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DETERMINATION OF DRIVER'S BEHAVIOR FOR CAR-FOLLOWING MODEL USING GPS DATA

Phongsavanh Inthavongsa

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By	Phongsavanh Inthavongsa
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Thesis Advisor	Associate Professor Sorawit Narupiti, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

……………………………… Dean of the Faculty of Engineering
(Professor Direk Lavansiri , Ph.D.)

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(Associate Professor Sorawit Narupiti, Ph.D.)

………………………………………………… Member
(Prapon Vongvichien, Ph.D.)

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การขับขี่ตามกันเป็นสิ่งสำคัญของการขับขี่ที่ บ่งบอกการเคลื่อนตัวของยานพาหนะโดยมีผลกระทบของยานพาหนะอื่นๆ ในช่องทางเดียวกัน ซึ่งผลจะนำไปสู่สภาพการเคลื่อนตัวของการจราจรโดยรวม ดังนั้นการศึกษาพฤติกรรมของผู้ขับขี่ในการขับขี่ตามกันนี้มีส่วนสำคัญในการอธิบายการเคลื่อนตัวของการจราจร งานวิจัยนี้ศึกษาพฤติกรรมของผู้ขับขี่ภายใต้สภาพการจราจรที่แตกต่างกันในประเทศไทย โดยแบ่งศึกษาบนทางพิเศษและถนนพื้นราบ โดยใช้ข้อมูลจากจีพีเอส ข้อมูลการเคลื่อนตัวของรถบันทึกโดยอุปกรณ์จีพีเอสที่มีความถูกต้องมากกว่า 1 เซนติเมตร ทุกๆ 0.1 วินาที จะถูกนำมาหาความเร็วและความเร่ง จากนั้นนำมาหาพฤติกรรมการขับขี่ซึ่งใช้อธิบายแบบจำลองการขับขี่ตามกันของ GM ได้แก่ เวลาตอบสนอง (Reaction time) และ ความไว (Sensitivity) ได้โดยวิธีกราฟฟิกและวิธีสมการถดถอยเชิงเส้น

ผลการวิจัยพบว่า เวลาตอบสนองผันแปรตามสภาพถนนและการจราจรโดยในสภาพการจราจรหนาแน่น เวลาตอบสนองในช่วงเร่งความเร็วจะยาวกว่าในช่วงลดความเร็ว อย่างไรก็ตามในสภาพการจราจรเบาบาง เวลาตอบสนองในช่วงเร่งความเร็วจะสั้นกว่าในช่วงลดความเร็ว การปรับแบบจำลอง GM ให้ค่าความไวที่ไม่คงที่ เมื่อเปรียบเทียบระหว่างผู้ขับขี่หลายคนในการศึกษาครั้งนี้ พบว่า ผู้ขับขี่บางคนจะประพฤติรุนแรง (Aggressive) มากกว่าในสภาพการขับขี่ที่วิกฤตกว่า (ขับขี่ตามกันกระชั้นชิดด้วยความเร็วสูง) แต่จะประพฤติรุนแรงน้อยกว่าในสภาพการขับขี่ที่ไม่วิกฤต ผลการศึกษาสร้างความเข้าใจในพฤติกรรมการขับขี่ของผู้ขับขี่ได้อย่างดี

ภาควิชา	วิศวกรรมโยธา	ลายมือชื่อนิสิต...
สาขาวิชา	วิศวกรรมโยธา	ลายมือชื่ออาจารย์ที่ปรึกษา.....................................
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Car following is the major driving task reflecting individual vehicle movements and interactions among vehicles in a single lane, resulting in overall characteristics of traffic flow. Thus, determination of the driver's behavior is fundamental to accurate explanation of traffic flow. In this research, the driver's behavior was determined under different traffic conditions in Thailand, especially expressway and surface street using GPS technology. The vehicle trajectories were collected by RTK-GPS device at 0.1 second interval with accuracy of less than ± 1 cm. The speed and acceleration profile were then constructed. Driver's behaviors described in the GM car following model parameters, namely reaction time and sensitivity parameters, were determined using Graphical method and Linear regression method, respectively. The results indicate that the reaction time of a driver varies by traffic and road conditions. In congested traffic condition, the reaction time for acceleration is longer than that for deceleration. However, the reaction time for acceleration is shorter than that for deceleration in uncongested traffic condition. The result of the 5^{th} GM model calibration shows that the sensitivity parameter of drivers is inconsistent. Compared among subject drivers, some drivers are more aggressive in a more critical (close spacing, high speed) situation but less aggressive in a non-critical situation. The research brings about the better understanding of driver's behaviors.

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

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CHAPTER I

INTRODUCTION

1.1 General

For traffic engineering, reliable and accurate representation of driver's behavior is the key element of accurate modeling and analysis of traffic phenomenon. Modern traffic analysis is moving from macroscopic to microscopic simulation of traffic flow. This requires not only basic traffic flow data, (i.e. volume, speed, density), but also disaggregate driver's behavioral data at individual level. The microscopic consideration is proved more accurate, however given on the assumption of correct representation of inputs at individual level. Driver's behavior, thus, is the key element of accuracy of the traffic flow analysis result. The accurate driver's behavior is also needed for recent studies on interactions among traffic system components. Effects of driver, vehicle, and road on each other are the basics of the study of advanced traffic system, in the field of Intelligent Transport System (ITS), such as Advanced Highway System (AHS), and Advanced Collision Warning System (ACWS).

To obtain the accurate driver's behaviors, one needs to conduct well-designed experiment and proper analysis. So far, few researches attempt to determine driver's behavior, especially car following behavior, the fundamental driving task. Most of the researches were carried out in the controlled environment, such as test track or single-lane road, to avoid complexity in interpretation. Further study is still in need to capture more accurate behaviors, especially in real-world driving environment reflecting "local" or country habits.

Global positioning system, GPS, is an emerging technology which reports accurate location using satellite co-ordination, GPS can yield as millimeter in precision. GPS has been widely used in engineering application. GPS can also be applied to obtain vehicle trajectory data. Since the data from GPS is so accurate, it is possible to manipulate raw data from a single vehicle movement to determine driving behaviors.

Therefore, it is original that the driver's behavior can be interpreted from the experimental study using GPS data. This methodology could be applied to driving condition in the real-world, which can give accurate and "true" driver's behavior existing on the actual traffic flow. It is also expected that detail of driver's behavior, such as consistency of behaviors, can also be studied.

1.2 Problem Statement

Recently several studies have realized the potential of the use of GPS data to estimate the traffic state condition of human driver's driving behavior, such as position, speed, acceleration, driver's reaction time, sensitivity parameters and their relationships of vehicle in a single lane of traffic. Shekleton (2000) suggested that GPS data that obtained from GPS device could be used to estimate traffic state variables, and proposed an algorithm for estimating distance from the GPS data using the distance between any two points in three dimensional space and the speed and acceleration of vehicle was calculated by differentiating vehicle trajectory function, respectively. Wolshon, and Hatipkarasulu (2000) proposed a method using GPS technique for determining the exact position of vehicles anywhere on the earth and comparison of GM car following parameters, mainly driver's reaction time and sensitivity parameters. Recently, Ranjitkar, Nakatsuji, Asano, and Kawamura (2004) proposed an algorithm using GPS data for estimating the GM car following parameters such as driver's reaction time and sensitivity parameters using genetic algorithm and linear regression, respectively. The system equations were taken from individual vehicle motion. Even though the data collection of GPS data was applied for the obtainment of vehicle movement trajectories, this method and data analysis procedure have not been tested in Asian city condition. It is known that the precision of the GPS data depends on several technological and geographical factors. Thus, it is questionable that the use of the GPS data collection technique could yield, with sufficient accuracy, the useful data for modeling driver's behavior. Moreover, the analysis technique is experimented in order to find proper methods for data reduction and analysis

Furthermore, the driver's behaviors represented in the model, namely reaction time and sensitivity parameters, are important aspects that should be realized. The previous researches determined these parameters under various drivers and driving environment. None of researches attempt to capture the "real" Asian driver's behavior.

1.3 Research Objectives

- To study how the traffic data processed from very reliable traffic information that could be realistically represent real time traffic states condition
- To determine and compare the Driver's behavior on car following model using GPS data

1.4 Research Framework

The proposed method of this research is designed to study the driver's behavior in car following manner under real driving environments on selected streets and expressways in Bangkok, Thailand. The research can be divided into two tasks. The first task is to perform car – following experiment study the driver's behavior on expressway and another one on surface street. In this experiment, the investigations of driving behavior were carried out using the test vehicle with 5 selected drivers. Each test vehicle was fitted with GPS devices and driven under different traffic conditions following each other in a single lane of traffic.

The GM Car following parameters that are analyzed in this research consists of driver's reaction time and sensitivity parameters, which can be obtained from Graphical method and Least squares analysis, respectively. The following framework of proposed method, Driver's behavior based on GM car following model were measured or calculated from GPS data at 0.1 second interval during observation for both types of roadway condition as illustrated Figure 1.1. After that the driver's behaviors based on GM car following parameters, namely driver's reaction time and sensitivity parameters, are determined from Graphical method and Least squares analysis.

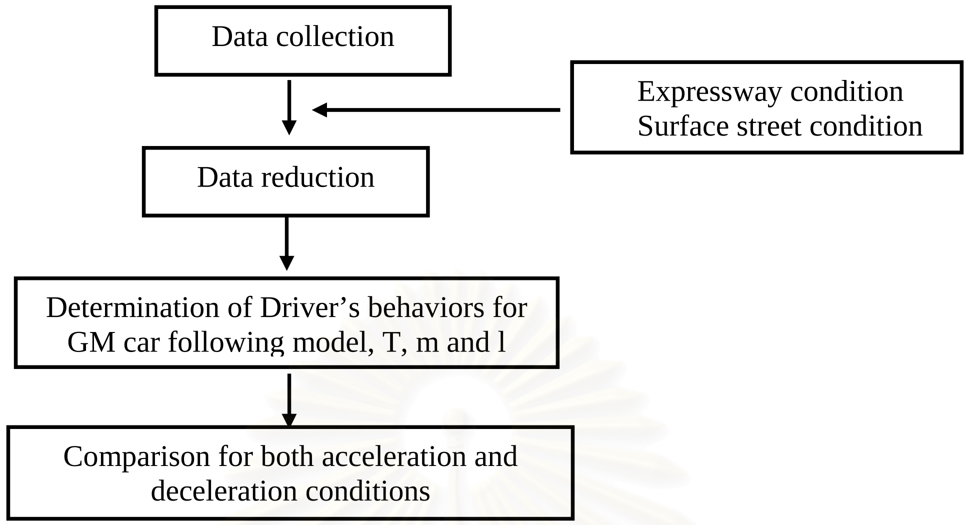


Figure 1.1 Framework of proposed method

For the framework of proposed method, the computer programs were developed using MATLAB and SPSS programming. In this study, MATLAB and SPSS programming are used to determine the GM car following parameters, mainly driver's reaction time and sensitivity parameters, respectively. SPSS programming was also used to test statistical analyses of each individual vehicle characteristic for both types of roadway, expressway and surface street conditions, to find representative driver's driving behavior characteristics.

1.5 Scope and Limitations

- To collect GPS data representing driver's behavior from a 5-car platoon on two types of roadway conditions in Thailand, namely expressway and surface street
- To calibrate the driver's behavior parameter, represented in common GM car-following model

1.6 Thesis Organization

In Chapter 2 a literature review of car following model, including mathematical model of car following behavior, experiment of car following model using GPS data and also comparison of the properties of car following model and the important parameters. Chapter 3 introduces the methodology, which considers how to collect the data, calibrate the GM car following parameters, and how to use the newly-developed program to determine the driver's reaction time and sensitivity parameters. Chapter 4 presents the detailed analysis results of driver's behaviors. Chapter 5 presents the summary and conclusions.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

It is important to have a clear understanding of the car following phenomenon, the human driver's driving behavior of car following. Therefore, in this chapter, the studies of car following models, experiment of car following using GPS data were reviewed and also compared the properties of car following model from different approaches and the important parameters based on GM car following model during the past 50 years as follows:

2.1 Overview of Car following model

The car following behavior is one of the key components of Traffic microscopic simulation model, where it controls the fundamental motion of the vehicles. Many car following models have been proposed during the past 50 years. The first study of car-following model was performed by Reuschel in 1950, which he assumed the driver behavior of following another vehicle could be modeled as illustrated in the equation 2.1, which indicates that the response of a driver to a change in traffic conditions. In this equation, the response can be the acceleration or deceleration of the vehicle ahead. In such case, the stimulus can be change in the relative speed or relative spacing between the lead and following vehicles.

$$\text{Response} = \text{Sensitivity} \times \text{Stimulus} \tag{2.1}$$

Pipes (1953) developed the first studies of car-following model as mentioned by relationship in (2.1), which he proposed the minimum safety distance between a lead and a following vehicle. In his model, the minimum safe distance between a lead and a following vehicle is assumed to be a function of the speed of the following vehicle and the length of the vehicle in front, as indicated in equation 2.2.

$$d_{Min} = \left[x_n(t) - x_{n+1}(t)\right]_{Min} = L_n\left[\frac{\dot{x}_{n+1}(t)}{1.47 \times 10}\right] + L_n \tag{2.2}$$

where,

$x_n(t)$ = position of lead vehicle at time (t), m

$x_{n+1}(t)$ = position of following vehicle at time (t), m

L_n = length of the lead vehicle, m

$\dot{x}_{n+1}(t)$ = speed of the following vehicle at time (t), m/s

Forbes (1958) later improved Pipes' safe distance model, which he considered the driver’s reaction time required by a driver to perceive the need to decelerate and apply the brakes. His research leads to the time headway model as illustrated in equation 2.3.

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

where,

Δt = driver’s perception-reaction time, sec

$\dot{x}_n(t)$ = speed of lead vehicle at time (t), m/s

Following the work of Pipes and Forbes, General Motors Laboratory in United State (1959) used the results of extensive field studies to develop a series of microscopic car-following models, and became the basic of modern microscopic traffic flow models, as given by equation 2.4.

$$\ddot{x}_{n+1}(t + \Delta t) = \alpha\left[\dot{x}_n(t) - \dot{x}_{n+1}(t)\right] \tag{2.4}$$

where,

$\ddot{x}_{n+1}(t + \Delta t)$ = acceleration of following vehicle at time ($t + \Delta T$), m/s^2

$\dot{x}_n(t) - \dot{x}_{n+1}(t)$= the relative speed at time (t), m/s

α = sensitivity factor of the driver in the following vehicle, sec^{-1}

Δt = reaction time for the driver in the following vehicle, sec

Later Equation 2.4, the General Motors Laboratory as they considered the spacing between the lead and following vehicles to reflect the assumption that the response of the driver of the following vehicle was inversely proportional to the distance between following vehicle and the leading vehicle , as show in equation 2.5

$$\ddot{x}_{n+1}(t+\Delta t)=\frac{\alpha}{x_n(t)-x_{n+1}(t)}\left[\dot{x}_n(t)-\dot{x}_{n+1}(t)\right] \quad (2.5)$$

where,

α = sensitivity factor of the driver in the following vehicle, m/s

$x_n(t)-x_{n+1}(t)$ = relative distance at time (t), m

And then after the equation above, in this model the driver of the following vehicle is assumed to be more responsive to relative speed of lead vehicle with respect to speed of his or her own vehicle as he accelerations or decelerations as seen in equation 2.6.

$$\ddot{x}_{n+1}(t+\Delta t)=\frac{\alpha\left[\dot{x}_{n+1}(t+\Delta t)\right]}{x_n(t)-x_{n+1}(t)}\left[\dot{x}_n(t)-\dot{x}_{n+1}(t)\right] \quad (2.6)$$

where,

$\dot{x}_{n+1}(t+\Delta t)$ = speed of following vehicle at time ($t+\Delta t$), m/s

In the final GM car following model, a group of researchers at General Motors Laboratories in United States (1963) improved the model structure of the GM car following model. The GM model is a stimulus-response model of car following which represented the function of the distance headway between the lead and following vehicle and the speed of following vehicle. The mathematically the model can be represented as:

$$\ddot{x}_{n+1}(t+\Delta t)=\frac{\alpha_{m,l}\left[\dot{x}_{n+1}(t+\Delta t)\right]^m}{\left[x_n(t)-x_{n+1}(t)\right]^l}\left[\dot{x}_n(t)-\dot{x}_{n+1}(t)\right] \quad (2.7)$$

where,

$m\ and\ l$ = exponents of following vehicle speed and relative distance, respectively.

Helly (1959) proposed a model that included additional terms for the adaptation of the acceleration according to whether the vehicle in front (or the two vehicles in front) was braking, which it was the first linear function used to model the car following behavior the simplified form of the model was as follow:

$$a_n(t) = C_1 \Delta v(t-T) + C_2[\Delta x(t-T) - D_n(t)],\ D_n(t) = \alpha + \beta v(t-T) + \gamma a_n(t-T) \tag{2.8}$$

where,

C_1 and C_2 = constant coefficients of relative speed and distance

$D(t+T)$ = desired relative distance (distance headway) at time ($t+T$), m

$D_n(t)$ = desired following distance at time (t), m/s.

Kometani and Sasaki (1959) introduced Safety distance or collision avoidance models. The idea was a simple manipulation of the basic Newtonian equations of motion that hope for a safe distance headway between the lead and the following vehicles, as follow:

$$x_n(t) - x_{n-1}(t) = \alpha \dot{x}_n^2(t) + \beta \dot{x}_{n-1}^2(t+T) + \beta \dot{x}_{n-1}(t+T) + b_0 \tag{2.9}$$

where,

α = coefficient of the lead vehicle speed at time

β = coefficient of the following vehicle speed at time.

Gipps's car following model (1981) took the form of a system of differential difference equations involving the common driver's reaction time, which stated that the minimum speed to which a vehicle n could accelerate during a time period (t, t+T) is given by:

$$V_a(n,t+T)=V(n,t)+2.5a(n)T\left(1-\frac{V(n,t)}{V^*(n)}\right)\sqrt{0.025+\frac{V(n,t)}{V^*(n)}} \tag{2.10}$$

where,

$V(n,t), V_a(n,t+T)$ = speed of the vehicle *n* at time (t), ($t+T$), respectively.

$V^*(n)$ = desire speed of the vehicle *n* for current section, m/s

$a(n)$ = maximum acceleration for vehicle *n*, m/s^2

T = reaction time.

On the other hand, the minimum speed that the same vehicle n can reach during the same time interval *(t, t+T)*, according to its own characteristics and the limitations imposed by the presence of the leader vehicle, is:

$$V_b(n,t+T)=d(n)T+\sqrt{d(n)^2T^2-d(n)\left[2\{x(n-1,t)-s(n-1)-x(n,t)\}-V(n,t)T-\frac{V(n-1,t)^2}{d'(n-1)}\right]} \tag{2.11}$$

where,

$d(n)$ = maximum deceleration desire by vehicle *n*

$x(n,t)$ = position of vehicle *n* at time (t)

$x(n-1,t)$ = position of preceding vehicle *(n -1)* at time (t)

$s(n-1)$ = effective length of vehicle *(n -1)*

$d'(n-1)$ =estimation of vehicle *(n -1)* desired.

In any case, the definitive speed for vehicle *n* during time interval *(t, t+T)* was the minimum of those previously defined speeds:

$$V(n,t+T)=\min\{V_a(n,t+T),V_b(n,t+T)\} \tag{2.12}$$

Then, the position of vehicle n inside the current lane is updated taking this speed into the movement equation:

$$V(n,t+T)=x(n,t)+V(n,t+T)T \tag{2.13}$$

2.2 Overview of Car following modeling using GPS data

A research group of Louisiana State University (LSU) developed a novel technique for collection, processing, and analysis of car following data and computed the driver's reaction time and sensitivity parameters from the GPS data that obtained from GPS techniques as illustrated in Table 2.1. Position, speed, and acceleration of two vehicle platoons are used to estimate driver behavioral responses, mainly driver's reaction time and sensitivity parameters using a least squares estimation method based on 1st and 3rd GM car following model, which the comparison of the results from both model are summarized in Figure 2.1.

Table 2.1 Sample segment of GPS data for lead and following vehicles (Wolshon and Hatipkarasulu, 2000)

UTC time (s) (1)	Coordinates: Latitude (degrees) (2)	Coordinates: Longitude (degrees) (3)	Speed (mi/h) (4)	GPS status (5)	UTC time (s) (1)	Coordinates: Latitude (degrees) (2)	Coordinates: Longitude (degrees) (3)	Speed (mi/h) (4)	GPS status (5)
(a) Lead Vehicle					(b) Following Vehicle				
70,418.25	30.4311029	−91.1912206	0.0	3D	70,419.75	30.4310481	−91.1912303	0.0	3D
70,419.25	30.4311101	−91.1912160	1.2	3D	70,420.75	30.4310517	−91.1912268	1.3	3D
70,420.25	30.4311166	−91.1912139	2.1	3D	70,421.25	30.4310552	−91.1912254	2.7	3D
70,421.75	30.4311275	−91.1912100	1.4	3D	70,422.25	30.4310652	−91.1912229	2.5	3D
70,422.25	30.4311299	−91.1912095	1.0	3D	70,423.75	30.4310783	−91.1912208	1.9	3D
70,423.75	30.4311356	−91.1912085	1.2	3D	70,424.75	30.4310860	−91.1912194	2.0	3D
70,424.25	30.4311389	−91.1912079	2.0	3D	70,426.25	30.4311044	−91.1912162	4.6	3D
70,425.75	30.4311609	−91.1912029	5.4	3D	70,426.75	30.4311151	−91.1912141	6.1	3D
70,426.25	30.4311735	−91.1911998	7.1	3D	70,427.75	30.4311459	−91.1912079	9.4	3D
70,427.75	30.4312319	−91.1911853	12.3	3D	70,429.25	30.4312085	−91.1911953	10.9	3D
70,428.75	30.4312862	−91.1911730	15.0	3D	70,429.75	30.4312312	−91.1911907	12.0	3D
70,429.75	30.4313505	−91.1911592	17.3	3D	70,432.25	30.4313842	−91.1911620	18.8	3D
70,430.75	30.4314233	−91.1911414	19.5	3D	70,432.75	30.4314230	−91.1911536	20.2	3D
70,432.25	30.4315472	−91.1911094	22.2	3D	70,435.25	30.4316465	−91.1910963	24.2	3D
70,432.75	30.4315921	−91.1910990	23.0	3D	70,436.25	30.4317463	−91.1910748	26.0	3D
70,433.75	30.4316868	−91.1910798	24.5	3D	70,437.25	30.4318540	−91.1910556	27.9	3D
70,435.25	30.4318408	−91.1910533	26.7	3D	70,437.75	30.4319109	−91.1910469	28.8	3D
70,435.75	30.4318949	−91.1910444	27.3	3D	70,439.75	30.4321560	−91.1910132	32.0	3D
70,436.75	30.4320066	−91.1910263	28.5	3D	70,440.75	30.4322865	−91.1909955	32.9	3D
70,438.25	30.4321838	−91.1910005	30.3	3D	70,411.25	30.4323530	−91.1909861	33.3	3D

Note: 1 mi = 1.61 km.

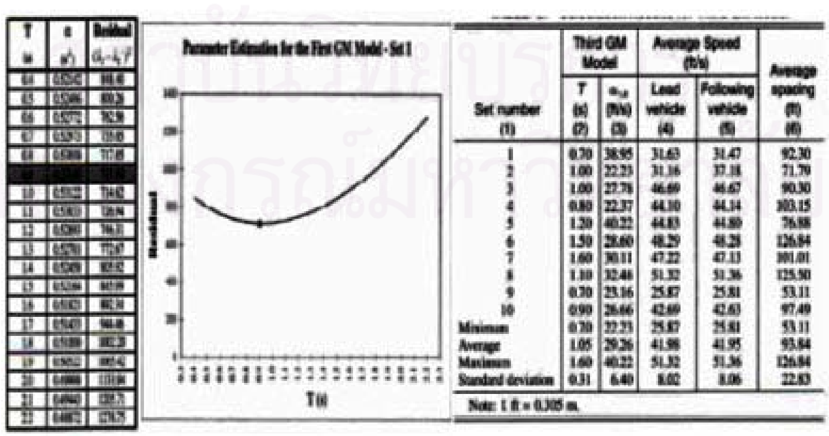


Figure 2.1 Calculation results of 1stand 3rd GM car following model (Wolshon and Hatipkarasulu, 2000)

Table 2.2 Comparison of original GM model and LSU GM car following parameters

	Calculated value	GM	LSU-GPS
Sensitivity (α)	Minimum	0.17	0.25
	Average	0.37	0.46
	Maximum	0.74	0.70
Reaction time(T)	Minimum	1.00	0.70
	Average	1.55	1.01
	Maximum	2.20	1.25
Headway (ft)	Minimum	87.60	60.28
	Average	136.24	97.45
	Maximum	200.46	152.23

Shekleton (2002) performed studies on car following theory using different GPS technique to analyze individual driver characteristics between two types of road conditions (dry and wet) using two test vehicles. Speed, spacing, acceleration, and their relationship of vehicle could be estimated from data output or GPS data. GPS data that obtained from the GPS receivers included corresponding x, y, and z coordinates and the error code of each data point, which were given directly by the GPS reading. Therefore, data for each vehicle enabled calculation of the instantaneous distance between their receivers for time matched data points using coordinate geometry, given that the distance between any two points in three dimensional spaces was given by:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{2.10}$$

where,

d = resulting displacement, m

x_i = coordinate x_i (north-south)

y_i = coordinate y_i (east-west)

z_i = coordinate (altitude).

Distance, speed, and acceleration of vehicle for both conditions can be calculated using mathematical models. Spacing vs. speed relationship plot for both types of roadway, dry and wet condition are illustrated in Figure 2.2 and 2.3. They represented minimum spacing between two vehicles depending on relative speed between them.

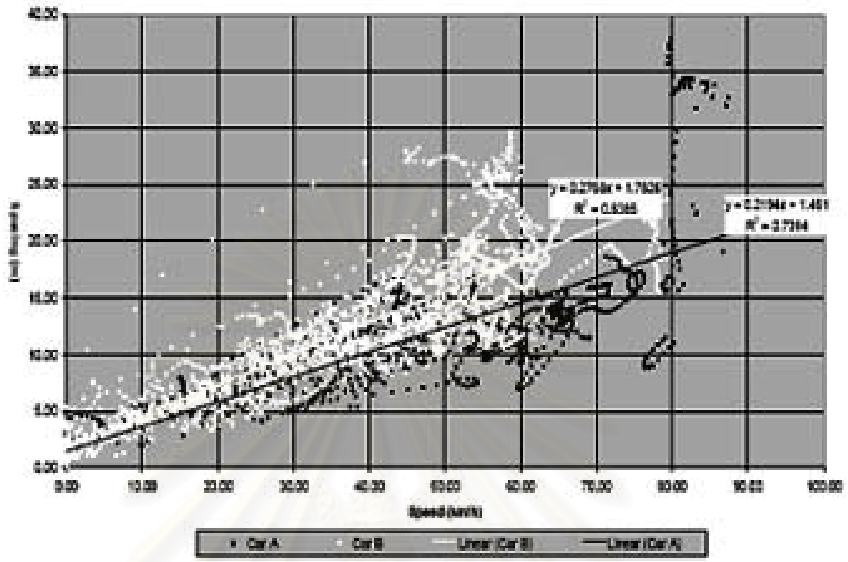


Figure 2.2 Overall speeds vs. spacing in dry condition (Shekleton, 2002)

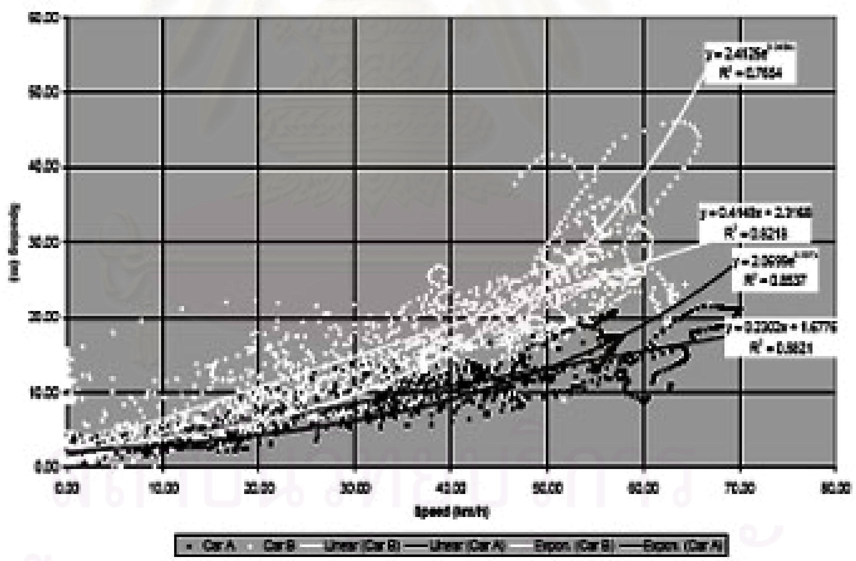


Figure 2.3 Overall speeds vs. spacing in wet condition (Shekleton, 2002)

Ranjikar, Nakatsuji, Asano, and Kawamura (2004) performed studies based on GM car following model as shown in the equation 2.7, which they described the algorithm to determine the driver's reaction time, T and sensitivity parameters, m, l and α using Genetic Algorithm and Linear Regression method as illustrated in

Figure 2.4 and Figure 2.5, respectively. The GM car following model can be converted to a linear form as given in the equation 2.11:

$$ln\,\ddot{x}_{n+1}(t+T) = ln\,\alpha_0 + ln[\dot{x}_n(t) - \dot{x}_{n+1}(t)] + m\,ln\,\dot{x}_n(t+T) - l\,ln[x_n(t) - x_{n+1}(t)] \qquad (2.11)$$

The equation 2.11 can be transformed into a simple linear form as shown in the equation 2.12:

$$Y = a \; + mX_1 + lX_2 \qquad (2.12)$$

where,

$Y = ln\left|\dfrac{\ddot{x}_{n+1}(t+T)}{\dot{x}_n(t) - \dot{x}_{n+1}(t)}\right|$ = dependent variable

$a_0 = \ln\alpha_0$, m and l = regression coefficients

$X_1 = \ln[\dot{x}_{n+1}(t+T)]$ = independent variable

$X_2 = -\ln[x_n(t) - x_{n+1}(t)]$ = independent variables.

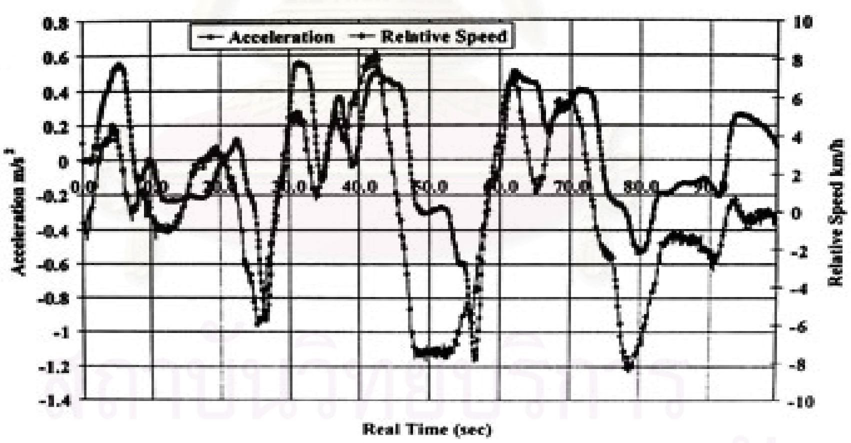


Figure 2.4 Graphical method for determination of driver's reaction time (Gurusinhe, Nakatsuji, Tanaboriboon, Takahashi and Suzuki, 2001)

2.3 Summary of Car following models and Driver's behaviors

According to several previous researches during the past 50 years, the properties of several car following models and the important parameters, mainly driver's reaction time and sensitivity parameters, were summarized in Table 2.4. The methods of determination illustrated different modeling approaches since the 1950s.

The driver's behaviors, as described by reaction time and sensitivity parameters, following GM car following model were determined by several past work. The estimated values of reaction time and sensitivity were presented in Table 2.5 and Table 2.6, respectively. From the tables, it is evident that there is yet no agreement on the values of reaction time and sensitivity parameters.

Table 2.3 Properties of car following model by different approaches

Model	Year	Stimulus	Response	Sensitivity	Reaction time	Explanations
Proportional Model Chandller et al.	1958	$\dot{x}_1(t) - \dot{x}_2(t)$	$\ddot{x}_2(t+T)$	α	T (const.)	
Linear model Helly	1959	$C_1(\dot{x}_1(t) - \dot{x}_2(t)) + C_2\begin{pmatrix} x_1(t) - x_2(t) \\ - D(t+T) \end{pmatrix}$	$\ddot{x}_2(t+T)$	C_1, C_2	T (const.)	D=desired Spacing
5th GM model Gazis et al	1961	$\dot{x}_1(t) - \dot{x}_2(t)$	$\ddot{x}_2(t+T)$	$\frac{\alpha(\ddot{x}_2(t+T))^m}{(x_1(t) - x_2(t))^l}$	T (const.)	m, l Constan

Table 2.4 Summary of car following parameters, driver's reaction time, in second

SOURCE	Reaction time(T), s
Chandler, Herman, and Montrooll (1958)	1.6
Herman and Potts (1959)	1.2
Kometani and Sasaki (1959)	0.5
Helly (1959	0.4
Michaels (1963)	1.4
Lee and Jones (1967), (acn/dcn	1.4/0.6
Aron (1988), (acn/ss/dcn)	1.8/0.5/3.9
Ozaki (1993), (acn/dcn)	1.9/1.9
Xing (1995), (acn/dcn)	0.8/3.4

Table 2.5 Summary of proposed optimal values for sensitivity parameters: l and m

SOURCE	m	l	Approach
Chandler, Herman and Montroll (1958)	0	0	Micro
Gazis, Herman and Potts (1959)	0	1	Macro
Herman and Potts (1959	0	1	Micro
Helly (1960)	1	1	Macro
Gazis, Herman and Rothery (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), (dcn no brk/dcn brk/acn)	1.5/0.2/0.6	0.9/0.9/3.2	Micro
Treiterer and Myers (1974), (dcn/acn)	0.7/0.2	2.5/1.6	Micro
Cedar and May (1976), (single regime)	0.6	2.4	Macro
Cedar and May (1976), (uncgd/cgd)	0/0	3/0-1	Macro
Aron(1988), (dcn/ss/acn)	2.5/2.7/2.5	1.7/0.3/0.1	Micro
Ozaki (1993), (dcn/acn)	0.9/-0.2	0.9/-0.2	Micro

Note: dcn/acn: deceleration/acceleration, dcn no brk: deceleration without use brakes, dcn brk: deceleration with use brakes, uncgd/cgd: uncontested/congested, ss: steady state

CHAPTER III

METHODOLOGY

3.1 Introduction

In this chapter provides a procedure for determination of driver's driving behavior for car following model using GPS data. Many models are developed to emulate the human driver's driving behavior in a single lane of traffic condition, such as proportional model, linear model, GM car following model, Gipps' model and so. In this research, we use GM car following model to represent the acceleration or deceleration of individual vehicle follows another in a single lane of traffic condition in Thailand, especially expressway and surface street conditions.

3.2 Car following experiment using GPS

3.2.1 Data collection

GPS data collections, in this experiment, were carried out using 5 test vehicles with 5 selected drivers, which the information of all drivers and their test vehicles were illustrated in Table 3.1. The device was manufactured by Leica company. Each test vehicle was equipped with a set of device collecting the traffic states information. The set of equipment consists of GPS antenna, GPS receiver, and GPS receiver cable as illustrated in Figure 3.1. The GPS antenna cable was fixed onto a roof rack on each vehicle and connected to the receiver via a cable as illustrated in Figure 3.2. Each GPS receiver basically needs signal from at least three GPS satellites to pinpoint the position of each vehicle during observation at 0.1second intervals. The data was saved in the internal memory and later downloaded to the storage in office for future analysis at the end of the experiment.

Since the driver's behavior on actual driving is required, several routes and some specific driving instructions are specified. In this study, few routes are selected to represent various geometry and flow conditions. Basically expressways represents an uninterrupted flow facility while surface streets (on the signalized network) represents an interrupted flow facility. Time of experiment was selected so that test vehicles experience both "uncontested" and "congested" flow condition. Special consideration was made on route selection to assure the receiving of signal from GPS satellites.

In this study, the investigation route was approximately 60 km in length between the first, second stage and Ramindra-Arjnarong on expressway as illustrated in Figure 3.3 and on surface street was approximately 45 km in length between Buddha Monthol Sai 4 Rd and Asa Road, Bangkok, Thailand as illustrated in Figure 3.4. Each driver was assigned a simple instruction to follow the lead vehicle. The driver was told to "drive normally" and avoid any event interfering his driving habit. In the case of unavoidable incident, e.g. a vehicle cut in the platoon, the driver was instructed to drive normally and avoid any corrective manner.

The raw output or GPS data that obtained from the GPS receivers were illustrated in Table 3.2, including corresponding x, y, and z coordinates and the error code of each data point at 0.1second interval for each vehicle. Downloading the data from each receiver, the data can be directly transferred into Microsoft Excel. Distance, speed, and acceleration of vehicle platoons can be later calculated from the vehicle locations. It was noted that the length of vehicle and the location of GPS from front and rear ends of vehicle were measured. These values were used to correct the spacing between the front and end bumpers of the two following vehicles.

The initial screening of the raw GPS data indicated that many of data points were not recorded (loss or "error") due to inability of receiving GPS satellite signal at specific locations. This may be caused by dense tree, high building, etc...And thus some "usable" parts of GPS data were selected as the set of data for further analysis. The number of data points representing a period of driving on expressway and Surface Street were shown in Table 3.3.

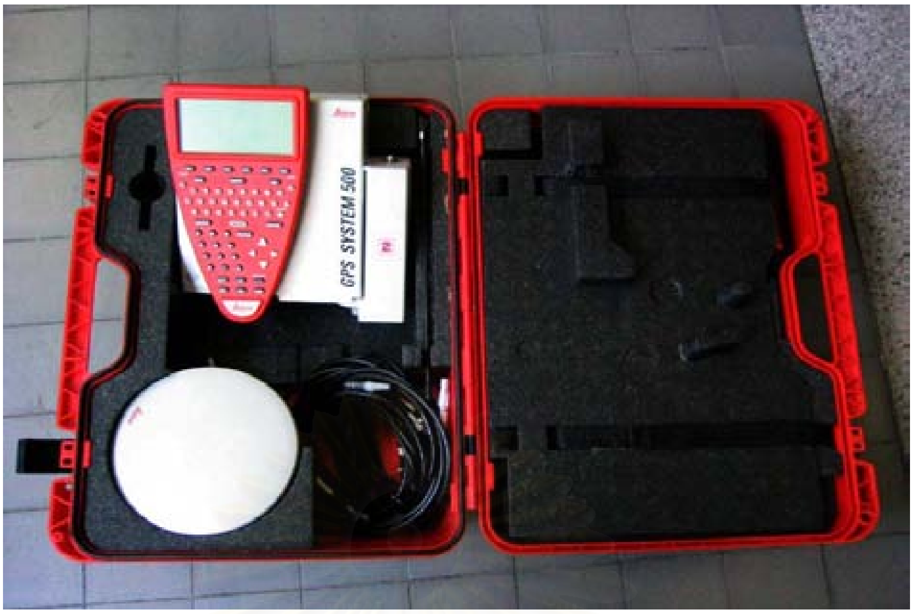


Figure 3.1 GPS apparatus, antenna, receiver, and receiver cable

Figure 3.2 Installation of GPS antennas on a test vehicle's roof

Figure 3.3 Driving route on expressway

Figure 3.4 Driving route on surface street

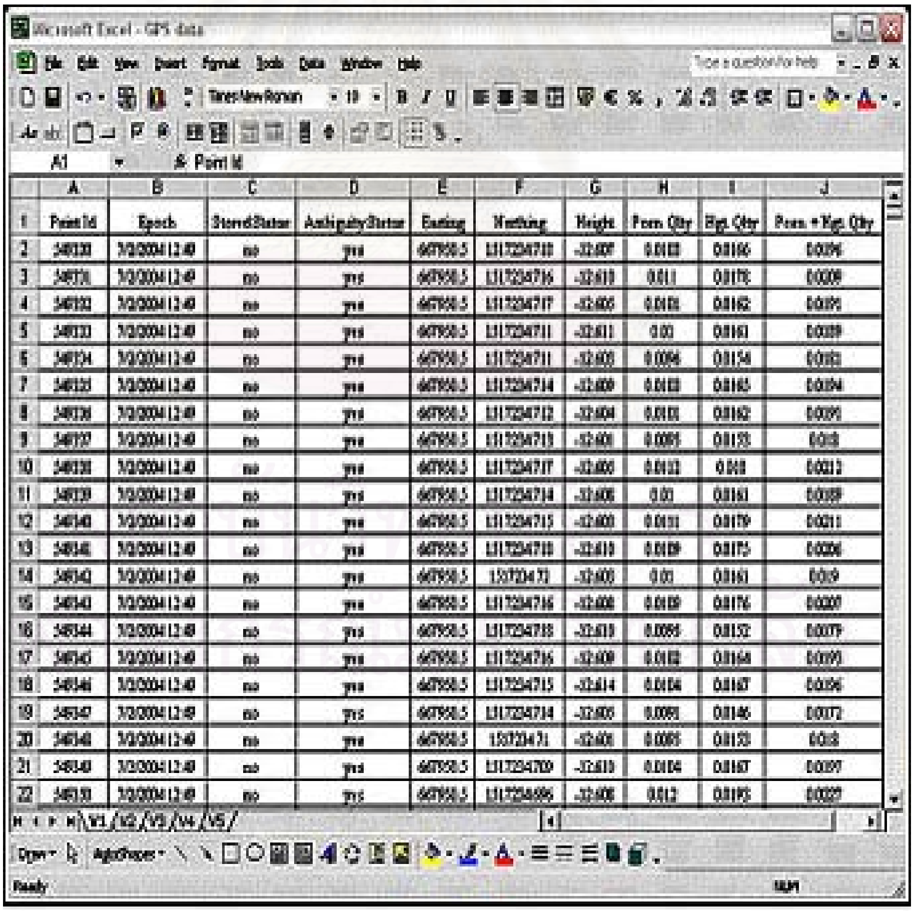
Table 3.1 General information of drivers and their test vehicles

Drivers	Sex	Ages	Vehicle model
V1	Male	21	BMW 318I
V2	Male	24	HONDA CIVIC
V3	Male	22	HONDA CIVIC
V4	Male	22	TOYOTA CORONA
V5	Male	25	TOYOTA CORONA

Table 3.3 Sample of time series and number of data points in this study

Expressway		Surface Street	
Time, s	Number of data points	Time, s	Number of data points
257	2751	164.5	1646

Table 3.2 Sample segments of GPS data output



	A	B	C	D	E	F	G	H	I	J
1	Point Id	Epoch	StoredStatus	AmbiguityStatus	Easting	Northing	Height	Posn. Qlty	Hgt. Qlty	Posn. + Hgt. Qlty
2	549130	3/2/2004 12:49	no	yes	667950.5	1517234710	-32.607	0.0103	0.0166	0.0096
3	549131	3/2/2004 12:49	no	yes	667950.5	1517234716	-32.610	0.011	0.0178	0.0098
4	549132	3/2/2004 12:49	no	yes	667950.5	1517234717	-32.606	0.0101	0.0162	0.0095
5	549133	3/2/2004 12:49	no	yes	667950.5	1517234711	-32.611	0.01	0.0161	0.0089
6	549134	3/2/2004 12:49	no	yes	667950.5	1517234711	-32.603	0.0096	0.0154	0.0092
7	549135	3/2/2004 12:49	no	yes	667950.5	1517234714	-32.609	0.0103	0.0165	0.0094
8	549136	3/2/2004 12:49	no	yes	667950.5	1517234712	-32.604	0.0101	0.0162	0.0095
9	549137	3/2/2004 12:49	no	yes	667950.5	1517234713	-32.601	0.0095	0.0153	0.010
10	549138	3/2/2004 12:49	no	yes	667950.5	1517234717	-32.606	0.0112	0.018	0.0112
11	549139	3/2/2004 12:49	no	yes	667950.5	1517234714	-32.606	0.01	0.0161	0.0089
12	549140	3/2/2004 12:49	no	yes	667950.5	1517234715	-32.603	0.0111	0.0179	0.0111
13	549141	3/2/2004 12:49	no	yes	667950.5	1517234710	-32.610	0.0109	0.0175	0.0106
14	549142	3/2/2004 12:49	no	yes	667950.5	151723471	-32.603	0.01	0.0161	0.009
15	549143	3/2/2004 12:49	no	yes	667950.5	1517234716	-32.608	0.0109	0.0176	0.0097
16	549144	3/2/2004 12:49	no	yes	667950.5	1517234718	-32.613	0.0095	0.0152	0.0079
17	549145	3/2/2004 12:49	no	yes	667950.5	1517234716	-32.609	0.0102	0.0164	0.0093
18	549146	3/2/2004 12:49	no	yes	667950.5	1517234715	-32.614	0.0104	0.0167	0.0096
19	549147	3/2/2004 12:49	no	yes	667950.5	1517234714	-32.605	0.0091	0.0146	0.0072
20	549148	3/2/2004 12:49	no	yes	667950.5	151723471	-32.601	0.0095	0.0153	0.010
21	549149	3/2/2004 12:49	no	yes	667950.5	1517234709	-32.613	0.0104	0.0167	0.0097
22	549150	3/2/2004 12:49	no	yes	667950.5	1517234696	-32.606	0.012	0.0193	0.0097

3.2.2 Data processing

As mentioned before, the GPS data that obtained from the GPS receivers were location, corresponding x, y, and z coordinates, and the error code at 0.1second interval, data from each vehicle enabled calculation of the instantaneous distance between their receivers using coordinate geometry, given that the displacement (distance) between any two points in three dimensional space was given by equation 3.1 below:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{3.1}$$

where,

d = resulting displacement

x_i = coordinate x_i (north-south)

y_i = coordinate y_i (east-west)

z_i = coordinate (altitude).

GPS data at discrete points in time need to be processed and smoothed to reduce measurement errors using regression procedure. The method employed a set of time-series position measurements and construct a polynomial in time-distance to fit the selected data given by equation 3.2:

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

Where,

x = distance of vehicle

t =time

a and b = coefficient of the second order polynomial equation

c = constant.

Therefore, from equation 3.2 speed and acceleration of vehicle can be calculated by differentiating a polynomial in time-distance curve. Therefore, the instantaneous speeds and accelerations of vehicle can be calculated by the Equation 3.3 and Equation 3.4, respectively.

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

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

3.3 Speed and acceleration noise study

Speed and acceleration noise of vehicle during observation at 0.1second interval can be identified as a measurement of the smoothness of original data, which the speed and acceleration noise are dependent upon the three basic elements of the traffic stream, namely the driver, the road, and the traffic condition. This research assumption states that the “real” vehicle trajectory should be “smooth”, according to physical limitation on sudden acceleration (speed and movement) change. Sine the data measured by GPS may contain some noise of measurement; the smoothing of the measured data is the corrective way to improve the accuracy of the data. It is believed that the corrected data bring about closer figure to the actual vehicle movement. As seen in Figure 3.5. The smoothing process results in a smoothed value that is a better estimate of the original value because the noise has been reduced.

An original program was written on MATLAB to manipulate smoothing procedure. Basically the smoothing utilized local information to eliminate sudden changes or noise. In other word, moving average operation was performed, with a user-selected window of data points to be considered.

The window moves across the data set as the smoothed original value is calculated for each predictor value. A large span size increases the smoothness but decreases the resolution of the smoothed data set, while a small span size decreases the smoothness but increases the resolution of the smoothed data set as illustrated in Figure 3.6. The optimal span value depends on data set and the smoothing method. The procedure of smoothing data (noise elimination) consists of four steps as follows:

- Preparation of the original data set of vehicle movement
- Double click on the MATLAB program icon to begin your MATLAB session , which the program will directly open to command window
- Select the function name and select the window size that is needed
- Finally, click on button “Enter”, the program will plot the acceleration vs. time and speed vs. time curve with measurement noise removed the smoothed data results will directly show in Microsoft Excel files.

In this study, the window of nine local points was used to smooth the curve and determine the predictor value (noise - elimination). Due to the magnitude of noise visually obtained from the data set, the use of this window size was sufficient to reduce the noise, yet minimally deviate the figure that caused the shift in time and affected the later calculation. The data described in Table 3.3 was then processed with the above procedure, to eliminate acceleration and speed noise and yielded a corrective data set to for the determination of driver’s behaviors in the later section.

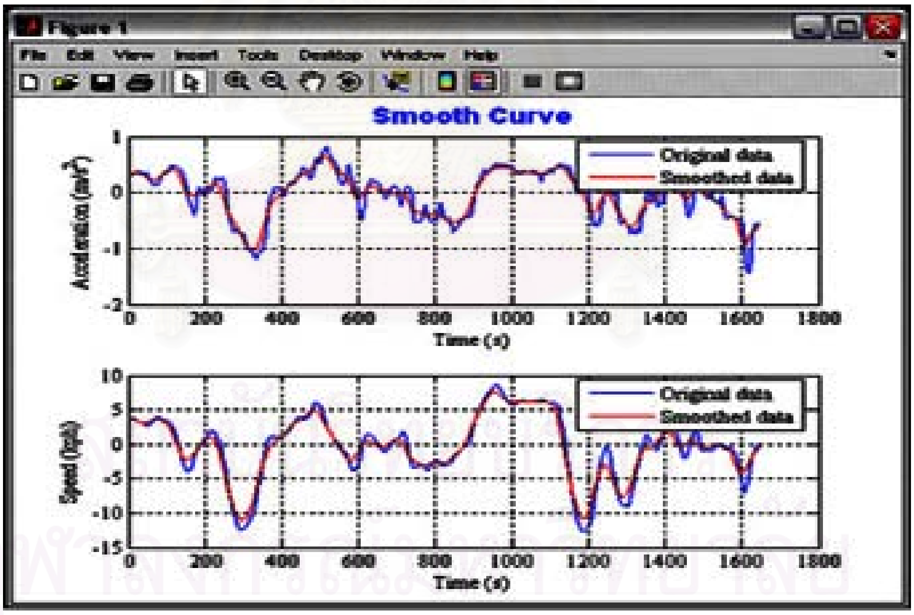


Figure 3.5 Speed and acceleration of vehicle with noise removed

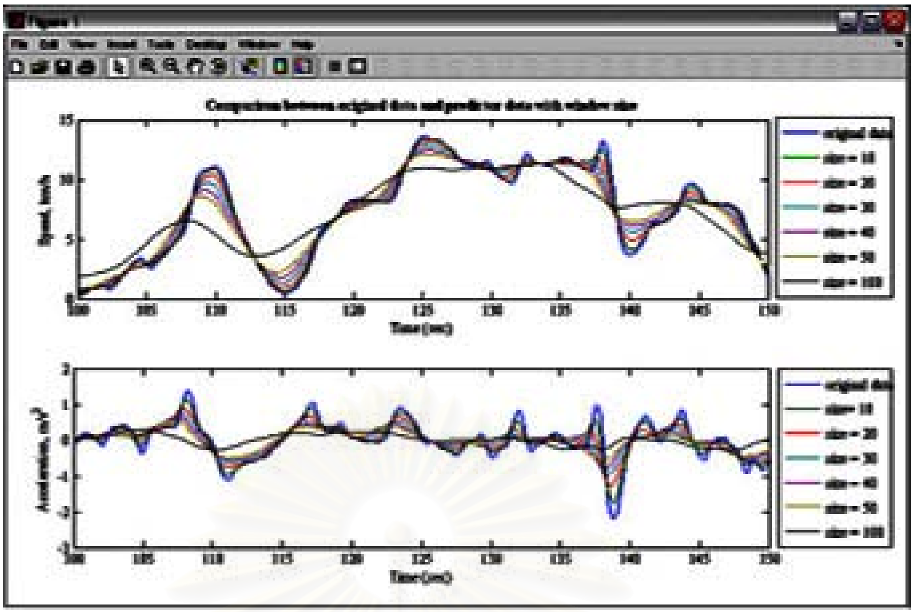


Figure 3.6 Comparison of original data and predictor data of vehicle for selection the window size of acceleration and speed

3.4 Driver's reaction time study

In this study, driver's reaction time of a following vehicle can be determined using the Graphical method as illustrated in Figure 3.7. The Graphical method was used to select the significant point of stimulus and to detect their corresponding points of response. Therefore, this procedure was used in this study according to the definition of the driver's reaction time; the time that occurred between change in relative speed and corresponding change in acceleration of following vehicle. A special program was written on MATLAB to manipulate the deceleration of point (in time) of reaction time in relation to two following vehicle speeds (and acceleration). The procedure of determining the driver's reaction time consists of five steps as follows:

- Preparation of the data set of vehicle including time, acceleration of following vehicle and relative speed between lead and following vehicle
- Double click on the MATLAB program icon to begin the MATLAB session the program will open to command window
- Select the function name , click on button "Enter" the program will open the driver's reaction time window and then select the file name of data set and click on button "Open"

- Select the range of data set and then click on button “View” the program will show the acceleration curve of following vehicle and relative speed curve plotted on a common base of time
- Finally, select the maximum or minimum point that is needed to determine the driver’s reaction time and then click on button “Run” the program will show the driver’s reaction time results on small window as illustrated in Figure 3.7.

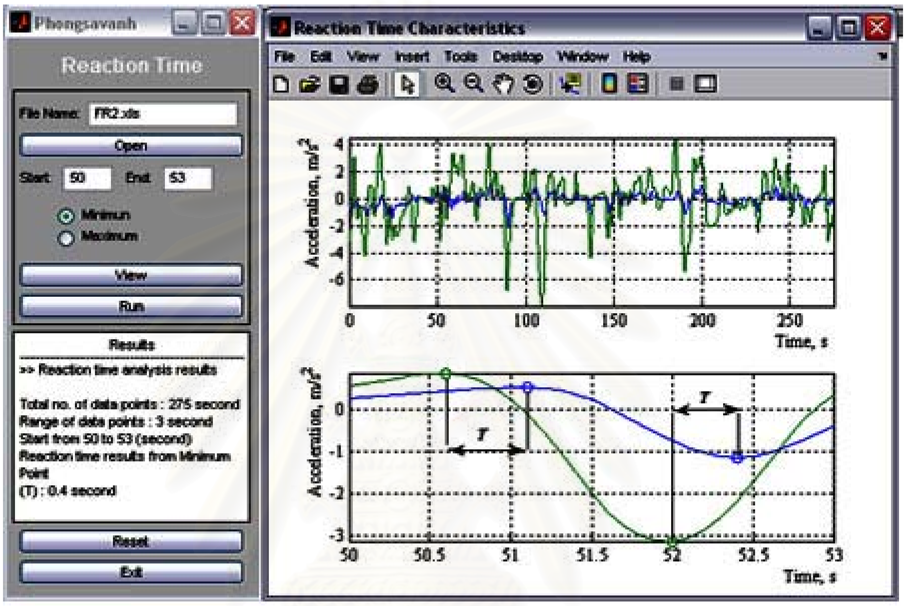


Figure 3.7 Graphical analyses of stimulus and response, T

After obtaining the driver’s reaction time from Graphical method for both types of roadway condition, expressway and surface street, each of the driver’s reaction time results was applied to determine the sensitivity parameters using Least squares regression method.

3.5 Driver’s sensitivity parameter study

As mentioned before, the driver’s reaction times obtained from Graphical method were used to determine the driver’s sensitivity parameters using Least squares regression method based on GM car following model. In this research, the sensitivity parameters of following vehicle can be determined by log transformed of GM car following model as illustrated in equation 3.5.

$$ln\,\ddot{x}_{n+1}(t+T) = ln\,\alpha_0 + ln[\dot{x}_n(t) - \dot{x}_{n+1}(t)] + m\,ln\,\dot{x}_n(t+T) - l\,ln[x_n(t) - x_{n+1}(t)] \quad (3.5)$$

And from the equation 3.5, a simple functional form can be by the equation as follows:

$$Y = a \;\; + mX_1 + lX_2 \qquad (3.6)$$

where,

$Y = ln\left|\dfrac{\ddot{x}_{n+1}(t+T)}{\dot{x}_n(t) - \dot{x}_{n+1}(t)}\right|$ = the independent variable

$a_0 = \ln \alpha_0$, m and l = regression coefficient

$X_1 = \ln[\dot{x}_{n+1}(t+T)]$ = the dependent variable

$X_2 = -\ln[x_n(t) - x_{n+1}(t)]$ = the dependent variables

The unknown coefficients a, m, and l can be computed by fitting a least squares regression, which minimizes the sum of the squares of the deviations of the data from the model. The procedure of obtaining the driver's sensitivity parameter of car following model results for both conditions consists of four steps as follows:

- Preparation of the data set of vehicle including an independent variable and two dependent variables as shown in Table 3.4
- Double click on the SPSS program icon to begin your SPSS session. The program will open to SPSS window
- Select the file name of data set click on button "Open". The program will open the data set and then click on button "analyzed", "regression", and "linear", respectively
- Finally, select the independent and dependent variable and click on button "Ok". The program will show the driver's sensitivity parameter results as illustrated in Table 3.5.

Table 3.4 Sample of data preparation for determination of sensitivity parameters

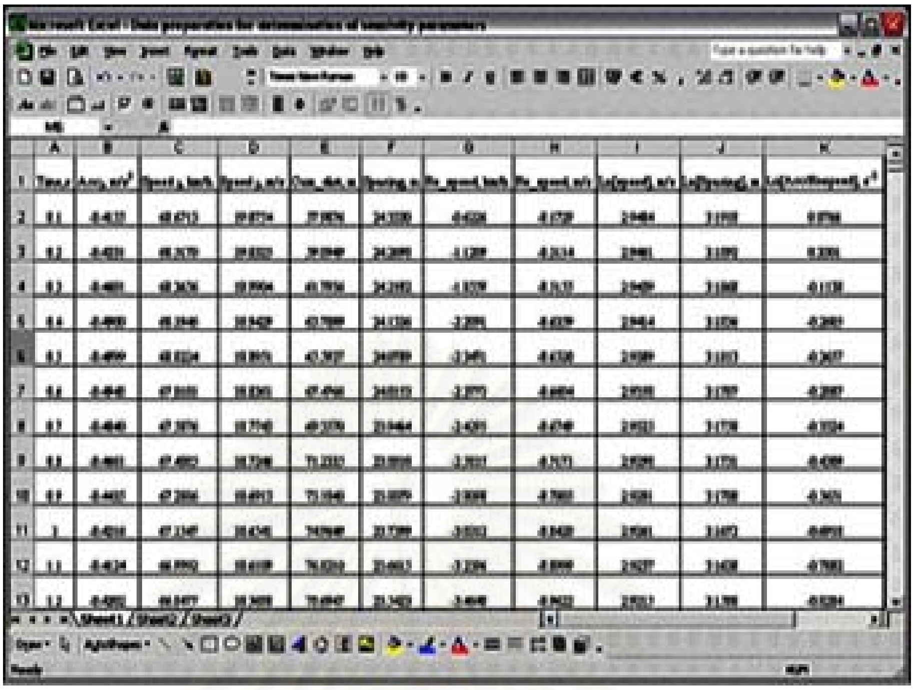


Table 3.5 Descriptive statistic of sensitivity parameters based on linear regression

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
	a	1.1380	.4231		2.6895	.0072
	m	-.0328	.0412	-.0265	-.7948	.4268
	l	.5889	.1980	.0992	2.9736	.0030

CHAPTER IV

DRIVER'S BEHAVIOR ANALYSIS

4.1 Introduction

This chapter describes the analysis of driver's behavior from vehicle data, including vehicle test, speed, and acceleration. The GPS data were calculates for several descriptive variables used for determining driver's behaviors. The procedure included the calculation of vehicle trajectories, speed, and acceleration of each driver in the platoon. The series of speed data was used to determine "reaction time" of the driver at the specified location and car following condition. Then, the differences in speed acceleration between two successive were used in calculating the sensitivity parameters of each driver. The statistical analyses were carried out under different road conditions, mainly expressway and surface street. All the problems encountered in the identification of the driver's behavior, basic traffic parameters, reaction time and sensitivity parameters are studies as follows.

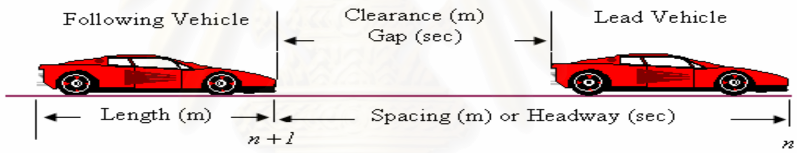


Figure 4.1 A car following situation and terms used

4.2 Statistical analysis of driver's behavior on expressway and surface street

4.2.1 Expressway condition

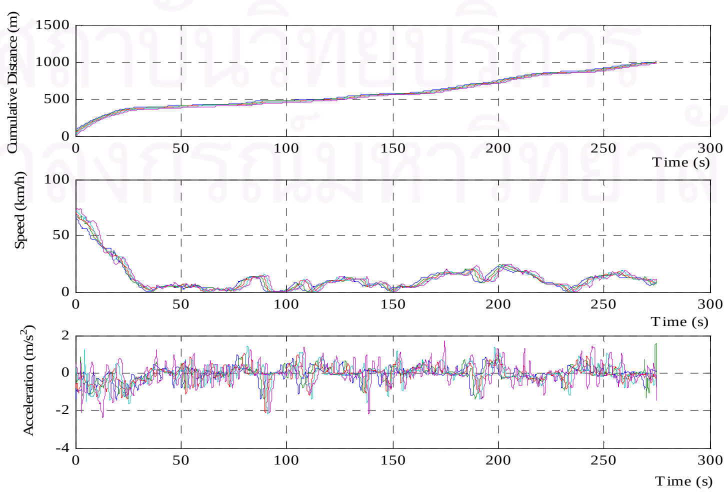


Figure 4.2 Detailed motions of trajectories of the five vehicles on expressway

Figure 4.2 shows the detailed motion of trajectories of the five vehicles on expressway condition used in the analysis. The speed and acceleration are the results of numerical computation of vehicle for each time sequence (at intervals of one tenth second) from GPS data using individual vehicle motion as mentioned before in chapter 3, which the total period of vehicle movements are 275 seconds.

The figure describes the vehicle movement characteristics under consideration. Even though driving on Expressway, the platoon moves slowly and experience stop and go condition. Most of the time, vehicles crawls at the speed less than 20 kph. The acceleration and deceleration ranges of -2 to 2 m/s^2 are illustrated. The detailed of distance headway, speed (absolutes and relative), acceleration, and their relationship are presented as follow:

4.2.1.1 Distance headway characteristics

Figure 4.3 shows the vehicle distance headway for each time sequence (at intervals of one tenth second), which is important parameter to analyze traffic safety. However, distance headway data can be defined or calculated as the relative distance between two vehicles, such as relative distance between the front bumper of a lead vehicle and the front bumpers of a following vehicle.

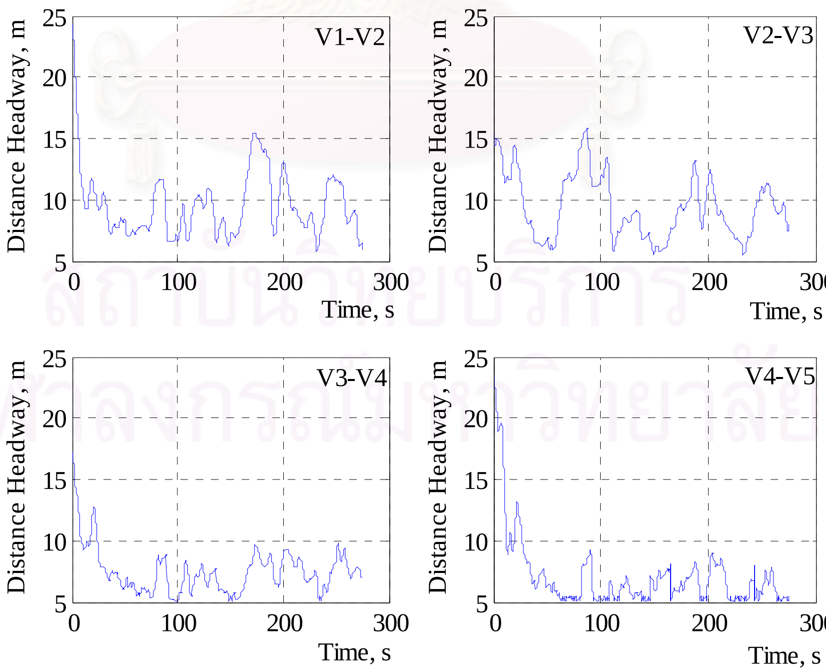


Figure 4.3 Sample vehicle distance headway profile on expressway

It is observed from Figure 4.3 that drivers maintain various headways during their movements. Although drivers encounter different driving environment and belong to different positions in the platoon, they also behave differently under similar situation. For example, at time 90-100 seconds when all vehicles stopped or visually crawled, the drivers maintained different distance headways. Disregarding the first 40 second when all drivers decelerated to stop (or nearly stop), all drivers maintained their headway with approximately 15 meters. The closest headway occurs on vehicle 4 and 5 at value of 5.00 m.

Table 4.1 indicates that the statistical analysis results of distance headway value in meters, including number of data points, mean, standard deviation, variance, range, minimum, and maximum of each vehicle for each time sequence at interval of one tenth second. As shown in Table 4.1, the mean value for distance headway is estimated to be 9.59, 9.42, 7.50, and 6.55 m with the standard deviations of 2.78, 2.60, 1.87, and 3.30 m for vehicle 1 to 5, respectively. The highest distance headway value is 24.39 m and the lowest distance headway value is 5.00 m.

Table 4.1 Statistical analysis results of vehicle distance headway on expressway

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V1-V2	2751	9.59	2.78	7.73	5.76	24.38
V2-V3	2751	9.42	2.60	6.75	5.43	15.85
V3-V4	2751	7.51	1.87	3.48	5.00	17.18
V4-V5	2751	7.10	2.99	8.94	5.00	23.54

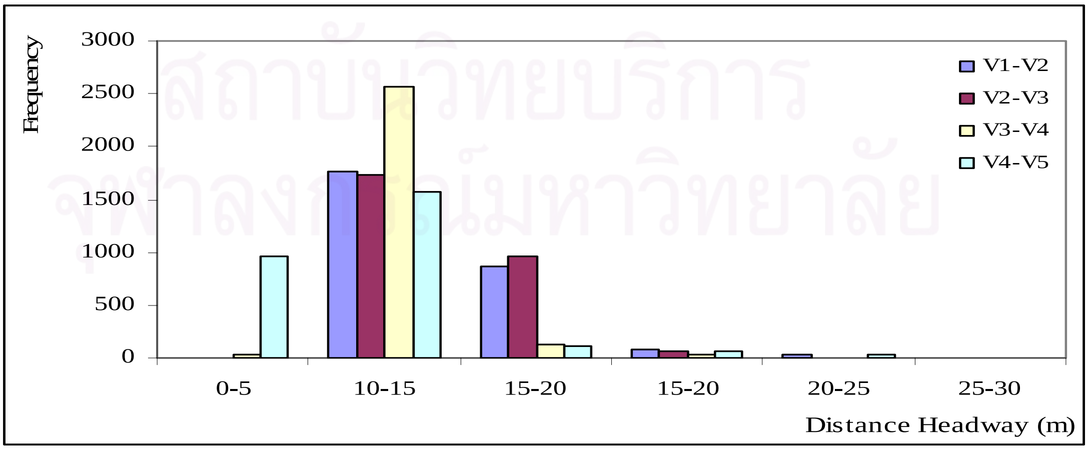


Figure 4.4 Histogram of vehicle distance headway on expressway

Figure 4.4 describes the distribution of the headways in the sample data for the traffic condition on expressway. In the study, the vehicles largely maintain their headway between 10-15 m. It is remarked that Table 4.1 and Figure 4.4 are used to illustrate the data and driving condition under study and thus no future analysis is conducted on these aggregate statistics.

4.2.1.2 Speed characteristics

Figure 4.5 shows the results of numerical calculation of vehicle speed data from trajectories of five vehicles for each time sequence (at intervals of one tenth second) from GPS data showing the individual vehicle motions. Details of speed data is presented in Table 4.2.

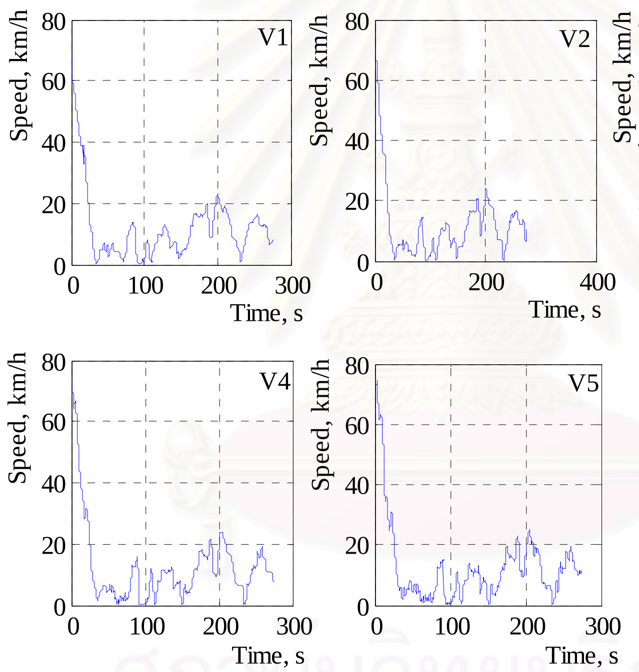


Figure 4.5 Sample vehicle speed profile on expressway

As shown in Table 4.2, the mean values for a speed of each vehicle are estimated 12.03, 12.29, 12.39, 12.52 and 12.79 km/h with standard deviations of 11.59, 12.39, 12.55, 12.97 and 13.57 km/h, respectively and the highest speed value is 74.70 km/h and the lowest is 0.13 km/h.

Table 4.2 Statistical analysis results of speed on expressway

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V1	2751	12.03	11.59	134.35	.13	68.47
V2	2751	12.29	12.39	153.54	.19	68.80
V3	2751	12.39	12.55	157.47	.13	71.93
V4	2751	12.52	12.97	168.13	.19	71.66
V5	2751	12.79	13.57	184.19	.32	74.70

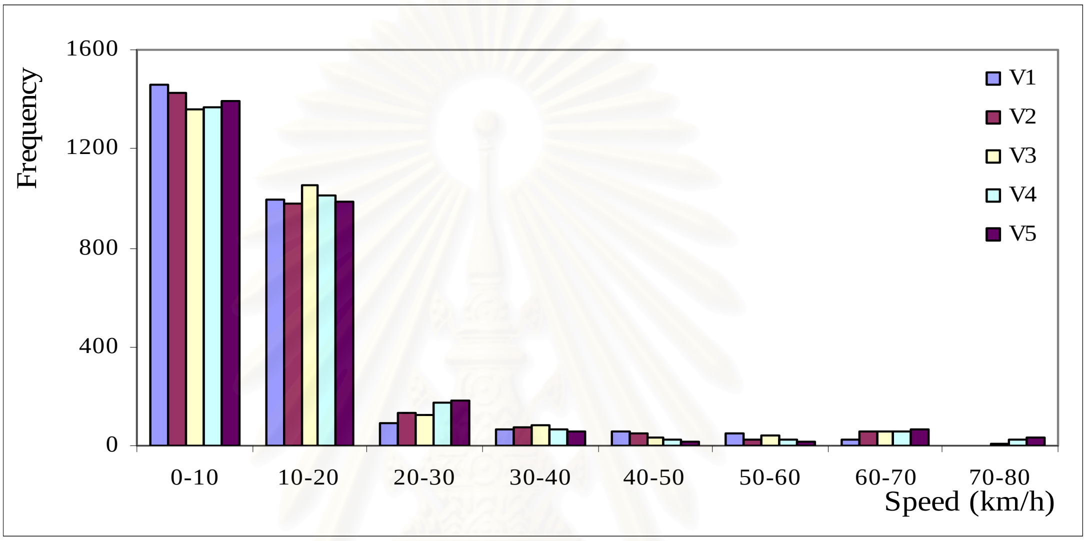


Figure 4.6 Histogram of vehicle speed on expressway

Table 4.2 and Figure 4.6 confirm the traffic condition that the sample data used in the study falls in congested condition where all vehicles in platoon moved slowly. Most of the time, vehicles move at 0 - 20 kph. It is noted that, even though 5 vehicles move in the same platoon, the vehicles do not have the same (aggregate) average speeds. Vehicle 1 has the lowest average speed while vehicle 5 has the highest.

4.2.1.3 Relative speed characteristics

Figure 4.7 shows the relative speed results, which are measured from the difference in speeds between the lead and following vehicle at the same time. From the figure, the two successive vehicles mostly have speed differences not more that -1 to + 1 m/s (measured at 0.1 second).

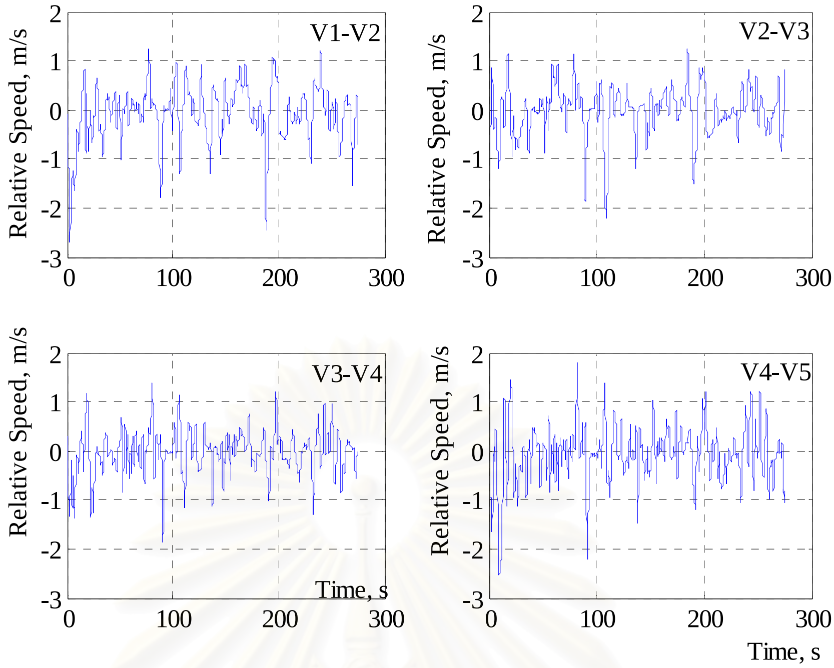


Figure 4.7 Sample vehicle relative speed profile on expressway

Table 4.3 shows the analysis results of aggregate descriptive statistics of vehicle relative speeds in meters per second. The mean values for relative speed are estimated -0.07, -0.03, -0.04, and -0.07 with standard deviations of 0.58, 0.50, 0.45, and 0.58 for vehicle 1 to 5, respectively. The highest relative speed data is 1.89 m/s and the lowest is -2.70 m/s.

Table 4.3 Statistical analysis results of vehicle relative speed on expressway

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V1-V2	2751	-.07	.58	.34	-2.70	1.25
V2-V3	2751	-.03	.49	.24	-2.20	1.25
V3-V4	2751	-.04	.44	.20	-1.88	1.38
V4-V5	2751	-.07	.58	.34	-2.53	1.81

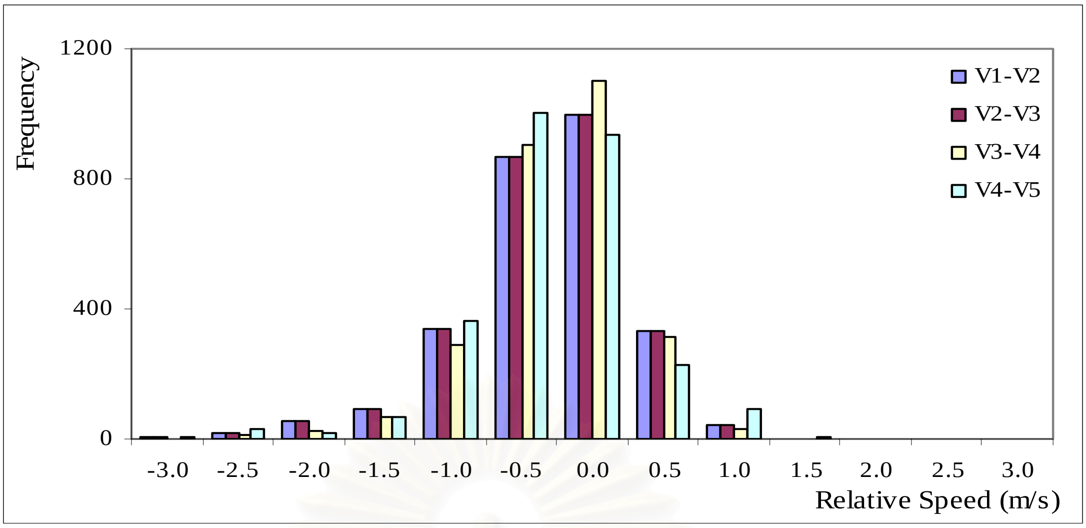


Figure 4.8 Histogram of vehicle relative speed on expressway

Figure 4.8 shows that during the test run vehicles majority maintain their speed differences with -1.0 to 1 m/s (measured at 0.1sec interval).

4.2.1.4 Acceleration characteristics

Figure 4.9 shows the acceleration results of numerical calculation for each time sequence at intervals of one tenth second from GPS data. Acceleration results derived from trajectories of the five vehicles were calculated using Equation 3.4 as mentioned before.

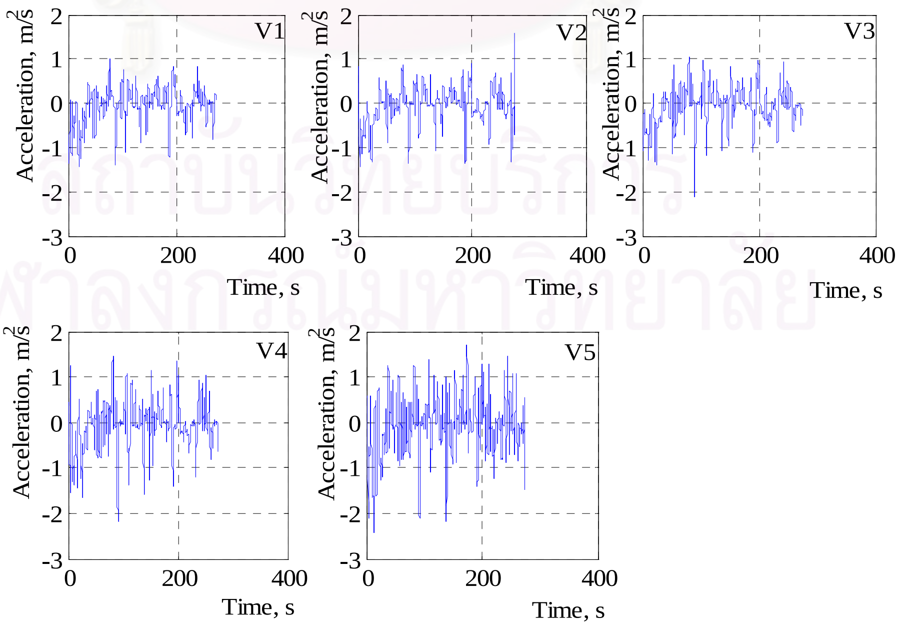


Figure 4.9 Sample vehicle acceleration profile on expressway

Table 4.4 indicates that the statistical analysis results of average vehicle acceleration value in meters per square second, are estimated to be -0.06, -0.06, -0.07, -0.06, and -0.06 m/s^2 with standard deviations of 0.39, 0.40, 0.42, 0.49, and 0.59 m/s^2 for vehicle 1 to 5, respectively. The highest acceleration value is 1.71 m/s^2 and the lowest is -2.42 m/s^2.

Table 4.4 Statistical analysis results of acceleration on expressway

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V1	2751	-.06	.39	.15	-1.44	1.00
V2	2751	-.06	.40	.16	-1.44	1.60
V3	2751	-.07	.42	.18	-2.13	1.04
V4	2751	-.06	.49	.24	-2.18	1.46
V5	2751	-.06	.59	.34	-2.42	1.71

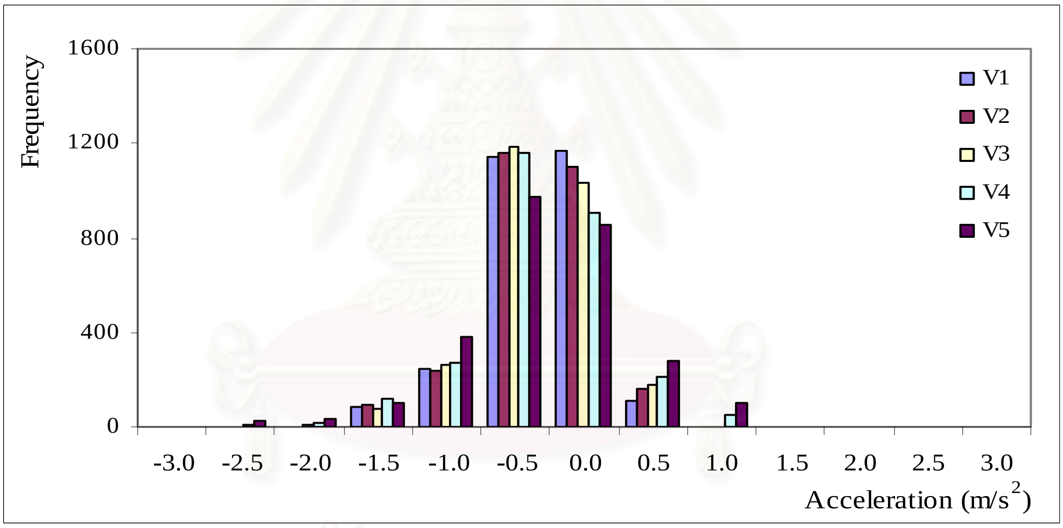


Figure 4.10 Histogram of vehicle acceleration profile on expressway

From figure 4.10, the traffic and driving conditions of the sample data result in the acceleration of the platoon basically in the range of -2.5 to 1.0 m/s^2 with the majority of the acceleration occurs between -0.5 to 0.5 m/s^2 for all vehicles.

4.2.1.5 Speed and distance headway relationship

Speed – distance headway relationship as illustrated in Figure 4.11 demonstrates the minimum spacing tolerance of vehicle following phenomenon. In this study, regression lines of both linear and exponential are used for curve fitting. A higher significance of regression coefficients, R^2, as shown in Table 4.5, means that the model has a greater goodness of fit. In other word, the higher R^2 regression line has greater prediction power on the relationship between speed and distance headway. The coefficients in the constructed models indicate slight different driving behaviors among drivers. This implies that drivers have slightly different ways to maintain different headways at the same speed. The raw data plots in figure 4.11 show how a driver dynamically changes his vehicle headway when encountering speed change. There is no observable difference in the headway change among 4 drivers in changing speed condition.

Table 4.5 shows some statistic associated with minimum speed – spacing tolerance models. Based on significance of regression coefficients, R^2, the linear model fits better in all cases.

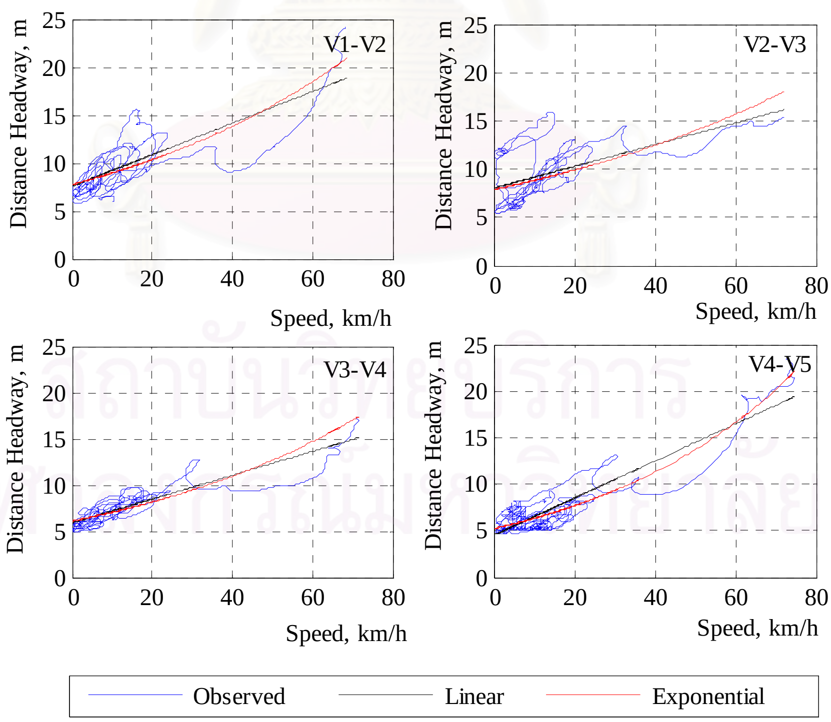


Figure 4.11 Sample vehicle distance headway – speed profile plot on expressway

Table 4.5 Speed – spacing tolerance model on expressway

	N	R^2	F-Test	Model
V1-V2	Linear	0.54	3221.18	$y = 7.56 + 0.17x$
	Exponential	0.50	2697.83	$y = 7.74e^{0.0145x}$
V2-V3	Linear	0.30	1161.06	$y = 8.02 + 0.11x$
	Exponential	0.28	1065.58	$y = 7.87e^{0.0115x}$
V3-V4	Linear	0.80	10653.60	$y = 5.89 + 0.13x$
	Exponential	0.72	7089.32	$y = 6.08e^{0.0147x}$
V4-V5	Linear	0.81	11615.80	$y = 4.52 + 0.20x$
	Exponential	0.73	7563.71	$y = 5.22e^{0.02x}$

The models in Table 4.5 can be interpreted in several matters. First, it must be stated that the applicable range of the model estimation is the range of calibrated variables that is 0-70 km/h of speed. From the linear models ($y = a + bx$), the coefficient represents the intercept point or in this context, distance headway at vehicle stopped condition. The models result in the “jam” spacing ranging between 4.52 – 8.02 m. The jam spacing determined from exponential models ($y = ae^{bx}$) are between 5.22 – 7.87 m. Although this analysis is unable to evaluate the correctness of these values, the jam spacing implied from both linear and exponential form are found consistent; driver 5 maintains the shortest spacing while driver 3 maintains the longest. The coefficient b implies the change in distance headway at a specified speed. In other word, it shows how a driver adjusts his/her headway at a different speed. The values from the linear models range from 0.11- 0.20 and can be concluded that the subject drivers maintain their headways at a speed differently.

4.2.1.6 Relative speed and acceleration relationship

Figure 4.12 presents the relationship between relative speed and acceleration of following vehicle, to show how drivers accelerate or decelerate when they perceive difference in speed following the lead vehicle. The figure visually shows that the acceleration scatters around relative speed for all drivers.

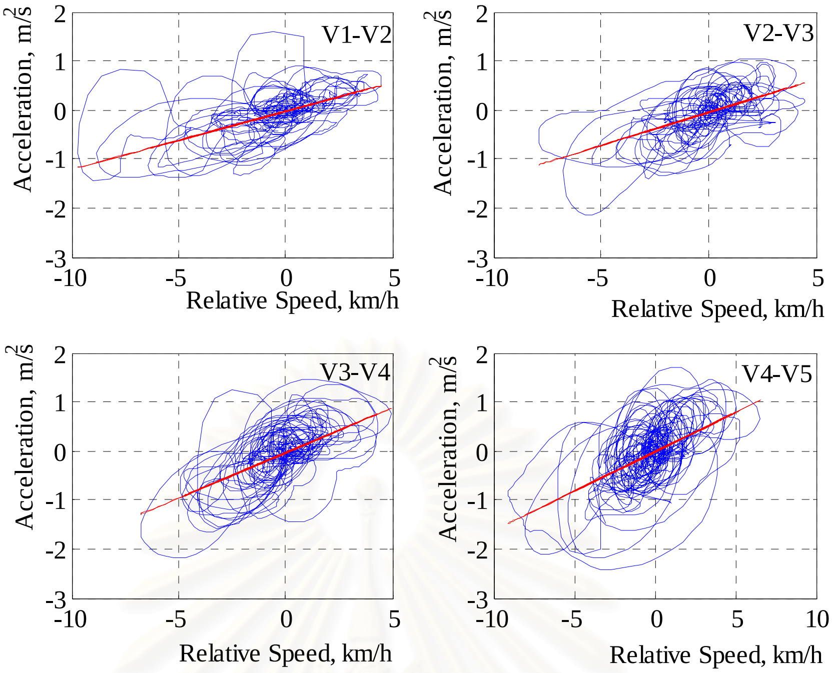


Figure 4.12 Sample vehicle acceleration - relative speed profile plot on expressway

The relationship between acceleration and relative speed is also studied by the construction of linear regression model. The results in Table 4.6 indicate that the relationship between acceleration and relative speed is not significant as the R^2 ranges from 0.32 to 0.38. This implies that the relative speed alone may not a good indication of driver's behavior on acceleration.

The models in Table 4.6 ($y = a + bx$) show that the intercept coefficient (a), which is theoretically assumed zero, ranges from -0.02 to -0.05. This may be the result of insufficient data and possible statistical errors. Comparing Model 1 and Model 2, both models produce similar b coefficient. The coefficients are between 0.12.to 0.18. It is noted that this relationship, as mentioned before can only fairly represented by linear relationship and valid only at the relative speed range between -7 to 5 km/h, approximately.

Table 4.6 Linear model for acceleration-relative speed relationship on expressway

		R^2	F-Test	Model 1	Model 2
V1-V2	Linear	0.38	1705.66	$y = -0.03 + 0.12x$	$y = 0.12x$
V2-V3	Linear	0.32	1315.09	$y = -0.05 + 0.14x$	$y = 0.14x$
V3-V4	Linear	0.37	1576.79	$y = -0.04 + 0.18x$	$y = 0.18x$
V4-V5	Linear	0.33	1336.81	$y = -0.02 + 0.16x$	$y = 0.16x$

4.2.2 Surface Street condition

Figure 4.13 shows the detailed motion of trajectories of the five vehicles on surface street condition used in the analysis. The results come from numerical computation of raw vehicle movement data for each time sequence (at intervals of one tenth second) obtained from GPS data. A total period of vehicle movements is 165 seconds. The basic traffic parameters, mainly distance, speed, and acceleration of vehicle can be directly calculated using individual vehicle motion. However, more detailed analysis of this study are presented in the following subsections.

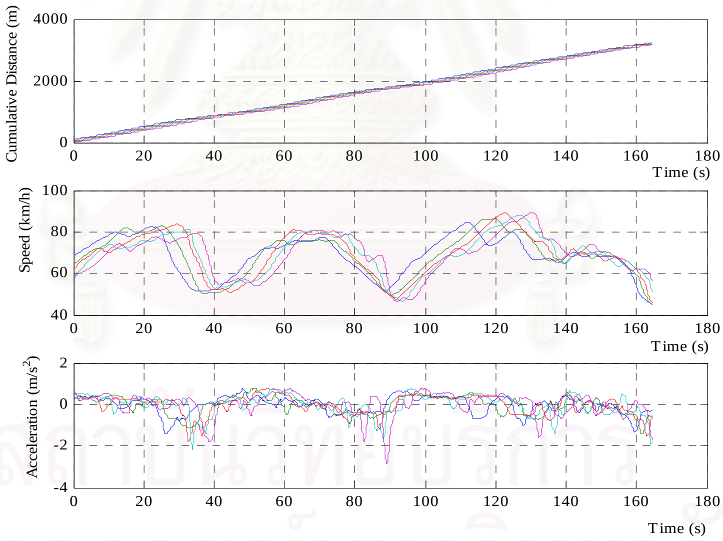


Figure 4.13 Detailed motions of trajectories of the five vehicles on surface street

4.2.2.1 Distance headway characteristics

As seen also in Figure 4.13, the platoon is moving at all time period of 160 seconds. The platoon experiences acceleration or deceleration situation. However, all drivers do not come to stop-and-go situation. Figure 4.14 shows that, in the study sample vehicles maintain their headways between 11 to 56 m with the speed ranges of 48 to 90 km/h.

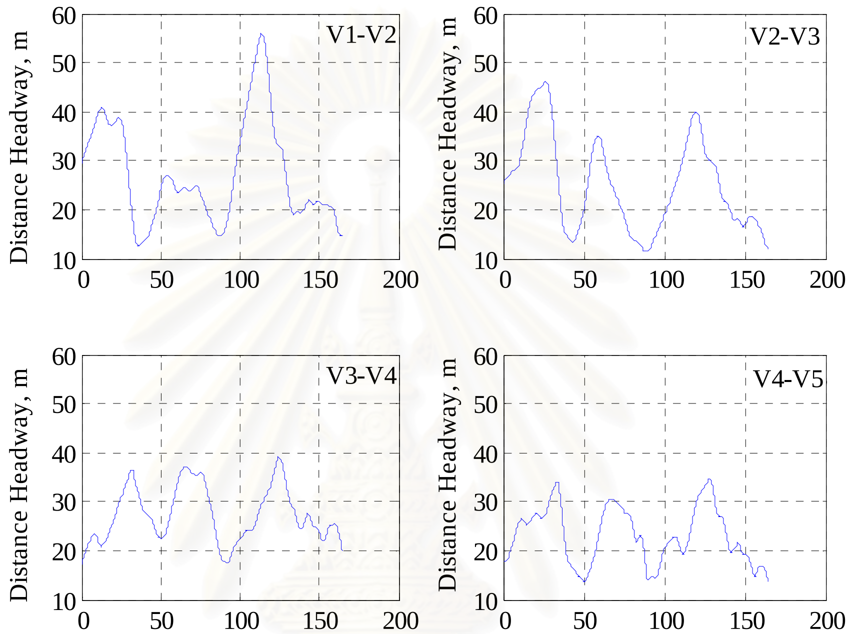


Figure 4.14 Sample vehicle distance headway profile on surface street

Table 4.7 shows the distance headway value, in meters. The mean values are estimated to be 27.41, 25.11, 27.44, and 23.15 m/s with standard deviations of 10.57, 9.64, 5.64, and 5.78 m/s for vehicle 1 to 5, respectively. The highest distance headway value is 56.04 m and the lowest distance headway is 11.54 m.

Table 4.7 Statistical analysis results of distance headway on surface street

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V1-V2	1646	27.41	10.57	111.76	12.61	56.04
V2-V3	1646	25.11	9.64	93.00	11.54	46.25
V3-V4	1646	27.44	5.65	31.89	17.13	39.12
V4-V5	1646	23.15	5.78	33.37	13.72	34.67

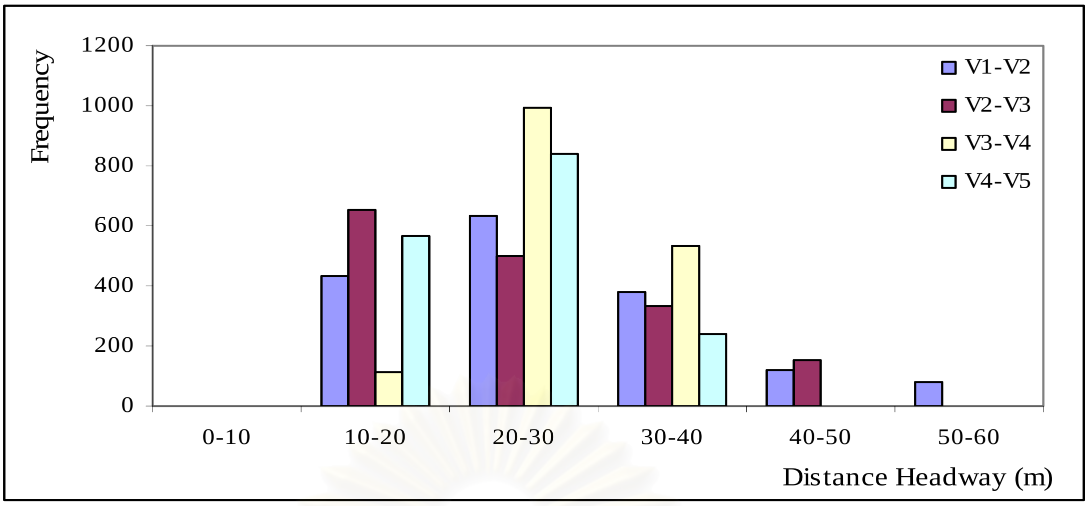


Figure 4.15 Histogram of vehicle distance headway on surface street

Figure 4.15 displays the distribution of the headways in the sample data. Traffic movement in the sample on surface street is rather uninterrupted by any external control device. Moreover, the movement speed is high, thus the headway, according to higher speed, is greater than that in the expressway condition. From Figure 4.15, there is no discernable difference in headway among 4 drivers, noticeable except driver 3 who maintains shorter distance headway than others (on average).

4.2.2.2 Speed characteristics

Figure 4.16 shows the results of numerical calculation of vehicle speed data from trajectories of five vehicles for each time sequence. From the Figure, there is no distinctive difference in speed characteristics among vehicles.

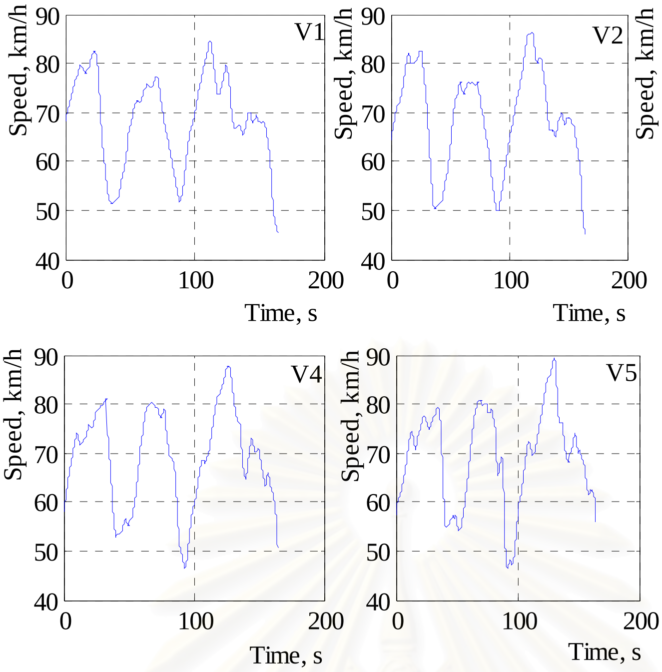


Figure 4.16 Sample vehicle speed profile on surface street

As shown in Table 4.8, the mean values for speed of each vehicle are estimated 69.65, 68.97, 69.26, 68.65 and 68.97 km/h with the standard deviations of 9.25, 10.04, 10.35, 9.25 and 10.04 km/h for driver 1 to 5, respectively. The highest speed value is 88.91km/h and the lowest speed is 44.99 km/h.

Table 4.8 Statistical analysis results of speed on surface street

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V1	1646	68.65	9.25	85.58	45.25	84.63
V2	1646	68.97	10.04	100.85	44.99	86.31
V3	1646	69.26	10.35	107.20	45.77	88.91
V4	1646	68.65	9.25	85.58	45.25	84.63
V5	1646	68.97	10.04	100.85	44.99	86.31

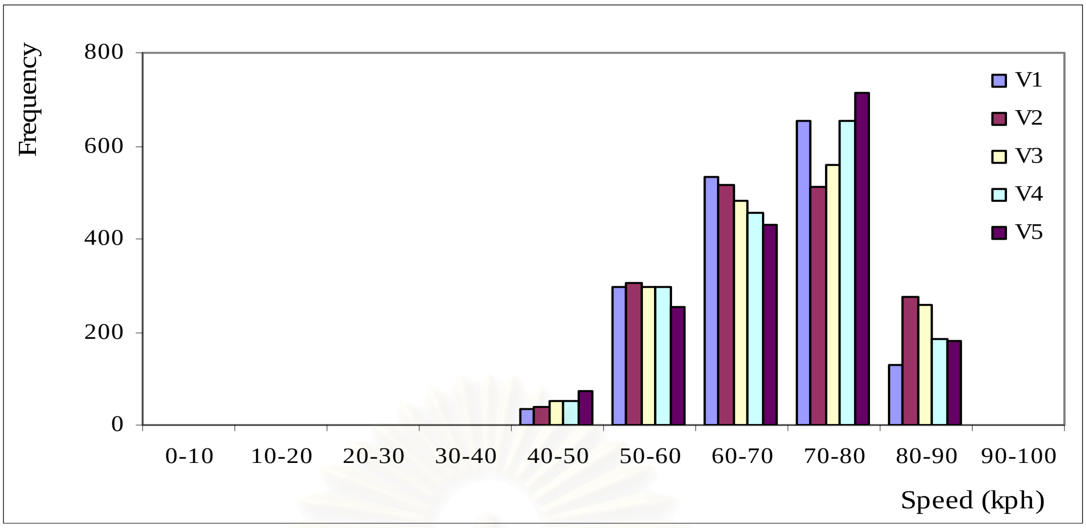


Figure 4.17 Histogram of vehicle speed on surface street

As seen in Figure 4.16 and Table 4.8, Figure 4.17 illustrates the speed range of each driver in the study sample. Mostly drivers drive between 40-90 km/h.

4.2.2.3 Relative speed characteristics

Figure 4.18 shows the relative speed results which are measured from difference speeds between the lead and following vehicle at the same time. The sample data show that vehicles in the platoon hold the differences in speed between -4 to 2 m/s (following vehicle).

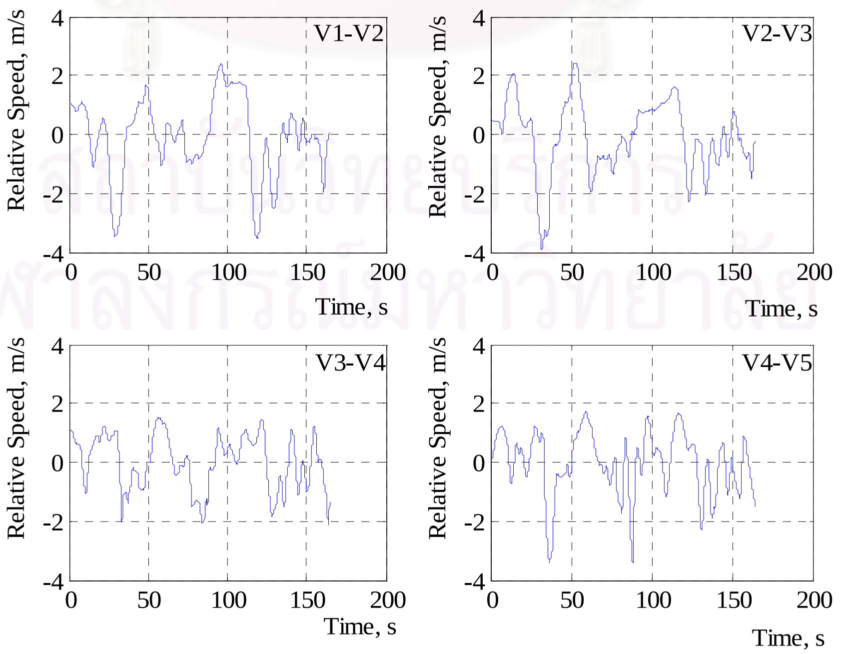


Figure 4.18 Sample vehicle relative speed profile on surface street

Table 4.9 presents the aggregate statistic of vehicle relative speed in meters per second, including number of data points, mean, standard deviation, variance, range, minimum, and maximum. The mean values for relative speed are estimated -0.089, -0.08, -0.02, and -0.02 m/s with standard deviations of 1.32, 1.25, .92, and 1.06 m/s for driver 1 to 5, respectively and the highest relative speed data is 2.46m/s and the lowest speed data is -3.93 m/s.

Table 4.9 Statistical analysis results of relative speed on surface street

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V1-V2	1646	-.09	1.32	1.75	-3.52	2.39
V2-V3	1646	-.08	1.25	1.56	-3.93	2.46
V3-V4	1646	.02	.92	.85	-2.13	1.54
V4-V5	1646	-.02	1.06	1.13	-3.43	1.73

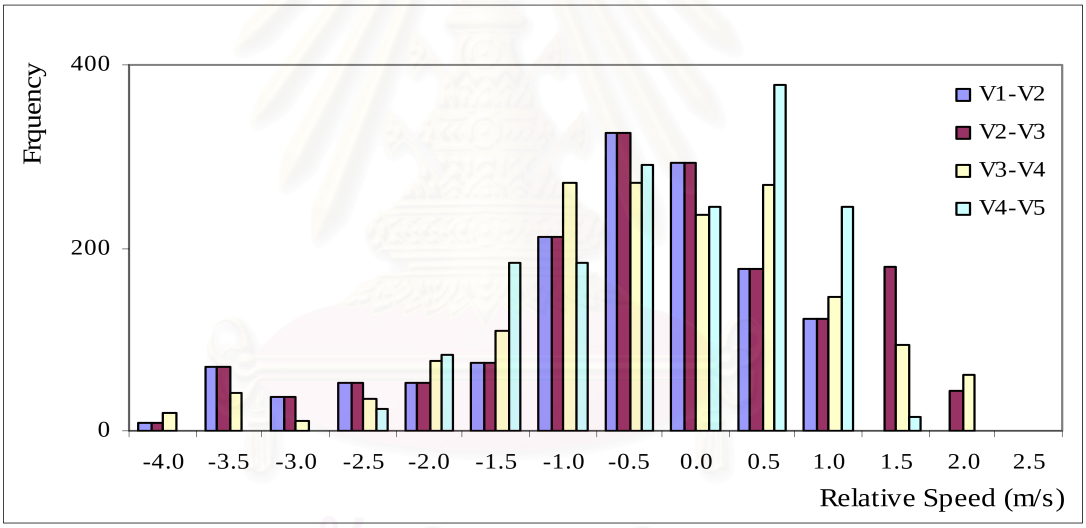


Figure 4.19 Histogram of relative speed on surface street

Figure 4.19 shows that the vehicles have various speed differences, ranging between -4.0 to 2.0 m/s compared to Figure 4.8, it is observable that the driving situation on surface street results in higher dispersion of speed difference than the situation on expressway.

4.2.2.4 Acceleration characteristics

Figure 4.20 shows the acceleration results of numerical calculation from vehicle trajectories for each time sequence. The Figure illustrates that the acceleration of subject vehicles is in the range between -2.8 and 0.8 m/s^2. The odd deceleration occurs on vehicle 5 at time 87 seconds with a great deceleration of -2.8 m/s^2.

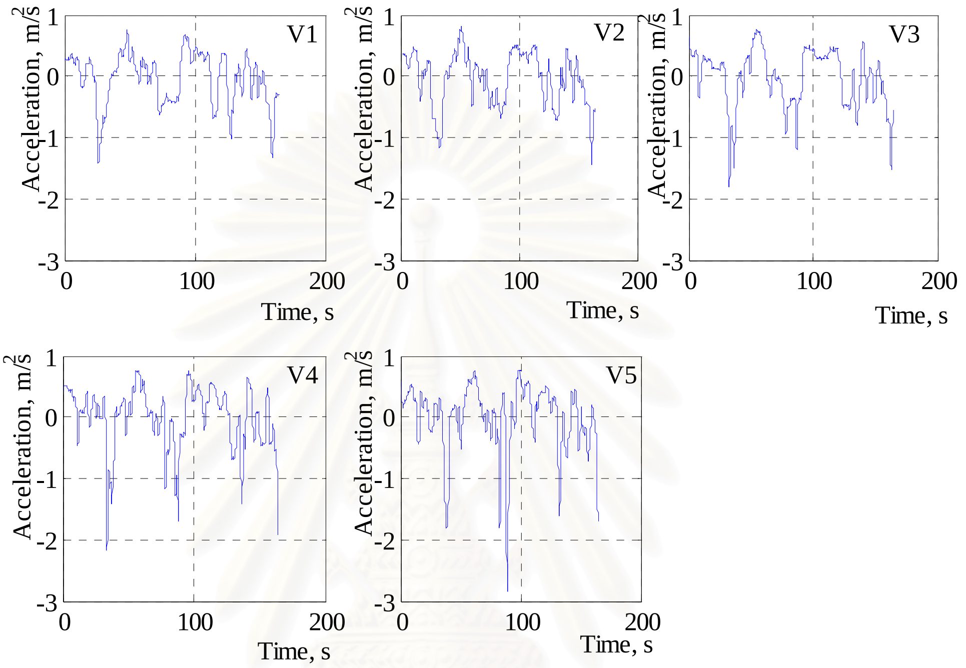


Figure 4.20 Sample vehicle acceleration profile on surface street

Table 4.10 displays the statistical analysis results of vehicle acceleration value in meters per square second. The mean value for acceleration are estimated -0.04, -0.03, -0.03, -0.01, and -0.00 m/s^2 with standard deviations of 0.43, 0.43, 0.48, 0.51, and 0.55 m/s^2, respectively. The highest acceleration is 0.83 m/s^2 and the lowest speed is -2.85 m/s^2.

Table 4.10 Statistical analysis results of acceleration on surface street

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V1	1646	-.04	.42	.18	-1.43	.75
V2	1646	-.03	.43	.19	-1.44	.83
V3	1646	-.03	.47	.22	-1.82	.75
V4	1646	-.01	.51	.26	-2.17	.78
V5	1646	.00	.55	.30	-2.85	.77

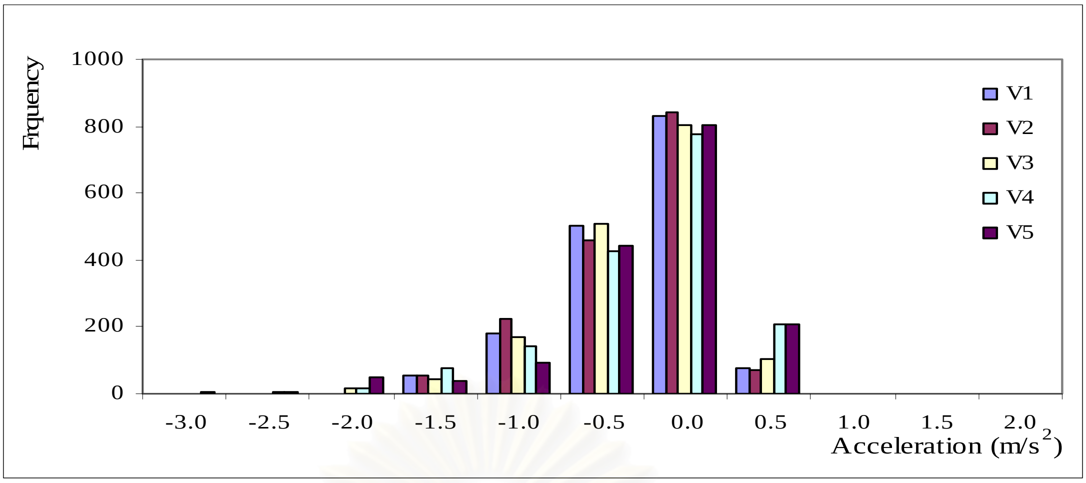


Figure 4.21 Histogram of vehicle acceleration on surface street

Figure 4.21 shows that the acceleration of each driver. It is noted that vehicle 1 to 5vehicles have various acceleration, ranging between -2 to 1 m/s^2 .

4.2.2.5 Speed and distance headway relationship

Figure 4.22 presents the minimum spacing tolerance model of vehicle following phenomenon. The regression lines of both linear and exponential forms are used for curve fitting and constructing models for difference driving behaviors among drivers.

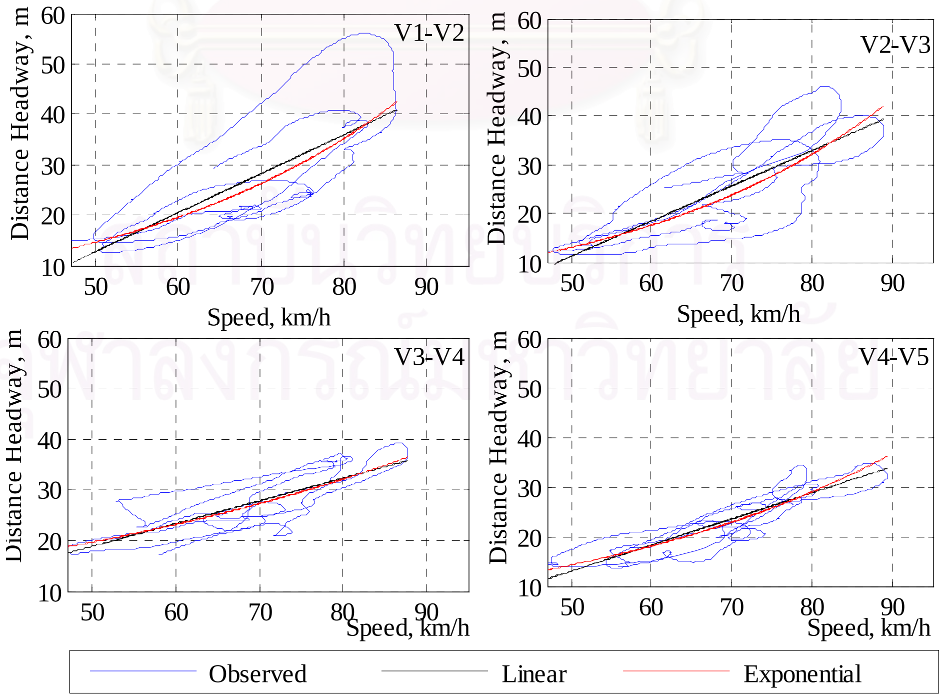


Figure 4.22 Sample vehicle distance headway – speed profile plot on surface street

Table 4.11 shows the minimum spacing tolerance model of a following vehicle. The exponential models fit better in all cases.

Table 4.11 Speed – spacing tolerance model on surface street

		R^2	F-Test	Model
V1-V2	Linear	0.54	1919.56	$y = -25.87 + 0.77x$
	Exponential	0.63	2751.20	$y = 3.38e^{0.03x}$
V2-V3	Linear	0.60	2498.88	$y = -24.98 + 0.72x$
	Exponential	0.65	3093.17	$y = 2.87e^{0.03x}$
V3-V4	Linear	0.60	2503.50	$y = -3.45 + 0.45x$
	Exponential	0.60	2508.42	$y = 8.71e^{0.02x}$
V4-V5	Linear	0.80	6287.98	$y = -13.26 + 0.53x$
	Exponential	0.80	6657.33	$y = 4.38e^{0.02x}$

In Table 4.11, the model estimation is valid in the range between approximately 48 and 88 km/h. the linear model ($y = a + bx$) imply that the intercept coefficient, b, are in the range of -3.45 to -25.87. it is clearly that the estimates can not represent the “jam” headway at stopped condition (speed is zero). It suggests that the speed-spacing relationship should not hold linear throughout the speed range. The exponential models ($y = ae^{bx}$), on the other hand, show different interpretation. When extrapolating the model to estimate the headway at speed zero, the “jam density” between 2.87 to 8.71 m can be obtained from these drivers. Although it is difficult to evaluate the correctness of the result from the extrapolation, the estimates are plausible since the “known” jam spacing is approximate 5-10 m. the coefficient b of the exponential models has a narrow range between 0.02 and 0.03. it can be concluded that within the study driving condition, these drivers behave similarly on headway adjustment due to speed.

4.2.2.6 Relative speed and acceleration relationship

Figure 4.23 presents the relationship between relative speed and acceleration of following vehicles, to show how drivers accelerate or decelerate when they perceive difference in speed following the lead vehicle. The Figure visually shows that the acceleration scatters around relative speed for all drivers. It is observed that the acceleration/deceleration characteristics vary among drivers. The forth vehicle driver has the least variation in acceleration given the same speed difference. Driver 5 has the wildest action, a wide range of deceleration up to -2.8 m/s^2 when speed is 10 km/h difference.

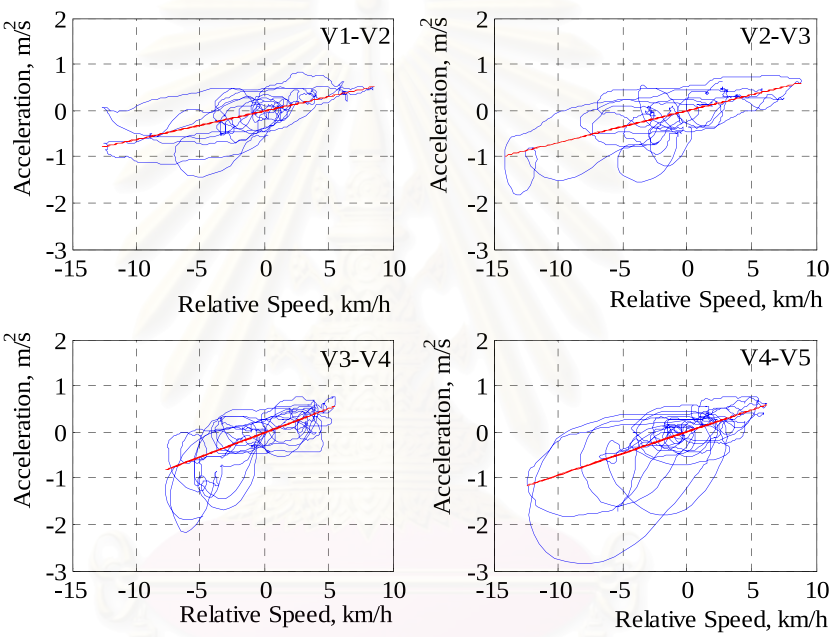


Figure 4.23 Sample vehicle acceleration – relative speed profile plot on surface street

Table 4.12 shows that the relationship of acceleration and relative speed is less than significant, as the significant of regression coefficients, R^2 range from 0.43 to 0.47 fairly (lower than 0.5).

The b coefficients in the linear models, model 1, and model 2 imply the aggressiveness of the drivers. The value ranges from Model 1 and Model 2 are similar. It is noted that the linear relationship should be interpreted within the valid relative speed range of approximately -10 to 5 km/h.

Table 4.12 Linear model for acceleration- relative speed relationship on surface street

	N	R^2	F-Test	Model 1	Model 2
V1-V2	Linear	0.46	1410.80	$y = -0.01 + 0.06x$	$y = 0.06x$
V2-V3	Linear	0.43	1224.66	$y = -0.01 + 0.07x$	$y = 0.07x$
V3-V4	Linear	0.47	1462.19	$y = -0.02 + 0.11x$	$y = 0.11x$
V4-V5	Linear	0.43	1220.11	$y = -0.01 + 0.09x$	$y = 0.09x$

4.2.3 Comparison of statistical analyses results in both conditions

4.2.3.1 Distance headway data characteristics

Table 4.13 shows the comparison results of vehicle distance headway value, in meters for both expressway and surface street. The results show that the mean value and standard deviation of following vehicle of the same drivers. It is noted that the distance headway on surface street is higher than the distance headway on expressway in all drivers, as seen from the standard deviation. The 4 drivers have a wider range of mean distance headway on surface street (23.15 to 27.44 m) than the range of mean distance headway on expressway (7.10 to 9.59 m).

Table 4.13 Comparison of distance headway on expressway and surface street

	EXPRESSWAY CONDITION			**SURFACE STREET CONDITION**		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
V1-V2	2751	9.59	2.78	1646	27.41	10.57
V2-V3	2751	9.42	2.60	1646	25.11	9.64
V3-V4	2751	7.51	1.87	1646	27.44	5.65
V4-V5	2751	7.10	2.99	1646	23.15	5.78

4.2.3.2 Speed data characteristics

Table 4.14 shows the comparison results of vehicle speed, in kilometer per hour for both expressway and surface street, the mean value of speed for all drivers on surface street is higher than the speed on expressway. Even though driving as a platoon, the 5 drivers have a wider range of mean speed on surface street (68.65 to 96.26 km/h) than the range of mean speed on expressway (12.03 to 12.79 km/h).

Table 4.14 Comparison of speed on expressway and surface street

	EXPRESSWAY CONDITION			SURFACE STREET CONDITION		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
V1	2751	12.03	11.59	1646	68.65	9.25
V2	2751	12.29	12.39	1646	68.97	10.04
V3	2751	12.39	12.55	1646	69.26	10.35
V4	2751	12.52	12.97	1646	68.65	9.25
V5	2751	12.79	13.57	1646	68.97	10.04

4.2.3.3 Relative speed data characteristics

Table 4.15 shows the comparison results of vehicle relative speed, in meter per second for both expressway and surface street, the mean value of relative speed for all drivers on surface street is higher than the speed on expressway. The 5 drivers have a wider range of mean relative speed on surface street (-0.09 to 0.02 m/s) than the range of mean relative speed on expressway (-0.07 to -0.03 m/s).

Table 4.15 Comparison of relative speed on expressway and surface street

	EXPRESSWAY CONDITION			SURFACE STREET CONDITION		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
V1-V2	2751	-.07	.58	1646	-.09	1.32
V2-V3	2751	-.03	.49	1646	-.08	1.25
V3-V4	2751	-.04	.44	1646	.02	.92
V4-V5	2751	-.07	.58	1646	-.02	1.06

4.2.3.4 Acceleration data characteristics

Table 4.16 shows the comparison results of vehicle acceleration, in meter per square second for both expressway and surface street, the mean value of acceleration for all drivers on surface street is higher than the acceleration on expressway. The 5 drivers have a wider range of mean acceleration on surface street (-0.04 to 0.00 m/s^2) than the range of acceleration on expressway (-0.07 to -0.06 m/s^2).

Table 4.16 Comparison of acceleration on expressway and surface street

	EXPRESSWAY CONDITION			SURFACE STREET CONDITION		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
V1	2751	-.06	.39	1646	-.04	.42
V2	2751	-.06	.40	1646	-.03	.43
V3	2751	-.07	.42	1646	-.03	.47
V4	2751	-.06	.49	1646	-.01	.51
V5	2751	-.06	.59	1646	.00	.55

4.2.3.5 Speed – spacing model characteristics

Table 4.17 shows the comparison results of minimum spacing model on expressway and surface street, the significance of regression coefficients, R^2, on expressway the liner model fits better in all cases, and on surface street, the exponential model fits better in all cases.

Table 4.17 Comparison of minimum spacing model on expressway and surface street

		EXPRESSWAY CONDITION		SURFACE STREET CONDITION	
		R^2	Model	R^2	Model
V1-V2	Linear	0.54	$y = 7.56 + 0.17x$	0.54	$y = -25.87 + 0.77x$
	Exponential	0.50	$y = 7.74e^{0.0145x}$	0.63	$y = 3.38e^{0.03x}$
V2-V3	Linear	0.30	$y = 8.02 + 0.11x$	0.60	$y = -24.98 + 0.72x$
	Exponential	0.28	$y = 7.87e^{0.0115x}$	0.65	$y = 2.87e^{0.03x}$
V3-V4	Linear	0.80	$y = 5.89 + 0.13x$	0.60	$y = -3.45 + 0.45x$
	Exponential	0.72	$y = 6.08e^{0.0147x}$	0.60	$y = 8.71e^{0.02x}$
V4-V5	Linear	0.81	$y = 4.52 + 0.20x$	0.80	$y = -13.26 + 0.53x$
	Exponential	0.73	$y = 5.22e^{0.02x}$	0.80	$y = 4.38e^{0.02x}$

It can be seen that the same drivers produce different speed-spacing relationship on expressway and surface street. This may imply that they behave differently on the facility and/or traffic moving condition. It is noted that the results are difficult to directly be computed since the valid range of speed differs (0-80 km/h with mainly 0-20 km/h on expressway and 40-90 km/h on surface street). Considering exponential models driver s behaves very similarly on both expressway and surface street. However, other drivers do differently.

4.3 Reaction Time

Reaction time is a time that usually occurred between change in relative speed between a lead and following vehicle and corresponding change in acceleration of the following vehicle. In this study graphical method is used to determine the reaction time, as the basic of the graphical method is the selection of significant points of stimulus and the detection of their corresponding points of response and the reaction time results are used to later determine the sensitivity parameters, a, m, and l by regression method.

Figure 4.24 shows the acceleration curves of following vehicle and relative speed between the lead and following vehicle plotted on a common base of time. It is noted that the solid line represents acceleration while the dotted line represents relative speed.

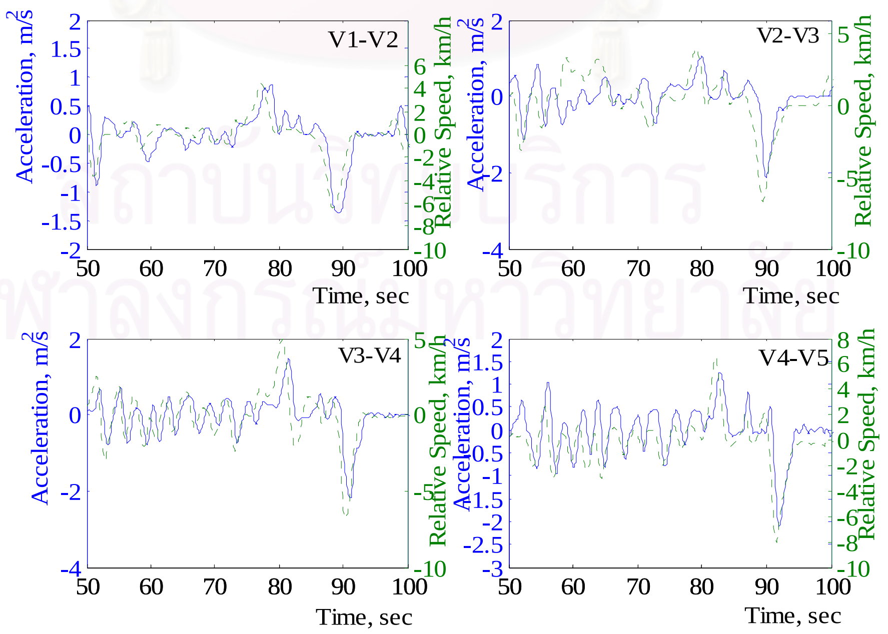


Figure 4.24 Sample vehicle relative speed and acceleration – time profile data

As described previously in section 3.4 about the relative speed and acceleration profile of each pair of drivers, Figure 4.25 were scanned to find the time lagged between the two curves, which the solid line represents acceleration while the dotted line represents relative speed. A sample of determination is illustrated in the figure below:

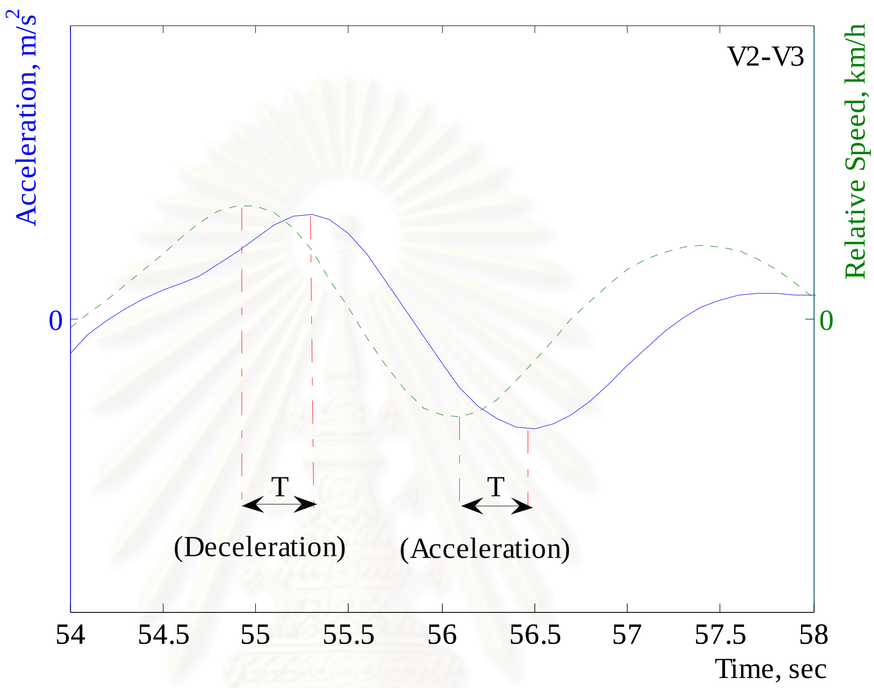


Figure 4.25 Illustration on the determination of reaction time

With the scanning through the entire sample vehicle data, the reaction times for both deceleration and acceleration condition are determined. A total number of reaction times that could be obtained from the sample data is summarizes in Table 4.18.

Table 4.18 Number of reaction times obtained from the sample

	EXPRESSWAY CONDITION		**SURFACE STREET CONDITION**	
	Acceleration	Deceleration	Acceleration	Deceleration
V2	38	35	8	8
V3	27	26	1	11
V4	35	38	12	15
V5	50	32	9	14

4.3.1 Expressway condition

4.3.1.1 Acceleration condition

Table 4.19 shows the statistical analysis results of reaction time values, in seconds, which the results show that the mean value of reaction times for acceleration condition on expressway condition is determined to be 0.73, 0.80, 0.74, and 0.67 seconds with the standard deviations of 0.41, 0.42, 0.31, and 0.34 seconds, respectively.

Table 4.19 Statistical analysis results of reaction times for acceleration condition

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V2	38	.73	.41	.17	.10	1.60
V3	27	.80	.42	.17	.40	2.00
V4	35	.74	.31	.10	.30	1.80
V5	50	.67	.34	.12	.10	1.80

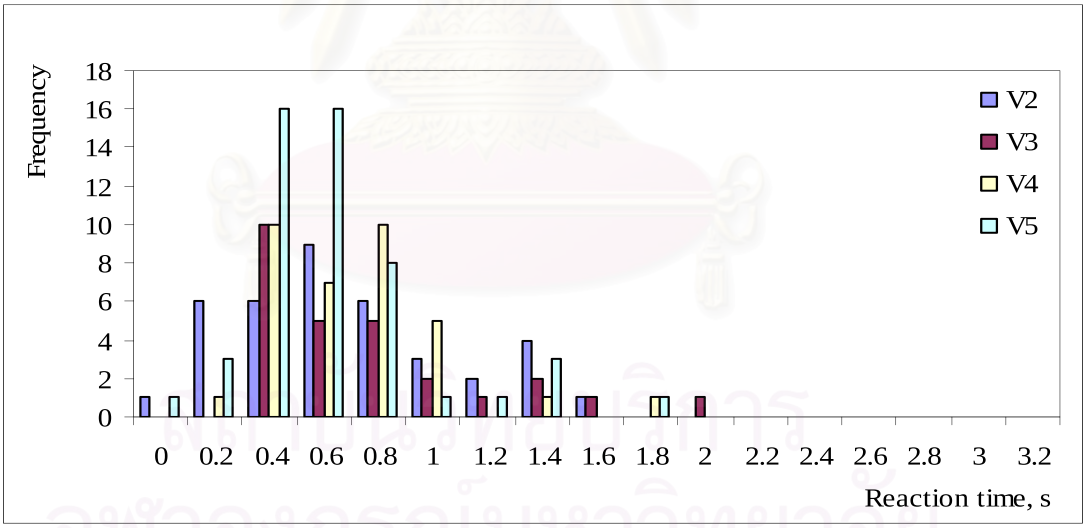


Figure 4.26 Histogram of reaction times for acceleration condition on expressway

Figure 4.26 shows that under acceleration condition, the reaction times are scattered around 0.4 to 0.7 second with some are as high as 2.0 second. Only 2 out of 150 samples have the reaction less than 0.2 second. The shapes of reaction time distributions of all drivers are fairly similar.

4.3.1.2 Deceleration condition

Table 4.20 shows the statistical analysis results of reaction time values, in second, which the results show that the mean value of reaction times for deceleration condition on expressway condition is determined to be 0.62, 0.61, 0.61, and 0.60 seconds with standard deviations of 0.28, 0.26, 0.20, and 0.30 seconds, respectively.

Table 4.20 Statistical analysis results of reaction times for deceleration condition

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V2	35	.62	.28	.08	.20	1.20
V3	26	.61	.26	.07	.30	1.40
V4	38	.61	.20	.04	.40	1.10
V5	32	.59	.30	.09	.20	1.40

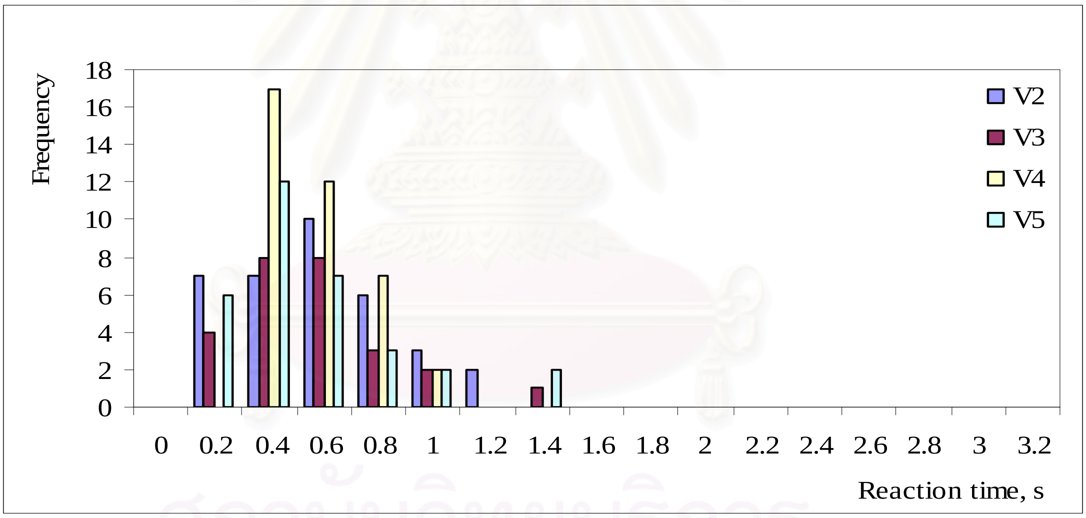


Figure 4.27 Histogram of reaction times for deceleration condition on expressway

Figure 4.27 shows that under deceleration condition, the reaction times are distributed fairly normally around mean only two reaction time data are above 1.2 and none of the data is below 0.2 second.

4.3.1.3 Comparison of reaction times in both acceleration and deceleration conditions on expressway

Table 4.21 shows the comparison results of reaction times in both acceleration and deceleration conditions on expressway, which the results show that the mean value and standard deviation of following vehicles for both acceleration and deceleration conditions of the same drivers. It is consistently seen that reaction times under acceleration condition are longer than those in deceleration condition in all drivers. Moreover, the variation in reaction time is always smaller in deceleration conditions for all drivers (as seen from standard deviation values). Data from 4 drivers can not imply a trend that the driver who has short reaction time in acceleration condition would have also short reaction time in deceleration condition. The 4 drivers have a wider range of reaction time under acceleration condition (0.67 to 0.80 s) than the range of reaction time under deceleration condition (0.591 to 0.62 s).

Table 4.21 Reaction time results for both acceleration and deceleration condition

	ACCELERATION CONDITION			DECELERATION CONDITION		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
V2	38	.73	.41	35	.62	.28
V3	27	.80	.42	26	.61	.26
V4	35	.74	.31	38	.61	.20
V5	50	.67	.34	32	.59	.30

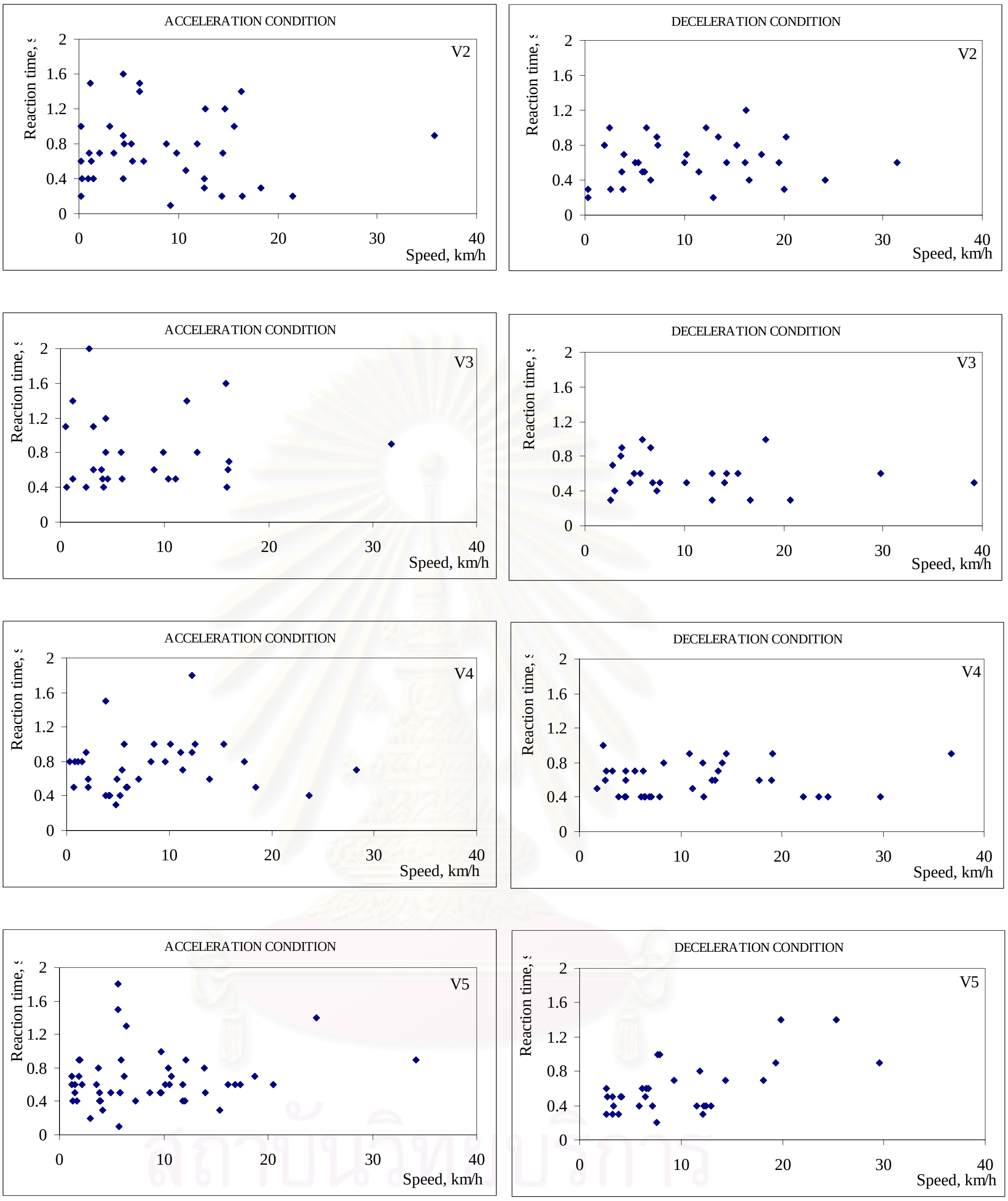


Figure 4.28 Reaction time - speed profile plot on expressway

Figure 4.28 presents the relationship between reaction time and speed for acceleration and deceleration condition on expressway. The scatter plots illustrate no relationship that reaction time and speed. Therefore, it is concluded that there is no evidence that reaction time varies due to speed.

4.3.2 Surface Street condition

4.3.2.1 Acceleration condition

Table 4.22 shows the analysis results of reaction time values, in seconds. The mean value of reaction time for acceleration condition on expressway is determined to be 0.81, 2.40, 1.46, and 1.32 seconds with the standard deviations of 0.46, -, 0.59, and 0.54 second for vehicle 2 ,4 ,and 5, respectively.

Table 4.22 Statistical analysis results of reaction times for acceleration condition

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V2	8	.81	.46	.22	.20	1.40
V3	1	2.40	-	-	-	-
V4	12	1.46	.59	.35	.30	1.90
V5	9	1.32	.54	.30	.60	2.20

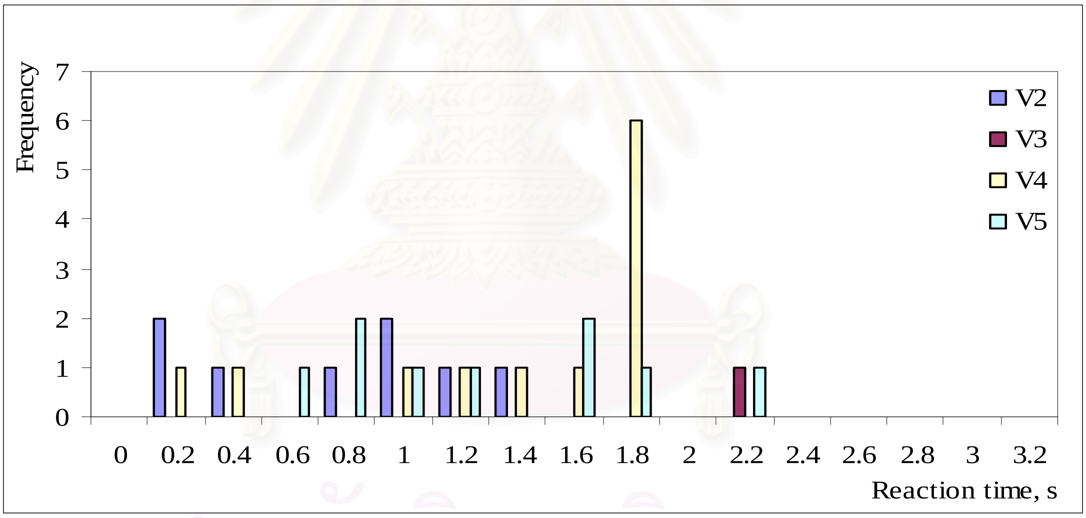


Figure 4.29 Histogram of reaction times for acceleration condition on surface street

As seen in Figure 4.29, shows that under acceleration condition, the reaction time range of each driver is wide. Mostly drivers have the reaction time between 0.8 to 1.8 seconds.

4.3.2.2 Deceleration condition

Table 4.23 shows the statistical analysis results of reaction time values, in seconds. The mean value of reaction times for deceleration condition on surface street is determined to be 1.15, 1.31, 1.02, and 1.35 seconds with standard deviations of 0.61, 0.63, 0.46, and 0.58 seconds, respectively.

Table 4.23 Statistical analysis results of reaction times for deceleration condition

	N	Mean	Std. Deviation	Variance	Minimum	Maximum
V2	8	1.15	.61	.37	.30	2.10
V3	11	1.31	.63	.39	.60	2.50
V4	15	1.02	.46	.21	.40	1.70
V5	14	1.35	.58	.34	.70	2.80

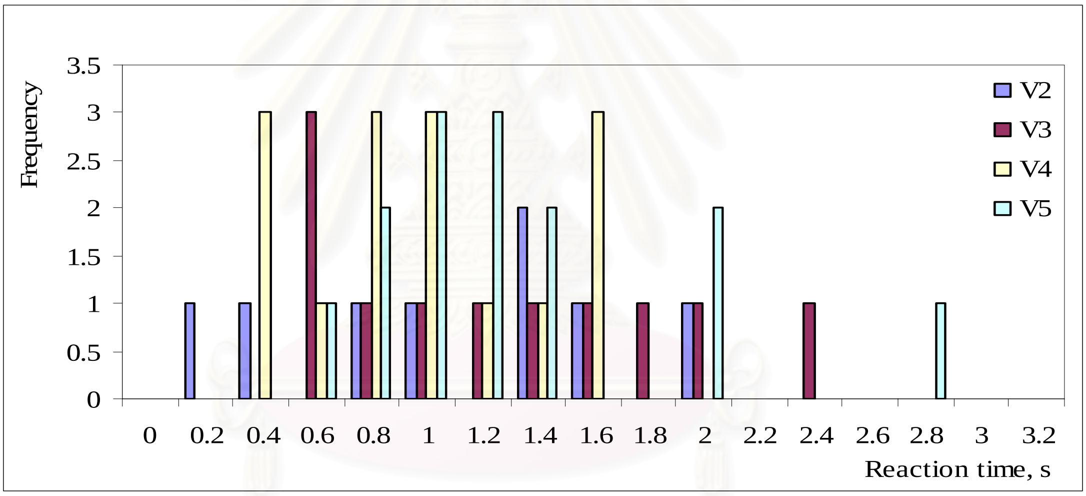


Figure 4.30 Histogram of reaction times for deceleration condition on surface street

Figure 4.30 shows that under deceleration condition, the reaction times are distributed fairly normally around mean only two reaction time data are above 2.8 seconds and none of the data is below 0.2 second.

4.3.2.3 Comparison of reaction times in both acceleration and deceleration condition in surface street condition

Table 4.24 shows the comparison results of reaction times in both acceleration and deceleration conditions on surface street. It is noted that the reaction times in acceleration condition and deceleration of the same drivers are differenced. Moreover, the variation in reaction time in acceleration condition for vehicle 4 is longer than in deceleration. The 4 drivers have a wider range of reaction time in acceleration condition (0.81 to 2.40 s) than the range of reaction time in deceleration condition (1.02 to 1.35 s).

Table 4.24 Reaction time results for both acceleration and deceleration condition

	ACCELERATION CONDITION			DECELERATION CONDITION		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
V2	8	.81	.46	8	1.15	.61
V3	1	2.40	-	11	1.31	.63
V4	12	1.46	.59	15	1.02	.46
V5	9	1.32	.54	14	1.35	.58

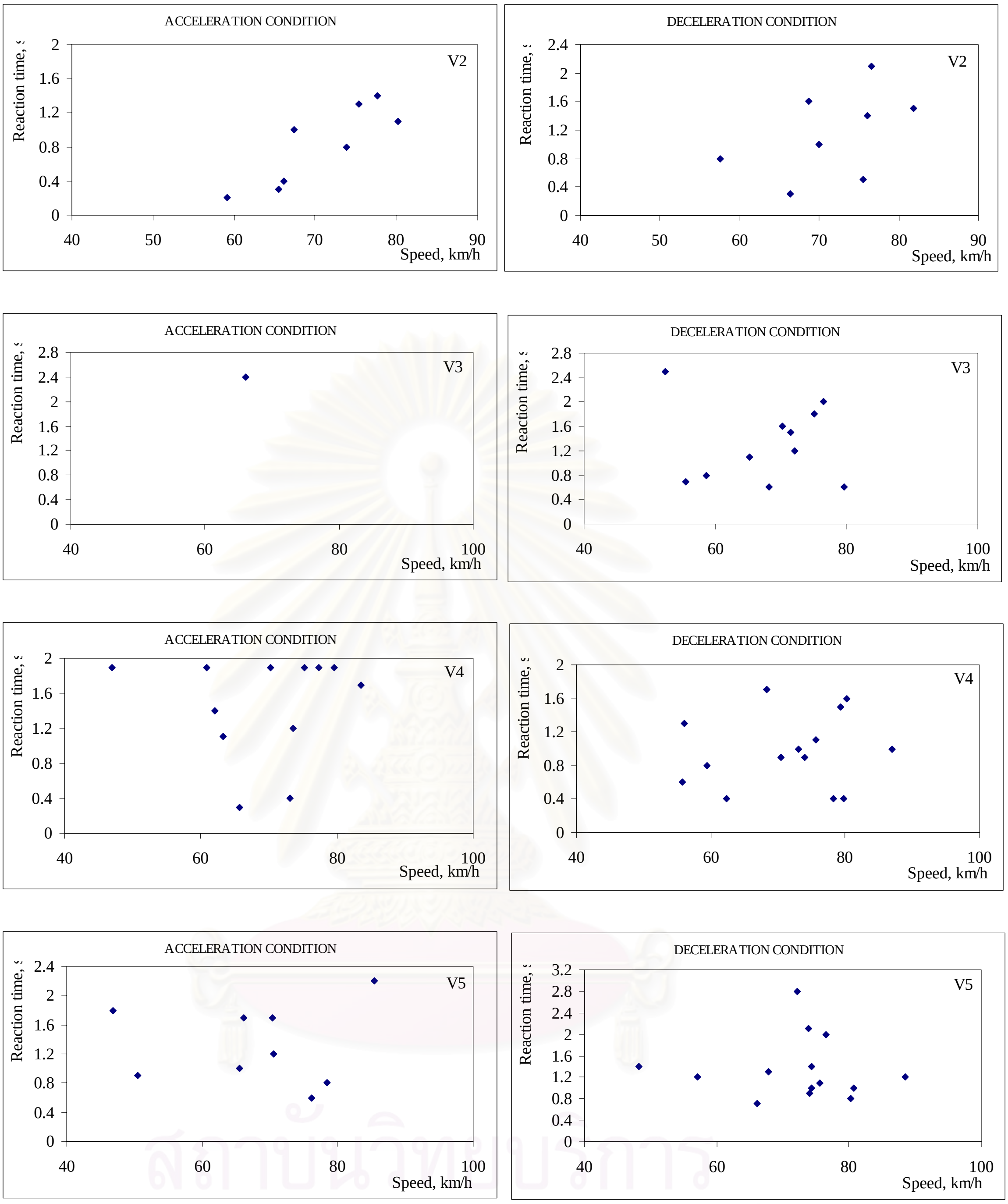


Figure 4.31 Reaction time - speed profile plot on surface street

Figure 4.31 presents the relationship between reaction time and speed in acceleration and deceleration condition on surface street. The scatter plots illustrate no relationship that reaction time and speed. Therefore, it is concluded that there is no evidence that reaction time varies due to speed.

4.4 Sensitivity parameters

As mentioned in section 3.5, in case of the GM car following model with variable reaction time concept, only the data near peak points in relative speed and acceleration time series are used to determine the sensitivity parameters using linear regression method.

A sample of determination is illustrated in Figure 4.32, where data points near a peak point were scanned to determine the sensitivity parameters between the two curves. However, according to several previous researches nine points of stimulus-response data (before four points and after four points) near the peak points in the acceleration and relative speed time series are considered appropriate for determining the sensitivity parameters a, m and l using a least mean square method.

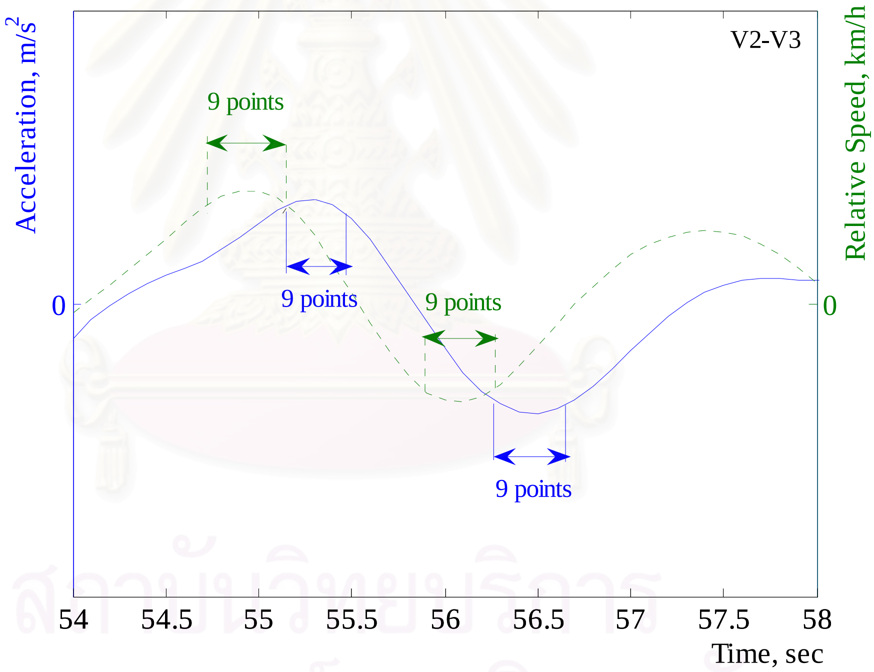


Figure 4.32 Illustration on the determination of sensitivity parameters

4.4.1 Expressway Condition

4.4.1.1 Acceleration Condition

Table 4.25 shows the results of sensitivity parameters from a least mean squares method, which the results show that the ranges of sensitivity parameters, mainly a, m, and l for acceleration condition are determined to be [-2.109 to 1.760], [-.259 to .231], and [-.874 to .836], respectively.

Table 4.25 Sensitivity parameter for acceleration condition on expressway

	N	a	m	l
V2	38	-2.11	-.26	-.87
V3	27	1.76	-.11	.84
V4	35	.81	.23	.44
V5	50	.82	.00	.40

4.4.1.2 Deceleration condition

Table 4.26 shows the results of sensitivity parameters from the least mean squares method, which the results show that the ranges of sensitivity parameters, mainly a, m, and l for acceleration condition are determined to be .929 to 3.245], [-.130 to .106], and [.322 to 1.548], respectively.

Table 4.26 Sensitivity parameters for deceleration condition on expressway

	N	a	m	l
V2	35	3.245	.094	1.548
V3	26	.929	.106	.349
V4	38	2.368	.002	1.109
V5	32	.954	-.130	.322

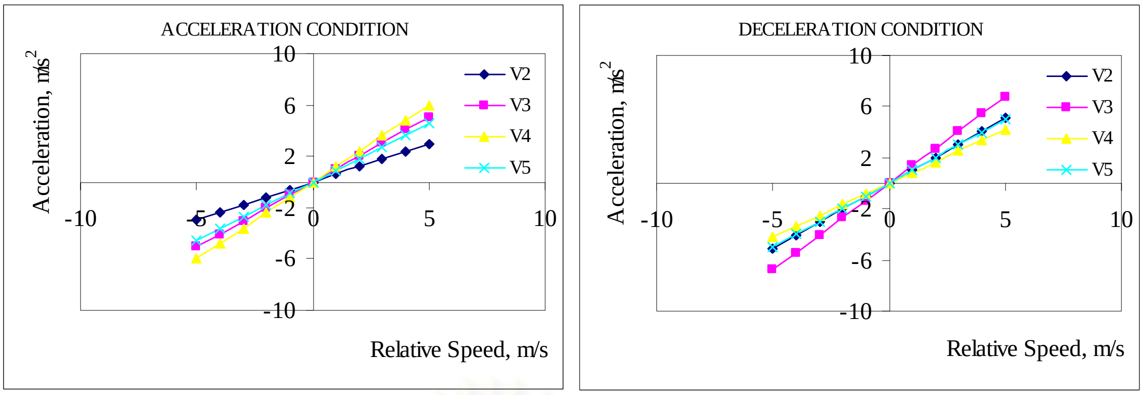
4.4.1.3 Comparison of sensitivity parameters for both acceleration and acceleration condition on expressway condition

Table 4.27 shows the comparison results of sensitivity parameters from the least mean squares method for both acceleration and deceleration conditions in expressway condition. The results show that the ranges of sensitivity parameters, a, m, and l in the same driver under different traffic conditions are quite different.

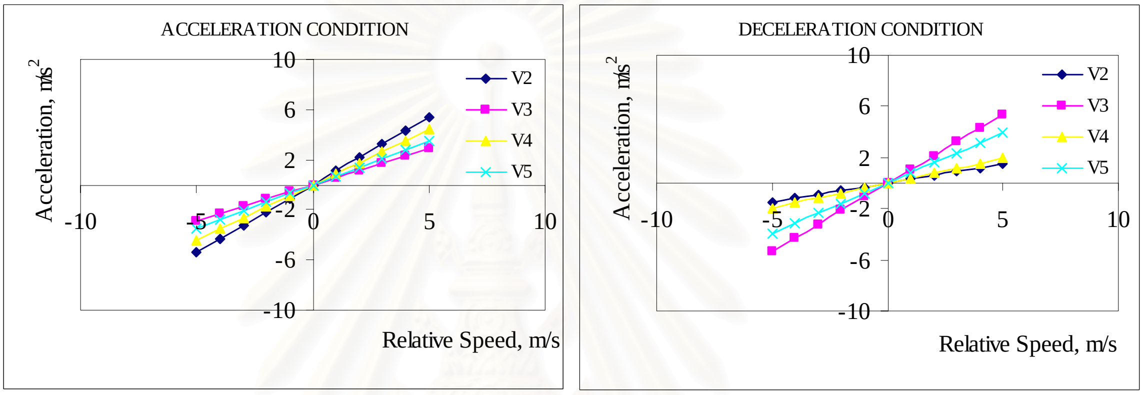
Table 4.27 Sensitivity parameters for both acceleration and deceleration conditions

	ACCELERATION				DECELERATION			
	N	a	m	l	N	a	m	l
V2	38	-2.11	-.26	-.87	35	3.25	.09	1.55
V3	27	1.76	-.11	.84	26	.93	.11	.35
V4	35	.81	.23	.44	38	2.37	.00	1.11
V5	50	.82	.00	.40	32	.95	-.13	.32

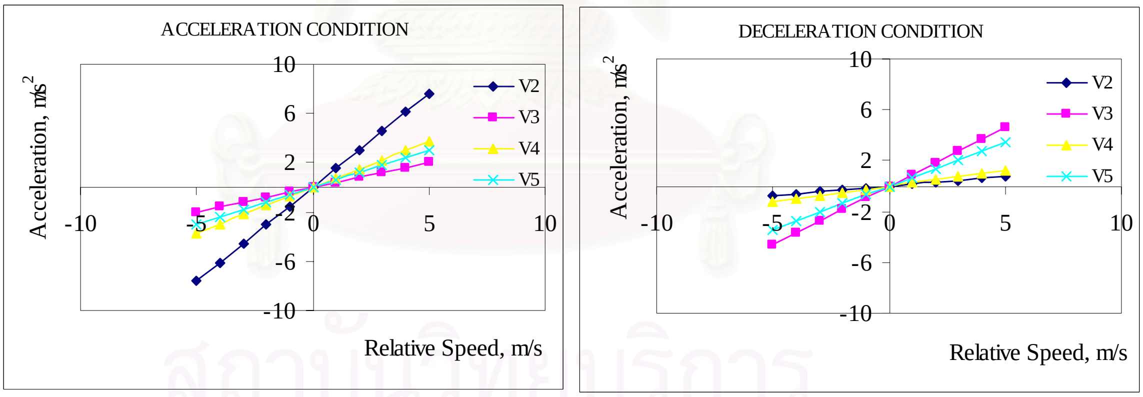
To illustrate the differences in sensitivity of drivers under various conditions, the calibrated GM model using the estimated a, m, and l were tested and the relationships between relative speed and acceleration for each driver are plotted. Three initial headway conditions were selected; 10, 20, and 30 m with initial speed of 20 km/h



a) Initial headway = 10 m



b) Initial headway = 20 m



c) Initial headway = 30 m

Figure 4.33 Acceleration vs. relative speed of each driver following the calibrated 5th GM model on expressway

Figure 4.33 shows the driver's behavior reflecting his sensitivity under acceleration and deceleration condition. The figure shows the varying degree of aggressiveness under various driving condition (i.e. initial headway and relative speed). Under acceleration condition, driver 3, 4, and 5 behave similarly. Driver 2 seems very aggressive at non-critical headway condition (30 m) while non-aggressive at critical headway condition (10 m), compared with other drivers. The same driver 2 is the least aggressive in non-critical headway condition (30 m) under deceleration condition, whereas driver 3 is the most aggressive in all headway conditions. The figure shows no distinct difference between acceleration and deceleration rate under the same driving condition. It is noted that the deceleration rates among drivers seem to be more disperse than the acceleration rates. This is probably true in the stop-and – go condition where all vehicles follow the front vehicles closely in the platoon.

4.4.2 Surface Street condition

4.4.2.1 Acceleration condition

Table 4.28 shows the results of sensitivity parameters from the least mean squares method, which the results show that the ranges of sensitivity parameters, mainly a, m, and l for acceleration condition are determined to be [-.742 to 3.749], [-2.804 to 62.954], and [-4.103 to 1.1.657], respectively.

Table 4.28 Sensitivity parameters for acceleration condition on surface street

	N	a	m	l
V2	8	-.21	.08	.31
V3	1	-196.71	62.95	-4.10
V4	12	3.75	-2.80	-1.07
V5	9	-.74	1.88	1.66

4.4.2.2 Deceleration condition

Table 4.29 shows the results of sensitivity parameters from the least mean squares method, which the results show that the ranges of sensitivity parameters, mainly a, m, and l for acceleration condition are determined to be [1.559 to 12.927], [-3.539 to .312], and [.154 to 1.008], respectively.

Table 4.29 Sensitivity parameters for deceleration condition on Surface Street

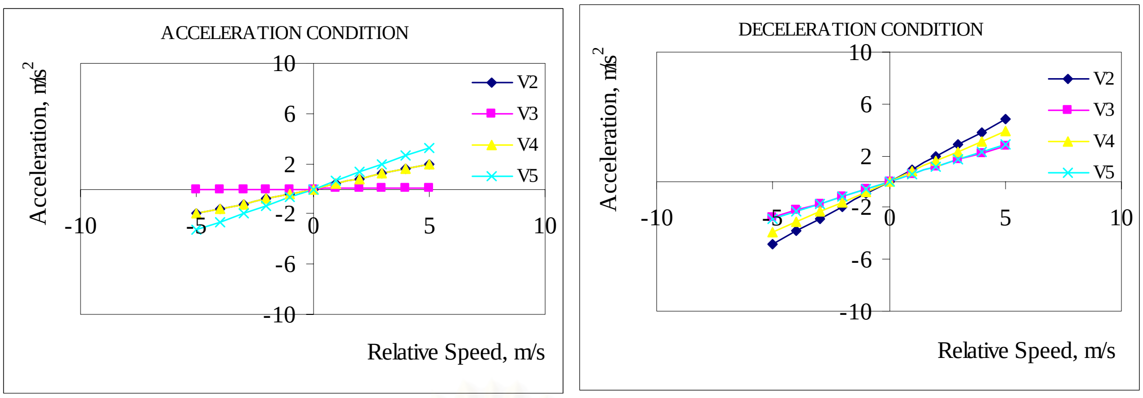
	N	a	m	l
V2	8	12.93	-3.54	1.01
V3	11	1.56	.31	1.01
V4	15	6.68	-2.30	.15
V5	14	3.30	-.87	.47

4.4.2.3 Comparison of sensitivity parameter for both acceleration and deceleration condition on surface street condition

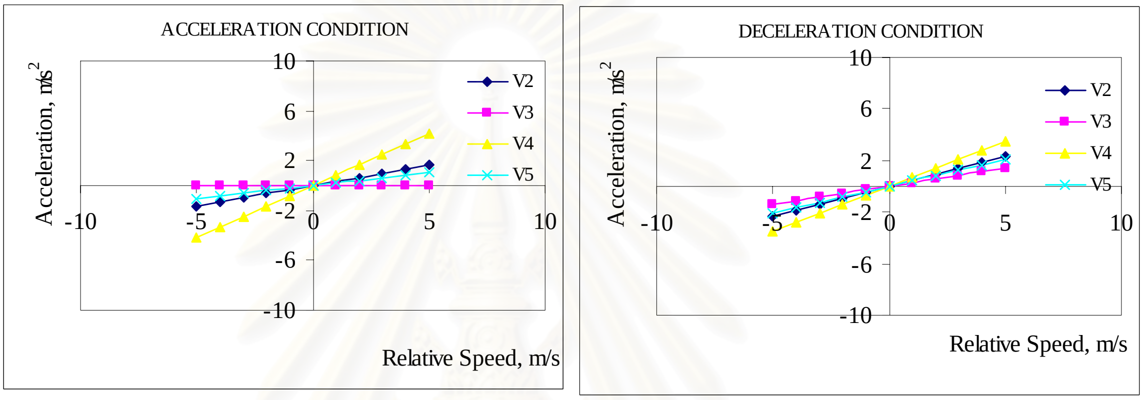
Table 4.30 shows the comparison results of sensitivity parameters from the least mean squares method for both acceleration and deceleration conditions on surface street condition. The results show that the range of sensitivity parameters, a, m, and l in the same driver under different traffic conditions are quite different for both conditions in surface street condition.

Table 4.30 Sensitivity parameters for both acceleration and deceleration conditions

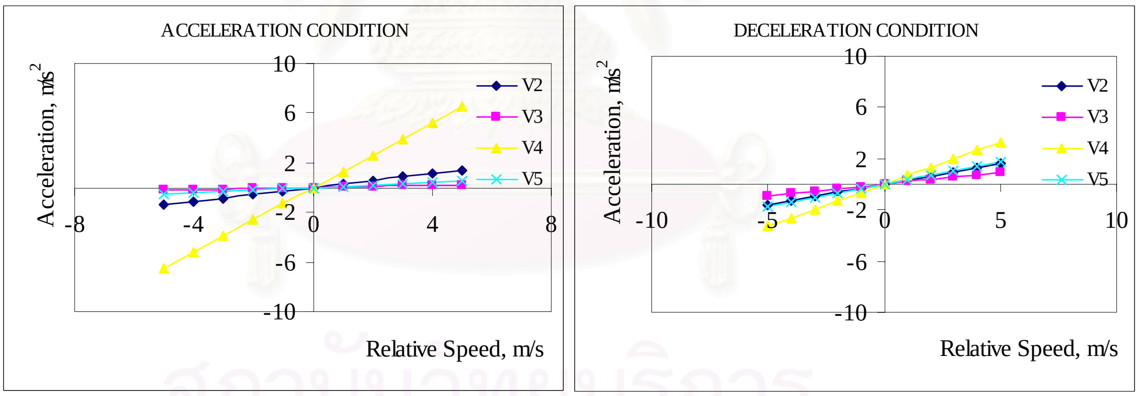
	ACCELERATION				**DECELERATION**			
	N	a	m	l	N	a	m	l
V2	8	-.21	.08	.31	8	12.93	-3.54	1.01
V3	1	-196.71	62.95	-4.10	11	1.56	.31	1.01
V4	12	3.75	-2.80	-1.07	15	6.68	-2.30	.15
V5	9	-.74	1.88	1.66	14	3.30	-.87	.47



a) Initial headway = 20 m



b) Initial headway = 40 m



c) Initial headway = 60 m

Figure 4.29 Acceleration vs. relative speed of each driver following the calibrated 5th GM model on surface street

Figure 4.29 demonstrates the implication of the calibrated GM model on surface street. Under acceleration condition, all drivers behave similarly except driver 4 who are the most aggressive under non-critical headway condition (30 m)

On average all drivers are more aggressive under critical condition, as seen by the higher acceleration rate at closer headway.

Comparing Figure 4.28 (expressway, slow moving traffic condition) and Figure 4.29 (surface street, high speed traffic condition), it is found that on average the acceleration on high speed condition is lower, or sensitivity factor is lower. Drivers seem to be more relax and not so aggressive. Drivers have more aggressive deceleration under the slow moving and stop-and-go as on the expressway than under the high speed flow on surface street.

CHAPTER V

CONCLUSION AND RECOMMENDATION

This research presented an approach to collect the GPS data, to reduce the computational requirements of traffic data, including distance headway, relative speed, and acceleration based on GM car following model, and to present the algorithm for determination of driver's behavior, namely reaction time and sensitivity parameters based on the stimulus-response concept. The traffic information from the GPS technique, which has the capability to capture the driver's behavior under different traffic condition in Thailand, especially on expressway and surface street (congested and uncontested)

To achieve this goal, algorithm procedure was developed based on Matlap programming. In this study, the algorithm was divided into two tasks: the first is to reduce the noise of speed and acceleration trajectories of five vehicles for each time sequence (at intervals of one tenth second) and another to determine driver's behavior, namely reaction time and sensitivity parameters. However, the major findings can be summarized as follows:

- Experimental work using GPS technology can be applied to capture the real traffic condition under different traffic condition especially, expressway and surface street, which the data quality is acceptable and sufficient to represent the Thai's driver behavior under different traffic condition, congested and uncontested condition
- Traffic flow variable including distance headway, speed, relative speed, and acceleration obtained from GPS data. The results indicate that the driver characteristics on surface street is higher than the driver characteristics on expressway for all drivers
- Speed-spacing relationship show that driver maintain different headway under the same speed condition for both expressway and surface street, (the significance of regression coefficients, R^2, on expressway the linear model fits better in all cases, and on surface street, the exponential model fits better in all cases)

- Reaction time results for both acceleration and deceleration conditions on expressway and surface street are extremely difficult to determine. However, based on stimulus – response concept, the results indicate that the reaction times under acceleration conditions are longer than those in deceleration condition on expressway and on surface street, the reaction times in acceleration and deceleration conditions of the same drivers are quite differences. On average the reaction time in congested condition is 0.70 second and in un-congested condition is 1.4 second
- Sensitivity parameters on expressway and surface street, it is found that the acceleration of following vehicle on high speed condition for both expressway and surface street is lower or sensitivity parameters is lower.

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APPENDICES

APPENDIX- SIMULATION PROGRAM MODULE (MATLAB)

```
function [x] = smooth(xlsfile,Win)
% Function smooth(xlsfile,Win);
% xlsfile is represented to File name (*.xls).
% Notice!: The format of *.xls should be consisted of 3 colums
% _| A | B | C |
%  | . | . | . |
%  | . | . | . |
%  | . | . | . |
%  | . | . | . |
% Win is represented to size of smooting windows.
% This program will return the value by re-*.xls
% Example:
%     >> smooth('test.xls',100);
%     >> x = smooth('test.xls',100);
w = round(Win/2);
copyright = xlsfinfo(xlsfile);
fprintf('\n')
fprintf('Resoure : %s\n\n',copyright)
x = xlsread(xlsfile);
x1 = x(:,1);
x2 = [x(1,2).*ones(w,1); x(:,2); x(length(x),2).*ones(w,1)];
x3 = [x(1,3).*ones(w,1); x(:,3); x(length(x),3).*ones(w,1)];
t = [1:length(x1)];
for i=w+1:length(x1)+w
        q2 = x2(i-w:i+w);
        xq3 = x3(i-w:i+w);
         x2(i) = mean(xq2);
         x3(i) = mean(xq3);
end
x2 = x2(w+1:length(x2)-w);
```

```
x3 = x3(w+1:length(x3)-w);
subplot(2,1,1);
plot(t,x(:,2)); hold on;
plot(t,x2,'Color','r','LineWidth',1); hold off;
xlabel('Time (s)'); ylabel('Acceleration (m/s^2)');grid on; title('Smooth urve','color',[1 1 1],'FontWeight','bold','FontSize',14);legend('Original ata','Smoothed data');
subplot(2,1,2);
plot(t,x(:,3)); hold on;
plot(t,x3,'Color','r','LineWidth',1); hold off; xlabel('Time (s)'); ylabel('Speed kph)');
legend('Original data','Smoothed data');grid on;
x = [x1 x2 x3];
fid = fopen(['re-',xlsfile],'w');
fprintf(fid,'Time\t Acc\t Speed\n');
fprintf(fid,'%f\t %f\t %f\n',x');
fclose(fid);
disp('********* Smooth Curve Terminated Successfully **********')

function [T,msg,t1,t2,ma,ms]=reactiontime(x,S,E,m1,m2,lam)
if isempty(S)==1|isempty(E)==1|S>E
   T=[];
   msg = {['Not enough or aviable input paramaters'];['Please check again!']};
elseif length(x)<E
   T=[];
   msg = ['End point must be less than the length of data'];
else
[k,n]=size(x);
t=x(S:E,1); %
a=x(S:E,2); %
s=x(S:E,3); %
if m1>m2
         m='Min';
          [ma,p1]=min(a); %
          [ms,p2]=min(s); %
else
```

```
        [ma,p1]=max(a); %
        [ms,p2]=max(s); %
        m='Max';
end
T = abs(p2-p1)/lam;
t1 = t(p1);
t2 = t(p2);
msg = {'>> Reaction time terminated successfully!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!';'';['Total Data Point : ',num2str((k-1)/lam),' second'];...
        ['Data Range : ',num2str(((length(t)-1)/lam)),' second'];...
        ['From ',num2str((S-1)/lam),' To ',num2str((E-1)/lam),' (second)'];...
        ['Reaction Time of ',m,'imum Point'];['(T) : ',num2str(T),' second']};
end

function [k,x,msg]= readfile(file)
x=[];
k=[];
plot1=[];
if isempty(file)
         msg={'Please enter *.xls file name !'};
else
[p,n,t]=fileparts(file);
if isempty(t)
          file=[file,'.xls'];
end
fid=dir('*.xls');
co =0;
for i=1:length(fid)
        om=isequal(file,fid(i).name);
 if com==1&fid(i).isdir==0
        co=co+com;
   end
   if sum(co)>0
```

```
            x=xlsread(file);
             [m,n]=size(x);
 if n~=3
            msg={'';'File format is not permission';'Excel should be contain 3 column'};
             return;
else
             k=1;
end
            f isempty(x)
            sg={[file,' can not read!'];[' or ',file,' is not excel file format']};
else
            sg={'';['Open file ( ',file,' ) successful!']};
end
else
            msg ={'';'File not found !'};
end
end
end

a = dir('reactiontime.m');
b = dir('readfile.m');
c = dir('history.bk');
d = dir('l1.mat');
if (length(a)*length(b)*length(c)*length(d))>0
File=[''];
close all;
fid = fopen('history.bk','rb');
File = fscanf(fid,'%s');
fclose(fid);
n1=[];
n2=[];
m1=1;
m2=0;
load l1.mat
```

```
s = get(0,'ScreenSize');mainfig = figure('Name','Phongsavanh' ,'Units','pixels','Number
Title','off','MenuBar','none','color',[0.8 0.8 0.8],'Position', [50 s(4)*1/4 200 450]);
a=get(mainfig,'Position');TitleName = uicontrol(gcf,'style','text','backgroundcolor',[0.8
0.8 0.8],'position',[0 420 200 20],'HorizontalAlignment','center','string',... 'Reaction
Time','fontunit','pixels','fontsize',16,'fontweight','bold','ForegroundColor',[1 1 1]);
Frame = uicontrol(gcf,'style','frame','backgroundcolor',[0.8 0.8 0.8],'position',[5 220
190 190],'ForegroundColor',[0 0 0]);
Text1 = uicontrol(gcf,'style','text','backgroundcolor',[0.8 0.8 0.8],'position',[10 382 60
15],'ForegroundColor',[0 0 0],'string','File Name:','HorizontalAlignment','left');
inputfile = uicontrol(gcf,'style','edit','backgroundcolor',[1 1 1],'position',[65 380 120
20],'ForegroundColor',[0 0 0],'HorizontalAlignment','left','string',File,'callback',['File
= get(inputfile,"string");']);Open = uicontrol(gcf,'style','push','backgroundcolor',[0.8
0.8 0.8],'position',[10 355 180 20],'string','Open','callback',['if isempty(File);
msg={"Please enter *.xls file name !"};else;[ck,x,msg]=readfile(File);'...
        if ck==1;if isempty(strfind(File,".xls"))~=0;'...
        F=[File,".xls"];else; F=File;end;'...
        'fid=fopen("history.bk","wb");'...
        'fprintf(fid,"%s",F);fclose(fid);'...
        'lam = 1/(x(2,1)-x(1,1));'...
        'set(Start,"enable","on");'...
        'set(End,"enable","on");'...
        'set(Max,"enable","on");'...
        'set(Min,"enable","on");'...
        'set(Run,"enable","on");'...
        set(Plotfig,"color",[1 1 1]);'...
        'set(View,"enable","on");'...
          'figure(Plotfig);subplot(2,1,1);plot(x(:,1),x(:,2),x(:,1),x(:,3));axis([0
(length(x)-1)/lam min(min(x(:,2),x(:,3))) max(max(x(:,2),x(:,3)))]);grid on;'...
'n1=0;set(Start,"string",n1);n2=(length(x)-1)/lam;set(End,"string",n2);'...
 'end;end;a=get(mainfig,"Position");'...
 'set(Plotfig,"Position",[a(1)+a(3)+8 a(2) 500 400]);'...
'set(Text7,"string",msg,"HorizontalAlignment","left");']);
Text2 = uicontrol(gcf,'style','text','backgroundcolor',[0.8 0.8 0.8],'position',[10 330 40
15],'ForegroundColor',[0 0 0],'string','Start:','HorizontalAlignment','left');
```

```
Start = uicontrol(gcf,'style','edit','enable','off','backgroundcolor',[1 1 1],'position',[45
328 40 20],'ForegroundColor',[0 0 0],'HorizontalAlignment','left','string',n1,'callback'
,['n1 = str2double(get(Start,"string"));']);
Text3 = uicontrol(gcf,'style','text','backgroundcolor',[0.8 0.8 0.8],'position',[95 330 40
15],'ForegroundColor',[0 0 0],'string','End:','HorizontalAlignment','left');
End = uicontrol(gcf,'style','edit','enable','off','backgroundcolor',[1 1 1],'position',[125
328 40 20],'ForegroundColor',[0 0 0],'HorizontalAlignment','left','string',n2,'callback'
,['n2= str2double(get(End,"string"));']);
Text4 = uicontrol(gcf,'style','text','backgroundcolor',[0.8 0.8 0.8],'position',[60 300 90
15],'ForegroundColor',[0 0 0],'string','Minimun','HorizontalAlignment','left');
Min = uicontrol(gcf,'style','radio','enable','off','backgroundcolor',[0.8 0.8 0.8],'position'
,[40 298 20 20],'ForegroundColor',[0 0 0],'value',m1,'callback',['m2=0; set(Max,
"value",0); set(Min,"value",1); m1=get(Min,"value");']);
text5 = uicontrol(gcf,'style','text','backgroundcolor',[0.8 0.8 0.8],'position',[60 283 90
15],'ForegroundColor',[0 0 0],'string','Maximum','HorizontalAlignment','left');
Max = uicontrol(gcf,'style','radio','enable','off','backgroundcolor',[0.8 0.8
0.8],'position',[40 280 20 20],'ForegroundColor',[0 0 0],'value',m2,'callback',['m1=0;
set(Min,"value",0); set(Max,"value",1); m2=get(Max,"value");']);
Run = uicontrol(gcf,'style','push','enable','off','backgroundcolor',[0.8 0.8
0.8],'position',[10 225 180
20],'string','Run','callback',['[T,msg,t1,t2,ma,ms]=reactiontime(x,(n1*lam+1),(n2*lam
+1),m1,m2,lam);'... 'figure(Plotfig);hold on;subplot(2,1,2);plot(t1,ma,"o",t2,ms,"o");
hold off;'... 'set(Text7,"visible","on","string",msg,"HorizontalAlignment","left")']);
View = uicontrol(gcf,'style','push','enable','off','backgroundcolor',[0.8 0.8 0.8],
'position',[10 250 180 20],'string','View','callback',
        ['xn=x([(n1*lam+1):(n2*lam+1)],:);'...
        'a=get(mainfig,"Position");'...
        'set(Plotfig,"Position",[a(1)+a(3)+8 a(2) 500 400]);'...
         'figure(Plotfig); subplot(2,1,2); plot(xn(:,1),xn(:,2),xn(:,1),xn(:,3)); axis([n1
n2 min(min(xn(:,2),xn(:,3))) max(max(xn(:,2),xn(:,3)))]);grid on;']);
Reset = uicontrol(gcf,'style','push','enable','on','backgroundcolor',[0.8 0.8 0.8],
'position',[10 35 180 20],'string','Reset','callback',['close all; louis']);
Exit = uicontrol(gcf,'style','push','backgroundcolor',[0.8 0.8 0.8],'position',[10 10 180
20],'string','Exit','callback',['close(mainfig); close(plotfig); clear all; clc']);
```

```
Frame = uicontrol(gcf,'style','frame','backgroundcolor',[1 1 1],'position',[5 60 190 155],
'ForegroundColor',[0 0 0]);
Text61 = uicontrol(gcf,'style','text','enable','on','backgroundcolor',[1 1 1],'position',[10
186 180 15],'string',{'-------------------------------------------------------'},
'HorizontalAlignment','center');
Text62 = uicontrol(gcf,'style','text','enable','on','backgroundcolor',[1 1 1],'position',[10
195 180 15],'string','Results','HorizontalAlignment','center');
Text7 = uicontrol(gcf,'style','text','backgroundcolor',[1 1 1],'position',[10 65 180
125],'string',{'';'Reaction Time (T), Copy@right 2004';'This programe is based on
MATLAB';'By '' Phongsavanh INTHAVONGSA'''},'HorizontalAlignment','center');
Plotfig = figure('Name','Reaction Time Characteristics','visible','on','Units','pixels',
'NumberTitle','off','color',[0 0 0],'Position', [a(1)+a(3)+8 a(2) 500 400]);
subplot(2,1,1);imshow(x)
else
error(['Error called system files!'])
return;
end
```

VITA

Phongsavanh Inthavongsa was born in Khammouane, Laos, in 1978. He received the B. Eng. Degree in Road – Bridge and Transportation Engineering from Dept. of Communication and Transportation Engineering, National University of Laos, in 2001. He entered the Master’s degree program at Civil Engineering, Chulalongkorn University, in 2003. His research areas are Traffic and Transportation Engineering.