster as compared to heavy vehicles. Hence, it is always important to educate and remind the truck drivers about the HV performance capability. This can be done in many ways and one of them is through the road side real-time advisory sign by informing the truck drivers about their right minimum safe headway.

Based on the above findings, a preferred minimum headway model from drivers' perspective is proposed, which incorporate the LV class and FV GVW. Fig. 6.5 shows the relationship between wheelbase and vehicle class. Hence, vehicle wheelbase will be used as the variable of interest to develop the proposed model.

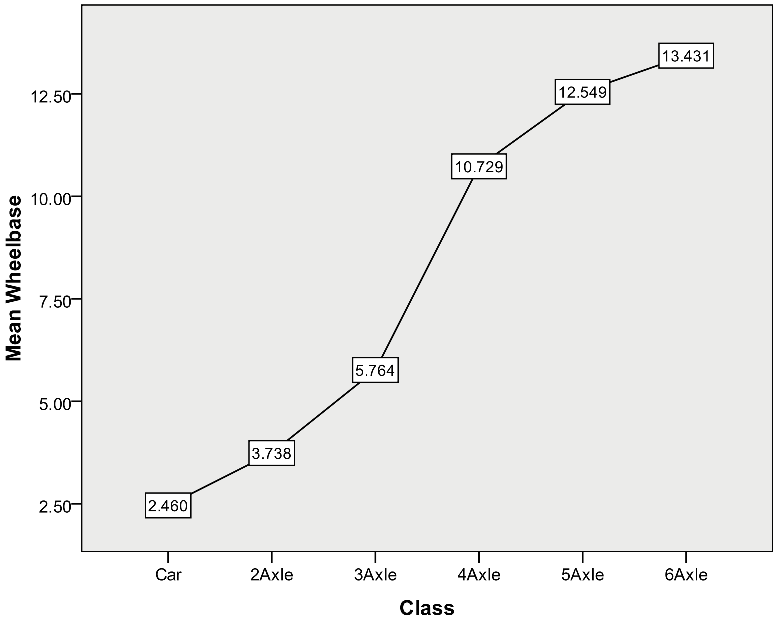


Fig. 6.5. Vehicle class is proportionate to wheelbase

Then, a proposed preferred minimum headway is expressed as follows:

$$T_{\min} = C_1 l_r + C_2 w_r + C_3 \qquad (1)$$

where $T_{\min}$ is preferred minimum headway, l_r and w_r are relative wheelbase and GVW, respectively. C_1 and C_2 are regression coefficients, and C_3 is regression constant which represent minimum headway in the case of PC follows PC situation. Regression coefficients l_r and w_r can be expressed as follows:

$$\begin{aligned} l_r &= l_{LV} - l_{PC\max} \\ w_r &= w_{FV} - w_{PC\max} \end{aligned} \qquad (2)$$

with the condition that $l_r = 0$ if $l_{LV} < l_{PC\max}$ and $w_r = 0$ if $w_{FV} < w_{PC\max}$. Here, in Equation (2), maximum wheelbase, $l_{PC\max}$ and maximum GVW, $w_{PC\max}$ of PC is used as a reference for relative wheelbase and relative GVW calculation. The reason is, as mentioned earlier, many countries use minimum safe headway for PC-PC following pairs as a reference to set the minimum safe headway for HV.

From Equation (1), this can be explained as, when PC follows PC, l_r and w_r are negligible and weight and size factor are eliminated. Preferred minimum headway in Equation (1) becomes a constant value which can be expressed as in Equation (3).

$$T_{\min} = C_3 \qquad (3)$$

The constant, C_3 in Equation (3) can be set as 2 seconds if it is assumed that certain percentage of PC drivers (based on percentile calculation) follow a leading PC with a recommended minimum safe headway rule of thumb.

However, in this study, from the observed data, 2 second headway or less is particularly common where 66.96% of drivers of PC-PC following pairs follow less then 2 seconds. Lay (2009) stated that 2 second can be the value of 85th percentile. If this value is suggested as minimum safe headway, this obviously will not gain public support and would have the potential to interfere with traffic flow as mentioned also by Hutchinson (2008). Hence, selection of the optimum value of minimum safe headway is crucial when all those factors, i.e. human reaction time, public support and traffic flow are to be considered.

For the regression analysis purposes, the data are then grouped according to LV wheelbase and FV GVW. There are total 60 groups of data and number of sample for each group is given in Table 6.7.

Table 6.7 Number of sample of each group

Relative FV GVW (t), w_r	Relative LV Wheelbase (m), l_r					
	0	0-2	2-4	4-6	6-8	>8
0	12658	11065	3302	1406	886	3274
0-5	6453	2220	570	220	144	513
5-10	2624	687	179	74	48	130
10-15	2531	669	179	80	53	126
15-20	929	358	120	60	26	81
20-25	687	280	129	47	26	57
25-30	619	259	205	50	25	52
30-35	936	418	352	110	40	81
35-40	685	328	224	85	27	66
>40	381	178	93	44	28	34

Coefficients of the regression lines, C_i where $i = 1,2,3$ in Equation (1) and coefficients of determination, R^2 at various percentile values is presented in Table 6.8.

Table 6.8 Regression coefficients with p-value and coefficients of determination of the preferred minimum headway with different percentile

	C_1	C_2	C_3	R^2 (Means)	N
T_{min_5th}	.025	.011	.796	0.565	60
(p-value)	<0.001	<0.001	<0.001		
T_{min_10th}	.030	.014	.957	.686	60
(p-value)	<0.001	<0.001	<0.001		
T_{min_25th}	.037	.017	1.332	.742	60
(p-value)	<0.001	<0.001	<0.001		
T_{min_50th}	.031	.021	1.906	.784	60
(p-value)	<0.001	<0.001	<0.001		
T_{min_75th}	.017	.018	2.693	.646	60
(p-value)	=0.033	<0.001	<0.001		
T_{min_90th}	.007	.010	3.386	.539	60
(p-value)	<0.001	=0.192	<0.001		

According to Table 6.8, if 25th percentile is chosen to represent the drivers' preferred minimum headway, 25 percent of all PC drivers follow the leading PC with equal or less than 1.332 second. This preferred minimum headway can be safe or not dependent on accident record on that particular road section (especially rear and front end collision). However, no accident record were found along the selected observed data road section which mean that 25 percent of the drivers preferred min headway (in this case 1.332 second) can be set as minimum safe headway in order to gain strong public support and to avoid traffic flow interference. But if the widely recommended 2 second minimum safe headway is strictly need to be considered, the 50th percentile preferred min headway would be suitable since the regression constant is 1.9 second. However, the model shows that, if 2 second is set to be the minimum safe headway, there are 50 percent drivers will violate this rule and the rule will not gain public support and most likely would interfere the traffic flow. The regression analysis also indicates that the estimate coefficients, C_i where $i = 1,2,3$ are significantly different from zero and the model adequately described the data (for each case, p-value<0.001). This show that the drivers' preferred minimum headway is longer when HV involve in the following composition.

CHAPTER 7

CONCLUSION

7.1 Summary

The need to obtain accurate and comprehensive traffic and vehicular data simultaneously and continuously in all weather conditions throughout the year is certainly a necessity and a mandatory for this study. As such, a comprehensive and continuous traffic data-collection system based on weigh-in-motion technology has been developed and installed at one of the federal roads in Malaysia.

The system comprises a sensor array embedded in roadway surface, camera set, and central processing unit. The sensor array consists of a vehicle presence detector such as inductive loop and WIM sensor for providing traffic and vehicle parameters. Image from a camera will be snapped when the vehicle passing through the sensor arrays. The central processing unit will then process all signals from sensing devices. The produced data will be displayed and recorded for study purposes.

The software to process, analyze and store data has been developed to incorporate features that can suit the specific needs of the study. It is flexible and can be easily customized accordingly. The current version has been designed to be user-friendly, interactive with user-define input as well as for integrated application. The system can provide continuous traffic and vehicular data collection and monitoring through an automated system that works in all weather conditions, 24 hours a day and seven days a week throughout the year.

The modular configuration concept of the system can also accommodate other peripherals such as vehicle height sensors and weather sensors. Details development and installation of the system have been discussed in Chapter 2.

Statistical analysis was then performed to the collected data to quantify that the gross vehicle weight can have a significant effect in traffic flow characteristics in both free flow and following situations. The results lead to explore the driver behavior in controlling the vehicle from two different perspective: driver’s visual input and vehicle dynamics capability. This has been discussed in detail in Chapter Four to Chapter Six.

In Chapter Three, the study concludes that the prospect of using WIM system to enhance weight limit enforcement will definitely benefit not only the road authorities but also the motorist at large. The results of the study may be summarized as follows:

1. Significant percentage of violation involving overweight commercial vehicles is observed.
2. Extend and degree of overloading in heavy commercial vehicles is very significant and alarming.
3. Not only does overloading accelerate pavement damage (which in turn may contribute to accidents), overloaded heavy vehicles would be hazardous to other road users.

4. Monitoring and enhancing enforcement of weight limits of heavy vehicles may be a step in the right direction.
5. Comprehensive and continuous data is needed, especially at critical locations in the road network.

In Chapter Four, the study found that vehicle class did have an effect on speed but only in the case where the size of the vehicles is significantly different. In the case where vehicles are almost similar in size but only differ in number of axles the weight is a dominant factor that has an effect on speed. Furthermore, the study also found that speed monotonically decreases with GVW for GVW range less than 20 tons. In the case where a heavy vehicle has a loading of over 20 tons, the speed appears to stabilize to a particular value regardless of an increase in GVW.

The study also shows that the current speed limit is relatively high for heavy vehicle with a GVW of over 20 tons. The study proposes a new concept of setting the speed limit for heavy vehicle by incorporating the weight parameter. The speed limit for heavy vehicle, using 85th percentile principle, is proposed to be 70 km/h for vehicle with GVW less than 20 tons and 60 km/h for more than 20 tons. Finally, the weigh-in-motion technology can be fully utilized for implementing the enforcement of the proposed speed limits incorporating GVW for heavy vehicle as proposed in this study.

Chapter Five provides a detailed empirical analysis of car-following situations with different compositions of follower-leader pairs in terms of weight and size. Analysis explored the driver behavior in controlling the speed under car-following from two different perspective: driver's visual input and vehicle dynamics capability as shown in Figure 7.1.

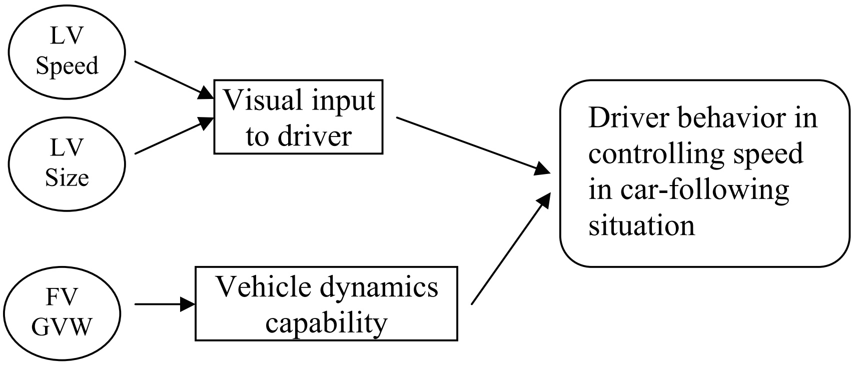


Figure 7.1 Significant source of variation in speed in car-following situation

The results of this study may be summarized as follows:

1. The study suggests that the FV GVW, LV size and LV speed were significant sources of variation in FV speed.

2. Drivers of a heavy vehicle in average are constrained by their vehicle dynamic's limitations. In the case where the leader has better performance capability, the results, in average, show that the heavy vehicle followers are unable to maintain closely with the speed of small size leader vehicles.
3. Whereas, in the case where the follower-leader pair has almost same performance capability or the follower has better performance capability, the follower in average is impeded by its leader speed and/or size.
4. Light and heavy vehicles maintain different safe desired speed with LV according to LV size. This can be caused by the large vehicle moved at a low speed in comparison to small size leading vehicle or FV drivers cannot anticipate future traffic conditions due to drivers visual regarding the forward scene may be obstructed by large size vehicle.
5. The observation provides a preliminary step for considering vehicle weight as an additional variable of interest in a car-following study.

In Chapter Six, the study aims to make a preliminary analysis of the influence of HV size and its GVW on headway characteristics in a vehicle following situation and then provide a drivers' preferred minimum headway model incorporating both factors. In order to gain more specific observation in a vehicle following situation, the effect of both HV GVW and its class on headway were analyzed under different leader-follower composition such as PC-Truck pairs with leading PC, PC-Truck pairs with lagging PC, and Truck-Truck pairs were examined under near optimal driving conditions characterized by dry weather, daytime, no changes in surrounding, small relative speed.

The results of this study may be summarized as follows:

1. The study suggests that the FV GVW and LV size were significant sources of variation in headway when HV involves in vehicle following situation.
2. Drivers of a heavy vehicle on average are constrained by their vehicle dynamic's limitations. The results in this study lead to the observation that, in the case of PC-truck pairs with lagging PC, it is FV GVW rather than FV size that affects HV headway and GVW should be considered as one of the variables of interest in a vehicle following study.
3. This study also confirmed that, in the case of PC-tuck pairs with lagging PC following composition, the size of LV is a dominant factor that affects the headway as compared to LV GVW.
4. In the case where the follower-leader pair is a truck, both FV GVW and LV size has a significant effect on headway.
5. The study proposed a drivers' preferred minimum headway incorporating LV size and FV GVW.
6. The study also suggests the selection of the optimum value of preferred minimum headway based on percentile value if human reaction time, public support and traffic flow interference are to be considered.

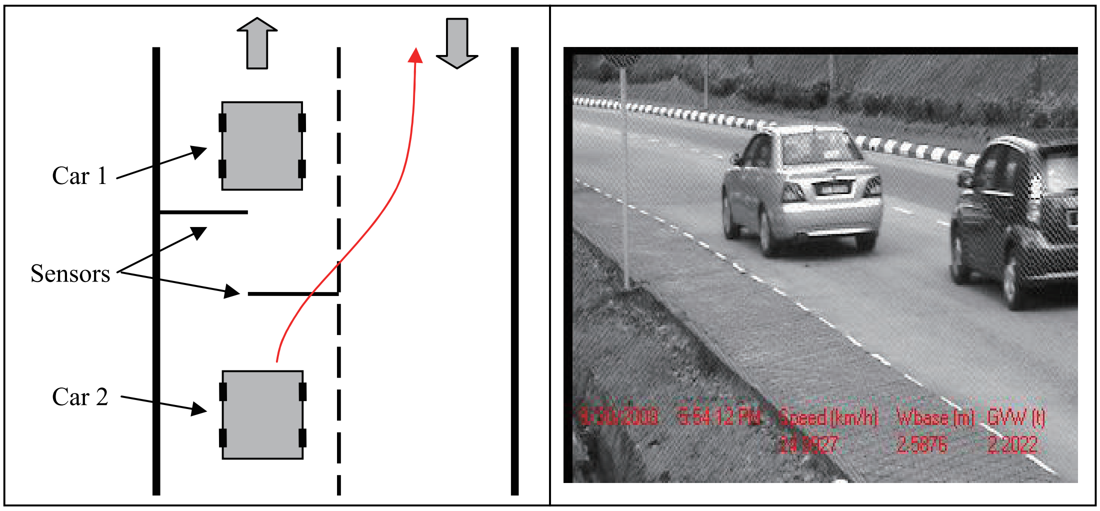
7.2 Future Work

Several things could be done to expand upon work described here. Future study should aim at further improvement of measurement accuracy and efficiency, especially when involve special conditions as will describe later and system flexibility for broader applications, in particular, future research should address the following needs.

First, studies from the snapshot image, the following cases have been observed as the cause for false detection and improvement such as adding more sensors is needed to filter unnecessary data and improve the overall data quality.

<u>Case 1: Overtake of following vehicle</u>

This happens when the lead vehicle moving at a very slow speed and the following vehicle overtake at short section where the sensor has been installed as shown in Figure 7.2.

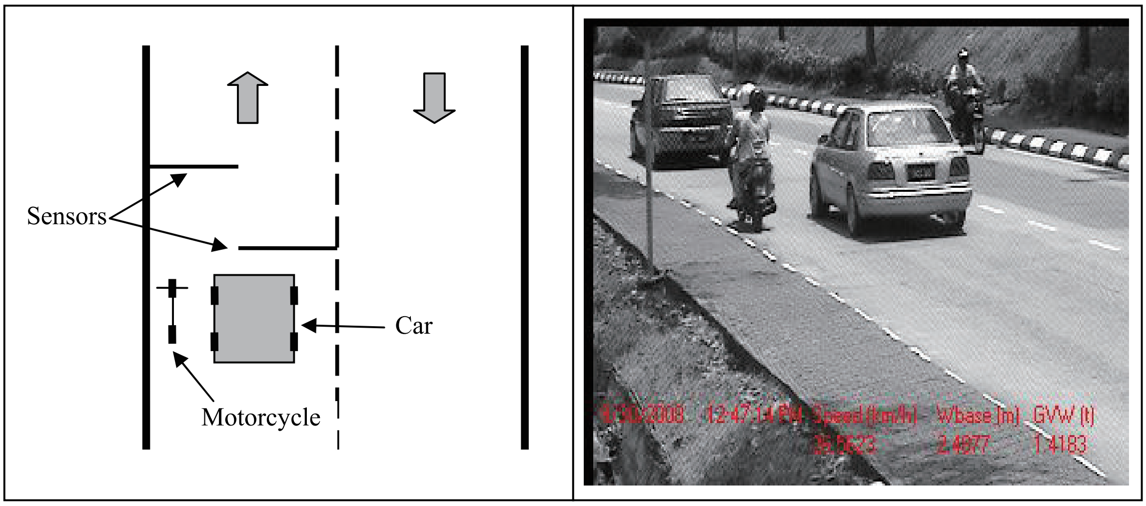


(a) (b)

Figure 7.2 Case 1 schematic diagram and snapshot

<u>Case 2: Motorcycle Interference</u>

In a country where the population number of motorcycle is dominant, the situation such as shown in Figure 7.3 can be happened.



(a) (b)

Figure 7.3 Case 2 schematic diagram and snapshot

Second, several new fundamental studies can be explored by integrating the developed system with various types of sensors. For instance, the developed system can be integrated with road side air quality sensors to investigate the effect of heavy vehicle weight on environmental issues such as a global warming, air pollution and health concerns. The developed system can also be integrated with vehicle on-board measurement devices to investigate the heavy vehicle characteristics during cornering on shape curves and other specific accident prone locations. These are among examples of the use of the developed system for future work.

REFERENCES

ASTM Standard E 2300-06 (2007) Standard Specification for Highway Traffic Monitoring Devices, ASTM International, US.

ASTM Standard E 1318-02 (2002) Standard Specification for Highway Weigh-in-motion (WIM) Systems with User Requirements and Test Methods, ASTM International, US.

Ahmed U., (2010). Passenger Car Equivalent Factors for Level Freeway Segments Operating under Moderate and Congested Conditions. Master Thesis, Marquette University.

Bando M, Hasebe K, Nakayama A, Shibata A, Sugiyama Y. (1995) Dynamical model of traffic congestion and numerical simulation, Phys. Rev. E 51, 1035–1042.

Bixel, R. A., Heydinger, G. J., Durisek, N. J. and Guenther, D. A. (1998) Effect of loading on Vehicle Handling, SAE Paper 980228, SAE International Congress and Exposition.

Brackstone, M and McDonald, M. (1999) Car-following a historical review, Transportation Research Part F: Traffic Psycology and Behavior, Elsevier.

Brooks C., 2002. Speed and Heavy vehicle safety. National Heavy Vehicle Safety Seminar, Melbourne.

Cebon, D., (1989). Vehicle-generated road damage: A review. Vehicle System Dynamics, 18, pp 107-150.

Cebon, D., (1993). Interaction Between Heavy Vehicles and Roads. SAE 930001, SP–951, 81p, 1993. Society of Automotive Engineers (LR Buckendale Lecture), ISBN 1–56091–336–3.

CEDR's TG Road Safety, (2010). Safe distance between vehicles. Conference of European Directors of Roads, CEDR report.

Chandler, R.E., Herman, R., Montroll, E.W. (1958) Traffic Dynamics: Studies in Car Following, Operations Research 6, Operations Research Society of America, pp. 165-184.

Chang K and Chon K. (2005) A car-following model applied reaction times distribution and perceptual threshold, Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp.1888-1903.

Chung S. B., Song K. H., Hong S. Y. and Kho S. Y. (2005) Development of sensitivity term in car-following model considering practical driving behavior of preventing rear end collision, Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp.1354-1367.

Clarke D. D., Ward P., Bartle C., Truman W., (2010). Killer Crashes: Fatal road traffic accidents in the UK. Accident Analysis and Prevention 42, 764-770.

Conway A. and Walton C. M. (2004), Potential application of ITS technologies to improve commercial vehicle operations, enforcement, and monitoring, Research Report SWUTC/04/473700-00069-1, The University of Texas at Austin, Texas.

Dee T. S., Sela R. J., (2003). The fatalities effect of highway speed limits by gender and age. Economics Letter 79, 401-408.

Elvik R., Christensen P., Amundsen A., (2004). Speed and road accidents. The Institute of Transport Economics, TOI Report 740/2004.

Evans, L., & Wasielewski, P., (1982). Do accident-involved drivers exhibit riskier everyday driving behavior? Accident Analysis and Prevention, 14 (1), 57-64.

Fairclough, S. H., May, A. J., Carter, C., (1997). The effect of time headway feedback on following behaviour. Accident Analysis and Prevention, 29 (3), 387-397.

Fancher P.S., Ervin R. D., Winkler C. B., Gillespie T. D., (1986). A Factbook of the Mechanical Properties of the Components for Single Unit and Articulated Heavy Trucks. Report No. UMTRI-86-12, U.S. Department of Transportation, Washington, DC.

Fancher P. S., Campbell K. L., (1995). Vehicle Characteristics Affecting Safety and Trucks Size and Weight Regulations. U.S. Department of Transportation, Washington, DC.

Farmer C. M., Retting R. A., Lund A. K., (1999). Changes in motor vehicle occupant fatalities after repeal of the national maximum speed limit. Accident Analysis and Prevention 31, 537-543.

Garber N. J. and Hoel L. A. (2001) Traffic and Highway Engineering, 3rd Edition, CL-Engineering.

Gartner N. H., Messer C. J. and Rathi A. K. (1992) Traffic Flow Theory: A State of the Art Report, Revised Monograph on Traffic Flow Theory, U.S. Department of Transportation, Transportation Research Board, Washington, D.C.

GRSP, (2008). Speed management: a road safety manual for decision-makers and practitioners, Global Road Safety Partnership, Geneva.

Harb R., Radwan, E., Yan, X. Abdel-Aty, M.A., (2007). Light truck vehicles (LTVs) contribution to rear-end collisions. Accident Analysis and Prevention, 39 , 1026-1036.

Harwood, D.W., Potts I.B., Torbic D.J., and Glauz W.D., (2003). Commercial Truck and Bus Safety: Synthesis 3 – Highway/Heavy Vehicle Interaction. Transportation Research Board. Washington, DC.

Hutchinson, T.P., (2008). Tailgating. Centre for Automotive Safety Research, CASR Report CASR046.

Jazar. R.N. (2008) Vehicle Dynamics Theory and Application, Springer, New York.

Kahane, C. J. and Hertz, E., (1998). The Long-Term Effectiveness of Center High Mounted Stop Lamps in Passenger Cars and Light Trucks. NHTSA Technical Report Number DOT HS 808 696.

Knipling R.R., Wang J.S., Yin H.M., (1993). Rear-end Crashes: Problem size assessment and statistical description. NHTSA Tech. Report DOT HS 807 994.

Kockelman, K. and Shabih, R. (2000). Effect of Light-Duty Trucks on the Capacity of Signalised Intersections. Journal of Transportation Engineering, 126(6), pp. 506-512.

Lay M. G. (1986) Handbook of Road Technology: Volume 2 Traffic and Transport, Gordon and Breach Science Publishers.

Liu R., Chen X., Li J., Guo L. and Yu J. (2005) “Evaluate innovative sensors and techniques for measuring traffic loads”, Final Report TxDOT 0-4509, Texas Department of Transportation and the Federal Highway Administration.

LTSA Online, (Year Unknown). Heavy Vehicle Stability Guide, Version 1.0. Land Transport Safety Authority,. Wellington, New Zealand.

Martin, P. T., Feng, Y. and Wang, X. (2003). Vehicle Detector Evaluation, MPC Report No. 03-154, http://www.mountain-plains.org/pubs/html/mpc-03-154/

Matthew J. Titus (1996), "Benefits of Electronic Clearance for Enforcement of Motor Carrier Regulations", Transportation Research Record, TRB, Vol. 1522, pp64-68.

Michael, P.G., Leeming, F.C., Dwyer, W.O., (2000). Headway on urban streets: observational data and an intervention to decrease tailgating. Transport. Res. Part F 3 (2), 55–64.

Ni, R., Kang, J., Andersen, & G. J. (2010). Age-related declines in car following performance under simulated fog conditions. Accident Analysis & Prevention, 42(3), 818-826, Elsevier.

Nichols A. P. and Bullock D. M. (2004) Quality Control Procedures for Weigh-in-Motion data, Final Report FHWA/IN/JTRP-2004/12, Joint Transportation Research Program, School of Civil Engineering, Purdue University.

OECD/ECMT Report, (2006). Speed Management Report, Transport Research Centre, Paris.

Ossen S. and Hoogendoorn S. P. (2011) Heterogeneity in car-following behavior: Theory and empirics, Transportation Research Part C: Emerging Technologies, 19(2), 182-195, Elsevier.

Postans, R. L., & Wilson, W. T., (1983). Close-following on the motorway. Ergonomics, 26 (4), 317-327.

Rob Bushman, Curtis Berthelot and Brian Taylor (2003), Commercial Vehicle Loading in an Urban Environment, Paper presented at the Emerging Technologies in Traffic Operations Session of the 2003 Annual Conference of the Transportation Association of Canada St. John's, Newfoundland and Labrador.

Saifizul A.A., Yamanaka H., Karim M.R. (2011), Empirical analysis of gross vehicle weight and free flow speed and consideration on its relation with differential speed limit. Accident Analysis and Prevention, 43, 1068-1073. Elsevier.

Saifizul A.A., Yamanaka H., Karim M.R., and Okushima M. (In Press), Empirical Analysis on the Effect of Gross Vehicle Weight and Vehicle Size on Speed in Car Following Situation", Journal of the Eastern Asia Society for Transportation Studies, Vol.9.

Saifizul A.A., Yamanaka H., Karim M.R. (2010), Development of integrated data collection and enforcement system. 17th Intelligent Transportation System (ITS) World Congress, 25-29 Oct 2010, Busan, Korea.

Saifizul A.A., Yamanaka H., Karim M.R. (2010), Prospect of using Weigh-in-Motion based system for enhancing vehicle weight enforcement – A case study of Malaysian Roads. 17th Intelligent Transportation System (ITS) World Congress, 25-29 Oct 2010, Busan, Korea.

Sandy H. Straus and John Semmens (2006), Estimating the Cost of Overweight Vehicle Travel on Arizona Highways, Arizona Department of Transportation, Final Report 528.

Santero, Nicholas J., William Nokes, John T. Harvey (2005), Virtual Weigh Stations: The Business Case. Institute of Transportation Studies, University of California, Davis, Research Report UCPRC-TM-2005-03.

Sawada, S. (2002) Generalized optimal velocity model for traffic flow, Int. J. Mod. Phys. C 13, No. 1, 1-12.

Sayer, J.R., Mefford, M.L., Huang, R.W., (2000). The Effect of Lead-Vehicle Size on Driver Following Behavior (Report number UMTRI-2000-15). Ann Arbor, MI: The University of Michigan Transportation Research Institute.

Seegmiller L. W. (2006) Utah Commercial Motor Vehicle Weigh-in-motion Data Analysis and Calibration Methodology, Master Thesis, Brigham Young University.

Smith B. L., Williams B. M. and Oswald R. K. (2002) Comparison of parametric and nonparametric models for traffic flow forecasting, Transportation Research Part C: Emerging Technologies, Volume 10, Issue 4, Elsevier, 303-321.

Special Report 225 (1990), Truck Weight Limits: Issues and Options. Transportation Research Board, National Research Council, Washington, D.C., 1990, p.141.

Stewart P. M. (1989) New sensors for axle detection and weigh-in-motion, IEE 2nd Int. Conf. on Road Traffic Monitoring, London, UK.

Stoneman B. G. and Moore R. C. (1989) Dynamic axle and vehicle weight measurements, IEE 2nd Int. Conf. on Road Traffic Monitoring, London, UK.

Suzuki H., Ranjitkar P., Nakatsuji T. and Takeichi Y. (2005) An extended car-following model combined with a driver model, Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp.1545-1556.

Tiwari G., Fazio J. and Pavitravas S. (2000) Passenger Car Units for Heterogeneous Traffic Using a Modified Density Method, Transportation Research Circular EC018, Transportation Research Board, Washington, D. C.

Vangi D., (2009). Simplified method for evaluating energy loss in vehicle collisions. Accident Analysis and Prevention 41, 633-641.

Wang J. and Wu M. (2004) An overview of research on weigh-in-motion system, Proceeding of 5th World Congress on Intelligent Control and Automation, China.

Wang, L. J., Zhang H., Meng H. D., and Wang X. Q., (2008) A model based on TTC to describe how drivers control their vehicles, Eur. Phys. J. B 66, 149-153.

Wong J. Y. (1993) Theory of Ground Vehicle, John Wiley & Sons Inc.

Wood D. P., (1997). Safety and the car size effect: A fundamental explanation. Accident Analysis and Prevention 29, 139-151.

Wood D. P., Simms C. K., (2002). Car size and injury risk: a model for injury risk in frontal collisions. Accident Analysis and Prevention 34, 93-99.

Zhang H. M. and Kim T. (2005) A car-following theory for multiphase vehicular traffic flow, Transportation Research Part B: Methodological, Volume 39, Issue 5, Elsevier, 385-399.

PUBLICATIONS

LIST OF PUBLICATION

Refereed Journal

Saifizul A.A., Yamanaka H., Karim M.R., and Okushima M. (2011), The effect of gross vehicle weight and vehicle size on headway characteristics in vehicle following situation. Accident Analysis and Prevention, (submitted on March 25, 2011, current status – under review). Elsevier.

Saifizul A.A., Yamanaka H., Karim M.R. (2011), Empirical analysis of gross vehicle weight and free flow speed and consideration on its relation with differential speed limit. Accident Analysis and Prevention, 43, 1068-1073. Elsevier.

Saifizul A.A., Yamanaka H., Karim M.R., and Okushima M. (2011), Empirical Analysis on the Effect of Gross Vehicle Weight and Vehicle Size on Speed in Car Following Situation", Journal of the Eastern Asia Society for Transportation Studies, Vol.9 (In Press).

Yasin A. M., Karim M.R., Saifizul A.A. (2009), Travel Time Measurement in Real-Time using Automatic Number Plate Recognition for Malaysian Environment, Journal of the Eastern Asia Society for Transportation Studies, Vol.8, 1-14p.

Conference Proceedings

Saifizul A.A., Yamanaka H., Karim M.R., and Okushima M. (2011), Empirical Analysis on the Effect of Gross Vehicle Weight and Vehicle Size on Speed in Car Following Situation", 9th Eastern Asia Society for Transportation Studies (EASTS) Conference, June 20th-23rd 2011, Jeju Korea. (Best Paper Award – Discovering New Facts).

Saifizul A.A., Yamanaka H., Karim M.R., Development of integrated data collection and enforcement system. 17th Intelligent Transportation System (ITS) World Congress, 25-29 Oct 2010, Busan, Korea.

Saifizul A.A., Yamanaka H., Karim M.R., Prospect of using Weigh-in-Motion based system for enhancing vehicle weight enforcement – A case study of Malaysian Roads. 17th Intelligent Transportation System (ITS) World Congress, 25-29 Oct 2010, Busan, Korea (Outstanding Paper Award).

Saifizul A.A., Karim M.R., Yamanaka H., Evaluation of Quartz Based Automatic Traffic Monitoring System, 10th International Conference on Applications of Advanced Technologies in Transportation, 28-30 May 2008, Athens, Greece.

Yasin A. M., Saifizul A.A., Karim M.R., Travel Time Measurement in Real-time using Automatic Number Plate Recognition for Malaysian Environment, Proceedings of Eastern Asia Society for Transportation Studies, Vol 7, 2009, Surabaya Indonesia.

Yasin A. M., Saifizul A.A., Karim M.R., Development of Automatic Number Plate Recognition Software for Malaysian Environment, International Conference for Technical Postgraduates, 14 – 15 Dec 2009, Malaysia

Wah, Y.C., Karim, M. R., Saifizul, A. A., Real Time Video Vehicle Detection And Classification System, Proceedings of the Eastern Asia Society for Transportation Studies, Vol.7, 1-11pp , 2009, Surabaya Indonesia.

Yasin A. M., Karim M.R., Saifizul A.A., Algorithm Development for Automatic Number Plate Recognition System, Proceedings MUTRF Conference and EASTS International Seminar, August 2008, Malaysia.