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นายสุวัจชัย เป้าประยูร

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MODELING OF CAR-FOLLOWING BEHAVIOR IN BANGKOK USING GPS

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สุวัจชัย เป้าประยูร: การจำลองพฤติกรรมการขับขี่ตามกันในกรุงเทพมหานครโดยใช้จีพีเอส. (MODELING OF CAR-FOLLOWING BEHAVIOR IN BANGKOK USING GPS) อ. ที่ปรึกษา : รองศาสตราจารย์ ดร. สรวิศ นฤปิติ, 60 หน้า. ISBN 974-53-1208-8.

งานวิจัยนี้เป็นการศึกษาพฤติกรรมการขับขี่ตามกันของผู้ขับขี่ทดสอบในสภาพการจราจรจริงของกรุงเทพมหานคร โดยการให้รถยนต์ส่วนบุคคล 5 คันซึ่งติดตั้งอุปกรณ์จีพีเอสขับตามกันบนถนน 2 ประเภท ซึ่งได้แก่ ถนนพื้นราบและทางด่วน ซึ่งมีสภาพการจราจรที่แบ่งได้เป็น 2 รูปแบบได้แก่ สภาพจราจรติดขัดและไม่ติดขัด ข้อมูลพิกัดแบบ 3 มิติของรถยนต์แต่ละคันที่ทุกๆ 0.1 วินาทีซึ่งได้จากอุปกรณ์ จีพีเอสจะนำมาคำนวณระยะทาง, อัตราเร็ว, อัตราเร่งและระยะห่างของรถแต่ละคัน เพื่อเป็นข้อมูลในการวิเคราะห์พฤติกรรมการขับขี่และสร้างแบบจำลองการขับขี่ตามกันโดยใช้แบบจำลอง GM ผลการวิเคราะห์พฤติกรรมการขับขี่ระบุว่า ผู้ขับขี่เว้นระยะห่างเพียงเล็กน้อยจากรถคันหน้าในขณะที่ใช้ความเร็วสูงบนทางด่วน ซึ่งขัดแย้งกับทฤษฎีระยะห่างปลอดภัย ปัจจัยที่มีอิทธิพลสูงสุดต่อพฤติกรรมการขับขี่ของรถคันตามคือความเร็วสัมพัทธ์ระหว่างรถคันนำและคันตาม โดยที่ระยะห่างและปัจจัยอื่นๆมีอิทธิพลเพียงเล็กน้อย นอกจากนี้ยังพบว่ารถคันท้ายๆของขบวนโดยเฉพาะอย่างยิ่งรถคันที่ 4 และ 5 จะมีความอ่อนไหวต่อการเปลี่ยนแปลงสภาวะการขับขี่ของรถคันนำ (Sensitivity) มากกว่า

ผลการวิเคราะห์การถดถอยเพื่อศึกษาพฤติกรรมการขับขี่ตามกันโดยใช้แบบจำลอง GM ระบุว่าผู้ขับขี่มีค่าสัมประสิทธ์ความอ่อนไหว (Sensitivity factor) ในสภาพการจราจรไม่ติดขัดน้อยกว่าสภาพการจราจรติดขัด และมีเวลาตอบสนอง (Reaction time) ในสภาพการจราจรไม่ติดขัดมากกว่าสภาพการจราจรติดขัดโดยสอดคล้องกันบนถนนทั้ง 2 ประเภท โดยค่าสัมประสิทธิ์การตัดสินใจมีค่าในช่วง 0.4-0.8 สำหรับแบบจำลอง GM ที่ 1 และ 0.4-0.9 สำหรับแบบจำลอง GM ที่ 5 ซึ่งแสดงว่าแบบจำลอง GM ที่ 5 ปรับปรุงประสิทธิภาพในการพยากรณ์พฤติกรรมการขับขี่ตามกันได้ดีกว่าแบบจำลอง GM ที่ 1 เพียงเล็กน้อย ผลการประเมินแบบจำลองทั้งสองรูปแบบในระดับจุลภาคแสดงว่าค่าพารามิเตอร์ของพฤติกรรมการขับขี่ที่ได้ สามารถอธิบายพฤติกรรมการขับขี่จริงได้อย่างสอดคล้อง ขณะที่เมื่อนำแบบจำลองไปพยากรณ์การจราจรระดับมหภาคพบว่ามีความคลาดเคลื่อนพอสมควร เมื่อเปรียบเทียบพฤติกรรมการขับขี่ตามกันของผู้ขับขี่ทดสอบในกรุงเทพมหานครกับสหรัฐอเมริกาและญี่ปุ่น พบว่าพฤติกรรมการขับขี่ตามกันในสภาพการจราจรแบบไม่ติดขัดคล้ายคลึงกับพฤติกรรมการขับขี่ที่ได้จากงานวิจัยของ GM (สหรัฐอเมริกา) ขณะที่ในสภาพการจราจรติดขัดกลับพบว่าพฤติกรรมดังกล่าวแตกต่างกับงานวิจัยอื่นๆ อย่างมาก

ภาควิชา	วิศวกรรมโยธา	ลายมือชื่อนิสิต..
สาขาวิชา	วิศวกรรมโยธา	ลายมือชื่ออาจารย์ที่ปรึกษา......................................
ปีการศึกษา	2547	

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KEY WORD: CAR-FOLLOWING / DRIVER BEHAVIOR / GM / GPS / MICROSCOPIC / REACTION TIME

SUWAJCHAI PAOPRAYOON : MODELING OF CAR-FOLLOWING BEHAVIOR IN BANGKOK USING GPS. THESIS ADVISOR: ASSOC. PROF. SORAWIT NARUPITI, Ph.D., 60 pp. ISBN 974-53-1208-8.

The investigation of car-following behavior of test drivers on Bangkok's roadways is presented in this research. The experiment was carried out on surface streets and freeways in Bangkok with actual traffic conditions using five passenger cars equipped with global positioning system devices. Traffic flow characteristic was classified into congested and uncongested conditions, resulting in four regimes of driving characteristics on the two roadway types (i.e. uncongested surface street, congested surface street, uncongested freeway, and congested freeway conditions). The experimental GPS data consisting of distance, speed, and acceleration of the vehicles at every 0.1 sec were employed for the calibration of the 1st and the 5th GM models in order to determine various driving behaviors in different traffic and roadway conditions. The consequences of the analyses of fundamental car-following parameters indicated that the drivers maintained very close separation distance at very high speed ranges under uncongested freeway condition, which absolutely violated the safe-distance concept. The change in individual speed patterns influenced on the follow driver's behavior more remarkably than other factors. Further, the increasing speed disturbance indicating more aggressive driving was found from the last two drivers of platoon.

The results of model calibration showed that the drivers would have lower sensitivity under uncongested conditions and higher in congested conditions. Moreover, they would have faster reaction when drove in congested conditions. The model calculation gave the R^2 between 0.4-0.8 and 0.4-0.9 for the 1st and the 5th GM models respectively, indicating that the 5th GM model did not contribute much improvement to another. The evaluation of the models at microscopic level revealed that the predicted speed values from both models agreed well with the measured speed data, meanwhile more obvious deviation between predicted and measured traffic volumes was exhibited for macroscopic evaluation. Finally, the comparison of car-following characteristics from a few researches conducted in USA (GM and LSU) as well as Japan (HU) vs. those from this study (so called CU) concluded that the GM's original car-following data were close to the CU results for both uncongested surface street and freeway conditions. However, it was evident that CU car-following characteristics were remarkably different from the others for congested conditions.

Department	Civil Engineering	Student's signature	....
Field of study	Civil Engineering	Advisor's signature	....
Academic year	2004		

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I would like to thank some bachelor degree students of Civil Engineering Department, and a master student of Survey Engineering Department, who cooperated with this research for collecting GPS data. Finally, I dedicate this thesis to my loving mother who encourages me to achieve successfulness.

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CHAPTER 1

INTRODUCTION

1.1 Rational Statement

Driving characteristic reflects the inherent characters of an individual driver which is influenced by many factors, for instance, road type, age of driver, type of vehicle used, and so on. Moreover, it also depends upon the action of other drivers who are surrounding or particularly leading. The more number of vehicles running on the road, the more complicated the driving behavior would be. Car following is one of driving phenomena which the following driver's reaction is directly influenced by the simultaneous action of the driver of the vehicle in front. Nevertheless, the driving behavior, or more specifically car-following behavior, of drivers is also different from country to country due to the differences in culture, education, attitude, and so forth. The drivers in the western countries could behave remarkably different from those in the Asian countries. A large number of researchers around the world have accomplished many research works regarding the investigation of driving characteristics. One implication which could be extracted from those works is that it is worthwhile and necessary to determine the driving characteristics of their own countries or situations. For example, traffic composition in several South East Asian nations like Thailand, Vietnam, Indonesia, and Philippines consists primarily of a considerable number of motorcycles and local vehicles. This results in the unique and more perplexing driving patterns. An application of some data or parameters from the others might lead to the fallacious results and interpretation. In case of Thailand, the understanding of driving behavior is not well established. A small number of researches attempt to find out what happens in this microscopic traffic phenomenon; however, the elementary data of driving behavior are needed. The lack of useful driver's behavioral information leads to the unsuccessfulness of applying advanced traffic technology. One of the most critical problems for collecting data is quality, reliability, and sufficient size. Previously, the data collection of driving characteristics required a big amount of budget and effort. However, their quality was not good enough and the number of data collected was not reliably sufficient. Fortunately, a novel global positioning system or GPS technology which is becoming an effective device can reduce such the problems by providing the very high quality data with the less money and effort spent.

According to the benefits of the GPS as mentioned, this study thus attempts to utilize such the device for collecting the driving characteristics of drivers in Bangkok in car-following situation. The main purposes of this study are to determine the basic driving characteristics and to investigate the relationship among them in order to explain the interaction of drivers to the changing driving situations. This will describe how each driver controls or manipulates his/her car as the other vehicles are surrounding. Furthermore, the experiment is designed for collecting the data on surface street and freeway environments in both congested and uncongested traffic conditions. The calibration of model with the same technique developed by General Motors (GM) researchers provides driving parameters which reveal the differences in driving behaviors under various traffic and roadway conditions. Also, car-following behaviors gained from the study are compared with those from the other researches to show the country-to-country distinctions on driving characteristics.

1.2 Objectives

According to traffic congestion problem in the metropolitan areas of Bangkok, one of the most effective ways to understand the nature of such the problem is to investigate the microscopic driving behavior. Car-following is probably an important driving regime which becomes paramount for setting up the congestion mitigation strategies. Unfortunately, the study on car-following has never been conducted in Bangkok's traffic conditions. This research thus can be said to be the first effort to study such the driving behavior. The car-following data are collected using the Differential GPS (DGPS) device, providing the highly accurate (centimeter-accurate) data. The model is then developed with the collected data to represent the car-following task of drivers in Bangkok. In addition, the developed model is also tested to determine its validity and accuracy with the field data. The results which represent drivers' behavior in Bangkok road conditions are also compared with the US and Japanese researches. In conclusion, the main objectives of this research effort can be summarized as follows:

- To collect microscopic driving behavioral data of car-following regime in real traffic and roadway situations in Bangkok using DGPS.
- To analyze fundamental driving parameters of vehicle trajectory, headway, speed, and acceleration.
- To examine the model parameters of the car-following models for each designed scenarios.
- To evaluate the models with regard to its validity and accuracy against the field measurement data at both microscopic and macroscopic levels.
- To investigate the distinctions of car-following characteristics among countries.

1.3 Research Framework

The experiment is designed for collecting driving data of drivers in car-following situation using a multiple-vehicle platoon. The experiment is divided into four subtasks. Two of them are to study the driving characteristics in uncongested and congested surface street conditions and the others are conducted in uncongested and congested freeway conditions. All experiments are carried out in realistic roadway situation. The fundamental driving characteristics including vehicle trajectory, distance headway, speed, and acceleration are analyzed for being used in model calculation. The car-following models selected are the 1st and the 5th GM models being linear and nonlinear equations, respectively. The reaction time, sensitivity factor, and other model parameters for each data set are estimated by applying least-squared regression analysis techniques. The models are validated and evaluated at both microscopic and macroscopic levels by comparing the measured and predicted driving information (e.g. speed, flow, density). The validation and evaluation of models are performed by means of a visual inspection and a statistical test for microscopic and macroscopic levels, respectively. The comparison of car-following characteristics among countries is performed using information from the following research works: GM (Chandler *et al*., 1958; USA), LSU (Wolshon and Hatipkarasulu, 2000; USA), and HU (Ranjitkar *et al*., 2003; Japan).

1.4 Research Contributions

This research is mainly to collect and analyze car-following data gained from GPS tracking device. It is anticipated that techniques proposed in this study will have practical and methodological implications in other traffic behavioral studies. In contrast to many previous researches conducting the experiments on test track, this research proposes the car-following experiment conducted in realistic roadway situation, the occurred problems and the rectification methods stated herein will be practicable and useful. Moreover, the classification of car-following characteristics into 4 regimes (uncongested street, congested street, uncongested freeway, and congested freeway) shows significant differences among them and benefits to future researches because such the comparative investigation of car-following behavior on different road types and traffic conditions has not been explored before.

1.5 Outline of Thesis

This report is organized into 5 chapters. It initially provides the rationale, objectives, research framework, and benefits of the research. Chapter 2 provides the review of some literatures pertaining to GPS for car-following experiments and car-following modeling. Chapter 3 explains the research methodology including equipments for data collection, experimental design, data preparation, driving characteristics analysis, car-following modeling and evaluation methods. Chapter 4 presents the results of the study. Finally, the conclusions and recommendations for future researches are addressed in Chapter 5.

CHAPTER 2

LITERATURE REVIEWS

Car-following is a complicated traffic phenomenon given attention for years. Until now, dozens of researches have been conducted on car-following modeling and analyses. To have an insight into the car-following studies, this chapter addresses background and historical development of car-following models including the application of a novel global positioning system (GPS) technology in this kind of traffic research.

2.1 Fundamental Car-following Theory

Traffic flow models are generally classified into two main types: macroscopic and microscopic models. Macroscopic models focus on the traffic flow of the whole platoon or traffic stream (i.e. flow, average speed, and density), whereas microscopic models study the movement of individual vehicles. Car-following is one of microscopic vehicle movement phenomena which describe how one vehicle follows another. The relatively common driving task of a vehicle following another on a straight roadway where there is no passing can be categorized in the following subtasks (Rothery, 1992):

1) *Perception*-The driver collects relevant information through visual channel. This information arises primarily from the motion of the lead vehicle. The obvious information which the driver is sensitive to is, for example, vehicle speed, acceleration, relative distance, and relative speed.

2) *Decision making*-The driver interprets the received information over time and then makes a decision. The interpretation depends on his/her experience which allows for the development of driving strategies becoming "automatic" or driving skills.

3) *Control*-The skilled driver can execute or control his/her action based on the decision made which is superimposed on the dynamics of lead vehicle and roadway condition.

As shown in Figure 2.1, the actions of the lead vehicle will be perceived by the follower. The follower will then make a decision in several ways such as turning the steering wheel or adjusting vehicle speed. Primarily, car-following is the reaction on either decelerating, accelerating, or maintaining his/her cruise speed. The difference between the time at which the leader's action is perceived and the time at which the follower performs his/her dynamic response is the reaction time or time lag.

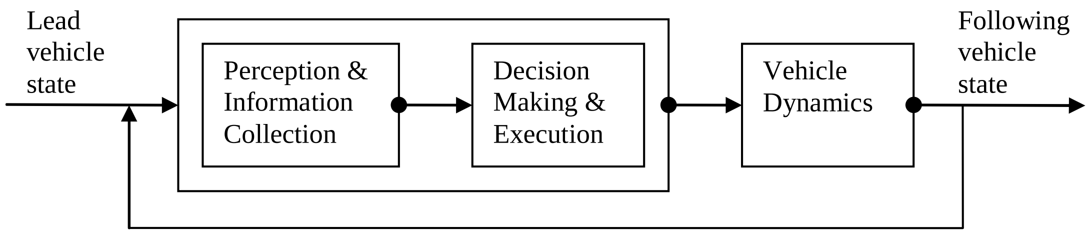


Figure 2.1 Block diagram of car-following (Adapted from Rothery, 1992).

2.2 Historical Review of Car-following Models and Experiments

Car-following studies have been carried out for half a century. Reuschel and Pipes were, perhaps, pioneers in the development of car-following theories in the early 1950s. Three parallel efforts were undertaken in the late 1950s continued to the mid-1960s. Kometani and Sasaki in Japan, Forbes at Michigan State University, and a General Motors research group contributed significant developments to car-following study and modeling. The work at General Motors became the most important because of the field experiments and discovery of the mathematical linkage between microscopic and macroscopic traffic flow theory (May, 1990). Other car-following models which were developed later on, are, for example, excess critical speed model, safe distance model, Helly's model, and Psychophysical model.

2.2.1 Pipes's and Forbes's Models

Pipes stated about the motion of vehicles in the traffic stream that "a good rule for following another vehicle at a safe distance is to allow yourself at least the length of a car between your vehicle and the vehicle ahead for every ten miles per hour of speed at which you are traveling". The equation used to explain Pipes's theory is shown in the following equation (May, 1990).

$$d_{\min} = \left[x_n(t) - x_{n+1}(t)\right]_{\min} = L_n\left[\frac{\dot{x}_{n+1}(t)}{(1.47)(10)}\right] + L_n \tag{2.1}$$

where $d_{\min}$ is the minimum distance headway (ft); L_n is the vehicle length (ft); and $\dot{x}_n(t)$ and $\dot{x}_{n+1}(t)$ are the speed values of the lead and following vehicles (ft/sec), respectively.

Assuming a vehicle length of 20 feet and selected speeds are between 0-88 ft/sec (96 km/h), the minimum safe time headway (h_{min}) is expressed as follows:

$$h_{\min} = 1.36 + \frac{20}{\dot{x}_{n+1}(t)} \tag{2.2}$$

Forbes later improved Pipes' safe distance model by considering the reaction time needed for the following vehicle to perceive the need to decelerate and apply the brakes. That is, the time gap between the rear of the lead vehicle and the front of the following vehicle should always be equal or greater than the reaction time. Therefore, the minimum time headway is equal to the reaction time and the time required for the lead vehicle to traverse a distance equivalent to its length. The mathematical expression is as follows (May, 1990):

$$h_{\min} = \Delta t + \frac{L_n}{\dot{x}_n(t)} \tag{2.3}$$

Forbes conducted many field studies of minimum time gaps and found considerable variations between drivers and sites. Minimum time gaps (reaction time) varied from 1 to 3 seconds. Assuming a reaction time of 1.5 seconds and a vehicle length of 20 feet, Eq. (2.3) can be rewritten as follows:

$$h_{\min} = 1.50 + \frac{20}{\dot{x}_n(t)} \tag{2.4}$$

Selecting speeds from 0 to 88 ft/sec (96 km/h), the associated minimum distance headways can be determined by the following equation.

$$d_{\min} = 1.50\left[\dot{x}_n(t)\right] + 20 \tag{2.5}$$

2.2.2 General Motors Models

The General Motors model was put forward in the late 50s by Chandler, Herman, and Montroll at General Motors research laboratory in Detroit. The model was further developed by Gazis, Herman, and Rothery and became the most well-known model, so called "GM" or "GHR" model. The model was based on an intuitive hypothesis that a driver's acceleration (or response) was proportional to relative speed or distance (or stimulus) which could itself be speed dependent. The stimulus-response concept can be mathematically described as follows:

$$\textit{Response} = f\,(\textit{Sensitivity, Stimuli}) \tag{2.6}$$

Firstly, the experiment was conducted using two vehicles linked with a cable on a pulley to examine the responses of 8 test subjects. In this experiment the lead vehicle was trained to drive with speed varied from 16 to 128 km/h over 30 minutes on a test track. It was concluded that distance headway was not a significant variable in sensitivity term, even though it was highly correlated with R^2 greater than 0.8. After the calibration process, high variation of sensitivity term λ (0.17 – 0.74 sec^{-1}) and reaction time T (1.0-2.2 sec) was obtained. The leading vehicle was instructed to follow a pre-specified speed instruction, while the driver in the following vehicle was unaware of the pre-specified speed pattern and instructed to maintain a safe minimum distance behind the lead vehicle (Chandler et al., 1958). The most convenient function, shown in Eq. (2.7), known as 1st GM model, was used to fit the collected data.

$$\ddot{x}_{n+1}(t+T) = \alpha\left[\dot{x}_n(t) - \dot{x}_{n+1}(t)\right] \tag{2.7}$$

where $\ddot{x}_{n+1}(t+T)$ is the acceleration of the following vehicle implemented at time $t+T$; $\dot{x}_{n+1}(t+T)$ is the speed of the following vehicle at time $t+T$; $\dot{x}_n(t)$ and $\dot{x}_{n+1}(t)$ are the speed values of the lead and the following vehicles at time t, respectively.

According to the 1st GM model, the high variation of acceleration was found to be influenced by sensitivity term (α). The 2nd GM model taking into account of separation distances of two vehicles was initiated, as shown in Eq. (2.8). The model separated the sensitivity term into two cases: close and far distances. When the following vehicle is close to the lead one, the driver would have higher sensitivity (α_1) and lower sensitivity (α_2) when shy away.

$$\ddot{x}_{n+1}(t+T) = \alpha_{1 or 2}\left[\dot{x}_n(t) - \dot{x}_{n+1}(t)\right] \tag{2.8}$$

Gazis, Herman, and Potts (1959) found that introducing the relative distance term into the sensitivity term could make the linkage between macroscopic and microscopic relationships. The relative distance included in the model could express the sensitivity term more practically than α_1 and α_2 in Eq. (2.8). The 3rd GM model was then shown as follows:

$$\ddot{x}_{n+1}(t+T) = \frac{\alpha_{1,0}}{x_n(t) - x_{n+1}(t)}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \tag{2.9}$$

where $\alpha_{1,0}$ is the sensitivity term in case that exponents l and m in Eq. (2.11) are equal to 1 and 0, respectively.

Edie (1960) examined the findings of Gazis et al. (1959) and found that the exponents of Eq. (2.9) should not be limited for only m = 0 and l = 1. He therefore developed a new model known as 4th GM model by giving m = 1 and l = 1 as follows:

$$\ddot{x}_{n+1}(t+T) = \frac{\alpha_{l,m}\left[\dot{x}_{n+1}(t+T)\right]}{\left[x_n(t) - x_{n+1}(t)\right]}\left[\dot{x}_n(t) - \dot{x}_{n+1}(t)\right] \tag{2.10}$$

The general form of GM model known as the 5th model is expressed in Eq. (2.11) based on the hypothesis that the stimulus is speed difference and the sensitivity of response depends upon the distance headway and instantaneous speed of the follower.

$$\ddot{x}_{n+1}(t+T) = \frac{\alpha_{l,m}\left[\dot{x}_{n+1}(t+T)\right]^m}{\left[x_n(t) - x_{n+1}(t)\right]^l}\left[\dot{x}_n(t) - \dot{x}_{n+1}(t)\right] \tag{2.11}$$

where $\ddot{x}_{n+1}(t+T)$ is the acceleration of the following vehicle implemented at time t+T; $\dot{x}_{n+1}(t+T)$ is the speed of the following vehicle at time t+T; $\dot{x}_n(t)$, $\dot{x}_{n+1}(t)$ are the speeds of the lead and the following vehicles at time t, respectively; $x_n(t)$, $x_{n+1}(t)$ are the positions of the lead and the following vehicles at time t, respectively; T is the driver reaction time; and m, l and α are the constants to be determined.

The 1st and 2nd GM model are expressed in linear form and the unit of sensitivity factor (α) in both equations is sec^{-1}. The 3rd, 4th, and 5th models are non-linear equations.

Few researches examined specifically on the exponents of the 5th GM model. Gazis, Herman, and Rothery (1961) calibrated the model using another series of data. The result showed that m and l were between 0-2 and 1-2, respectively. May and Keller (1967), using new data sets, found optimal integer solutions of m = 1, l = 3, (or assuming non-integer values, m = 0.8 and l = 2.8 with a scaling constant of approximately 1.33×10^{-4}). Ceder and May (1976), using a far larger number of data sets than previous works, found an optimum of m = 0.6 and l = 2.4. These relationships described behavior in the uncongested regime by the use of m = 0 and l = 3, and in congested conditions by m = 0 and l = 0-1. Treiterer and Myers (1974) divided the vehicle movement into acceleration and deceleration regimes, one (acceleration) with m = 0.2, l = 1.6, and the other (deceleration) with m = 0.7 and l = 2.5. Hoefs (1972) found m = 1.5, l = 0.9 for accelerating vehicles, m = 0.2 and l = 0.9 for those decelerating without braking, and m = 0.6, l = 3.2 for those decelerating using brakes. A summary of the varying parameter combinations to emerge from research on the GM equation is given in Table 2.1.

In recent years, a technique of car-following data acquisition has been much developed. The GPS technology is applied for collecting positioning and speed information of moving vehicles equipped with very accurate GPS devices. The outstanding benefits obtained from the use of this novel technology are that the experiment could be undertaken in actual roadway condition on the multi-vehicle platoon. Several researches which attempted to calibrate GM models with the experimental GPS data are reviewed as follows:

Wolshon and Hatipkarasulu (2000) at Louisiana State University developed their own techniques so called LSU-GPS to utilize GPS for collecting car-following data. Two passenger cars equipped with GPS were employed in this experiment. The car-following data were then analyzed to determine reaction time and sensitivity factor for the 1st and 3rd GM models, as shown in Table 2.2. Although this study simply applied the GPS for collecting vehicle movement data with no advanced technique and analytical method, it addressed that the use of GPS was superior to conventional techniques. Finally, the research compared the differences in car-following parameters (i.e. sensitivity factor, reaction time, and distance headway) calibrated with original GM data and LSU data.

Gurusinghe et al. (2003) used the RTK-DGPS for conducting a multiple car following experiment in Japan. This research aimed at collecting the car-following data from a 10-vehicle platoon running on a test track. In addition, the conventional equipment, i.e. distance meter, speedometer, and accelerometer, were used for collecting the data simultaneously with the GPS in order to compare the accuracy of both methods. The vehicles were driven in a circuit consisting two straights connected by two semicircular curves with 4 predetermined speed patterns for the lead vehicle (i.e. Half wave, one wave, two waves, and three waves). The collected data were then used for calibrating parameters in the GM model. The results showed that the reaction time varied between 0 and 3.0 sec with an average value of 1.5 sec. Further, the reaction time decreased whereas the sensitivity increased when the position from the lead vehicle increased. The study also indicated that the drivers did not have any fixed reaction time. The same driver could exhibit different reaction times during driving.

Table 2.1 Summary of optimal parameter combinations for the GM equation

Source	***m***	***l***	**Approach**
Chandler et al. (1958)	0	0	Micro
Gazis, Herman, and Potts (1959)	0	1	Macro
Herman and Potts (1959)	0	1	Micro
Helly (1959)	1	1	Macro
Gazis et al. (1961)	0-2	1-2	Macro
May and Keller (1967)	0.8	2.8	Macro
Heyes and Ashworth (1972)	-0.8	1.2	Macro
Hoefs (1972) (dec+no brk/dec+brk/acc)	1.5/0.2/0.6	0.9/0.9/3.2	Micro
Treiterer and Myers (1974) (dec/acc)	0.7/0.2	2.5/1.6	Micro
Ceder and May (1976) (uncong & cong)	0.6	2.4	Macro
Ceder and May (1976) (uncong/cong)	0/0	3/0-1	Macro
Aron (1988) (dec/ss/acc)	2.5/2.7/2.5	0.7/0.3/0.1	Micro
Ozaki (1993) (dec/acc)	0.9/-0.2	1/0.2	Micro

Note: dec is deceleration; brk is brake; acc is acceleration; uncong is uncongestion; cong is congestion; ss is steady state.
Source: Brackstone and McDonald (1999)

Table 2.2 Reaction times and sensitivity factors from LSU study

Model	***T*** **(sec)**	α **(sec^{-1})**	$\alpha_{1,0}$ **(ft/sec)**
1st GM model	0.86	0.46	-
3rd GM model	1.05	-	29.26

Source: Wolshon and Hatipkarasulu (2000)

2.2.3 Excess Critical Speed Model

Gurusinghe et al. (2001) modified the 1st GM model by incorporating excess critical speed concept (ECS). It was assumed that a follower considered safe speed with respect to the available space in making driving decisions. If the follower had freedom to increase his speed, he would speed up around the critical speed; on the other hand, if his speed was over this limit, the acceleration would be applied to keep safe distance with the lead vehicle. The model is mathematically defined as follows:

$$\ddot{x}_n(t+T) = \alpha_0 + \alpha_1[ECS] + \alpha_2\left[\dot{x}_{n-1}(t) - \dot{x}_n(t)\right] \tag{2.12}$$

$$ECS = v_{CR} - \dot{x}_n(t) \tag{2.13}$$

$$v_{CR} = \sqrt{2f[x_{n-1}(t) - x_n(t)]} \tag{2.14}$$

where f is the maximum deceleration rate of the following vehicle (m/s^2); v_{CR} is the critical speed (m/s).

It was found that ECS was able to improve the accuracy of the model with good regression fit of empirical data. As a result of ECS parameters, it can be concluded that the driver is more concerned about the space than the relative speed during the acceleration while the relative speed is more important than the space during deceleration.

A reaction time model for acceleration and deceleration phases, which relied on some explanatory variables such as space, speed, and acceleration, was also constructed with a linear regression model. The reaction time according their study thus varied to the explanatory variables, not a constant as explained by the original GM model.

2.2.4 Safety Distance or Collision Avoidance Model

Kometani and Sasaki (1959) generated a new car-following model, which was not described by a stimulus-response function as proposed by the General Motors researchers. They attempted to specify a safe following distance (through the manipulation of the basic Newtonian equations of motion), within which a collision would be unavoidable, if the driver of the vehicle in front were to act unpredictably. The full original formulation is as follows:

$$\Delta x(t-T) = \alpha v_{n-1}^{2}(t-T) + \beta_{1} v_{n}^{2}(t) + \beta v_{n}(t) + b_{0} \tag{2.15}$$

where Δx is vehicle spacing; v_{n-1} is the speed of the lead vehicle; v_n is the speed of the following vehicle; T is the reaction time; α, β, β_1, and b_0 are coefficients and constant of the model.

Subsequently, Gipps (1981) modified the original model by allowing an additional safety reaction time equal to T/2 and that the kinetic terms in Eq. (2.15) are related to braking rate of $-1/2b_n$ (b_n is the maximum braking rate the driver of the nth vehicle that can be applied) and $1/2b*$ ($b*$ is the maximum braking rate of the $(n-1)^{th}$ vehicle that the nth driver believes is likely to be used). This research focused on the simulation using the more realistic reaction time and parameters and it was found that the realistic results were presented between the successive vehicles as well as for a whole platoon. This model is expressed as follows:

$$v_n(t+T) \le b_n T + \sqrt{\frac{b_n^2 T^2 - 2b_n[X_{n-1}(t) - S_{n-1} - X_n(t)] - v_n(t)T - v_{n-1}^2(t)}{b_{n-1}}} \tag{2.16}$$

where S_{n-1} is the maximum safe distance headway between two successive vehicles; b_n is the maximum braking rate of the following vehicle; b_{n-1} is the maximum braking rate of the lead vehicle; $X_n(t)$ is the position of the following vehicle; v_n is the desired speed of the following vehicle at time t; T is the reaction time

In addition to the consideration of safe distance applying the maximum deceleration rate, the model was also adapted to incorporate the desired speed as shown in Eq. (2.17).

$$v_n(t+T) \le v_n(t) + 2.5a_n T(1 - \frac{v_n(t)}{V_n})(0.025 + \frac{v_n(t)}{V_n})^{1/2} \tag{2.17}$$

where V_n is the desired speed.

2.2.5 Helly's Linear Model

Helly (1959) proposed a model that included additional terms for the adaptation of the acceleration according to whether the vehicle in front (and the two vehicles in front) was braking. The simplified model is formulated as follows:

$$a_n(t) = C_1 \Delta v(t-T) + C_2[\Delta x(t-T) - D_n(t)] \tag{2.18}$$

$$D_n(t) = \alpha + \beta v(t-T) + \gamma a_n(t-T) \tag{2.19}$$

where a_n is the acceleration of the following vehicle; Δv is the relative speed; Δx is the relative distance; $D_n(t)$ is desired following distance; v is the speed of the following vehicle; T is reaction time; C_1, C_2, α, β, and γ are coefficients of the model.

The advantage of the linear model is its simplicity. The consideration of relative speed, relative distance, and desired speed as the stimuli makes the model more reasonable and practical than the original GM models.

Table 2.3 Summary of optimal parameter combinations for Helly equation

Source	$C_1(\Delta v)$	$C_2(\Delta x)$
Helly (1960)	0.5	0.125
Hanken and Rockwell (1968)	0.5	0.06
Burnham and Bekey (1977)	0.5	1.64
Aron (1988) (dec/ss/acc)	0.36/1.1/0.29	0.03/0.03/0.03
Xing (1995)	0.5	0.05

Note: dec is deceleration; acc is acceleration; ss is steady state.
Source: Brackstone and McDonald (1999)

2.2.6 Psychophysical or Action Point Models (AP)

Michaels (1963) proposed the concept that drivers would initially be able to tell they were approaching a vehicle in-front, primarily due to changes in the apparent size of the vehicle, by perceiving relative velocity through changes on the visual angle subtended by the vehicle ahead θ. In the other word, as illustrated in Figure 2.2, while the following vehicle gets close to the leader, the driver perceives the size of the leading vehicle getting larger. The threshold for this perception is well-known in perception literature and given as, $d\theta/dt$ (~ $\Delta v/\Delta x^2$) ~ 3-10×10^{-4} rad/sec with an average of 6×10^{-4} rad/sec. Once this threshold is exceeded, drivers will choose to decelerate until they can no longer perceive any relative velocity, and provided the threshold is not then re-exceeded. The driver therefore base all their actions on whether they can then perceive any changes in spacing. The derivation of the model is shown in Eqs. (2.20)-(2.22).

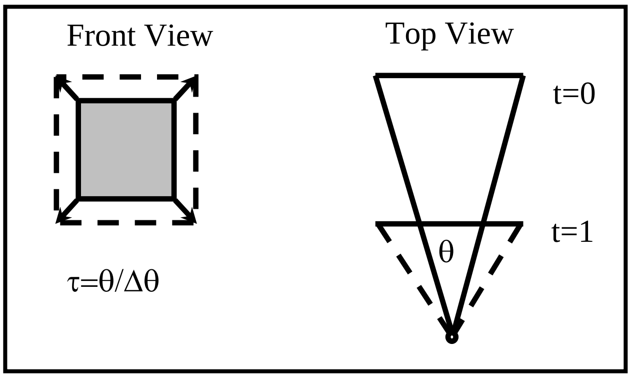


Figure 2.2 Change in visual angle and apparent size (Michaels, 1963).

$$\tan\left(\frac{\theta}{2}\right)=\frac{W}{DX} \tag{2.20}$$

$$\theta = 2\arctan\left(\frac{W}{DX}\right) \tag{2.21}$$

$$\frac{d\theta}{dt}=\frac{-4W\times DV}{4DX^2+W^2} \tag{2.22}$$

where θ is driver's visual angle; W is the width of the lead car; DX is the distance between the rear bumper of the lead car and the driver in the following car.

The Psychophysical model is employed by applying the collision avoidance concept which uses the constant acceleration rate as shown in Eq. (2.23). Even though, this model is quite conceptually reasonable because it considers the psychological aspects of drivers, there are only small number of evidences of using and testing the model so far ensuring how well the model fits to the actual driving behavior.

$$Dc_n = -\frac{[V_{n-1}(t-T)-V_n(t-T)]^2}{2[X_{n-1}(t-T)-X_n(t-T)-S]}+Dc_{n-1} \tag{2.23}$$

2.2.7 Miscellaneous Car Following Models

There are several recent algorithms in car following models that have been used in many computer simulation programs. The following is miscellaneous car-following models summarized by Ranjitkar (1998).

- Simonsson (1993)

$$a(t+T)=\gamma(\Delta x + vT_p - a\frac{T_p^2}{2})e^{-\alpha(\frac{\Delta x-1}{\Delta x})}+\rho(v_{Des}-v)e^{-\frac{\beta}{\Delta x}} \tag{2.24}$$

where T_p is the desired time headway. It is noticeable that this may reduced to simple Helly form, by setting some of the scaling constants less than one or for large Δx.

- Low and Addison (1995)

The conventional stimulus-response was examined with an additional term. The parameters were assumed to be $\alpha=0.3$, $m=0$ and $l=1$ and the cubic of distance between actual and desired headway (α_2=30) was included in the new model. However, no calibration has been made with this model.

$$\ddot{x}_n(t) = \beta[\dot{x}_{n-1}(t-T) - \dot{x}_n(t-T)] + b\left[\frac{x_{n-1}(t-T) - x_n(t-T)}{D}\right]^3 \tag{2.25}$$

where b is greater than zero and sensitivity to relative speed as in Eq. (2.26).

$$\beta = \alpha \frac{[x_n(t)]^m}{[x_{n-1}(t-T) - x_n(t-T)]^l} \tag{2.26}$$

where α, l and m are greater than or equal to zero.

- Bando et al. (1995)

$$a(t) = a[V(\Delta x) - v_n] \tag{2.27}$$

$$V(\Delta x) = \tanh(\Delta x - 2) + \tanh(2) \tag{2.28}$$

where Δx and v are expressed in reduced units i.e. of the order of 1, 2 multiples of a basic internal scale.

- Yukawa and Kikuchi (1995)

$$an(t) = \frac{v_{Des} - v_n(t)}{T(\alpha - 1)v_n(t)}[\Delta x(t) - v_n(t)] \tag{2.29}$$

It can be seen that there is a second headway equilibrium distance in this model.

2.3 Review of Fundamental Car-following Characteristics

Shekleton (2002) collected the car-following data using Differential GPS (DGPS) for tracking the position data of two test vehicles. The experiment was performed both in weather and dry conditions. He analyzed and determined the relationship between spacing and speed. As shown in Figures 2.3 and 2.4, the speeds of both driver A and B have a linear and exponential correlation to spacing in dry and wet condition, respectively. The minimum spacings in dry condition which can be drawn from the regression models are 1.45 and 1.78 m for driver A and B respectively. For wet condition, they are 1.68 and 2.32 m for driver A and B. It is likely that the roadway surface or weather affects drivers on keeping specific distances because of their own safety reason. The relationship between acceleration and speed using fourth degree polynomial shows insignificant correlation as indicated by low R^2 value. In addition, this study also addressed the benefits received from the use of GPS in car-following data collection in aspects of time saving, data quality, and expenses.

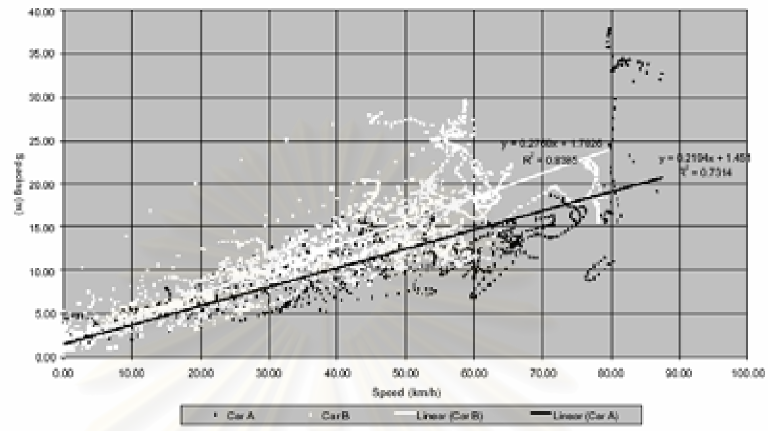


Figure 2.3 Speed vs. spacing in dry condition (Shekleton, 2002).

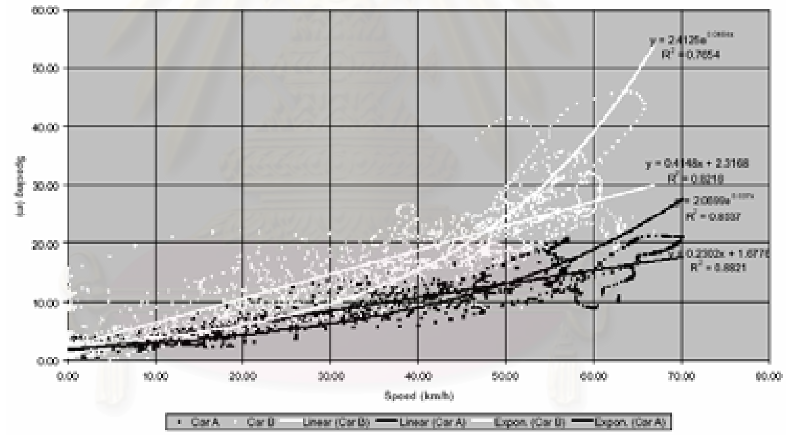


Figure 2.4 Speed vs. spacing in wet condition (Shekleton, 2002).

Dijker et al. (1998) studied car-following by relating distance gaps of following vehicle to speed. The observed distance gaps were plotted separately for congested and uncongested flow for each 5 km/h class. The plotted data was then derived for the empirical relationship. The quadratic equation as shown below was employed.

$$g_d = a + b \times v + c \times v^2 \tag{2.30}$$

where g_d is distance gap (m); v is speed (km/h); and a, b, and c are parameters.

Table 2.4 shows some findings on distance gap-speed relationship for passenger cars at a roadway near Amsterdam.

Table 2.4 Estimate of parameters of distance gap-speed relationship

Lane	Traffic state	*a*	*b*	*c*	R^2
Median lane	Congested	3.00	0.411	0.0001	0.99
	Non- Congested	3.00	0.000	0.0028	0.88
Middle lane	Congested	3.00	0.399	0.0003	0.97
	Non- Congested	3.00	0.000	0.0037	0.94
Shoulder lane	Congested	3.00	0.321	0.0034	0.95
	Non- Congested	3.00	0.000	0.049	0.89

Source: Dijker et al. (1998)

2.4 Review of Reaction Time

Two major approaches for estimating the driver's reaction time are the correlation method and graphical method. The first yields a constant reaction time value for a data set. The latter separates the data set into many parts based on number of peak points, yielding varied reaction time values. The following provides the examples of researches on driver's reaction time.

Brackstone and McDonald (1999) reviewed the history of car-following models development. The reaction time from the first GM experiment was between 1.0-2.2 sec., whereas the results from other researches are summarized in Table 2.5.

Kometani and Sasaki (1959) developed the safety distance model which did not describe a stimulus-response as proposed by GM models, but attempted to specify a safe following distance (See section 2.2.4). The model was calibrated by a pair of test vehicles driving on a city street with an average speed of less than 45 km/h. The obtained reaction time was 0.5 sec. After that, the second experiment was conducted with speeds varied between 40-60 km/h, resulting in reaction time of 0.75 sec.

Helly (1959) proposed a linear model that included additional terms for the adaptation of the acceleration according to whether the vehicle in front (and the vehicle two in front) was braking (See section 2.2.5). The reaction time ranged between 0.5 and 2.2 sec.

Rockwell and Treiterer (1966) showed that the reaction time decreased from 3.5 sec at deceleration rates of 0.5 m/s^2 to 2 sec at the rate of above 1.3 m/s^2 in case of driving without the braking light. In case of the existence of braking lights, the reaction time is reduced to 3.2 sec at a coasting condition, and to 0.8 sec at the higher speed condition.

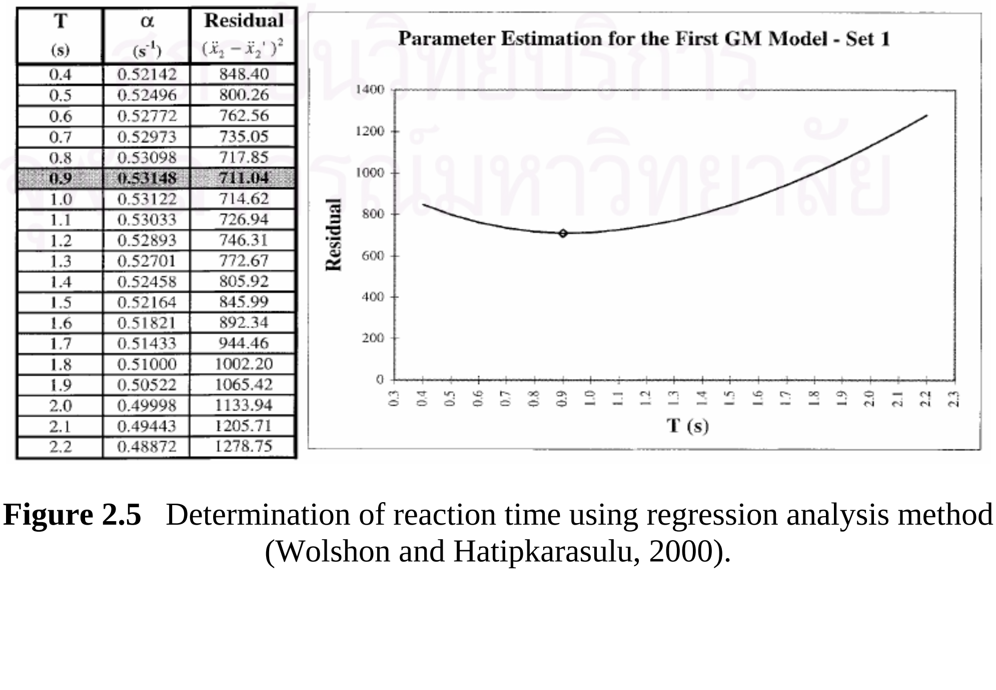
Table 2.5 Reaction time values from various researches

Source	Reaction time (sec)
Chandler, Herman and Montroll (1958)	1.6
Herman and Potts (1959)	1.2
Kometani and Sasaki (1959)	0.5
Helly (1960)	0.4
Michaels (1963)	1.4
Lee and Jones (1967) (acc/dec)	1.4/0.6
Aron (1988) (acc/ss/dec)	1.8/0.5/3.9
Ozaki (1993) (acc/dec)	1.9/1.9

Note: acc is acceleration; dec is deceleration; ss is steady state.
Source: Brackstone and McDonald (1999)

Sivak et al. (1981) conducted an experiment in uncongested condition with the average speed of 48-72 km/h. They found only 31% of the test cases that the followers brake according to the braking light of the vehicle in front. The average reaction time was 1.36 sec with a standard deviation of 0.56 sec.

Wolshon and Hatipkarasulu (2000) calibrated the 1st and 3rd GM models using the 10 sets of GPS data. The reaction time was estimated by applying regression analysis method. The resultant reaction time was determined from the value giving the minimum value of sum of square of error, as described in Figure 2.5. The average reaction time for the 1st GM model was 0.86 sec with a standard deviation of 0.16 sec and that for the 3rd GM model was 1.05 sec with a standard deviation of 0.31 sec.



T (s)	α (s^{-1})	Residual $(\ddot{x}_2 - \ddot{x}_2')^2$
0.4	0.52142	848.40
0.5	0.52496	800.26
0.6	0.52772	762.56
0.7	0.52973	735.05
0.8	0.53098	717.85
0.9	**0.53148**	**711.04**
1.0	0.53122	714.62
1.1	0.53033	726.94
1.2	0.52893	746.31
1.3	0.52701	772.67
1.4	0.52458	805.92
1.5	0.52164	845.99
1.6	0.51821	892.34
1.7	0.51433	944.46
1.8	0.51000	1002.20
1.9	0.50522	1065.42
2.0	0.49998	1133.94
2.1	0.49443	1205.71
2.2	0.48872	1278.75

Figure 2.5 Determination of reaction time using regression analysis method (Wolshon and Hatipkarasulu, 2000).

Gurusinghe et al. (2003) proposed the determination of reaction time with graphical analysis of stimulus and response. As shown in Figure 2.6, the reaction time is the time lag between stimulus and corresponding response which can be both negative and positive. The negative value shows the expected reaction of which the following driver takes acceleration or deceleration in advance.

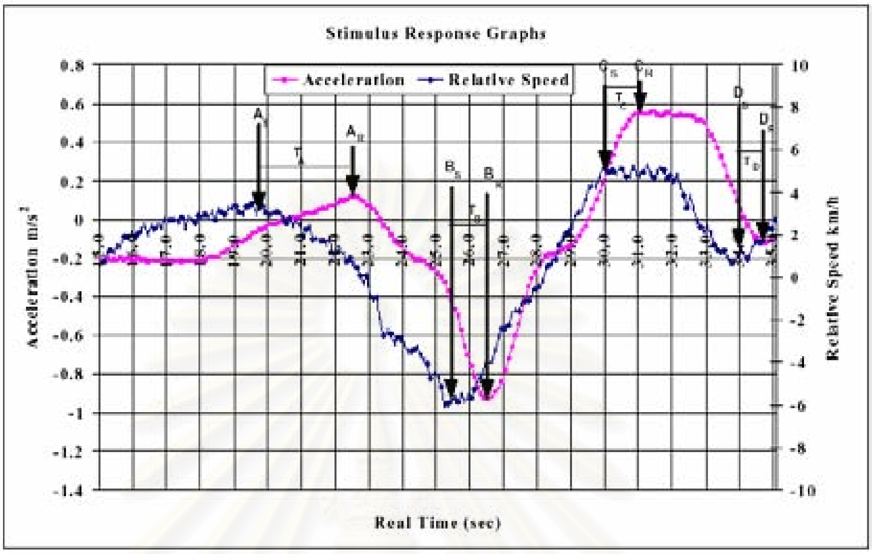


Figure 2.6 Graphical plot of stimulus and response for reaction time determination (Gurusinghe et al., 2003).

The analysis result showed that reaction time varied between 0 and 3 sec with an average of 1.5 sec. In addition, Gurusinghe et al. (2001) also attempted to determine the relationship between reaction time and explanatory driving variables corresponding to the assumption that the reaction time varied to changing driving situations. The reaction time is mathematically expressed as follows:

$$T = \beta_0 + \beta_1[x_1(t) - x_2(t)] + \beta_2[\dot{x}_2(t)] + \beta_3[\ddot{x}_1(t)] \tag{2.31}$$

where β_0, β_1, β_2, and β_3 are constants of the model.

However, the coefficients of determination (R^2) of the model for most series of data were quite low and other forms of the variables could not improve the reliability of the model, the authors concluded that a more appropriate model should be explored.

CHAPTER 3

RESEARCH METHODOLOGY

This research was conducted to collect and analyze car-following data received from the GPS tracking device. The experiment was carried out under congested and uncongested conditions on surface street and freeway facilities in order to investigate whether there are some significant differences in driving behaviors between the two. Generally, the characteristics of both facilities are remarkably different. Freeways are controlled access facilities, but surface streets can be interfered by roadside environments, leading to differences in driving behaviors. Even though the design of the experiment for both facilities was somewhat the same, in practice the collected data were not identical. The problems and difficulties of data collection would be addressed hereafter. This chapter describes the data preparation and model analysis methods including the model evaluation procedures.

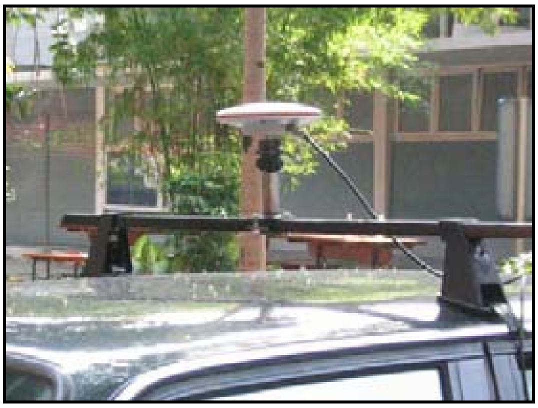
3.1 Data Collection

The experiment was undertaken on February 7, 2004 during good weather duration as well as ordinary traffic characteristics and travel behavior. This section explains the methodology for data collection including the equipments used, selection of study sites, and detail of test cars which provides an insight into the whole process of the experiment.

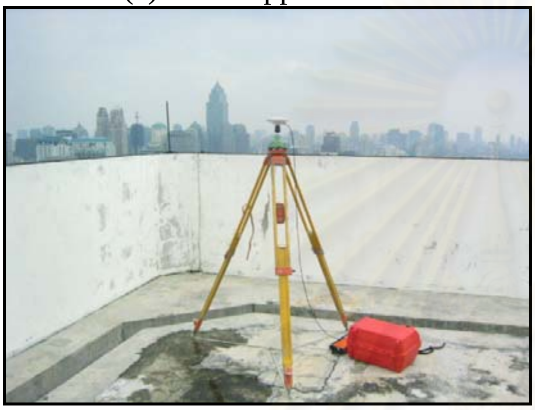
3.1.1 Equipment

The data collection was undertaken using five passenger cars equipped with GPS model LEICA System 500, as shown in Figure 3.1 (a). The GPS antenna was mounted on a steel rod which was fixed with a car roof rack and connected to the receiver via a cable, as illustrated in Figure 3.1 (b). Also, the differential GPS (DGPS) unit was located at a known stationary base station on a roof top of Faculty of Engineering's Building 4, Chulalongkorn University for the freeway experiment, as shown in Figure 3.1 (c) and on a walkway at Buddha Monthol Sai 4 Rd. for the surface street experiment. The position data from the base station were further used to correct those from the rover GPS units with post-processing calculation method. The GPS tracking units used in this study were capable of recording three-dimensional coordinates at every 0.1-sec interval. The maximum distance between the furthest position of the platoon and the base station must not exceed 10 km to ensure that the centimeter accurate position data would be obtained. The GPS receiver units provided output data as follows: the time at which each data point was recorded, the corresponding X, Y, Z coordinates, and the extent of the error of receiving coordinates. The arrangement of the vehicle platoon is illustrated in Figure 3.1 (d).

(a) GPS apparatus



(b) Installation of GPS antenna



(c) Differential GPS unit

(d) Test cars equipped with GPS devices

Figure 3.1 GPS apparatus for experimental data collection.

The test drivers were all males in their early 20s. Their driving experiences were between 3 and 10 years. The test vehicles used in this study were all passenger cars with good condition. The description of test cars and drivers are provided in Table 3.1. It should be noted that the driver/vehicle no.1 was at the front of the platoon and the driver/vehicle no.5 became the last one. Therefore, there were four following vehicles for further analysis of car-following characteristic.

Table 3.1 Description of test drivers and vehicles

Driver/Vehicle	**Sex**	**Age (yrs)**	**Driving experience (yrs)**	**Vehicle model**
D1/V1	Male	21	10	BMW 318I
D2/V2	Male	24	5	HONDA CIVIC
D3/V3	Male	22	5	HONDA CIVIC
D4/V4	Male	22	4	TOYOTA CORONA
D5/V5	Male	25	3	TOYOTA CORONA

3.1.2 Experimental Design

In general, driving behaviors on freeways and surface streets are apparently different. The behavior of a driver on freeways is governed by vehicle-vehicle interactions, traffic composition, and interactions between the vehicle and freeway infrastructure, whereas surface street traffic is mainly regulated by traffic signals in addition to the mentioned factors for freeways. Moreover, motorcycles and pedestrians are major factors influencing driving behavior on Bangkok's surface street. Therefore, the drivers must handle their vehicles on surface streets more vigilantly. According to such the differences between freeway and surface street traffic conditions, this study classified driving characteristics into four regimes by taking into account both types of roadways and traffic conditions, as shown in Table 3.2.

Table 3.2 Classification of driving conditions

Traffic condition / **Roadway type**	**Uncongested**	**Congested**
Surface street	Regime I	Regime II
Freeway	Regime III	Regime IV

As stated earlier, the experiments were undertaken on two types of roadway facilities: surface street and freeway. The selected surface streets were Buddha Monthol Sai 4 Rd. and Asa Rd. located in Nakornpathom province. The first consisted of two signalized intersections, causing stop-and-go and congested traffic situation whereas the latter was a low-volume roadway with no traffic light, yielding uncongested traffic condition. The freeway sites were part of the 1st stage, 2nd stage, and Ramindra-Arjnarong expressway, which are fully controlled access freeways. Both congested and uncongested traffic conditions occurred alternately during the study time period. The study locations on both surface street and freeway are illustrated in Figure 3.2.

The total traveling distance on surface streets was approximately 45 km, taking 45 min for completing the experiment. The total distance on freeway was approximately 60 km, taking 90 min. It should be noted that only some parts of the colleted data were chosen for analysis. Prior to the data collection, all the drivers would be instructed about the routes on which the experiment was conducted. After that, the test vehicles would drive in succession. The driving patterns would be up to their own driving behaviors and existing traffic condition. During the experiment, the locations and time periods at which other vehicles intervened the platoon were recorded and the corresponding data were discarded in subsequent analysis.

(a) Surface street sites (b) Freeway sites

Figure 3.2 Maps of study locations.

3.2 Data Preparation and Analysis

The first task of data preparation was to pick up four series of data which could properly represent all four driving regimes. A good series of data must be continuously arranged for at least 60 seconds so that it would reasonably explain driving behavior for each regime. The error in original time data were then corrected so that spacing, speed, and acceleration from the GPS coordinates could be calculated. Further, traffic parameters (i.e. traveling distance, spacing, speed, relative speed, and acceleration) of all vehicles were then plotted against time. The data analyses were to determine the correlation among them and to calibrate the GM models for investigating sensitivity factor, exponents, and reaction time. Eventually, the models were evaluated by comparing the predicted values with the measured ones both at microscopic and macroscopic levels. The step-by-step procedure for data analysis is presented in Figure 3.3 and the detailed descriptions of all processes are discussed in the following subsections.

3.2.1 Characteristics of GPS Data and Data Preparation

The experimental GPS data were originally stored in GPS receivers and then converted to MS Excel file for data processing. As Table 3.3 shows, the GPS receivers provided ten attributes of data, primarily consisting of Greenwich mean time and local time in columns 1 and 2, respectively. Three dimensional coordinates are shown in columns 3-5, indicating the positions of the five GPS antennas, placed at the vehicle roofs, at every 0.1 sec. The last three columns describe the extent of position error or quality of data.

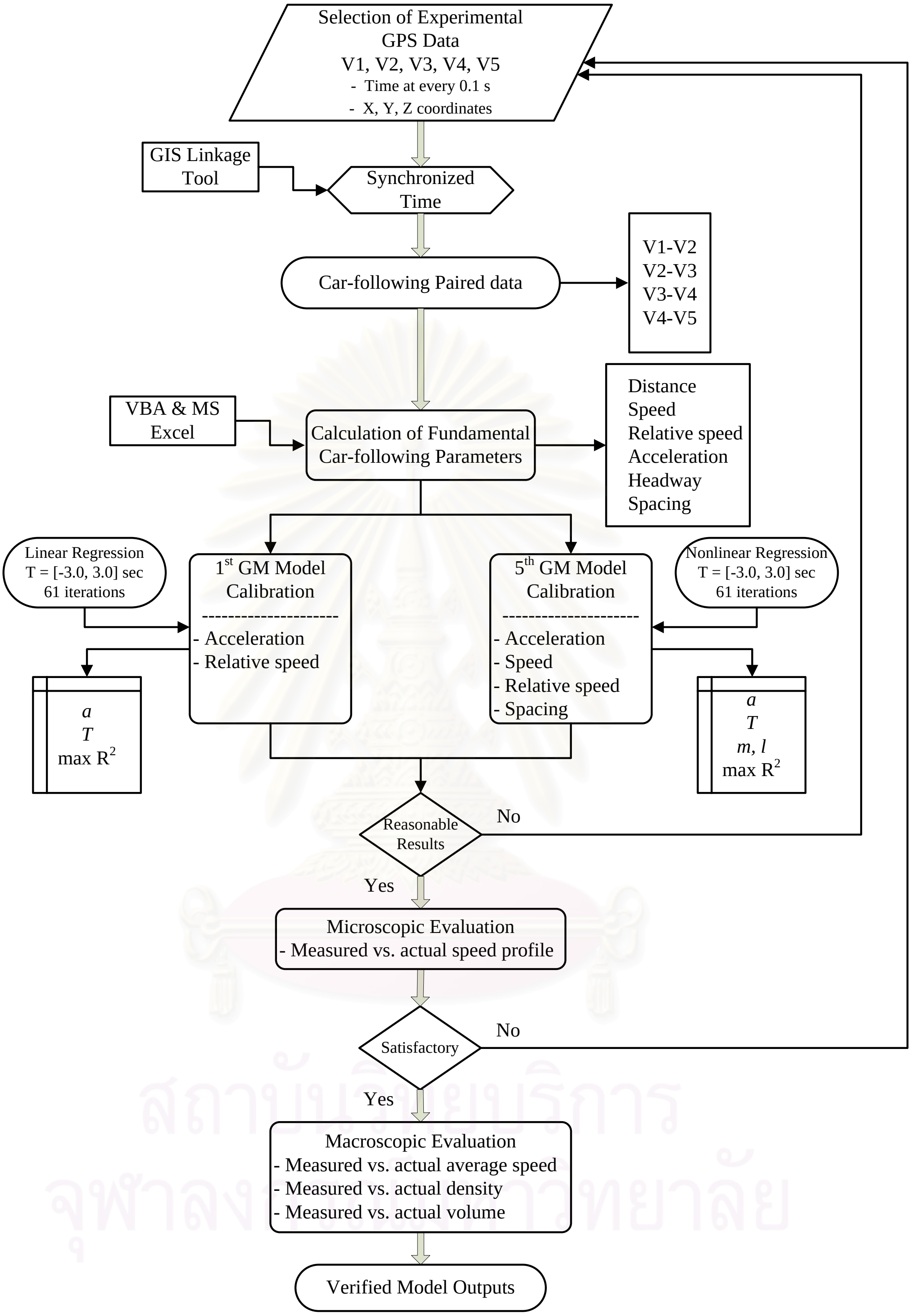


Figure 3.3 Analysis procedure of car-following data.

Table 3.3 Example of GPS data in MS Excel

1	2	3	4	5	6	7	8
Point Id	**Epoch**	**Easting**	**Northing**	**Height**	**Posn. Qlty**	**Hgt. Qlty**	**Posn. + Hgt. Qlty**
549330	2/7/2004 12:49	667945.4	1517257	-12.3205	0.0009	0.0014	0.0017
549331	2/7/2004 12:49	667945.4	1517257	-12.3268	0.0009	0.0015	0.0017
549332	2/7/2004 12:49	667945.4	1517257	-12.3351	0.0009	0.0015	0.0017

The original data contained the error of time recording. As shown in Table 3.4, the GMT at the last row should be 551600 instead of 551000, such the erroneous time data led to the wrong calculation results of headway, speed, and acceleration. This kind of error occurred when the time changed from the previous minute to the next one and needed to be corrected before further steps of the analysis.

Table 3.4 Error of time recording in original data

Point Id	Epoch	Easting	Northing	Height	Posn. Qlty	Hgt. Qlty	Posn. + Hgt. Qlty
550598	2/7/2004 12:51	668020.9	1517104	-12.7676	2.4372	4.1844	4.8425
550599	2/7/2004 12:51	668020.9	1517104	-12.7606	2.4372	4.1843	4.8424
551000	2/7/2004 12:51	668021	1517104	-12.7817	2.4372	4.1842	4.8423

3.2.2 Analyses of Fundamental Car-following Parameters

The original GPS data consisting of time and corresponding X, Y, Z coordinates would be calculated to provide the data necessary for the model calculation. First, the distance between a pair of GPS antennas so called distance headway was calculated from those coordinates using Eq. (3.1).

$$D = \sqrt{(X_L - X_F)^2 + (Y_L - Y_F)^2 + (Z_L - Z_F)^2} \tag{3.1}$$

where D is the displacement between the lead and following vehicle (m); X_L, Y_L, and Z_L are X, Y, and Z coordinates of the lead vehicle (m); X_F, Y_F, and Z_F are X, Y, and Z coordinates of the following vehicle (m).

The spacing of a pair of vehicles was then calculated by subtracting D with the distance between the rear edge of the lead car and its antenna plus the distance between the front edge of the follow car and its antenna. The correction distances for determining vehicle spacing are shown in Table 3.5.

Table 3.5 Correction distances for spacing calculation

Lead car/Follow car	Correction distance (m)
V1/V2	4.015
V2/V3	4.275
V3/V4	4.420
V4/V5	4.380

To calculate speed data, nine data points of distance (i.e. 4 data points before and 4 data points after the time point of interest) were plotted using the second-order polynomial curve. The first derivative or slope of the curve at the middle point yielded a speed value. The calculation of acceleration was performed in the same manner using the second derivative. The distance, speed, and acceleration were determined from Eqs.(3.2)-(3.4).

$$x = at^2 + bt + c \tag{3.2}$$

$$\frac{dx}{dt} = 2at + b \tag{3.3}$$

$$\frac{d^2x}{dt^2} = 2a \tag{3.4}$$

where x is the distance (m); t is the time (sec); a and b are coefficients of the second order polynomial equation; c is a constant.

The conventional speed determination method calculated from the change in distance over time period ($s = \Delta x/\Delta t$) was not practical and provided unsatisfactory results. As seen in Figure 3.4, the speed values calculated from the conventional method (Newtonian equation) are more likely to oscillate than those from the parabolic curve fitting. It should be noted that the distance, speed, and acceleration data were used without any smoothing operation.

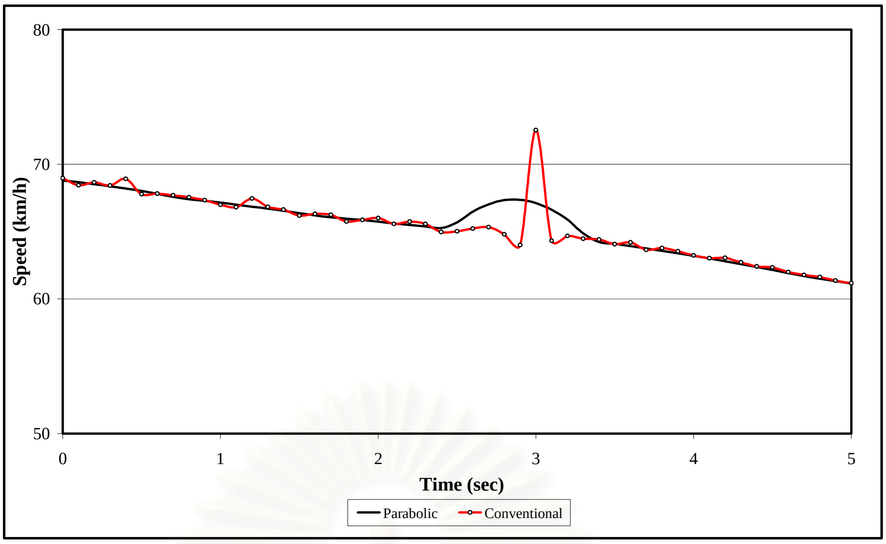


Figure 3.4 Calculation of vehicle speeds with conventional vs. parabolic method.

3.2.3 Calibration of Models

The GPS data consisting of speed, acceleration, relative distance, and relative speed of every pair of vehicles were used to calibrate the model. In this study, the selected models were the 1st and the 5th GM models. As shown again in Eq.(3.5), there was only an independent variable (i.e. relative speed) in the 1st GM model. The model parameters which were calibrated consisted of sensitivity factor (α) and reaction time (T). For the 5th GM model as expressed in Eq.(3.6), the independent variables were the follower's speed, relative speed, and relative distance. The model parameters determined were sensitivity factor (α), exponents m and l, and reaction time (T).

$$\ddot{x}_{n+1}(t+T) = \alpha\left[\dot{x}_n(t) - \dot{x}_{n+1}(t)\right] \tag{3.5}$$

$$\ddot{x}_{n+1}(t+T) = \frac{\alpha_{l,m}\left[\dot{x}_{n+1}(t+T)\right]^m}{\left[x_n(t) - x_{n+1}(t)\right]^l}\left[\dot{x}_n(t) - \dot{x}_{n+1}(t)\right] \tag{3.6}$$

The least-squared regression between the dependent and independent variables were performed with a reaction time (T) varying from -3.0 to 3.0 sec in 0.1-sec increment. As seen in Figure 3.5, the data of acceleration ($\ddot{x}_{n+1}(t+T)$) as the dependent variable, and other model parameters as independent variables with a time lag of 0.5 sec were selected for a regression analysis. Therefore, the regression must be performed repeatedly for 61 times for each data set.

Time (sec)	$\ddot{x}_{n+1}(t+T)$ (m/s^2)	$\dot{x}_{n+1}(t+T)$ (m/s)	$\left[\dot{x}_n(t)-\dot{x}_{n+1}(t)\right]$ (m/s)	$x_n(t)-x_{n+1}(t)$ (m)
0.0	-0.1465532	24.72945	0.984	19.586755
0.1	-0.2477163	24.705339	1.054	19.62352
0.2	-0.2999082	24.682452	1.118	19.751035
0.3	-0.2483247	24.646543	1.196	19.881694
0.4	-0.2264449	24.590807	1.297	20.022237
0.5	-0.2279864	24.535459	1.394	20.159239
0.6	-0.2357708	24.538425	1.432	20.286416
0.7	-0.2320968	24.627265	1.385	20.439967
0.8	-0.2172834	24.548123	1.509	20.596844
0.9	-0.1925962	24.486841	1.615	20.743032
1.0	-0.1579714	24.446963	1.698	20.90365
1.1	-0.0714397	24.428165	1.756	20.949621
1.2	0.2004343	24.426189	1.798	21.393237
1.3	0.4015407	24.455582	1.806	21.551896
1.4	0.5367398	24.505866	1.787	21.710409
1.5	0.6108863	24.572621	1.744	21.885847

Figure 3.5 Example of data selection for regression analysis.

The regression yielding the reaction time (T) value with the highest R^2 was selected as the best estimate of each data set. Figure 3.6 shows an example of the best estimate of the 1st GM model for the driver no. 2's data under Regime IV.

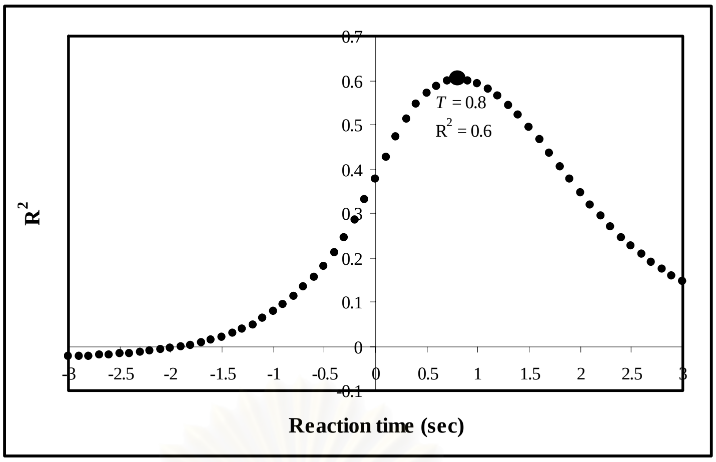
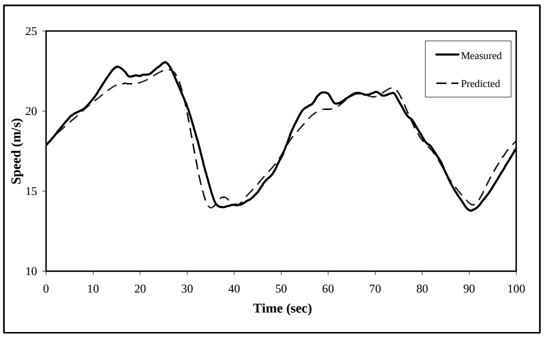


Figure 3.6 Determination of the best model giving the highest R^2.

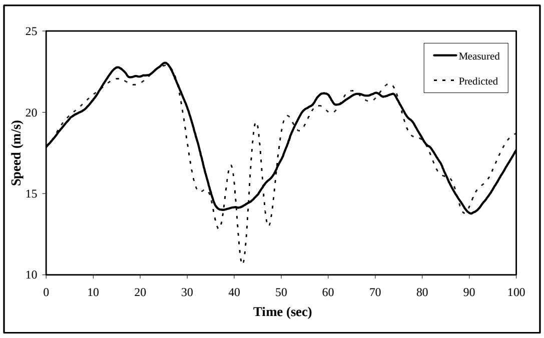
3.2.4 Evaluation of the Developed Models

The developed model needs to be checked for its validation and accuracy. Sargent (1982) proposed four steps in evaluating the model. The first step was the conceptual validation which ensured that the proposed model would be theoretically acceptable. The next was computerized validation to ensure that the predicted results were mathematically correct. The third one was the operational validation which would describe how well the model was in comparison with the real traffic condition. The last step was to examine whether the number of collected samples used for formulating the model were statistically sufficient and correct. The evaluation of the model could be performed at two levels: microscopic and macroscopic. At microscopic level, the predicted trajectories (e.g. speed versus time, position versus time) of individual vehicles were visually inspected whether they were close to the field data. But, at macroscopic level, the average fundamental traffic parameters (flow, speed, and density) were considered.

Microscopic evaluation compares the vehicle position, speed, and acceleration simulated from the model with those from field data. Those trajectories would be plotted against time. The selection of time interval in plotting the trajectory directly affects to the predicted results. The larger the time interval, the less accuracy of the prediction will be obtained. Benekohal (1989) suggested that the time interval should not exceed 2-3 seconds if the high accurate result was required. The evaluation of models at microscopic level is performed using only visual inspection without any statistical tests because the predicted values are very close to the measured ones, resulting in a small extent of error. The microscopic evaluation should emphasize on the shape of the curve in regard to how well the prediction results duplicate the field data. The deviation between such two curves is probably less significant than the closeness of their shapes because the deviation is caused from the instantaneous driving styles. The similar/unsimilar shape of the curves reflects the prediction ability of the model. Furthermore, the drivers with longer reaction times tend to cause a larger error of prediction than those with shorter reaction times. An example of an acceptable and unacceptable result from microscopic model evaluation is illustrated in Figure 3.7.



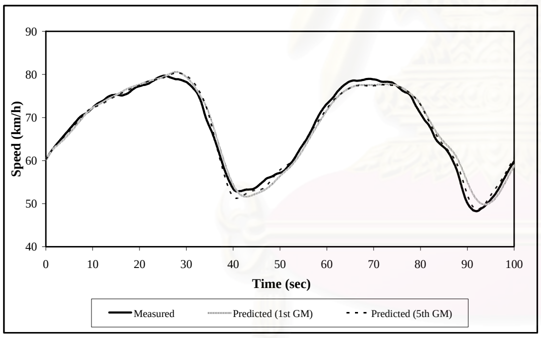
(a) An acceptable predicted result



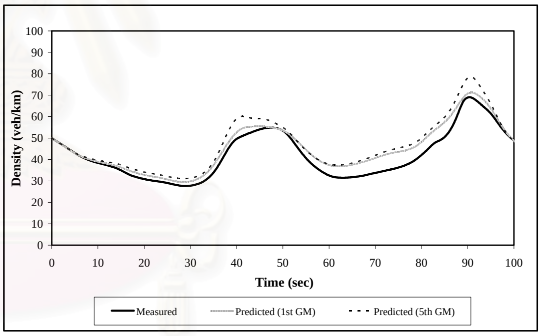
(b) An unacceptable predicted result

Figure 3.7 Example of microscopic model evaluation.

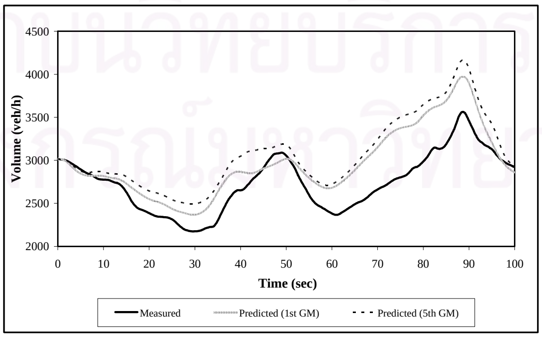
At macroscopic level, the overall performance of a vehicle platoon, rather than the performance of an individual vehicle, would be evaluated. For example, the average speed from the model should be close to that from the real data although the individual speeds between the prediction and the field might be considerably different. In this study, the comparison of flow parameters over time such as average speed vs. time, density vs. time, and volume vs. time would be carried out, as shown in Figure 3.8. However, it is noted that larger error between predicted and field volumes may be obtained because it is computed as product of speed and density.



(a) Average speed



(b) Density



(c) Volume

Figure 3.8 Example of macroscopic model evaluation.

Unlike the microscopic evaluation, a statistical test by plotting predicted flow parameters against measured ones would be used for describing how well the models developed from microscopic situation were able to predict macroscopic traffic flow parameters. A regression technique and analysis of variance (ANOVA) were selected to check the model prediction ability. To do so, regression analysis of speed in km/h, density in veh/km, and volume in veh/h from the models vs. those from the measurement were carried out. The general form of the regression is as follows:

$$P_{model} = \mathrm{b}_0 + \mathrm{b}_1 \times P_{measurement} \qquad (2.32)$$

where P_{model} is the average speed, density, and volume from the model; $P_{measurement}$ is the average speed, density, and volume from the measurement; b_0 and b_1 are y-intercept and slope of the curve, respectively.

CHAPTER 4

RESULTS AND DISCUSSION

The analysis results of car-following behavior and car-following model are presented in this chapter. The fundamental driving characteristics are addressed first in Section 4.1 in order to give a clear understanding in the experimental GPS data and driving characteristics. Later, the results of model calculation are provided in Section 4.2, which reveal the inherent driving behavior of tested drivers under different traffic conditions and road facilities as well as the differences between the two GM models. Section 4.3 addresses the evaluation of the models at microscopic and macroscopic levels, indicating how well the values calculated from the models can replicate the field measurements. The last section attempts to compare car-following characteristics obtained from this study with those from different research works so as to demonstrate their prediction capability in our different conditions.

4.1 Analysis Results of Fundamental Car-following Parameters

Fundamental car-following parameters include space-time diagram, headway vs. time, speed vs. time, and acceleration vs. time. Plots of those parameters for all driving regimes are presented in this section to exhibit the tentative characteristics of each driver and prevailing traffic condition.

4.1.1 Car-following Data Plotted on GIS Map

Figures 4.1 and 4.2 show 2-D GPS positions of test vehicles in car-following experiments at every 0.1 sec on surface streets and freeways, respectively. The plot of GPS coordinate data on Geographical Information System (GIS) is very useful for data processing, especially for mapping travel routes and matching vehicle data sets. Moreover, it shows the locations at which the data are continuous and good enough for further analyses. As seen, the quality of GPS points recorded on surface streets is superior to those on freeways due to less obstructions such as high buildings. Nevertheless, lots of cross bridges intermittently cause data missing and create a large number of short GPS data sets accordingly. As mentioned in Chapter 3, total traveling distance on surface streets is approximately 45 km, taking 45 min for accomplishing the experiment. The total distance on freeway is approximately 60 km, taking 90 min. However, only some part of the colleted data was chosen for analysis. The number of data points for Regimes I to IV are 1646, 700, 700, and 2751, respectively.

Figure 4.1 GPS points of test vehicles on surface streets.

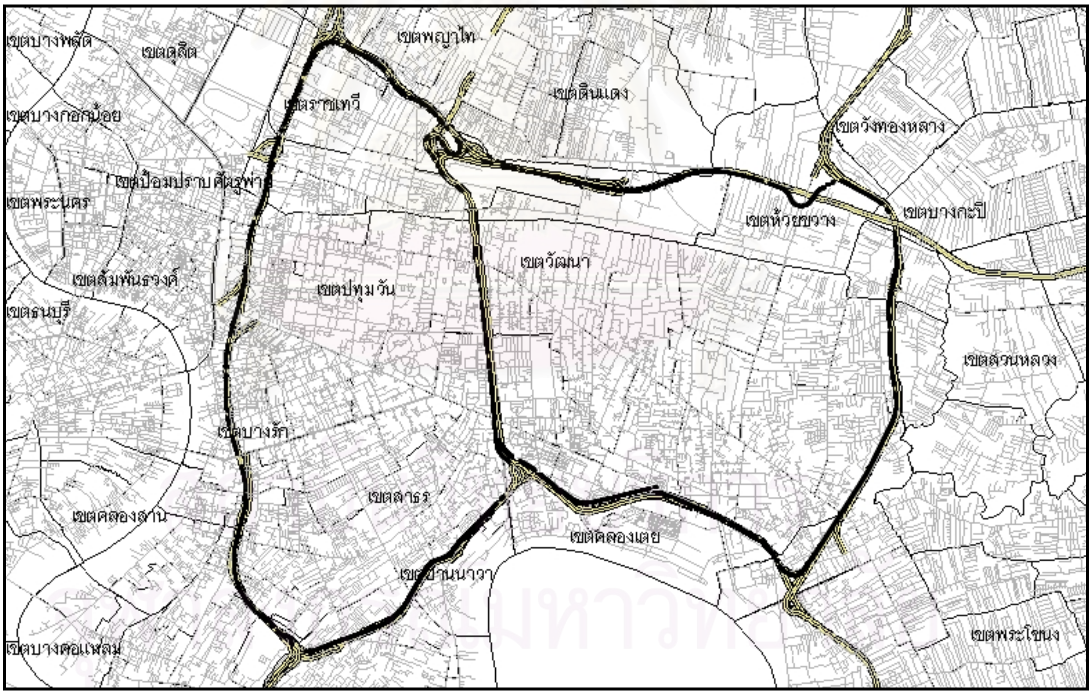
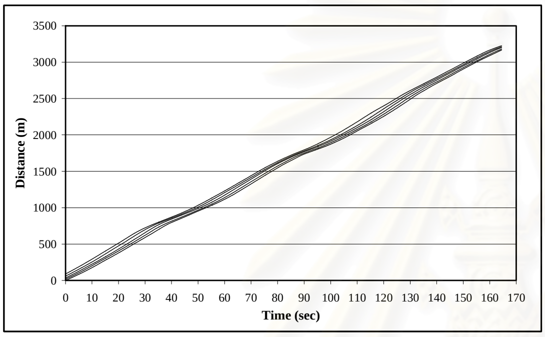


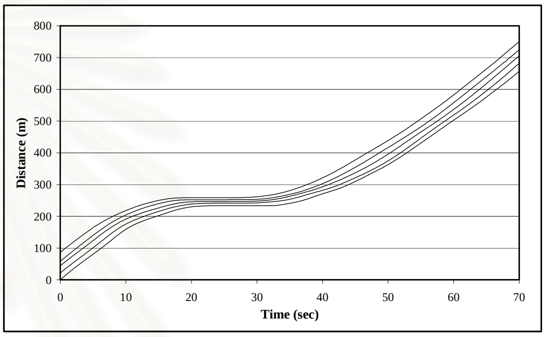
Figure 4.2 GPS points of test vehicles on freeways.

4.1.2 Space-Time Diagram

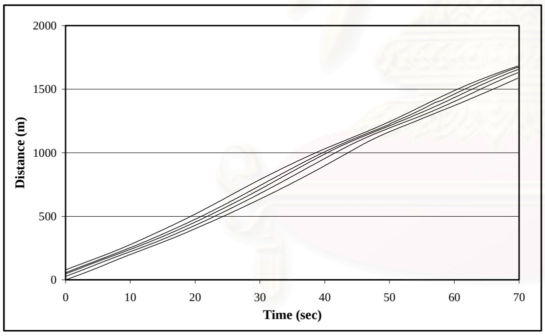
A space-time diagram shows the position of vehicles along a length of road over a period of time. Furthermore, it provides a rough image of traffic and driving stages, for example, stopping, cruising, separation distance, and so on throughout the experiment. As noticed in Figure 4.1 (a), during the experiment the tested vehicle platoon traveled on the surface street without any interruptions under Regime I, whereas a traffic light forced the platoon to stop under Regime II as indicated in Figure 4.1 (b). For Regime III in which experiment was undertaken on expressway in uncongested condition, the vehicles traveled with high speed without any stops as shown in Figure 4.1 (c). For Regime IV, it can be seen from Figure 4.1 (d) that the vehicles were in congested condition and stop-and-go phenomenon governed almost all of the study time.



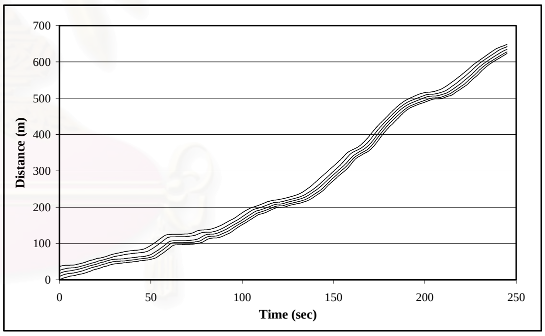
(a) Regime I



(b) Regime II



(c) Regime III

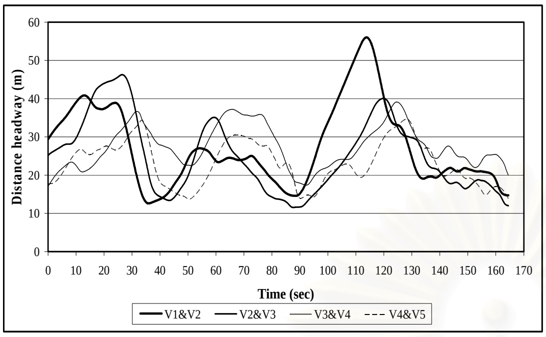


(d) Regime IV

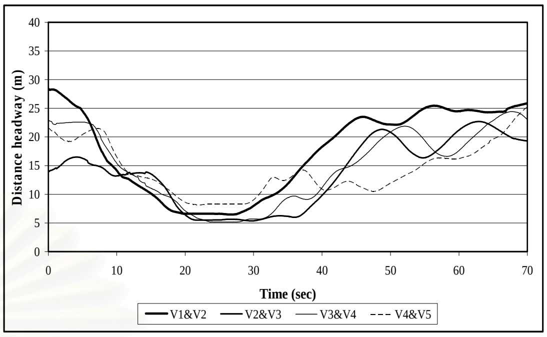
Figure 4.3 Space-Time diagrams for all driving regimes.

4.1.3 Distance Headway

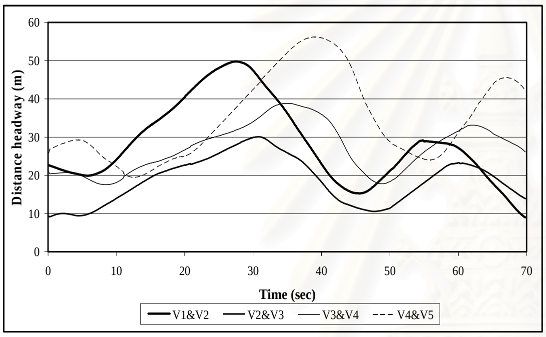
In car-following study, distance headway is the difference between the instantaneous lead vehicle's position and following vehicle's position, used for describing how far the follow driver is from the lead one in changing speed and traffic conditions. As indicated in Figure 4.4 (a)-(d), the vehicle-to-vehicle separations are between 12-56 m, 5-28 m, 9-56 m, and 5-16 m for Regimes I-IV, respectively. It is interesting to note that, under Regime II, all the test vehicles were forced to stop at a signalized intersection, resulting in the jam headways of 5-8 m. This is very similar to the jam headway observed in Regime IV. Another notable finding was observed in Regime III. On the whole, the headways under Regime III are not much different from Regime I; however, it is evident that the individual speeds of the drivers under Regime III were apparently higher. Using the Newtonian equation of motion, the analysis results revealed that the drivers were against the safe separation distance theory. As a result, the rear-end collision might occur in this situation if the lead vehicle stops suddenly.



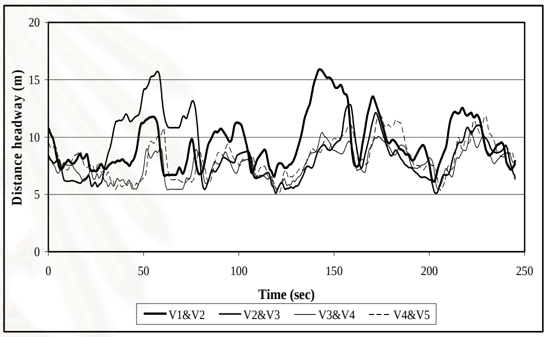
(a) Regime I



(b) Regime II



(c) Regime III

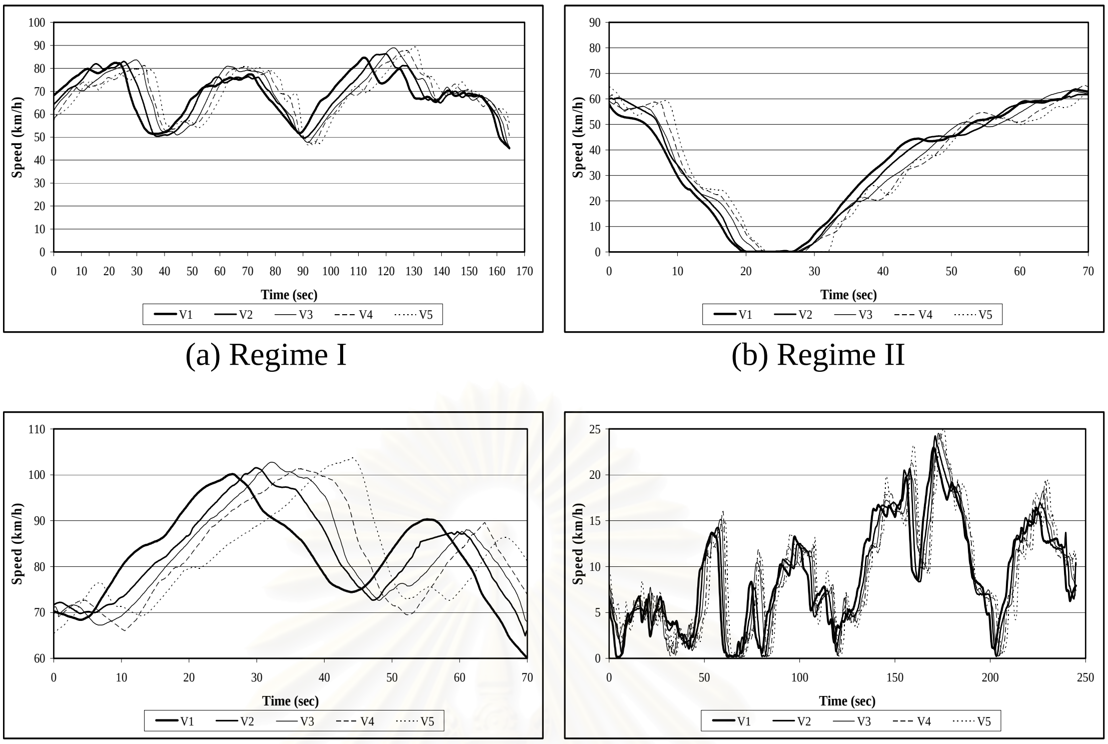


(d) Regime IV

Figure 4.4 Distance headways for all driving regimes.

4.1.4 Speed

The individual speeds of test vehicles are presented through Figure 4.5 (a)-(d). The individual speeds range from 48-90 km/h, 0-65 km/h, 60-105 km/h, and 0-25 km/h under Regimes I-IV, respectively. The shapes of speed profiles of the following vehicles are similar to the lead ones, but slightly shift to the right side, meaning that they are influenced by changing speed patterns of the leaders. From these speed profiles, it can be stated that the speed pattern or more specifically relative speed is more obviously dominant to the follower's reaction than headway. Nevertheless, the speed of vehicles under Regime II after the vehicles accelerate from the stopping condition seems to much oscillate, resulting in unstable traffic flow situation. Consequently, car-following regime might not strongly govern in that period of time.



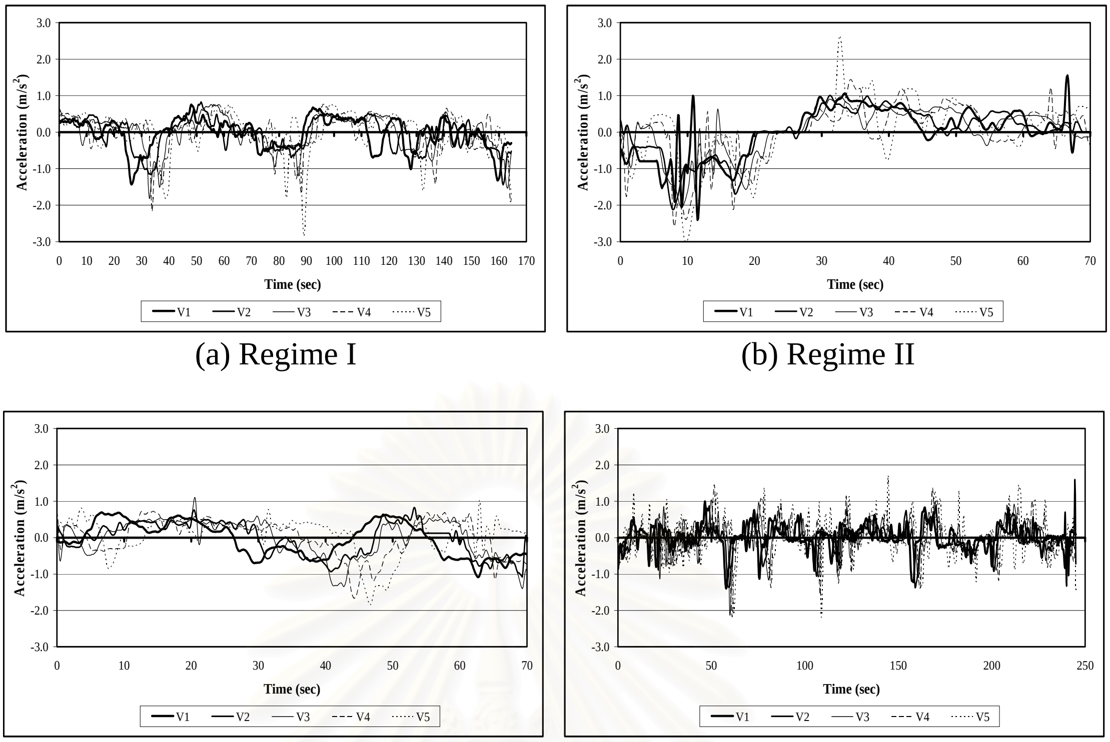
(a) Regime I (b) Regime II

(c) Regime III (d) Regime IV

Figure 4.5 Speed characteristics for all driving regimes.

4.1.5 Acceleration

The acceleration rates from the experiments are shown in Figure 4.6 (a)-(d). The maximum acceleration/deceleration rates are 0.8/2.8 m/s^2, 2.6/2.9 m/s^2, 1.2/1.8 m/s^2, and 1.7/2.1 m/s^2 for Regimes I-IV, respectively. As seen, the drivers tend to apply sharper acceleration and deceleration rates in congested condition than uncongested condition. Moreover, the last two positioned drivers in the platoon (V4 and V5) are likely to have greater acceleration fluctuations, meaning that the further positioned drivers would perform more aggressive acceleration/deceleration behavior.



(a) Regime I (b) Regime II

(c) Regime III (d) Regime IV

Figure 4.6 Acceleration characteristics for all driving regimes.

4.2 Results of Model Calibration

Using the experimental GPS data collected under four driving regimes, the calculation results for the 1st and the 5th GM models consisting of reaction time, sensitivity factor and model parameters, are shown in Tables 4.1 and 4.2, respectively.

The analysis results of the 1st GM model, assuming that responses of a following driver depend only on relative speed of his/her car and the preceding one, are shown in Table 4.1. The results explain that the drivers have the lowest sensitivity under Regimes I and III, ranging from 0.26-0.46 sec^{-1} and 0.30-0.35 sec^{-1}, respectively. The sensitivity factors for Regimes II and IV are 0.49-0.82 sec^{-1}and 0.54-0.92 sec^{-1}, respectively, which are obviously higher than those for Regimes I and III. This can be concluded that the drivers' reaction is highly influenced by the changes in speed patterns of the leaders under congested condition similarly on both facilities. It can be noticed that, for Regimes I, II, and IV, that the further position of the platoon the driver is, the higher sensitivity the driver has.

The reaction times, which are used to explain how fast the following drivers respond to the leader's instantaneous action, are also obtained from the regression analysis. The average reaction times of all drivers are 1.5, 1.2, 1.5, and 0.8 sec for Regimes I, II, III, and IV, respectively. It should be noted that the reaction times for Regimes I and III are very similar and Regime IV has the lowest reaction time value. It is plausible to state that the drivers under uncongested condition would have the same reaction time even on different facilities. However, this implication should be verified by conducting another experiment under uncongested surface street condition (Regime III) with the appearance of some roadside environments. The expected reaction time for Regime III might be reduced and the sensitivity factor might probably increase. The reaction times for Regimes II and IV seem a bit lower than those for Regimes I and III, implying that the drivers would have faster reaction in congested condition. Regime IV has the lowest reaction time value and remarkably different from others, resulting from the heavily congested traffic condition. The coefficients of determination obtained from the 1st GM model calibration for all regimes are approximately between 0.5-0.8.

The calibration of the 5th GM model was carried out differently from the 1st GM model by applying least-squared nonlinear regression analysis because the model variables are in nonlinear form. The independent variables in the 5th GM model consist of follower's speed at time $t+T$, relative speed at time t, and relative distance at time t. The calculations of the 5th GM model gave the very close results to the 1st GM model. However, the numerical comparison of model parameters between the two cannot be directly performed due to the fact that the 5th GM model comprises the exponents l and m. Moreover, the sensitivity factors (α) in either the 1st or the 5th GM model are in different unit. As shown in Table 4.2, the reaction times for Regime I to IV are 1.3, 1.0, 1.5, and 0.7 sec, respectively, which are close to the reaction times from the 1st GM model, when compared to the figure in the same regime.

An interesting conclusion which can be drawn from the comparison between the two models is that the R^2 values for the 5th GM model, especially under Regimes I and III, are obviously higher than those for the 1st GM model. In the other word, the 5th GM model shows its superiority to the 1st GM model for Regimes I and III. This is because under both regimes the vehicles are freely flowing at higher speed range, causing the inter-vehicle spacing becomes more dominant to their own safety. In spite of this, it is found that the R^2 values under Regimes II and IV for the 1st and 5th GM models are somewhat similar. The coefficients of determination obtained from the 5th GM model calibration for all regimes are approximately between 0.6-0.9. It should be noted from Table 4.2 that the values of m which is the exponent of the follower's speed are mostly close to zero, implying that the decision of a driver either to decelerate or accelerate is independent on his/her instantaneous speed at that time.

From the analyses of both GM models, the following conclusions can be drawn:

1) The drivers have lower sensitivity to respond to the leader's actions under uncongested condition, or in the other words, they are more aggressive when driving in congested traffic condition.
2) The sensitivity tends to increase as the vehicle position in the platoon for most regimes.
3) The drivers have the same reaction time under uncongested condition on either surface street or freeway facility because there are no other external factors disturbing the surface street experiment.
4) The reaction times under congested condition on freeway are a bit shorter than those on surface street, probably due to roadside environments (e.g. pedestrians, cross traffic, curb parking, and so on).
5) The follower's speed and relative distance contribute little to driver behavior, especially under Regimes II and IV, meaning that the 5th GM model does not significantly improve the prediction capability from the 1st GM model for congested condition.

6) The 5^{th} GM model, however, exhibits the significant difference of R^2 values from the 1^{st} GM model under Regimes I and III, meaning that the 5^{th} GM model is probably superior to the 1^{st} GM model for uncongested condition.

7) From the findings, car-following characteristics are remarkably distinguished by traffic conditions (i.e. congested and uncongested). However, the influence of different roadway facilities to car-following behavior has not been clearly emerged.

8) According to a slight increase of R^2 value for the 5^{th} GM model, the modeling of car-following behavior under Bangkok roadway and traffic conditions would be more convenient if the 1^{st} GM model is utilized.

Table 4.1 Calibration results for the 1^{st} GM model

Regime	**Driver no.**	**Model parameters**		
		α (sec^{-1})	***T* (sec)**	**R^2**
I	D2	0.26	1.7	0.65
	D3	0.30	1.8	0.65
	D4	0.44	1.0	0.63
	D5	0.46	1.3	0.77
	Average	***0.37***	***1.5***	-
II	D2	0.65	1.4	0.82
	D3	0.49	1.3	0.38
	D4	0.73	1.2	0.71
	D5	0.82	0.9	0.69
	Average	***0.67***	***1.2***	-
III	D2	0.35	1.3	0.58
	D3	0.31	1.6	0.68
	D4	0.34	1.8	0.58
	D5	0.30	1.3	0.57
	Average	***0.33***	***1.5***	-
IV	D2	0.54	0.8	0.60
	D3	0.64	0.8	0.55
	D4	0.92	0.7	0.68
	D5	0.85	0.7	0.70
	Average	***0.74***	***0.8***	-

Table 4.2 Calibration results for the 5th GM model

Regime	Driver no.	Model parameters				
		$\alpha_{l,m}$	***l***	***m***	***T***	**R^2**
I	D2	5.10	1.29	0.46	1.4	0.76
	D3	7.54	1.04	0.06	1.4	0.70
	D4	6.06	0.79	0.00	1.0	0.65
	D5	1.83	0.44	0.00	1.3	0.78
	Average	-	-	-	***1.3***	-
II	D2	8.30	1.00	0.10	0.9	0.89
	D3	4.01	0.88	0.07	1.0	0.40
	D4	2.14	0.43	0.05	1.2	0.72
	D5	1.54	0.29	0.08	0.9	0.69
	Average	-	-	-	***1.0***	-
III	D2	12.09	1.23	0.00	1.2	0.67
	D3	0.31	0.00	0.00	1.6	0.68
	D4	2.34	2.68	1.20	1.9	0.65
	D5	0.04	3.26	3.95	1.2	0.72
	Average	-	-	-	***1.5***	-
IV	D2	5.48	1.05	0.14	0.8	0.63
	D3	0.58	0.00	0.11	0.8	0.56
	D4	9.64	1.21	0.20	0.6	0.69
	D5	14.71	1.42	0.30	0.7	0.73
	Average	-	-	-	***0.7***	-

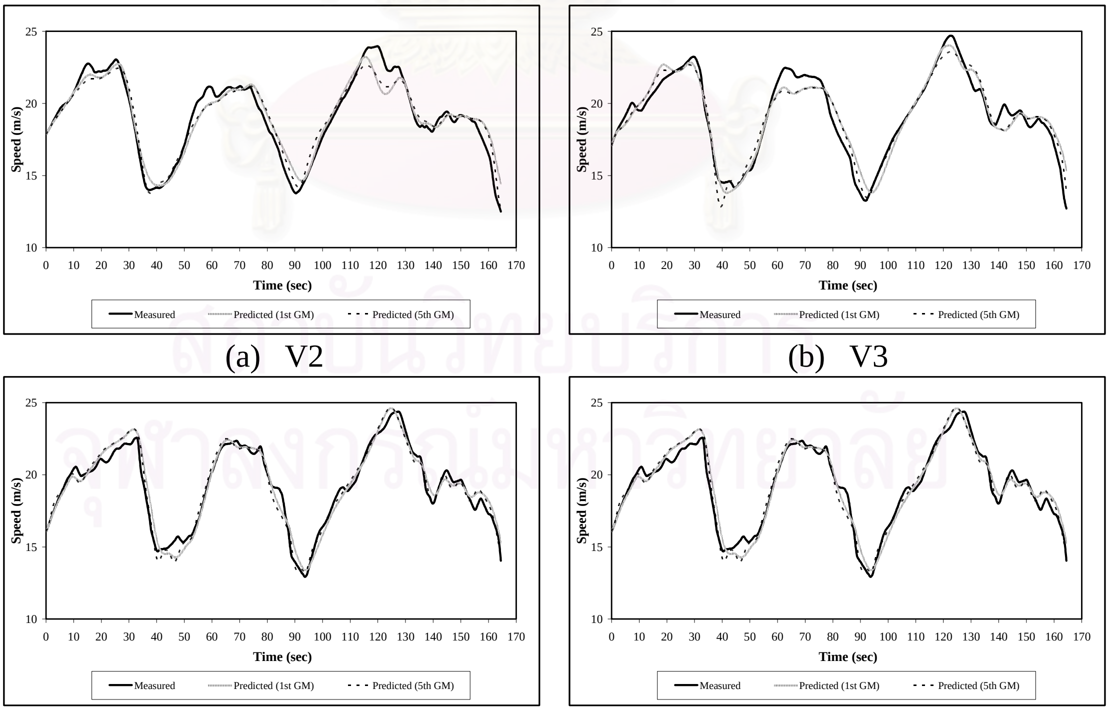
4.3 Evaluation of Models

The models were evaluated by the use of two approaches: microscopic and macroscopic. For microscopic evaluation, the variation of individual driving parameters (e.g. speed, position) from the model vs. the measurement was examined. The speed of an individual vehicle was computed from the model at every 0.1 sec time intervals and plotted against time for comparing with that from the measurement. The evaluation was performed by means of visual inspection with no statistical test but emphasizing on the shape of the paired speed profiles rather than the shift between the two. The similar/unsimilar shape of the curves would reflect the prediction capability of the model. For macroscopic evaluation, the overall performance of the platoon was evaluated to ensure that the microscopically verified model could properly predict the macroscopic traffic flow parameters (i.e. average speed, density, and flow). The evaluation at macroscopic level was to compare traffic flow parameters from the prediction vs. model in the same manner as the microscopic level. However, a statistical test was also carried out to show the extent of variation.

4.3.1 Evaluation at Microscopic Level

The comparisons of individual speed of each vehicle from the model vs. measurement under Regimes I-IV are explained through Figures 4.7-4.10, respectively. The speed profiles were calculated from both the 1st and 5th GM models using each driver and driving regime information. For Regimes II and IV, the measured speed of vehicles is sometimes equal to zero due to congestion. However, the predicted speed values could be less than zero, causing the error of calculation at next time steps for the 5th GM model. This is because the follower's speed as a variable in the 5th GM model with an exponent *m* cannot be negative value. In the calculation, manual manipulation by forcing the negative speed values to become zero was needed. This kind of operation was performed until the computed acceleration value returned to a positive value. The results of microscopic evaluation, as illustrated in Figures 4.7-4.10, display that the prediction results from both GM models duplicate the real speed profiles properly. However, the 5th GM model does not show superior performance of prediction to the 1st GM model, even if the 5th GM model gives larger R^2 values. Comparing among regimes, the predicted result for Regime IV seems to have smaller deviation from the measurement. This result agrees well with Benekohal (1989) stating that a driver with a shorter reaction time causes smaller shift than a driver with a longer reaction time.

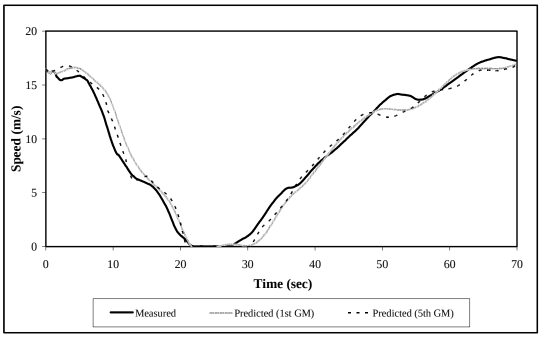
From an inspection of the speed profiles, it is found that the predicted speed values do not fit well with the measured data around the peaks of speed curves where the driver changes from acceleration to deceleration. This leads to an implication that in fact a driver behaves differently between acceleration and deceleration conditions, especially in the situation that the driver changes from speeding up to slowing down.



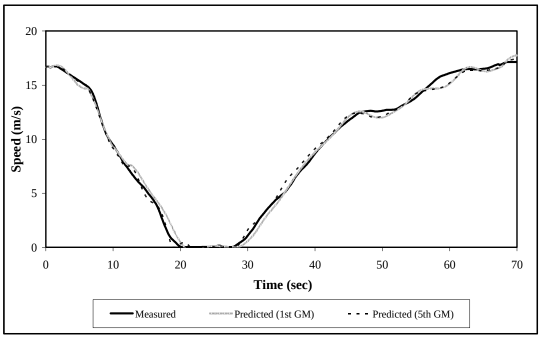
(a) V2 (b) V3

(c) V4 (d) V5

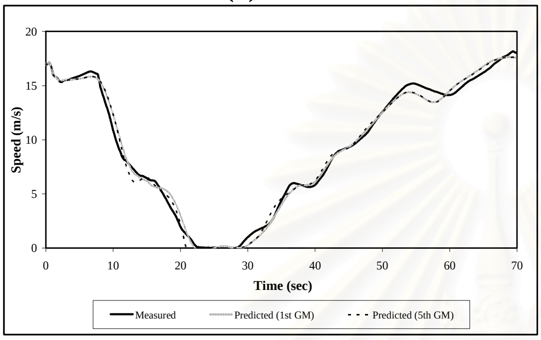
Figure 4.7 Comparison of the individual speeds from the models vs. measurement under Regime I.



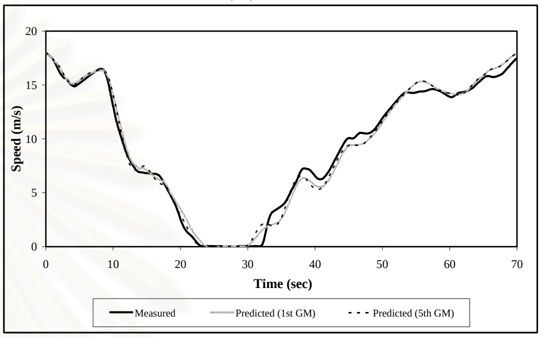
(a) V2



(b) V3

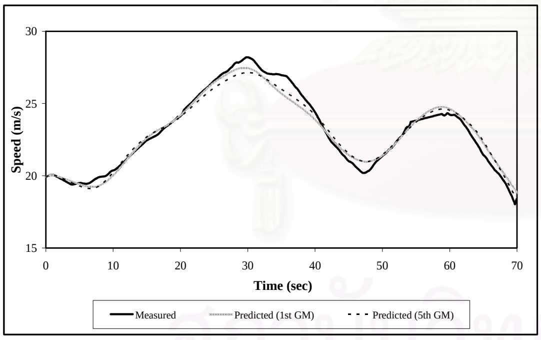


(c) V4

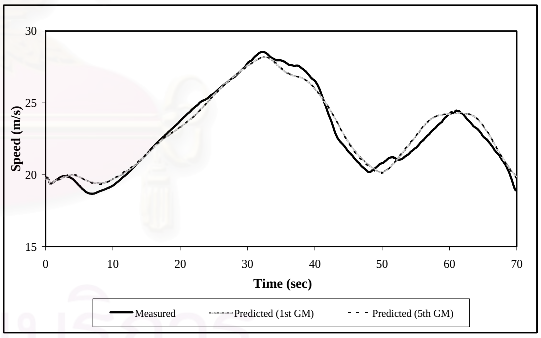


(d) V5

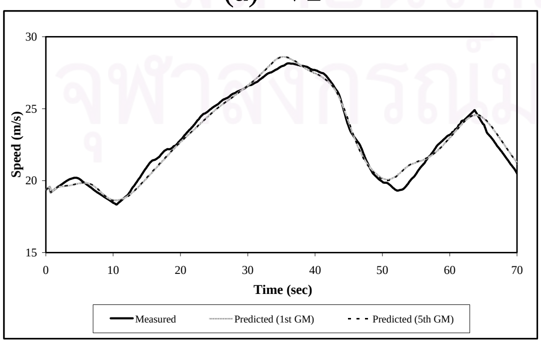
Figure 4.8 Comparison of the individual speeds from the models vs. measurement under Regime II.



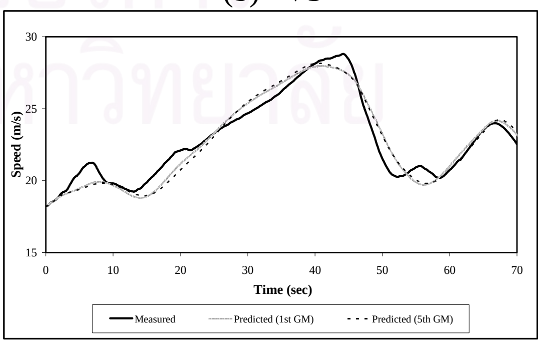
(a) V2



(b) V3

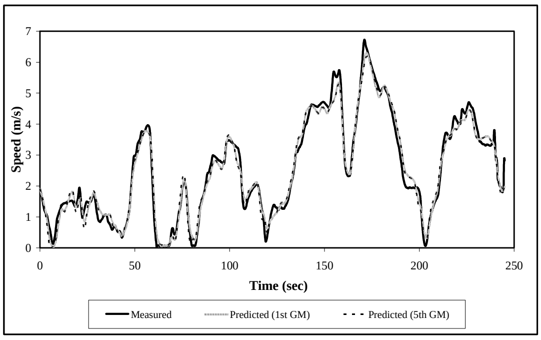


(c) V4

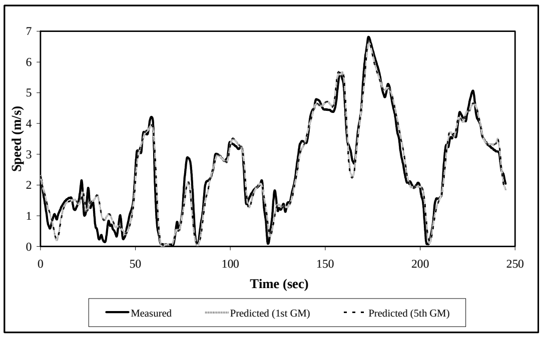


(d) V5

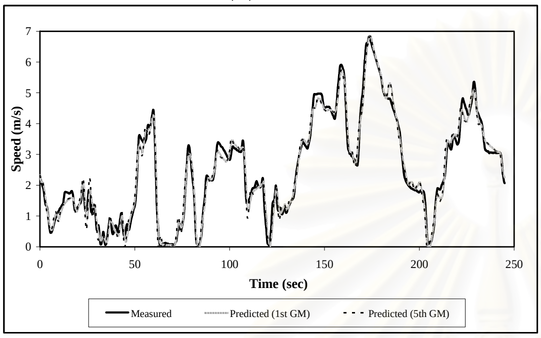
Figure 4.9 Comparison of the individual speeds from the models vs. measurement under Regime III.



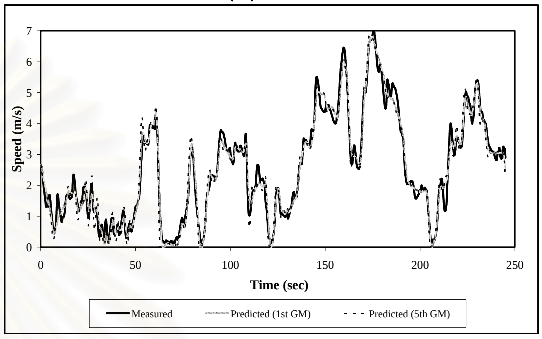
(a) V2



(b) V3



(c) V4



(d) V5

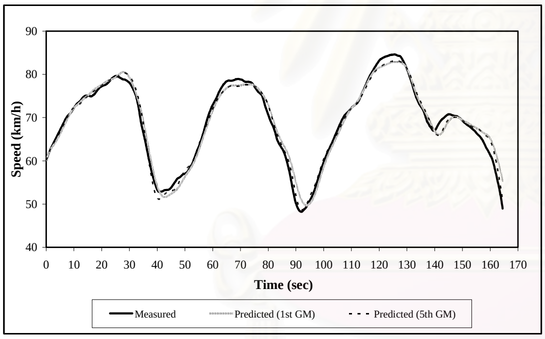
Figure 4.10 Comparison of the individual speeds from the models vs. measurement under Regime IV.

4.3.2 Evaluation at Macroscopic Level

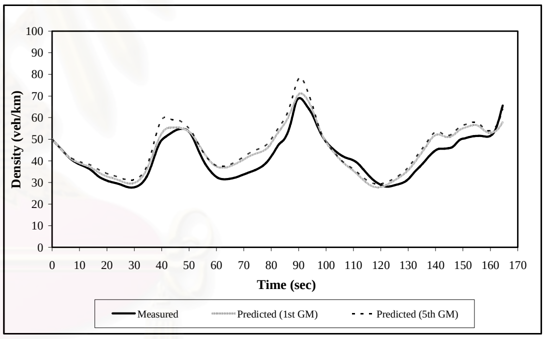
As stated earlier, the macroscopic evaluation is to examine the overall performance of the platoon movement. Although the macroscopic level evaluation may not provide as much detailed information about model capabilities as the microscopic level, it must be conducted to ensure that the model is able to predict the traffic flow parameters within an acceptable extent of error. Fundamental traffic flow parameters which were used in macroscopic validation consist of average speed of platoon (space-mean speed), platoon density, and average volume of platoon. In this study, the average speed was computed from the individual speed of all vehicles; density was the reciprocal of distance headway between the vehicles no.2 and no.5; and volume was product of speed and density. It should be noted that the computed traffic volume represents volume of traffic which was measured with a moving observer. However, the comparison of traffic volume is not recommended when traffic density reaches its critical condition because the difference may be large.

As shown in Figures 4.11-4.14, the comparison of average speed, density, and volume from model vs. measurement is made for all driving regimes. For Regime I, the predicted speed and density are more or less close to the measurement. The deviation of predicted volume comes from the multiplication of speed and density. For Regime II, the predicted density from both GM models largely deviates from the measurement especially when vehicles decelerate and stop at an intersection, resulting from the error of speed and distance prediction for vehicle no.2 (See Figure 4.8 (a)). Moreover, it is resulted from the fact that GM model has a limitation to predict an extreme case like stopping condition because it does not have any proper criterion to specify when and where a vehicle fully stops. The predicted density is not accurate accordingly. For Regime III, the deviation of density is apparently exhibited, resulting partly from the error of microscopically predicted speed of the vehicle no. 5 (See Figure 4.9 (d)). For Regime IV, the error of all the parameters is not so large.

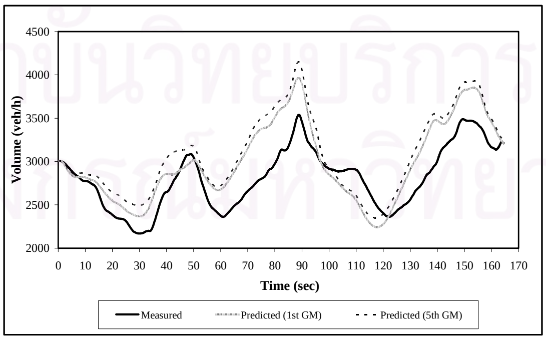
An innovative findings in traffic engineering gained from this car-following experiment is that the maximum measured traffic volume is up to 4,000 veh/h for uncongested condition (Regimes I and III) and 2,000-3,000 for congested conditions (Regimes II and IV), meaning that in car-following situation the drivers keep very close separation distance to the vehicle ahead. The advanced traffic technology like Automatic Highway System (AHS) which helps reduce inter-vehicle spacing and increase flow should be further developed and implemented to real world road traffic condition. It is also found that at the maxima and minima of speed curves the deviation of density seems to be larger according to a mentioned explanation that the predicted speed is far from the measured values at peaks of speed curves. The large error of predicted volume is caused by the consequence of multiplication of speed and density. Surprisingly, the differences between predicted and measured volume under Regimes II and IV are not as large as Benekohal (1989) expected because of the computation at every 0.1-sec interval and the goodness of fit on low speed profile. Moreover, small time step provides more accurate calculated values than large time step (e.g. 1 min or more). It is also found that both the 1st and 5th GM models give very close prediction results.



(a) Average speed

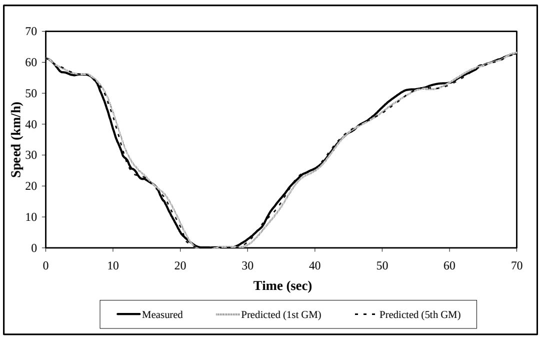


(b) Density

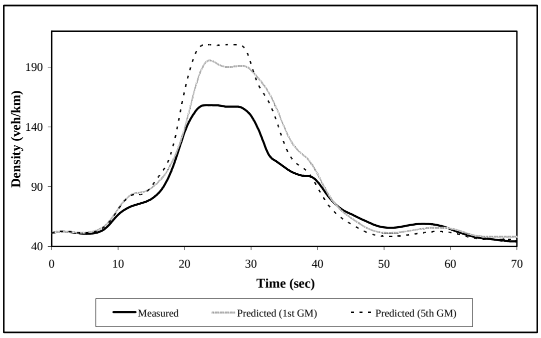


(c) Volume

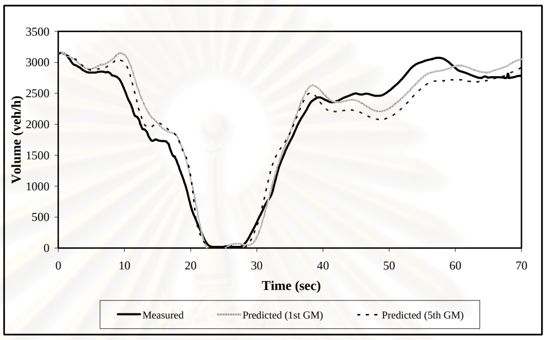
Figure 4.11   Comparison of the average speed, density, and volume from the models vs. measurement under Regime I.



(a) Average speed

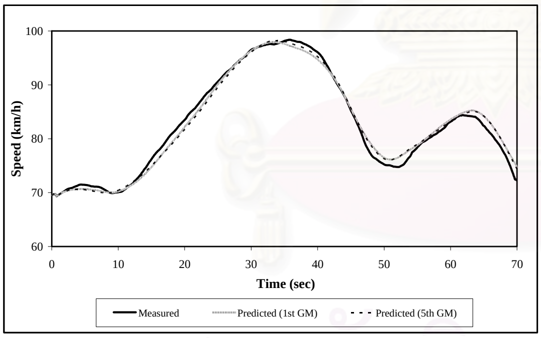


(b) Density

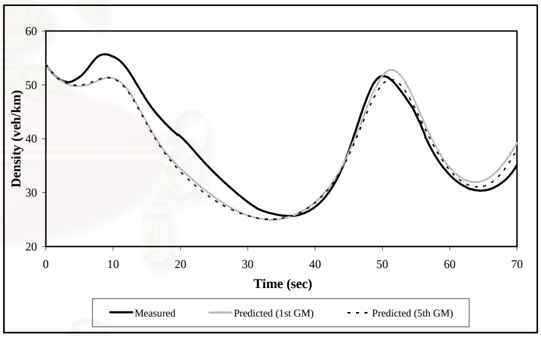


(c) Volume

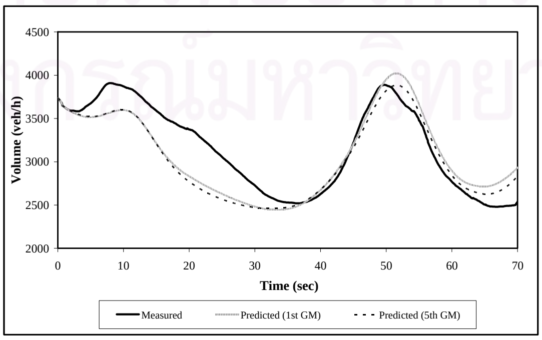
Figure 4.12 Comparison of the average speed, density, and volume from the models vs. measurement under Regime II.



(a) Average speed

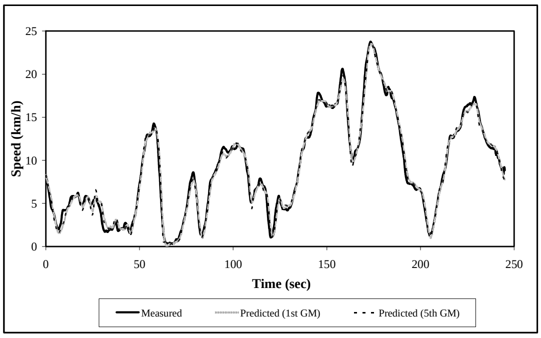


(b) Density

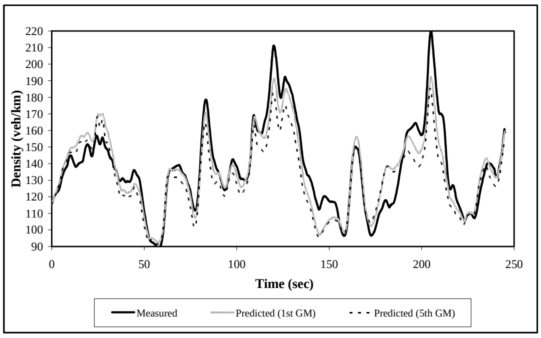


(c) Volume

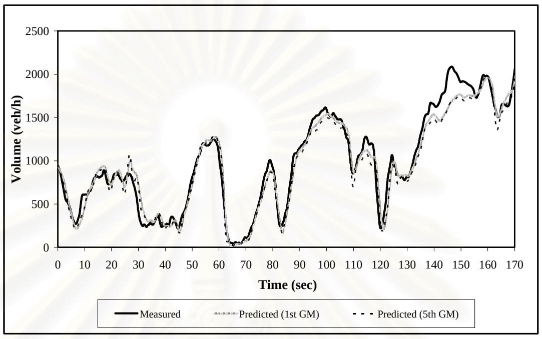
Figure 4.13 Comparison of the average speed, density, and volume from the models vs. measurement under Regime III.



(a) Average speed



(b) Density



(c) Volume

Figure 4.14 Comparison of the average speed, density, and volume from the models vs. measurement under Regime IV.

As stated, traffic flow parameters computed from the models should also be statistically tested. A regression technique and analysis of variance (ANOVA) were selected to check the model prediction capability. To do so, regression analysis of speed in km/h, density in veh/km, and volume in veh/h from the models vs. those from the measurement were carried out. The general form of the regression shown in Eq. (2.32) is expressed here again as follows:

$$P_{model} = \mathrm{b}_0 + \mathrm{b}_1 \times P_{measurement} \tag{4.1}$$

The regression outcomes and standard deviations of regression parameters are provided in Tables 4.3 and 4.4, respectively. The plots of measured vs. predicted parameters together with regression lines are also provided in Appendix.

Table 4.3 Regression results of the predicted vs. measured traffic parameters

Regime	Parameter	1st GM model			5th GM model		
		b_0	b_1	R^2	b_0	b_1	R^2
I	Speed	3.63	0.95	0.97	2.59	0.96	0.99
	Density	3.07	0.98	0.91	1.63	1.06	0.90
	Volume	-87.32	1.09	0.72	-15.06	1.10	0.71
II	Speed	-0.13	1.00	0.99	0.06	1.00	1.00
	Density	-18.62	1.34	0.97	-31.29	1.50	0.98
	Volume	90.21	0.98	0.95	160.58	0.91	0.93
III	Speed	2.48	0.97	0.99	2.10	0.97	0.99
	Density	1.94	0.92	0.92	1.63	0.92	0.93
	Volume	464.02	0.83	0.75	437.73	0.82	0.77
IV	Speed	0.09	0.98	0.99	0.04	0.99	0.99
	Density	21.00	0.83	0.87	29.95	0.74	0.82
	Volume	-8.06	0.96	0.97	-39.90	0.98	0.97

Table 4.4 Standard deviation of regression parameters

Regime	Parameter	1st GM model		5th GM model	
		$S(b_0)$	$S(b_1)$	$S(b_0)$	$S(b_1)$
I	Speed	0.28	0.002	0.20	0.007
	Density	0.33	0.013	0.37	0.016
	Volume	47.41	0.024	49.91	0.028
II	Speed	0.12	0.007	0.08	0.003
	Density	0.80	0.014	0.71	0.016
	Volume	20.04	0.016	20.97	0.011
III	Speed	0.34	0.006	0.35	0.004
	Density	0.41	0.018	0.38	0.016
	Volume	58.04	0.022	54.11	0.027
IV	Speed	0.02	0.005	0.02	0.008
	Density	0.93	0.013	0.99	0.012
	Volume	4.41	0.009	4.36	0.003

It can be explained through both tables that the predicted speed and density can, on the whole, duplicate the field data with small extent of error except for Regime II due to a full stopping condition. However, it can be observed from value of b_0 and b_1 that the predicted volume, especially for Regimes I and III, which is calculated from product of predicted average speed and predicted density shows quite large deviation from the measurement.

4.4 Comparison of Car-following Characteristics among Countries

Car-following researches have been widely carried out in various countries, for example, the United States, Australia, and Japan for years. This car-following research is the first effort which has been conducted in Bangkok's roadway and traffic situations. Therefore, it is noteworthy for an attempt to compare the results with other researches. Due to the limitations regarding the experimental conditions which are different among researches, the comparison should be made with care. This study intends to compare car-following model parameters of the 1st GM model from the following research efforts:

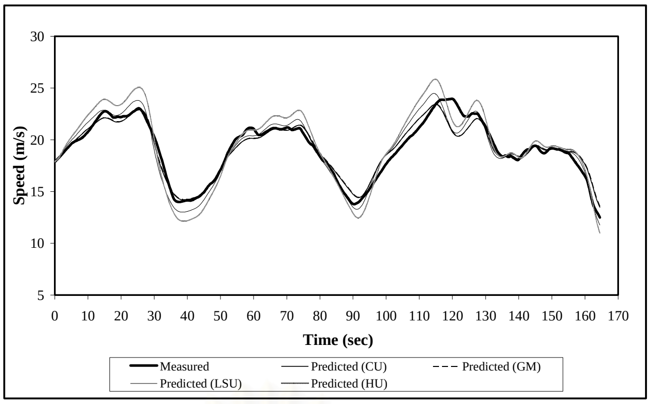
1) Chulalongkorn University car-following experiment, so called "CU".
2) Original GM experiment conducted by Gazis, Herman, and Rothery in 1958, so called hereafter as "GM".
3) Louisiana State University car-following experiment conducted by Wolshon and Hatipkarasulu in 2000, so called briefly as "LSU".
4) Hokkaido University car-following experiment done by Ranjitka *et al*. in 2002, so called as "HU".

The average model parameters of all the drivers from the 1st GM model calibration from CU experiment and those from the other researches are shown in Tables 4.5.

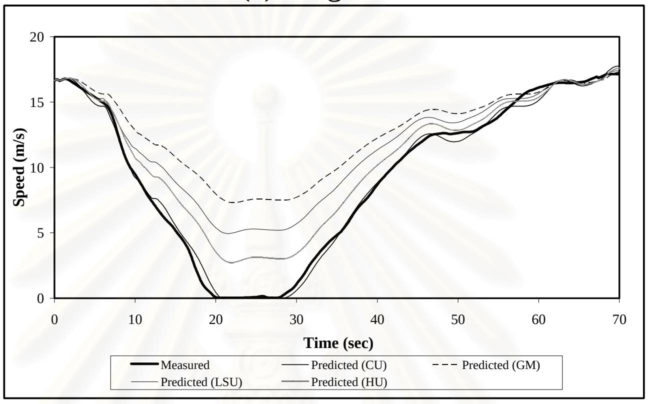
Table 4.5 GM model parameters from various studies

Source	Regime	α (sec^{-1})	T (sec)	Speed (km/h)	Study site	Country
CU	I	0.37	1.5	45-90	Surface street	Thailand
	II	0.67	1.2	0-65	Surface street	
	III	0.33	1.5	60-103	Expressway	
	IV	0.74	0.8	0-25	Expressway	
GM	All	0.37	1.55	16-128	Test track	USA
LSU	All	0.46	1.01	46 (avg)	Urban street	USA
HU	All	0.55	1.42	30-80	Test track	Japan

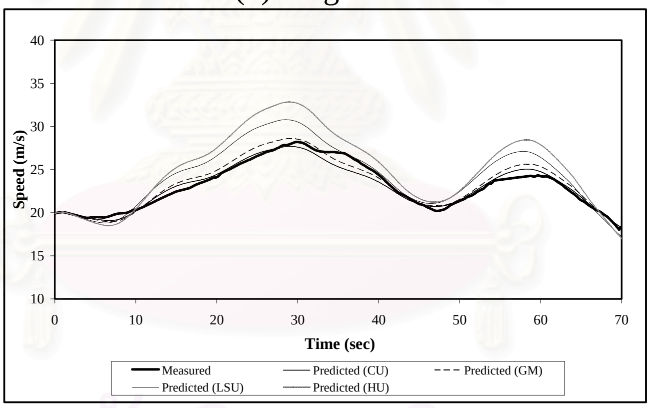
The speed profiles were computed using the 1st GM model together with car-following model parameters in Tables 4.5. The calculated speed profiles were then plotted with CU data separated into 4 regimes. The comparisons among various researches under Regimes I-IV are illustrated through Figure 4.15 (a)-(d), respectively. The figures indicate that GM car-following data are very close to the result from CU experiment for Regimes I and III. This is because the GM and CU sensitivity factor and reaction time are much similar, even if GM experiment was conducted on a test track. For Regimes II and IV, it is evident that car-following behavior from other researches is remarkably different from CU data. This explicitly displays a benefit of CU study which classifies car-following behavior according to traffic conditions and roadway types. The analysis of car-following characteristic by the aggregation of all kinds of traffic conditions and roadway types will decrease prediction performance of car-following model in some situations. Like LSU and HU experiments, car-following data were collected using highly accurate GPS apparatus to be used for calibrating a GM model. Only one set of car-following parameter was investigated for representing overall traffic conditions, as already shown in Table 4.5. The prediction using both LSU and HU are, therefore, not suitable for CU data. From this, it can be concluded that the implementation of car-following experiment under our own environments undoubtedly benefits to microscopic traffic engineering study in Thailand.



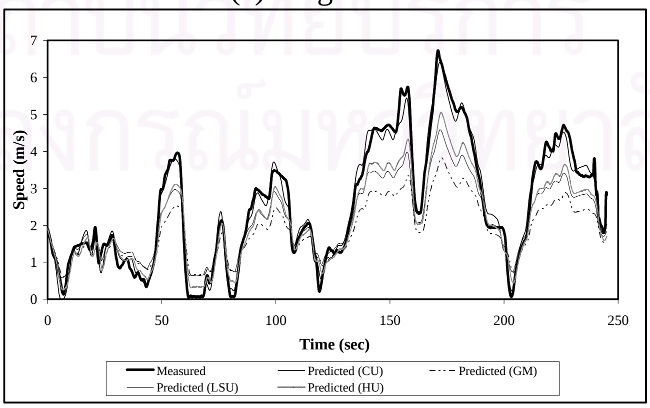
(a) Regime I



(b) Regime II



(c) Regime III



(d) Regime IV

Figure 4.15 Comparison of predicted speed profiles from CU car-following data vs. data from other countries.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The main tasks of this research are to collect and analyze car-following data of five passenger cars using global positioning system as a tool. The experiment is designed to take into account the driving characteristics in different traffic and roadway conditions, resulting in four driving regimes. Regimes I, II, III, and IV account for driving patterns in uncongested surface street, congested surface street, uncongested freeway, and congested freeway, respectively. The collected data, consisting primarily of fundamental traffic flow parameters, are utilized for calibrating the 1^{st} and the 5^{th} GM models. Finally, the obtained model parameters are tested for its validity both at microscopic and macroscopic levels. Moreover, the car-following characteristics from this study are also compared with those from other researches to reveal the country-to-country distinguishes of driving behavior. The results of the study and recommendations for future researches are thereby concluded in this chapter.

5.1 Conclusions

5.1.1 Data Collection and Processing

Car-following characteristics of test drivers in different traffic conditions and roadway types of Bangkok are investigated through this research effort. A global positioning system (GPS) technology is proved to be very powerful in collecting the 3D positions of vehicles in motion. The experiments were carried out with less effort, money spent, and time consuming. Besides, the outstanding benefit of using GPS is that the experiment was conducted in actual road and traffic conditions because the GPS device is portable. However, there were some limitations becoming drawbacks of the GPS device. First, the quality of experimental data in the urban areas surrounded by skyscrapers (Freeway sites) was in doubt in aspects of data continuity and accuracy. Moreover, the surface street sites having many cross bridges gave very poor results. The results of car-following behavior analysis depend directly on quality of GPS data, thus the design of experiment as to site selection needs to be seriously concerned.

To match the GPS data sets of all pairs of vehicles, a geographical information system (GIS) is utilized to synchronize GPS time of all vehicles. The GIS is also able to map and display the vehicle journey throughout the experiment. Besides, the superposition of GPS data layer to existing road networks and land data layers can display the locations of study sites and their surrounding areas. Nevertheless, this research only utilizes GIS in data preparation process, whereas data analysis and modeling are performed using MS Excel.

5.1.2 Fundamental Car-following Characteristics

This research is to investigate car-following characteristics of test drivers under four regimes: uncongested surface street (Regime I), congested surface street (Regime II), uncongested freeway (Regime III), and congested freeway (Regime IV), with a priori assumption that driving behavior would be different under changing conditions. The consequences of preliminary analyses indicate that the drivers maintained very close separation distance at very high speed ranges under uncongested freeway condition, which absolutely violate the safe-distance concept. This is because they believe the stability of traffic flow, or in the other word, they believe that the vehicles ahead will not stop suddenly. The change in individual speed patterns influences on the following driver's behavior more remarkably than other factors. Further, the increasing speed disturbance indicating more aggressive driving is found from the last two drivers of platoon.

5.1.3 Car-following Models

The calibration of the 1st and the 5th GM models shows that the drivers have lower sensitivity under uncongested conditions and higher in congested conditions. The average sensitivity factors for Regimes I to IV are 0.37, 0.67, 0.33, and 0.74 sec^{-1}, respectively. Moreover, it is found that the further position of the platoon the driver is, the higher sensitivity the driver has.

The drivers have faster reaction when driving in congested conditions. The average reaction times from the 1st GM model are 1.5, 1.2, 1.5, and 0.8 sec for Regimes I to IV, indicating that the drivers have faster reaction in congested condition. From the regression analysis, it is found that the 5th GM model does not contribute much improvement to the 1st GM model. Even though the sensitivity factor and reaction time for Regime III are close to those for Regime I, another experiment with the appearance of actual roadside environments is needed to verify the model calibration result. An interesting conclusion which can be drawn from the comparison between the two models is that the R^2 values for the 5th GM model, especially under Regimes I and III, are obviously higher than those for the 1st GM model. In the other word, the 5th GM model shows its superiority to the 1st GM model for Regimes I and III, implying that the inter-vehicle spacing becomes more dominant. Additionally, the decision of a driver either to decelerate or accelerate is independent on his/her instantaneous speed at that time.

5.1.4 Model Evaluation

The models are evaluated at microscopic and macroscopic levels. The microscopic evaluation by inspecting the shape of the predicted and measured speed curves demonstrates that both GM models can properly replicate the field data with no significant difference between the two. It is also observed that the drivers have large uncertainty in controlling their cars as they change from acceleration to deceleration. The evaluation at macroscopic level describes that GM models are not capable of predicting extreme driving situation, like stopping at an intersection under Regime II. Moreover, the maximum traffic volume in car-following regime can be up to 4,000 veh/h under uncongested condition because of very small following distance.

The volume computed from product of average speed and density of the platoon seems to largely deviate from the field data.

5.1.5 Comparison of Car-following Data among Various Researches

The CU car-following experimental data are compared with data from a few researches. The consequence of comparison shows that original GM result is very close to CU result under Regimes I and III. Traffic condition, perhaps, influences on car-following characteristic more obviously than study site (i.e. test track, actual roadway). The result of CU experiment is different from others for Regimes II and IV, implying that analysis of car-following behavior assuming homogeneous traffic situation will reduce the prediction capability of the model.

5.2 Recommendations for Future Researches

This research involved with car-following experiment using GPS which was carried out as the first effort in Thailand. There were some limitations regarding collection of data, site selection, instruments, and analytical methods which must be suggested for future researches.

a) Instruments

Even though the GPS apparatus used in this study yielded actually very high accurate positioning data, vehicle speed could not be recorded, resulting in more laborious data manipulation process. In case that the GPS which is able to report instantaneous speed is affordable, the time for data preparation will be reduced.

b) Site selection

The quality and continuity of GPS data are critical factors contributing to accuracy of resulting car-following models. The sites surrounded by skyscrapers or having too many cross bridges must be avoided.

c) Data collection

In future researches, the experiment under uncongested surface street should be carried out again. A criterion for selecting a surface street is that there should be some interfered road environments, for example, parked vehicle, pedestrians, etc. so as to reflect the actual driving behavior.

d) Model calibration

This research focused only on calibration of GM models. The attempts to study any other car-following models or develop a new model for Bangkok's conditions will be much useful.

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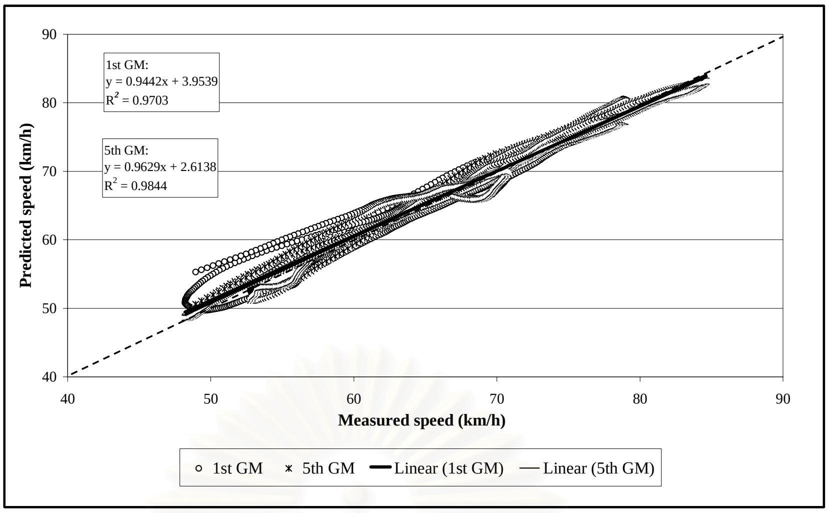
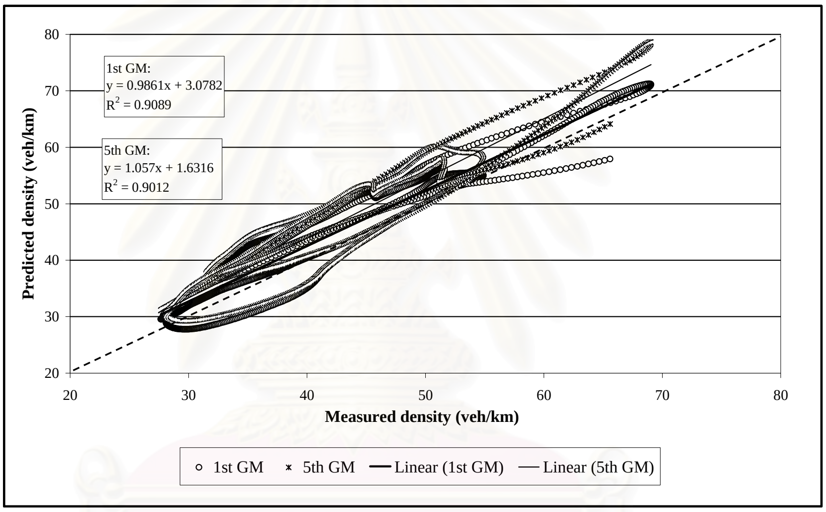
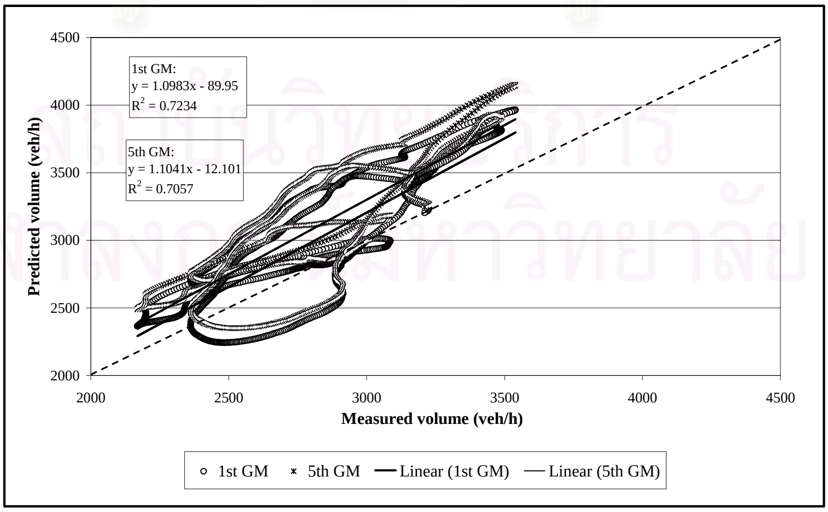
APPENDIX



(a) Average speed

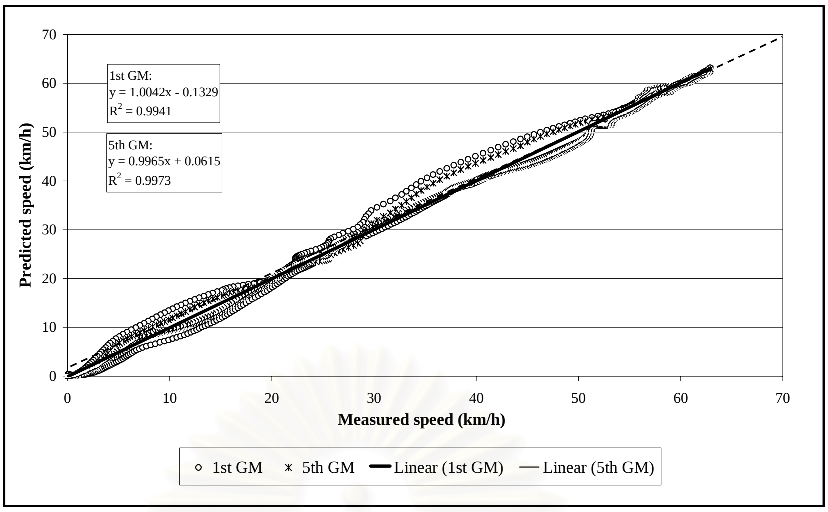


(b) Density

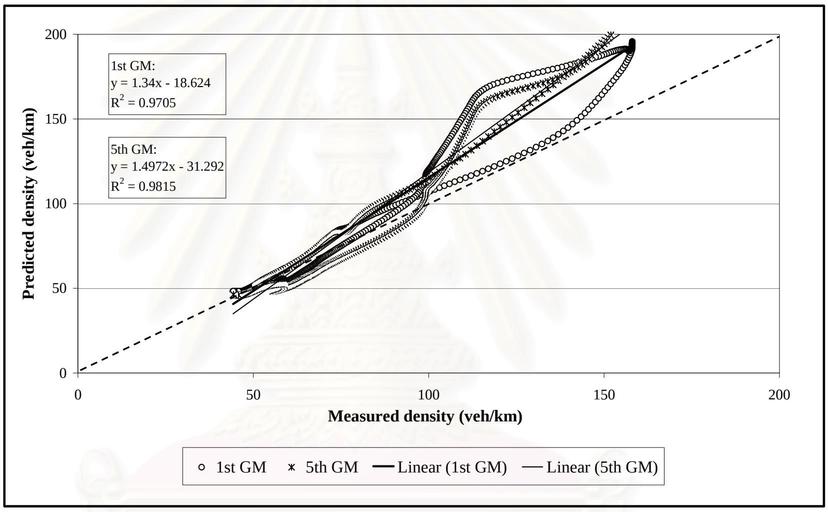


(c) Volume

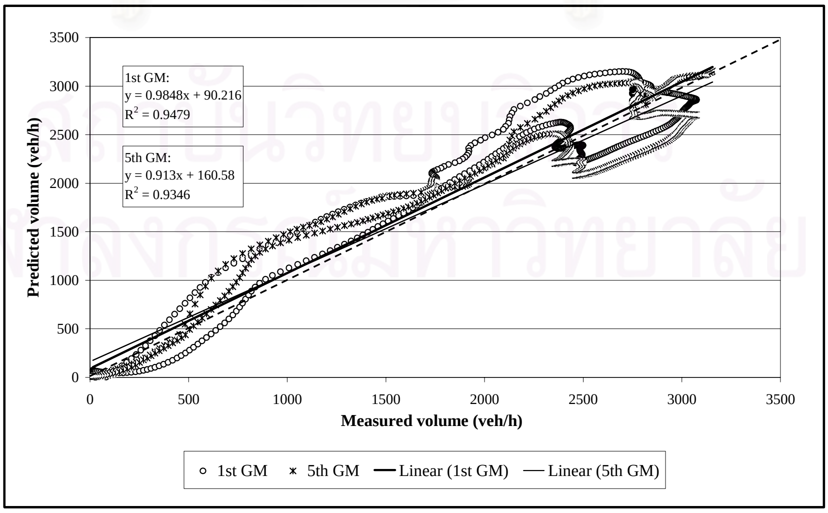
Figure A.1 Predicted vs. measured traffic flow parameters for Regime I.



(a) Average speed

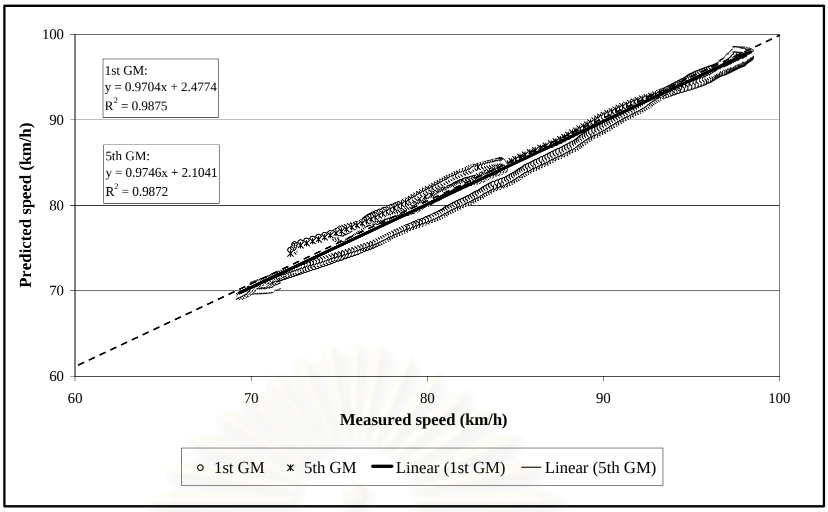


(b) Density

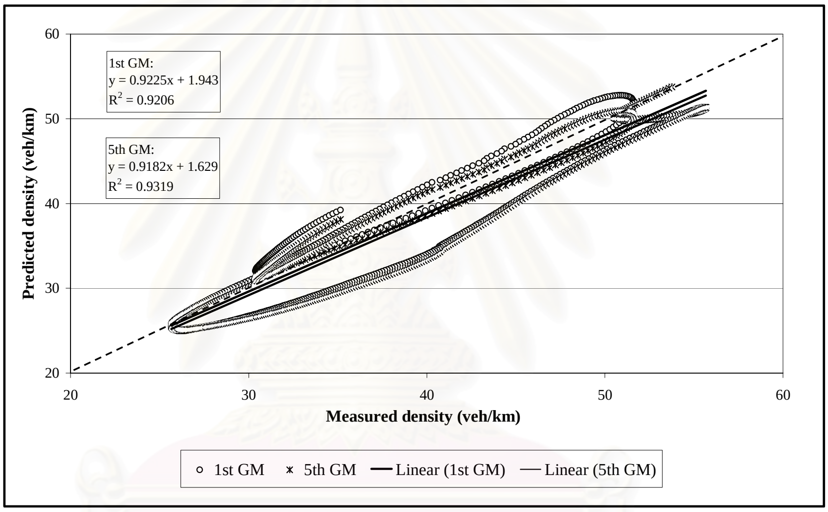


(c) Volume

Figure A.2 Predicted vs. measured traffic flow parameters for Regime II.



(a) Average speed



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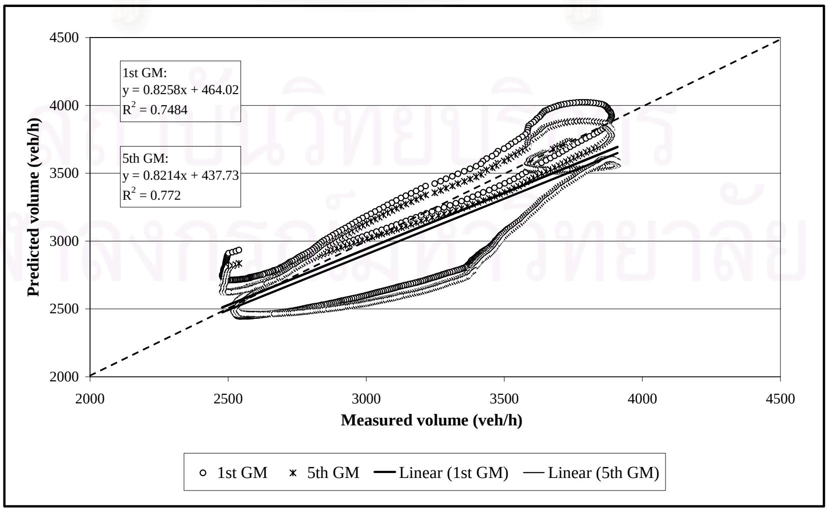
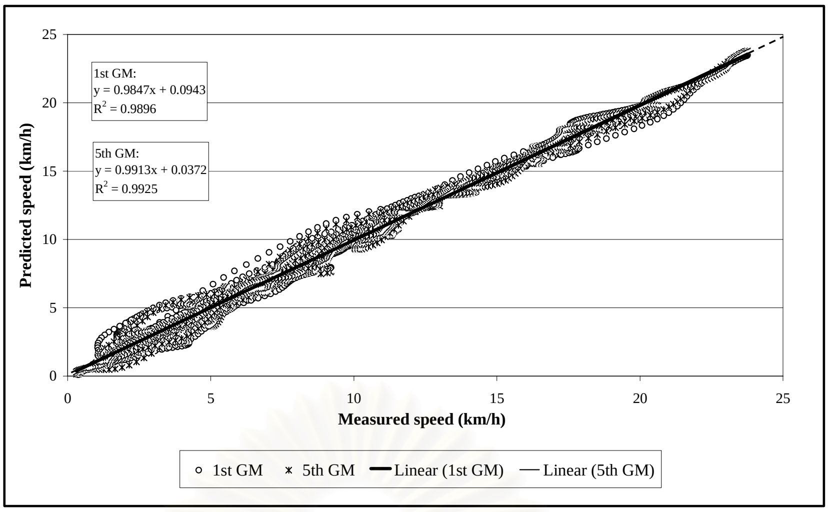
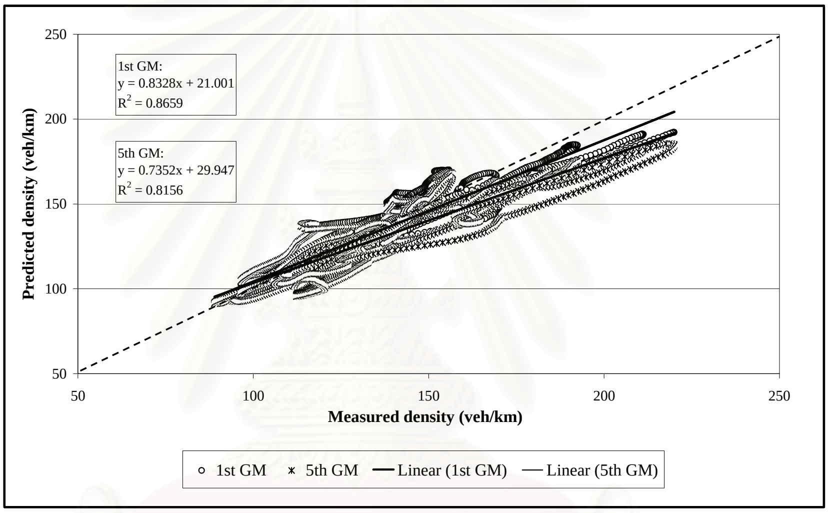


(c) Volume

Figure A.3 Predicted vs. measured traffic flow parameters for Regime III.



(a) Average speed



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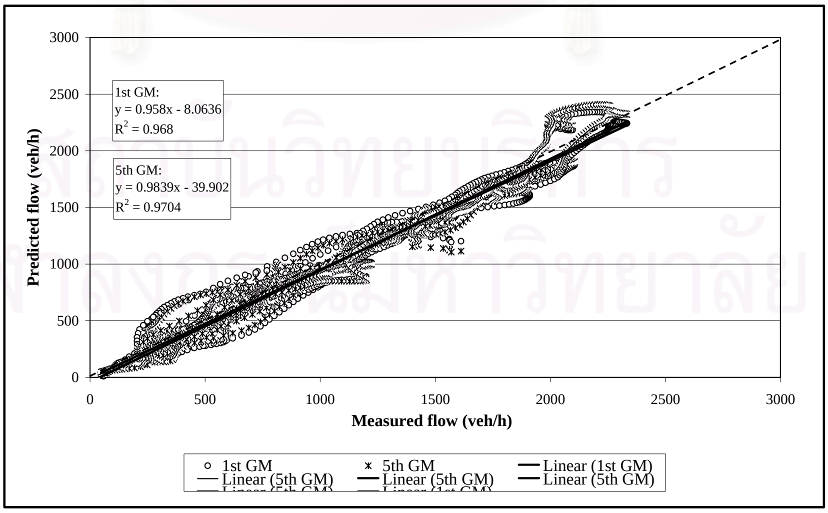

(c) Volume

Figure A.4 Predicted vs. measured parameters for Regime IV.

VITA

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