Dynamic Stability of Motorcycle:
Tyre Width Contribution to Road Crash

Chuthamat Laksanakit

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Civil Engineering

Prince of Songkla University

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This is to certify that the work here submitted is the result of the candidate's own investigations. Due acknowledgements have been made of any assistance received.

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I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

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(Miss Chuthamat Laksanakit)
Candidate

ชื่อวิทยานิพนธ์ เสถียรภาพของรถจักรยานยนต์ ปัจจัยความกว้างของยางที่มีอิทธิพลต่ออุบัติเหตุทางถนน
ผู้เขียน นางสาวจุฑามาศ ลักษณะกิจ
สาขาวิชา วิศวกรรมโยธา (วิศวกรรมขนส่ง)
ปีการศึกษา 2558

บทคัดย่อ

งานวิจัยนี้เป็นการวิเคราะห์ปัจจัยจากความกว้างของยางรถจักรยานยนต์ที่มีผลต่อเสถียรภาพในการขับขี่ เนื่องจากยางเป็นชิ้นส่วนสำคัญของรถจักรยานยนต์ที่ส่งถ่ายแรงและโมเมนต์จากผิวถนนมายังตัวรถ ขนาดยางที่เหมาะสมจะช่วยให้แรงต้านการเคลื่อนที่ซึ่งเกิดจากแรงเสียดทานระหว่างยางกับผิวถนนสมดุลกับแรงจากการเคลื่อนที่ในกรณีขับขี่ทั้งกรณีทางตรงและกรณีที่รถเลี้ยวเปลี่ยนทิศทางการเคลื่อนที่ งานวิจัยนี้แบ่งการทดสอบออกเป็น 2 แบบ คือแบบขับขี่ทางตรง (Straight Running Test) และแบบทางโค้งซ้ายและโค้งขวารูปตัวเอส (Slalom Test) โดยใช้ยางรถจักรยานยนต์ 3 ขนาดและความเร็วออกแบบ 4 ระดับ (สำหรับการทดสอบที่ 2 ใช้ความเร็วออกแบบ 3 ระดับ) เป็นตัวแปรอิสระ โดยที่ยางชุด A เป็นชุดที่ประกอบมาพร้อมตัวรถจากโรงงาน ยางล้อหน้ากว้าง 70 mm ยางล้อหลังกว้าง 80 mm ยางชุด B ยางล้อหน้ากว้าง 90 mm ยางล้อหลังกว้าง 90 mm และยางชุด C ยางล้อหน้ากว้าง 110 mm ยางล้อหลังกว้าง 120 mm ส่วนความเร็วอยู่ระหว่าง 20 km/h ถึง 60 km/h ส่วนตัวแปรควบคุมประกอบด้วย 1) รถทดสอบเป็นรถจักรยานยนต์มีกำลังเครื่องยนต์ 125cc ซึ่งเป็นรุ่นที่มีการจดทะเบียนสูงสุด และ 2) วงล้อของรถทดสอบเป็นแบบซี่ลวดซึ่งใช้กับยางทุกชุดตลอดการทดสอบและผู้ขับขี่ ตัวแปรตามประกอบด้วยค่าพลศาสตร์ เช่น ความเร็วเชิงมุม (Angular Velocity) ความเร่งเชิงมุม (Angular Acceleration) และการเคลื่อนที่เชิงมุม (Angular Rotation) จากนั้นใช้สถิติ t-test ของการวิเคราะห์ความแปรปรวนและทดสอบความแตกต่างของค่าเฉลี่ยที่ได้จากข้อมูลการทดลองเพื่อทดสอบสมมติฐานที่ว่าทุกขนาดความกว้างของยางมีผลเหมือนกันต่อเสถียรภาพของรถจักรยานยนต์ ที่ระดับนัยสำคัญ 0.05

สำหรับการทดสอบขับทางตรง ผลการทดสอบทางสถิติที่ได้แสดงให้เห็นว่าขนาดความกว้างของยางรถจักรยานยนต์ทั้ง 3 ชุด ไม่มีนัยสำคัญต่อความแตกต่างของเสถียรภาพในการขับขี่รถจักรยานยนต์ทางตรง อย่างไรก็ตาม ระดับความเร็วมีนัยสำคัญต่อเสถียรภาพของรถจักรยานยนต์ผ่านการตอบสนองค่าพลศาสตร์ต่างๆ ยกเว้นความเร็วเชิงมุมและการเคลื่อนที่เชิงมุมในแนวดิ่ง

ส่วนผลการทดสอบขับขี่แบบ Slalom พบว่ายางชุด C มีความแตกต่างต่อเสถียรภาพของรถจักรยานยนต์ผ่านการตอบสนองค่าพลศาสตร์เมื่อขับขี่ด้วยความเร็วประมาณ 40-60 km/h โดยมีค่าสัดส่วนของความเร็วเชิงมุมในแนวตามยาวต่อความเร็วเชิงมุมในแนวดิ่งต่ำสุด แสดงให้เห็นว่ายางรถจักรยานยนต์ที่มีขนาดความกว้างใหญ่ขึ้นจะช่วยให้ผู้ขับสามารถควบคุมรถในขณะเปลี่ยนทิศทางการเคลื่อนที่ได้อย่างมีเสถียรภาพกว่ารถที่มีขนาดยางแคบ

กล่าวโดยสรุป ความกว้างของยางรถจักรยานยนต์ที่กว้างกว่าชุดที่ประกอบมาจากโรงงานแม้จะไม่มีนัยสำคัญต่อเสถียรภาพในการขับขี่ทางตรง แต่มีผลต่อการเลี้ยวโค้งหรือเปลี่ยนทิศทางการเคลื่อนที่เพราะช่วยเสริมเสถียรภาพ ซึ่งเป็นประโยชน์อย่างมากต่อผู้ขับขี่ที่มีประสบการณ์น้อยเพราะต้องควบคุมคันบังคับรถ (Handlebar) ที่มีแรงบิดและโมเมนต์เพิ่มขึ้นจากการเปลี่ยนทิศทางการเคลื่อนที่ของรถ น่าจะส่งผลให้อุบัติเหตุรถจักรยานยนต์ประเภทล้มเองลดลงได้อย่างมีนัยสำคัญ

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Author	Miss Chuthamat Laksanakit
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ABSTRACT

This study examines the potential of dynamic properties of motorcycle on its stability. The focus was on motorcycle riding and cornering stability as influenced by tyre width which is the key component in the transfer of forces and moments from the vehicle to the road surface. The suitable tyre width could contribute to increased motorcycle stability. Straight running and slalom riding tests were carried out. Three tyre sets with varying tyre widths, and four speed levels (three speed levels for slalom test) were used to represent independent variables. Tyre set A which was an original equipment manufacturer one has 70 mm tyre width for the front wheel and 80 mm tyre width for the rear. Tyre set B comprises tyres with 90 mm width for both front and rear wheel; and set C comprises 110 mm tyre for the front and 120 mm for the rear. Four riding speeds of 20, 30, 40 and 60 km/h were used in the experiment. The controlled variables were a test motorcycle which was a typical lightweight 125cc engine, spoke rim diameter of wheel, and the same professional rider. The motorcycle dynamic behaviours including angular velocity, angular acceleration and angular rotation were measured as dependent variables. The t-test was then conducted to analyze the variance and mean comparison of the experimental data. The goal of this statistical test is to prove the null hypothesis that all tyre widths have the same effect to all response variables at a significant level of 0.05.

The results from the straight running test show that the three different sets of motorcycle tyre width gave insignificant effects, i.e. all the roll, pitch and yaw angles remain practically the same, to motorcycle stability when driven in straight path at speed lower than 17 m/s (60-62 km/h). However, speed level significantly affects the mean of the average value of angular acceleration and velocity and rotational displacement in x and y axes which are roll and pitch angle but has no influence on vertical velocity and yaw angle.

For the slalom test, it was found that tyre set C presented a significant influence on motorcycle stability when cornering at speed around 40-60 km/h; at these speeds, the ratio of roll to yaw rate of tyre set C displayed a minimum value. This indicates that motorcycle with wider tyre width can help motorcycle rider control the vehicle while cornering more easily with better stability than that with narrower-width tyre.

In summary, although motorcycle tyre width larger than the original manufactory equipped one did not influence driving stability in the straight path running tests but they significantly help motorcycle riders handle and control their vehicle more easily during cornering. This is advantageous to novice riders faced with high torque from the handlebar caused by leaning or cornering motion. The influence of the wider tyre width in this case could contribute significantly in reducing single vehicle crash of motorcycles.

Acknowledgements

I would like to take this opportunity to thank my Ph.D. advisor, Professor Dr. Pichai Taneerananoon, for supporting me during these past four years. He is a great person who spent his life work promoting road safety in Thailand. Over the course of writing this thesis, Professor Pichai has offered supports and technical advices whenever it was needed. I am thankful to his teaching and motivating techniques which are very ingenious and gracious. I am most grateful to Dr. Kitti Wichettapong, my co-advisor from Khon Kaen University for his kindness in advising me on issues relating to mechanics and statistics and offering knowledge and many insightful comments and suggestions. I am deeply indebted to Associate Professor Dr. Saiprasit Koetniyom, who has kindly accepted to chair my defense exam. Assistant Professor Dr.Paramet Luathep has been generous in passing on his experience, and knowledge. Thank you so much for the generous advice and knowledge during my PhD study.

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Chuthamat Laksanakit

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SYMBOLS AND ABBREVIATIONS

α	: Average Acceleration
α_x	: Angular Acceleration about Longitudinal Axis (x-axis)
α_y	: Angular Acceleration about Lateral Axis (y-axis)
α_z	: Angular Acceleration about Vertical Axis (z-axis)
$\dot{\beta}$	: Vehicle Side-slip Angular Velocity
ε	: Caster Angle
$\dot{\psi}$	: Vehicle Yaw Rate
ω_x	: Angular Velocity about Longitudinal Axis (x-axis), Roll Rate
ω_y	: Angular Velocity about Lateral Axis (y-axis), Pich Rate
ω_z	: Angular Velocity about Vertical Axis (z-axis), Yaw Rate
ω_x / ω_z	: Roll to Yaw Rate
a_y	: Vehicle Lateral Acceleration
G_x / G_z	: Roll to Yaw Rate
H_1	: The Alternative Hypothesis
H_0	: The Null Hypothesis
n	: Sample Sizes
$pitch$	: Rotation Angle in Lateral Direction
q_i	: Static Factors
$roll$	: Rotation Angle in Longitudinal Direction
$\dot{x}$	: Vehicle Velocity
x_i	: Speed Level, Responses Signals
yaw	: Rotation Angle in Vertical Direction
ABS	: Antilock Brake System
ADAS	: Advanced Driver Assistance System
ANCOVA	: Analyzed using an Analysis of Covariance
ANOVA	: The Analysis of Variance
ASEAN	: Association of South East Asian Nations
ATP	: Audio Tactile Profiled
BAC	: Blood Alcohol Content
cc, cm^3	: Cubic Centimeter
CPU	: Central Processing Unit
CSV file	: Comma Separated Value File
DIMEG	: Department of Innovation in Mechanics and Management
DLT	: The Department of Land Transport
DOE	: Design of Experiment
DPMC12	: Disaster Prevention and Mitigation Center 12 Songkhla
GPS	: Global Positioning System
Hz	: Hertz
I/O	: Input Output
IMU	: Inertial Measurement Unit

SYMBOLS AND ABBREVIATIONS (continued)

kg	: Kilogram
km/h	: Kilometer per Hour
kPa	: Kilo Pascal
LPF	: Low-Pass Butterworth Filter
MC, M/C	: Motorcycle
MCP	: Multiple Comparison Procedures
MF	: Median Filter
mHz	: Milli- Hertz
mm	: Millimeter
mph	: Mile per Hour
Min.	: Minimum
Max.	: Maximum
OEM	: Original Equipment Manufacturer
psi	: Pound per Square Inch
RAM	: Random Access Memory
RMS	: Root Mean Square
RVP	: Road Victim Accident Victims Protection
s	: Second
S.D	: Standard Deviation
SPSS	: Statistical Package for the Social Science for Windows
TCS	: Traction Control System
VSC	: Vehicle Stability Control
WF	: Wavelet Filter
WHO	: World Health Organization

LIST OF PAPERS AND PROCEEDINGS

1) Chuthamat Laksanakit and Pichai Taneerananoon. (2014). Motorcycle Defects On Motorcycle Safety In Thailand, 6th-8th August 2014, *Proceeding of the 9th APTE Conference* (pp.58). Colombo, Department of Civil Engineering of Moratuwa, University of Moratuwa.

2) Chuthamat LAKSANAKIT1, Pichai TANEERANANOON, and Kitti WICHETTAPONG. (2016). A Simple Investigation into the Stability of Lightweight Motorcycle. *ENGINEERING JOURNAL, 20(2)*. 199-210.

CHAPTER 1
INTRODUCTION

The purpose of this chapter is to give an introduction of the dissertation. The chapter covered an overview of the state of knowledge on motorcycle accident, the statement of problem, objectives and planned outcomes.

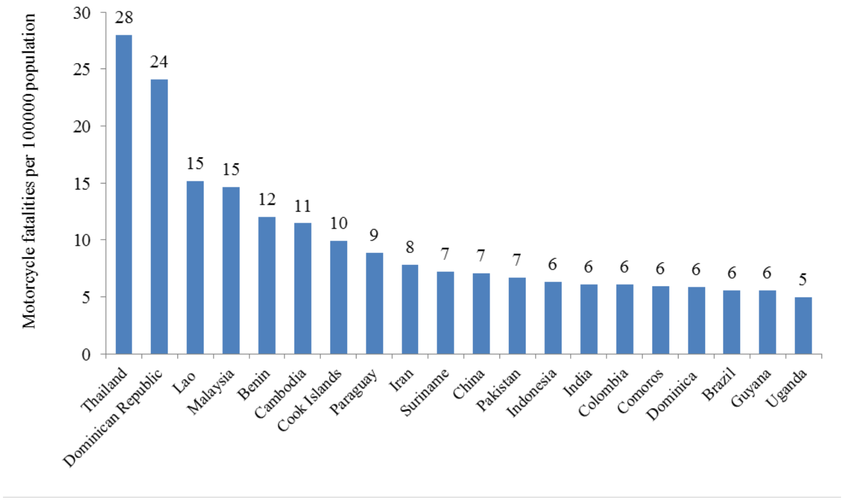
1.1 Background

Thailand has challenging road traffic accident problems the same as neighbors ASEAN countries with a high rate of fatality for the past decade. The statistics of the World Health Organization (WHO) reported that there were more than 300,000 fatalities across the world as a result of motorcycle crashes in 2010; seventy-eight percent of which occurred in Asian countries. Thailand has the highest motorcycle fatality rate of 28 per 100,000 populations (see Figure 1.1 (a)), nearly twice that of Lao, Malaysia and Cambodia (WHO, 2013) and (NGUYEN, 2013). In 2015, the motorcycle fatality rate per 100,000 was reduced to 26 as shown in Figure 1.1 (b). The decrease in motorcycle fatalities was partly due to the success of road safety countermeasures and regulations. It is surprising that these rates do not strongly depend on the increasing numbers of motorcyclists. Of these rates, predictable amounts of 19 percent which estimated from the findings of Kasantikul were single vehicle motorcycle crashes as slippery crash as shown in Figure 1.2 (Kasantikul, 2001a) and (Kasantikul, 2001b). Therefore, the estimated average number of single vehicle crash rate is almost 5.13 per 100,000 populations or almost 3,500 people per year. The cause of this type of collision can be more likely attributed to rider error (e.g. exceeding speed, drinking rider) and or can be attributed partially to infrastructure factors (e.g. defective surface conditions and sharp and steep curve) and or can also be attributed partially to vehicle defects (e.g. improper tyre and barking defects).

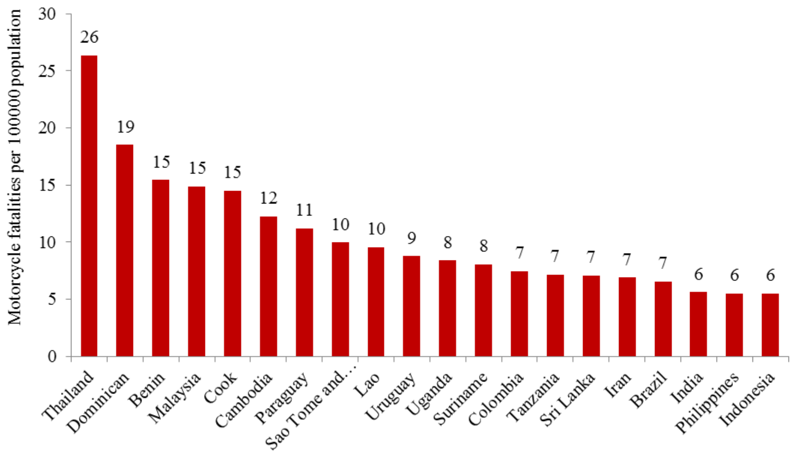
According to the statistics of Royal Thai Police (Figure 1.3 (a)), motorcycle accidents cases consist of more than 60 percent of total road traffic accidents during in 2006 to in 2009 more than double that of car accidents. Although the trend continuously decreased by 32 percent in 2014, there was still a considerable number of which almost 20,000 cases or more than 50 cases a day (Royal Thai Police, 2015). As regards the case of road traffic accident numbers, the fatality number (Figure 1.3 (b)-(c)) in 2010 was nearly 8,000 or nearly 13 per 100,000 population. Motorcycle fatality numbers shared about a half of that with more than 4,000 or every day 12 motorcycle users die in road crash. During the 2011 to 2013 period, the total number of road traffic deaths remained constant at around 8,000 before dramatically dropped to near 6,000 in 2014. From these statistics, it is clear that the vast majority of road traffic fatalities were motorcycle users. The large discrepancy between the number of police reported road traffic deaths (Royal Thai Police, 2015) and those by WHO (WHO, 2013) and (WHO, 2015), was due largely to the fact that police only recorded deaths that occurred at the scene or within a few days of the crash; and also, the secondary cause of deaths of crash victims in hospital was commonly recorded, not the primary cause which was traffic injury. Hence, many crash victims who died in hospital were not counted as traffic deaths.

Additionally, Road Victim Accident Victims Protection (RVP) report has shown that from 2011 to 2015 as shown in Figure 1.4 the total numbers of injuries are unacceptably high at more than 200,000 per year. Most importantly, fatality numbers were on average of 9,000 cases per year, or roughly 24 motorcyclists and passengers die on the road due to traffic accidents every day (Road Accident Victims Protection (in Thai), 2015). It is also highlighting that the fatality number in 2015 was a miniature decrease by about 1.2 percent; on the other hand the numbers of motorcycle user's injury was a rapid increase by almost 8 percent. With this motorcycle situation has come an increase in seriously social and economic losses.

Although motorcycle seems to be a dangerous mode of transport, it boasts a few strong points that make it popular including affordability, fuel economy, travel time saving and ease of parking. The statistics of WHO in 2013 (see Figure 1.5) shows the popularity of motorcycle in developing countries. Four Asian countries (Vietnam, Malaysia, Indonesia, and Thailand) have more than one motorcycle for every four people (NGUYEN, 2013). The production of motorcycle in Thailand has been continuously increasing with over 1 million units sold annually; the cumulative numbers are almost 20 million in 2012 as shown in Figure 1.6 (ASEAN Automotive Federation, 2015). These statistics, however, should be considered taking into account the increase in number of larger motorcycles as shown in Figure 1.7. In 2003, the percentage of motorcycle with engine smaller than 100 cc was similar to those with engine size 101-125cc, at about 50%. However, share of the 101-125 cc motorcycle showed an increasing trend from about 50 % in 2003 to more than 95% in the following decade. It is fair to say that trend in the use of motorcycles with larger engine could be a contributing factor to speeding. As traffic condition in Thailand is a mixture of two wheel and four wheel vehicles, without dedicated lanes for the two wheelers, as a result, the high percentage of motorcycle on the road has inadvertently contributed to many motorcycle accidents both single and multi-vehicle crashes.



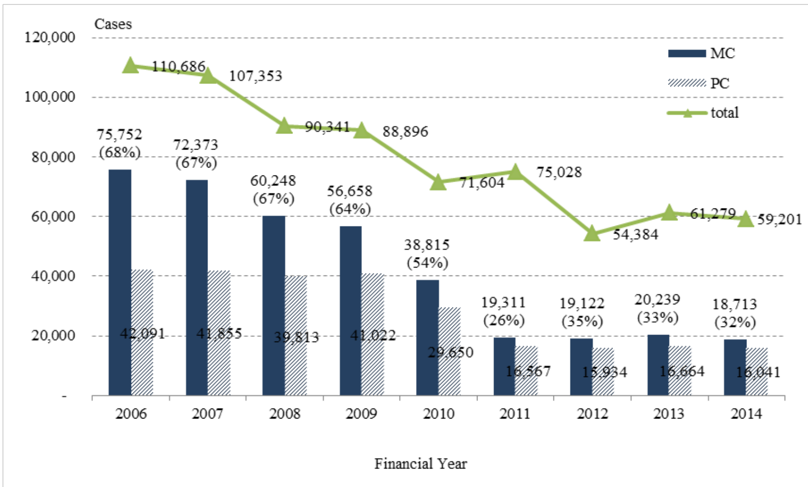
(a) WHO Statistics in 2013



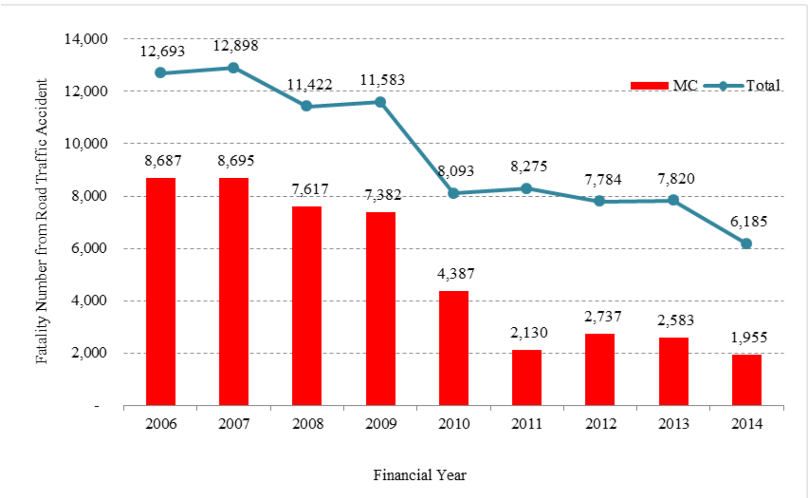
(b) WHO Statistics in 2015

Figure 1.1 Twenty Countries with the Highest Rate of Motorcycle Death per 100,000 Populations (WHO, 2013) and (WHO, 2015)

Figure 1.2 Slippery Motorcycle Crash (Saradee, 2016)



(a) Statistics of Road Accident Cases



(b) Fatality Number of Road Traffic Accidents

(c) Fatality Rate per 100,000 population of Road Traffic Crash

Figure 1.3 Road Traffic Crash Situations in Thailand (Royal Thai Police, 2015)

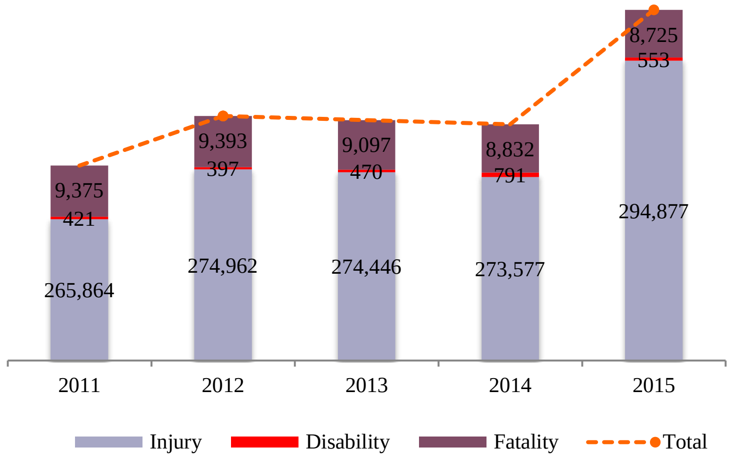


Figure 1.4 Injuries and Fatalities Involving Motorcycle Users
(Road Accident Victims Protection (in Thai), 2015)

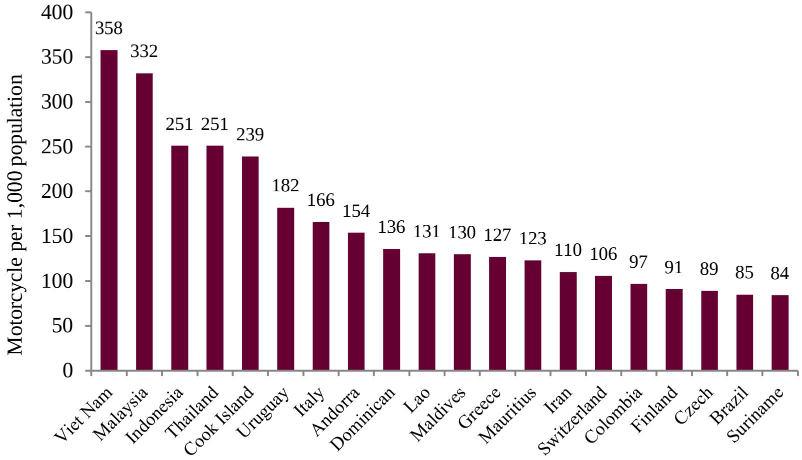


Figure 1.5 The Leading 20 Countries with High Number of Motorcycles
per 1,000 Populations
(Source: Nguyen, 2013, compiling from WHO 2013 data)

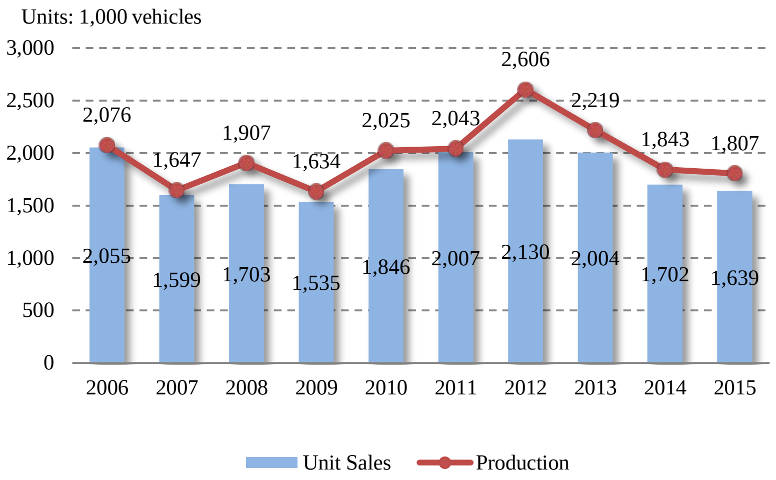


Figure 1.6 Thailand motorcycle production and domestic sales
(ASEAN Automotive Federation, 2015)

As with many developing countries, public transportation systems in Thailand are available only in the capital city, Bangkok, and the city of major provinces. It is perhaps not surprising that, people who live in other areas where public transportation systems are imitated normally use a motorcycle as a low-cost personal transportation system. The Department of Land Transport (DLT) reported that number of motorcycles has surged from 2000 to 2003 with a sharp increasing percentage of total registered motorcycle close to 40% or almost 1.6 million units. As expected, registered motorcycles continued to rise to nearly 2 million units in the following year, 2004. From these figures, it is seen that the vast majority of registered motorcycles were model 101-125cc engine which made up about 78%, followed by model 100cc engine or smaller (DLT, 2015). Currently, there is no universal definition of motorcycle and scooter in Thailand. The Department of Land Transport classifies a registered motorcycle by its engine size. The term lightweight motorcycle is used to refer to a motorcycle that has an engine generally between 101-125cc. and commonly includes scooters. Lightweight motorcycles are kinds of single track vehicle of manual transmission, while scooters are typically an automatic transmission. These vehicles are designed and generally used in urban area for various purposes such as going to school, commuting to work and shopping. The maximum speed is about 160 km/h. Because of growing motorcycling, young motorcycle riders who account for an increased share of and are rather inconspicuous in traffic known for careless driving are contributing to more motorcycle accidents throughout Thailand.

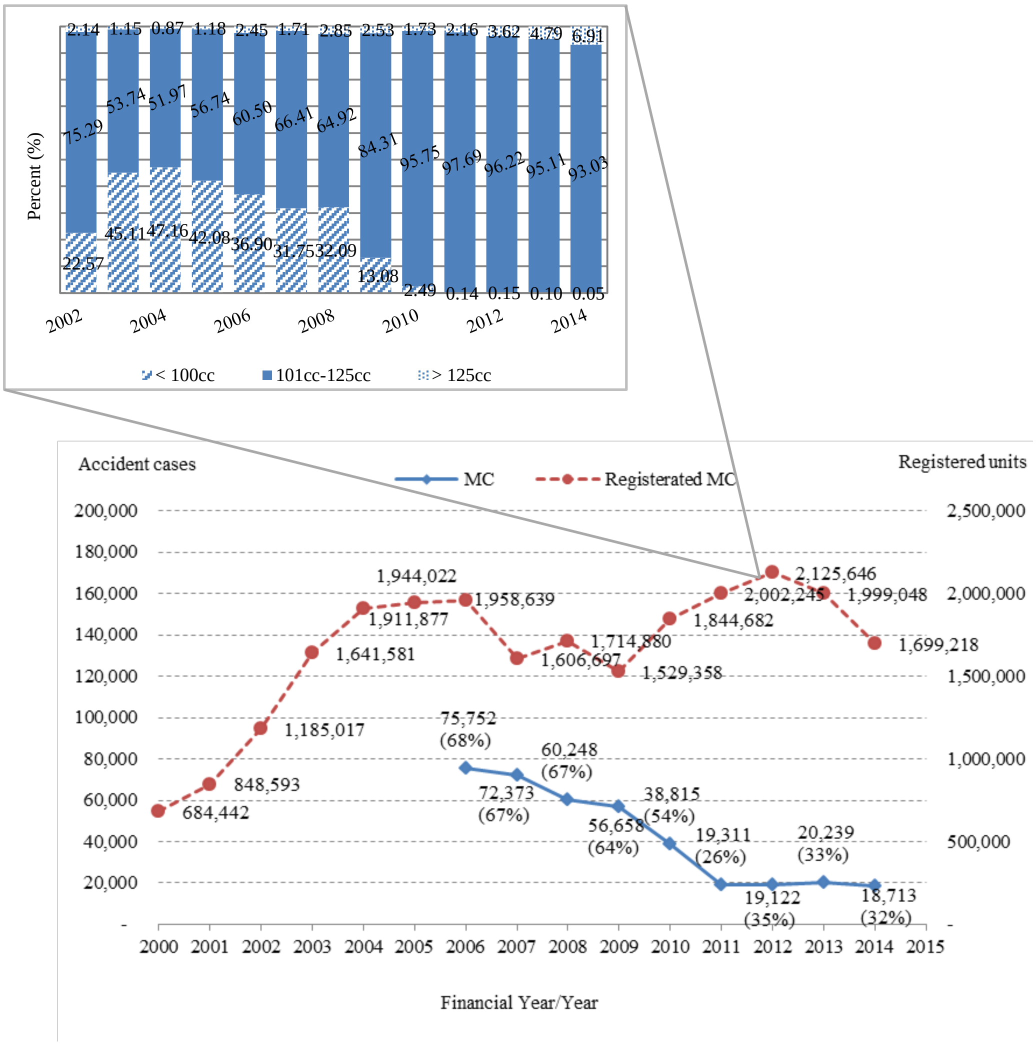


Figure 1.7 Comparison of Motorcycle Accident Cases and Registered Motorcycles and Proportion of Registered Motorcycle Type by Engine Size (DLT, 2015)

Motorcycles differ from other motor vehicles in several attributes. In general, they are inherently unstable systems with only two contact points and the likelihood of them falling over is therefore higher. With this characteristic, a motorcycle can easily become unstable and overturn when braking with heavy force, riding with very high acceleration or speeding on poor road surface conditions. So, motorcyclists in particularly play an important role in controlling a motorcycle in both critical and non-critical situations. The need to provide a safe motorcycle also means that a geometric design and its dynamic behaviours need to be carefully examined. In terms of dynamic behaviours, stability is one of the significant safety treatments that influence the control of the vehicle in both straight line and cornering motion. While competence in riding motorcycle is of great importance, a successful stabilizing and handling of a motorcycle depend critically on the forces between the tyres and the road surface. Motorcycle's frame, chassis, trail and breaking system do not only influence motorcycle dynamics but also the tyre which is one of the components that heavily affect dynamic behavior.

Over the past ten years, a number of researches were conducted in the field of motorcycle accidents. One of the most complete and in-depth study on motorcycle accidents in Thailand was conducted by Kasantikul, 2001 (Kasantikul V. , 2001a) and (Kasantikul V. , 2001b). The studies reported an under research aspect that about one-eighth of motorcycle accidents in Bangkok and about one-fourth in upcountry were single-vehicle collisions; and the most frequent form of collisions was rear-ending another vehicle and motorcycle falling on the road or running off the road, respectively. In terms of vehicle contribution to these crashes, it was found that half of accidents involved 101 to 125 cc engine (or lightweight motorcycle) with OEM (original equipment manufacturer) tyres; especially in such cases the state of tyre characteristics could play an important role in the occurrence of single-vehicle crash. These findings pose the question as to how much influence tyre characteristics have on the stability of a motorcycle. As the tyre is the only component of the motorcycle that transfers forces and moments between the vehicle and the road; a comprehensive understanding of tyre factors influencing motorcycle crashes will contribute to the prevention of crashes relating to defective/inappropriate tyre thus resulting in the saving of lives of motorcycle users.

The study of factors affecting lightweight motorcycle accidents have mostly focused on motorcycle riding behaviours (Yuen, Karim, & Saifiaul, 2014a), (Yuen, Karim, & Saifizul, 2014b), and (Yuen, Karim, & Saifuzul, 2015). There was little number of researches that addressed vehicle stability or other incidental causes of motorcycle crashes. Some recent studies on stability had investigated a variety of issues such as driving stability and braking stability (Seiniger, Schroter, & Gail, 2012), (Cheli, Pezzola, Leo, Ibrahim, & Saita, 2010), and (Cossalter V. , Doria , Basso, & Fabris, 2004). However, they were carried out on high performance motorcycles. These experimental studies were normally performed by using various high-performance sensors as devices for measuring real data and needed a huge funding for the researches. Fortunately, over the past few years the use of a smartphone, which is embedded with sensors for collecting real-time information has been shown to give satisfactory measurements in many researches (Ferrer & Ruiz, 2014), (Douangphachanh & Oneyama, 2014), (Douangphachanh & Oneyama, 2013), (Astarita, et al., 2012), and (Sekine, 2014). The high technology smartphone is thus capable of collecting accurate data.

In the 2011-2020 Decade of Action for Road Safety, the implementation of road safety strategies such as strengthening institutional capacity, improving road safety network, improving vehicle safety and developing better road user behaviors has been ongoing to reduce road traffic accident. However, on vehicle safety, the issue of safety of the motorcycle itself has received little attention, especially, on characteristics relating to safety, including the lack of stability, rider and passenger protection and hazard warning system. There is an urgent and great need to address them as they can significantly help improve safety of motorcycle users.

Under this perspective a comprehensive study on the contribution of tyre characteristics especially tyre width to motorcycle stability which has been an important cause of single-vehicle crash is proposed. The study aims to demonstrate that as the motorcycle tyre width increases the motorcycle stability increases, under different experimental conditions including vehicle speeds and riding pattern. The proposed experiments will show how OEM tyres affect motorcycle stability when the vehicle is being ridden in straight line or cornering motion. In addition, the study will help establish the suitable tyre width for commercial lightweight motorcycle in Thailand that takes into account the key element of safety. Relating studies will be conducted in order to evaluate the reliability of smartphone in measuring the dynamic stability parameters associated with straight running and cornering tests. This study will investigate a range of orientation of motorcycle during its movements in 3-global axis that correlate the stability of the motorcycle with specific speeds. Analysis of variances of dynamic measurements of different tyre sets at varying speeds that influence the motorcycle stability will be carried.in the study.

1.2 Objectives

1.2.1 To examine the potential of dynamic properties of a motorcycle on its stability by varying motorcycle tyre width using the full-scale physical riding test (Straight running test and Slalom test).

1.2.2 To recommend the suitable subsystem for Thai motorcycle model.

1.2.3 To promote vehicle safety research focusing on contribution of motorcycle tyre width in motorcycle single vehicle crash.

1.3 Scope of the Study

A typical lightweight motorcycle (SUZUKI SkyDrive 125) with a 124 cm^3 engine was selected for this study. Three different tyre characteristics were used for the full-scale physical riding test including straight running test and slalom test. With respect to the standard configurations, the SUZUKI Sky Drive has 14 inch spoke wheel rims with 70 mm tyre width/ 80 mm height for the front wheel and 80 mm tyre width/ 90 mm height for rear wheel, the configuration was designated as Tyre set A. Motorcycle tyre width with the same 90 mm tyre width/ 90 mm height for both the front and rear wheels was designated as Tyre set B and motorcycle tyre width with the front wheel of 110 mm width/ 70 mm height and the rear wheel 120 mm width/70 mm height as Tyre set C. The straight running test and slalom test were conducted based on the experimental design. Seven dynamic parameters of motorcycle of both running test were investigated. Furthermore, the multiple comparisons were tested at the 95 % confidence level.

1.4 Planned Outcomes

1.4.1 Better understanding of the effects of tyre width on the dynamic behaviours of motorcycle.

1.4.2 Significant safety benefits for Thai motorcycle users and manufacturers.

1.4.3 Vehicle safety recommendations for Thai government

1.5 Organisation of the Thesis

The organisation of this thesis is as follows: A literature review on the state of the art of stability research of motorcycle is presented in chapter 2. Methods to investigate the dynamic behaviours of vehicles are developed in chapters 3. The results of given experiments are presented in chapter 4. Finally, chapter 5 gives the discussions and conclusions.

CHAPTER 2
REVIEW OF LITERATURE

The purpose of this chapter is to give a literature survey on motorcycle accidents. The issues covered are presented roughly in chronological order and relate to theoretical studies through contribution factors to motorcycle crashes, vehicle defects and stabilities of motorcycle that have happened in the last decades. The literature review is divided into five topics. The magnitude of motorcycle accident problem, contribution to motorcycle crashes, the explanation of motorcycle stability measuring motorcycle stability including straight line test and non-straight line test, tyre characteristics and summary of key literature reviews were reviewed.

2.1 Magnitude of Motorcycle Accident Problem

A motorcycle accident is one of common traffic problems in Thailand, as widely occurred in other developing countries, and has an extensive impact at the personal, social and economic levels. Reports from the financial year 2015 of Royal Thai Police (Royal Thai Police, 2015) indicated that about three in ten road traffic accident cases take place in one of the general forms of a motorcycle accident. Over the five years from 2006 to 2010, speeding, improper passing and alcohol impairments involved in all accident with the top three causation, compared to 65 percent for motorcycle accidents.

With a parallel consideration of the report from the 2014 Road Accident Victims Protection (Road Accident Victims Protection (in Thai), 2015) stated that the greater share of the claims was a motorcycle user and more than 60 percent of all claims was motorcycle rollovers or run-off-road. The fatality rate of motorcycling varies across age and most fatalities range from 15 to 24 years (Table 2.1). Motorcycle rollovers or run-off-road is the most prevalent, affecting approximately 55 percent of all single vehicle crashes each year. Collectively referred to as a high percentage motorcycle run-off-road collision claims, these include an estimated average of 57 percent of injuries, 31 percent of disability and 26 percent of fatalities. It is not uncommon to see more male victims than female in a motorcycle accident, which account for about 60% of all victims. If part of these accidents can be ascribed to the error of riders and defect of vehicle components, the latter case which is more likely uncomplicated addressed seem to be dominant clarifying variables. Because not all motorcycles which are travelling on a real road are in safe conditions and for several reasons vehicle dynamics and safety have not been considered as much as rider behaviour despite the fact that vehicles are also important contributing factors of motorcycle safety. Therefore, there is an utmost need to further studies on vehicular defects to address the influence of motorcycle components on run-off-road accidents.

To increase the depth of understanding of motorcycle crash characteristics in Thailand, since the early of 2000s a number of related research works have been conducted to identify human factors associated with motorcycle crash causation. The key finding by Rojviroon was that young motorcycle riders had poor safe driving behaviour (Rojviroon, 2006). Their habits of poor driving need to be improved. Some similar results were reported regarding poor riding. A study by Ngamsom et al, 2009 shows that young motorcyclists in 18-35 age group tend to violate traffic laws more than other age groups (Ngamsom, Suttayamully, & Limanond, 2009). Moreover, it was stated that the key risk element, the inexperience of riders, would seem to be a primary contributing factor to motorcycle crashes (Pibool & Taneerananon, 2012).

In addition, Kasantikul found that alcohol was a major cause of motorcycle crashes (Kasantikul, Ouellet, Smith, Sirathranont, & Panichabhongse, 2005) Most of the alcohol effects were evident in the “loss of control” motorcycle crashes resulting in the run-off road or single vehicular crash. Contrary to conventional findings, Saisama found that most of the shuttle-motorcycle riders obeyed traffic laws, gave responsible services to their customers and possessed acceptable behaviours regarding, emotional control, awareness of protective behaviours against accidents from motorcycle riding (Saisema, 2005) and (Woratanarat, Ingsathit, Chatchaipan, & Suriyawongpaisal, 2013).

From the above literatures, it can be summarized that most young motorcycle riders in Thailand have been riding without proper concern of and awareness of road safety. It was suggested that education and the safety riding program should be used to bridge the safety gaps for motorcyclists in order to reduce motorcycle related injuries and fatalities (Woratanarat, Ingsathit, Chatchaipan, & Suriyawongpaisal, 2013). As far as human factors and its influences, studied have conducted in various aspects, but their specific influences to defected motorcycles on riding behaviours remain to be discovered.

The fact that these motorcycle accident figures are serious road traffic problems. All sectors of society, the government sector, the private sector and civil society: should continue to try to prevent or protect road user lives. Further, it should also ensure that each road networks, vehicles, environments would be safe. This situation can also be induced by the influence of vehicle factors, such as motorcycle tyre, count to the best safe and performance.

Table 2.1 Claims Involving Road Users

Year	Case	Injury	%	Disability	%	Fatal	%	Total
2011	All vehicles	**279,102**		**479**		**10,514**		**290,095**
	MC	265,864	(95)	421	(88)	9,375	(89)	275,660
	All vehicle rollovers / run-off-road	161,774	(58)	148	(31)	3,097	(29)	165,019
	Estimated MC rollovers/run-off-road	154,101	(55)	130	(27)	2,761	(26)	156,808
2012	All vehicles	**287,537**		**433**		**10,561**		**298,531**
	MC	274,962	(96)	397	(92)	9,393	(89)	284,752
	All vehicle rollovers / run-off-road	167,687	(58)	152	(35)	3,101	(29)	170,940
	Estimated MC rollovers/run-off-road	160,353	(56)	139	(32)	2,758	(26)	163,050
2013	All vehicles	**283,292**		**510**		**10,078**		**293,880**
	MC	274,446	(97)	470	(92)	9,097	(90)	284,013
	All vehicle rollovers / run-off-road	167,783	(59)	161	(32)	2,902	(29)	170,846
	Estimated MC rollovers/run-off-road	162,544	(57)	148	(29)	2,620	(26)	165,110
2014	All vehicles	**281,499**		**862**		**9,717**		**292,078**
	MC	273,577	(97)	791	(92)	8,832	(91)	283,200
	All vehicle rollovers / run-off-road	168,310	(60)	318	(37)	2,752	(28)	171,380
	Estimated MC rollovers/run-off-road	163,573	(58)	292	(34)	2,501	(26)	166,171

There is, therefore, an essential need to gain an understanding of the cause of serious run-off-road motorcycle accidents. These are believed to have been probably based on inexperience and violent behaviour of young riders and involvement in unusual condition of vehicle mechanism. Although this kind of motorcycle accident needs is yet to be thoroughly studied in order to attain a complete understanding of the causes of motorcycle accidents, there is a strong inclination towards the following reasons. Firstly, the motorcycle population shared the highest percentage, hence the more the motorcycle is used the more probability of an accident. Also, the single vehicle accidents of motorcycle would be directly boosted proportionality. Secondly, in case of in-depth investigations, other factors especially vehicle defects contributed to crash seem to be under-reported by related authorities because of the limitation of expertise and budgets. A total understanding of motorcycle mechanism accident phenomena which is a complicated system would not only lead to the attainment of solutions to these problems, but can also is used in the consequent actions imposed by the government. Further, these could be give valuable information for rider skill training development.

2.2 Contributing Factors to Motorcycle Crashes

Contributory factors of motorcycle crashes have been reported by several authorities which show a similar pattern to other road crashes, with the driver/rider errors as most prominent, followed by infrastructure defects and vehicle defects. For driver/rider errors, the police records (Royal Thai Police, 2015) show that speeding, high blood alcohol concentration, and improper passing were the key errors in a road crash. Additionally, the study of Kasantikul et al. proved that alcohol impairment was the most prominent cause factor of a motorcycle crash in Thailand (Kasantikul, Ouellet, Smith, Sirathranont, & Panichabhongse, 2005). In this study, moreover, drunk riders were found more likely to be in loss of control crashes. As for single vehicle crashes, findings by the Motorcycle Council of New South Wales show that unexpected percentage of drunk riding was twenty-five with around half of that was on curves (The Motorcycle Council of New South Wales, 2010). Also, a study of (Ngamsom, Suttayamully, & Limanond, 2009) confirmed that young motorcyclists (aged 15-35) tend to be inconspicuous in traffic similar to the finding of two other studies (Ponboon, Islam, Ponboon, Kanitpong, & Tanaboriboon, 2010). For infrastructure defects, poor traffic signage and road marking, sharp and steep curves and defective road surface were the most common factors involved in a motorcycle crash. A significant proportion of road surface hazards such as loose gravel, diesel spill or a pothole were involved in motorcycle single vehicle crash. For vehicle defects, the spotlight was on the motorcycle stability which is the heart of vehicle safety. Table 2.2 summarized the main findings of motorcycle stability studies.

Overall information of stability studies in Table 2.2 illustrated that most of the experimental research have been done on high-performance motorcycles with engine size 250cc or over. There were necessary measurement variables that can be classified into two groups of static variables and dynamic variables. Static variables were considered as a vertical load on a wheel and physical properties. In terms of dynamic variables, roll, pitch and yaw velocities, longitudinal, lateral and vertical accelerations, brake force, steering angle, steering torque and also vehicle speed were measured. It is important to note that a few research included motorcycle tyre characteristics. Therefore, investigating the influence of tyre characteristics especially tyre width on a lightweight motorcycle (lower 125cc) that constituted the highest percent of Thai motorcycle registrations (DLT, 2015) would seem more beneficial in the understanding of contributing factors to motorcycle crashes in Thailand.

Table 2.2 Studies Investigating the Stability of Motorcycle

Authors	Title	Method/ Experiment/ Vehicle	Measurement Variables	Main Findings
Jamieson et al. (2013)	*Stability of motorcycles on audio tactile profiled (ATP) road markings*	Full-scale physical test with HONDA CBR 1100XX and simulation modeling with PC-Crash	▸vertical rear wheel load ▸vertical accelerations of the front & rear wheel ▸pitch, roll, and yaw ▸longitudinal, lateral, and vertical accelerations	▸No evidence refers that ATP road markings create any instability matter for motorcycle
Seiniger et al., 2010	*Perspectives for motorcycle stability control systems*	Detect critical driving situation of Motorcycle Anti-Lock Brake Systems of BMW F800S	▸throttle ▸brake force ▸roll angle ▸roll rate ▸steering angle ▸physical properties of motorcycle such as wheel base, front wheel caster and vehicle weight	▸Motorcycle Anti-Lock Brake Systems (ABSs) have a positive effect on motorcycle and have the potential to reduce motorcycle fatalities ▸Vehicle dynamics control systems will be possible device for common motorcycle ▸ Full Electronic Stability Control for motorcycles will not be possible in the near future.
Cheli et al. (2010)	*Motorcycle Dynamic Stability Monitoring During Standard Riding Conditions*	a high performance sports motorcycle	▸steering angle ▸lateral acceleration	▸Advanced Driver Assistance System (ADAS) able to identify a dynamic instability of a generic motorcycle
Salvador & Fabris (2004)	*Study of Stability of a Two Wheeled Vehicle through experiments on the road and in laboratory*	a high performance sports motorcycle and a typical 250 cc scooter	▸steering angle ▸steering torque ▸vehicle roll and yaw velocities and acceleration ▸vehicle speed ▸front tyre characteristics	▸wobble mode damping increasing directly depends on increasing front tyre inflation, stiffness chassis, and front frame inertia about motorcycle head axis.

2.3 Explanation of Motorcycle Stability

The term stability was defined in (Merriam-Webster, 2015) as "stability is the property of a body that causes it when disturbed from a condition of equilibrium or steady motion to develop forces or moments that restore the original condition". Additionally, in field of motorcycle dynamics (Cossalter V. , 2006) offer the meaning of the motorcycle stability as "stability is the properties of motorcycle to maintain its equilibrium and follow a rectilinear path" and "stability means a motorcycle's ability to maintain equilibrium in response to outside disturbances like an uneven road surface or gusts of wind". The study of motorcycle stability will be presented as dynamics which includes two parts of kinematics and kinetics. The analysis of forces and moments causing the motorcycle motion will be considered in this part.

Motorcycle stability is a mechanism of the motion of a vehicle and its design that directly depend on forces (centrifugal force and gravitational force) and moment (the handle bars' torque) acting on them. Cossalter, 2006 stated that vehicle factors such as inertial properties of the motorcycle, speed, geometric properties of the steering head, gyroscopic effects and also tire properties are normally considered in directional stability and braking stability. The ability of motorcycle to remain in equilibrium or to keep in a vertical position while moving forward or cornering is a common definition of the motorcycle stability. These mechanisms are basically consisted of rider control when speed is very low and gyroscopic phenomenal when speed is sufficiently high. The driving stability of motorcycle in rectilinear translation condition is defined by the fact that available friction is higher than lateral acceleration (Cocco, 2013). Particularly, friction can be generated by the tyres and contributed to horizontal forces. The tyre width has a deep influence on centrifugal force.

There are various techniques for explaining stability behaviours of a motorcycle, such as objective measurements or subjective vehicle dynamic behaviour during a driving condition. The objective measurements are a validation of selected measured parameters. Whereas the subjective measurement is an evaluation of participant feeling by rating the decided subjects. The very effective of subjective method give to a widely used in many previous types of research (Cossalter V. , Doria , Basso, & Fabris, 2004), (Cossalter, Doria, & Maso, 2006), (Seiniger, Schroter, & Gail, 2012).and (Jamieson, Frith, Lester, & Dravitzki, 2013). On the objective study, for example, (Salvador & Fabris, 2004) have employed the riding experimental and modal analysis software for studying motorcycle (a scooter) stability. The three modes of frequency; wobble mode, weave mode and capsize mode; involved in yaw and yaw oscillations, steering angle and torque, vehicle roll and yaw velocities and accelerations and also vehicle speed were considered. The wobble mode is defined as an oscillation of the front end around the steering axis which does not involve the rear end. The weave mode is an oscillation of the entire motorcycle, but mainly the rear end. Whereas the capsize mode is a non-oscillation mode used and controlled by the rider. These modes of vibration are illustrated in Figure 2.1 (a)-(c) (Cossalter V. , 2006). The identification has consequently employed by studying the influence of tyre characteristics, front frame inertia, and chassis stiffness on vehicle stability. As observed by Cheli et al. 2010, that the frequency responses of weave mode of a sports motorcycle and a scooter between the experimental root loci and the numerical root loci have a good accordance, whereas frequency responses of wobble mode are hardly observed by the experimental method. Cossalter, Lot, & Rota, 2010 have validated riding feeling of the motorcycle simulator named the DIMEG motorcycle simulator by using the motorcycle test comparing with the simulator. The frequency measurement of the most relevant dynamic parameters consisting of roll angle, roll rate, pitch angle, yaw rate, yaw acceleration, steering torque and steering angle were evaluated for comparing the maneuvers of the real and the simulated.

(a) (b) (c)

Figure 2.1 Three Modes of Vibration of Motorcycle (Cossalter V. , 2006)
(a) Capsize Mode, (b) Wobble Mode (c) Weave Mode

From the theoretical point of view, motorcycle stability behaviour is normally recognized by monitoring the motion characteristics throughout the roll angle; the pitch angle and yaw angle (see Figure 2.1). The responses of roll angle are a representation of vehicle rotation respect to a vertical plane. Since a motorcycle has only two supporting points of the front and rear wheel along the longitudinal axis, the rotation in the vertical plane would be easily occurred. The vehicle seems to be less stable in the lateral direction. A roll angle or roll rate, therefore, strongly influence the stability of motorcycle. A high stability vehicle would have a minimum range of roll angle. More in detail, a lower quantity of roll means that the lateral acceleration is less than the available friction which conducted by the tyre and road surface. By these behaviours, the vehicle speed always involves and plays an important role on all dynamic parameters.

The pitch angle is a vehicle orientation with regard to the x-axis as shown in Figure 2.2. A feedback pitch angle of a motorcycle, in particular, was used for identifying the stability when braking or accelerating that can rotate a motorcycle around a lateral axis. Unlike an aircraft, the motorcycle pitch angle is limited by frame and suspension. Importantly, front and rear wheel that remain the ground act as a support of the vehicle. The observation of the pitch angle as a consequence of the motion of motorcycle around y-axis was required for identifying the stability state and the comfortable configuration of a motorcycle. As carried out by (Jamieson, Frith, Lester, & Dravitzki, 2013), the noticeable changes in the pitch and yaw responses from the full-scale physical riding test were not detected. By considering the pitch angle as a key parameter, they claimed that motorcycling over the audio tactile profiled (ATP) road marking as shown in Fig 2.3 could be maintained consistently. Furthermore, the work of (Saccon & Hauser, 2009) that study the kinematics of single track vehicles. By considering the general class of tyre and general vehicle geometry, it was found that the kinematic problem may be reduced if the pitch angle in a (single) nonlinear equation was a zero value.

The change of steering angle is related to torque performance on the handles bar of a motorcycle. This variable normally refers to the handling of the motorcycle. While cornering or braking, riders should grab the handle bars fast in order to deal with a high quantity of steering torque and at the same time to stabilize a vehicle. Steering angle was used for optimizing the worst-case closed-loop gain from road forcing disturbances by (Evangelou , 2003) and (Evangelou, Limebeer, Sharp, & Smith, 2007).

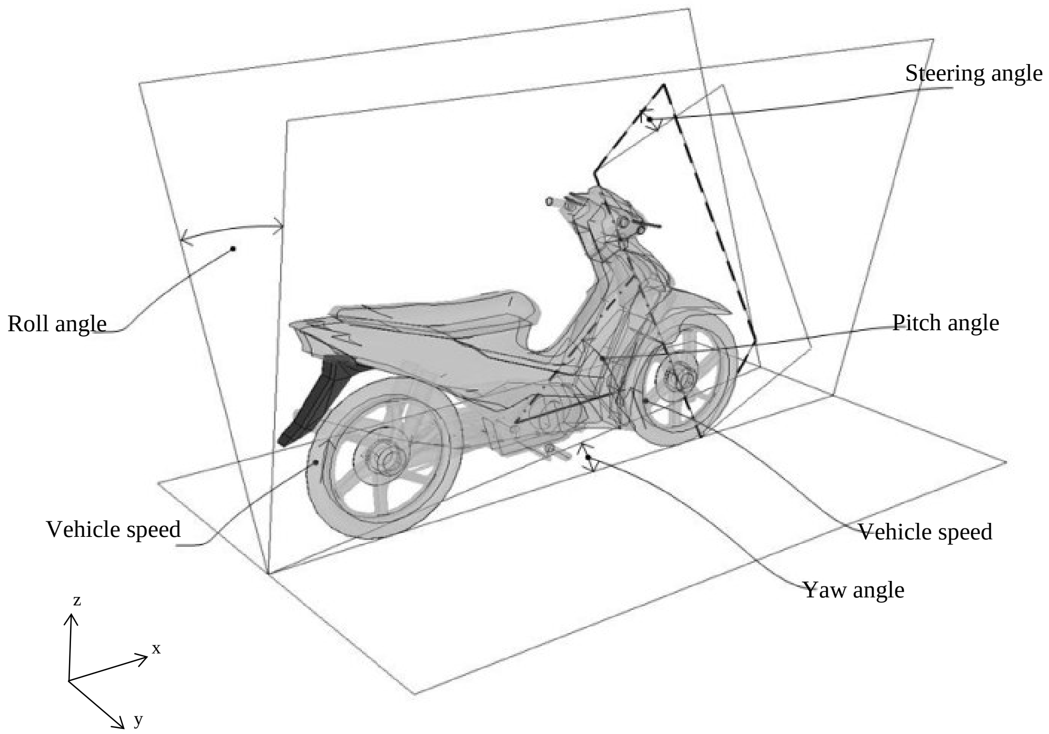


Figure 2.2 Schematic View of Motorcycle

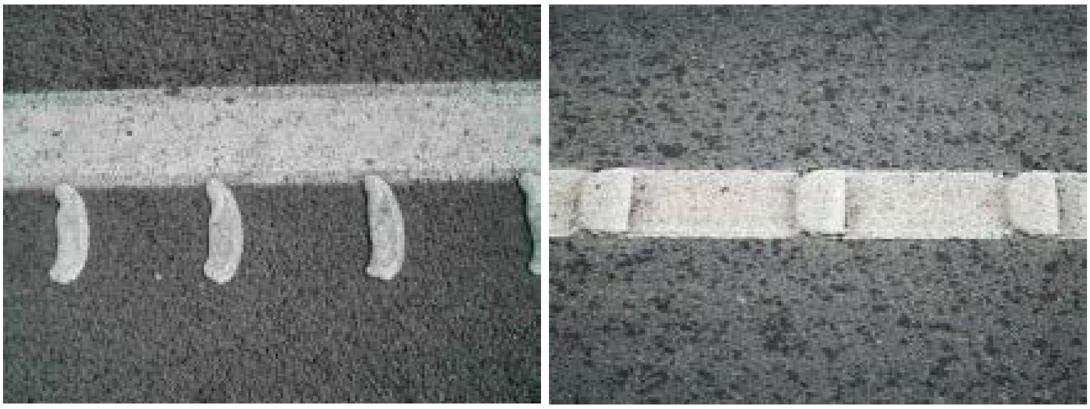


Figure 2.3 Audio Tactile Profiled (ATP) used in New Zealand
(Jamieson, Frith, Lester, & Dravitzki, 2013)

2.4 Measuring Motorcycle Stability

As widely presented in literature, motorcycle behaviours were considered as a control system. The appropriate inputs of such motorcycle properties and speed also contributed to stability output. The measurement of frequency and damping responses of motorcycling has more advantages for identifying a change of vehicle state. The stability state of this system could be defined as the responses of frequency and damping tend to be zero.

In the area of measuring the stability of conventional motorcycles, most existing work in motorcycle stability measurement can be grouped into three forms: those based on a mathematical model method, a numerical model method, and an experimental method. A numerical model is a kind of mathematical models that use some sort of numerical time-stepping procedure to achieve a more complex physical reality. All of these methods were based on the identification of characteristics of frequency and oscillation of the response vibration in 3-global axes such as roll, pitch yaw and steering torque. By the experimental observations of motorcycle dynamics (Cossalter V. , 2006). The study concluded that there are three major modes of vibration consisting of capsize mode (or kickback mode), weave mode and wobble mode. The capsize mode is the typical mode that normally controlled by the motorcyclist. The weave mode is the vibration and oscillation of the rear end assembly of a motorcycle. This mode is generally unstable when a vehicle is in a very low motion. For the wobble mode, it is defined as an oscillation of the front assembly around the motorcycle steering head. The important motorcycle characteristics like a centre of mass, wheel radius, rake angle (caster angle) and trail (see Fig. 2.4) and also dynamic factor such as vehicle weight, speed and coefficient of friction could determine the possible stability on a motorcycle.

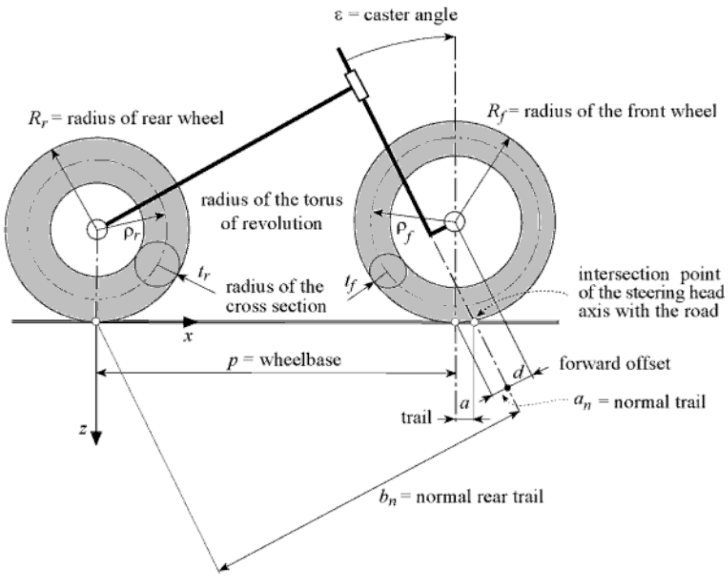


Figure 2.4 Motorcycle Geometry (Cossalter V. , 2006)

(Ghosh & Mukhopadhyay, 2009) used the C programing to simulate the stability of two-wheeler vehicle, considering two situations of curve negotiation with and without braking. The fundamental equations of forces (normal force on the wheel, centrifugal force, and lateral force), torque (at the handlebar) and angular momentum were analyzed as a function of various running speeds under different magnitudes of braking forces. The time responses of roll angle were revealed as a stability identification factor in terms of amplitude and oscillation characteristics. The results were obtained that stability of two-wheeler vehicle was contributed forward by the mass and the trail of the front wheel. Compared with stability parameters, a weight of mass and the trail was tolerable, but further study considered other parameters like tyre characteristics and road conditions would result in a series of contributing factors.

The experimental research conducted by (Seiniger, Schröter, & Gail, 2010) purposed to study the possibility of Antilock Brake System (ABS) and Traction Control System (TCS) development. The use of a test motorcycle (BMW S1000RR) equipped with outriggers and valuable sensor devices for measuring the driving and braking stability response parameters such as vehicle velocity $\dot{x}$, vehicle yaw rate $\dot{\psi}$ and vehicle lateral acceleration a_y could commonly be a great help for the researcher to assess the real behaviours of a motorcycle. In one typical experiment, the vehicle side-slip angular velocity $\dot{\beta}$ which is the angle between the alignment of the vehicle and the actual direction of travel were calculated. These extensive testing data were used to detect a critical and uncritical driving situation. The vehicle response parameters were not only measured, but the mental strains of the rider were also observed indirectly by using the heart rate. The findings from the three different braking conditions (straight braking, braking from 90 and 60 km/h and corner braking) presented that the braking distances with ABS in straight braking were shorter than in corner braking of about 60%. Without ABS the rider strain was higher.

The conclusion of this study was that ABS should be equipped to all motorcycles because it could provide a safer motorcycle component.

In order to observe whether typical stability characteristics of motorcycle riding tests, laboratory test and also computer simulation designed to identify and evaluate that conditions. Many of them such as (Cossalter V. , Doria , Basso, & Fabris, 2004), (Cossalter, Doria, & Maso, 2006) (Cheli, Pezzola, Leo, Ibrahim, & Saita, 2010) and (Salvador & Fabris, 2004) analysed their valuable data using the frequency response function (FRFs). The typical dynamic parameters effect on motorcycling stability as widely reported in the literature included three principal rotation of the vehicle (yaw, roll and pitch), lateral displacement, steering torque, a rotational of handle bar or steering angle, angular acceleration and lateral acceleration were used for identification instability state. Because almost data examined from high performance motorcycle as a super-sport motorcycle and a maxi-scooter with a 500 cc engine which used by Cossalter et al., a high performance sports motorcycle and a typical 250 cc scooter studied by Cheli et al. and a scooter. These may noted that the study on stability of a lightweight motorcycle which engine capacity lower 125 cc should be take into account exclusively as obtained by this study.

Existing research does not focus on the impact which motorcycle tyre width can have on dynamic driving and braking stability. After studying the possible of anti-lock brake system (ABSs) and traction control system (TCS) (Seiniger, Schröter, & Gail, 2010) came to the conclusion that motorcycle ABSs have a positive consequence on motorcycling with 60 percent shorter braking distance when running in straight path than when cornering. However, (Ghosh & Mukhopadhyay, 2009) conducted their research using C language computer simulation with different levels of braking force and speeds in upright and lean angle conditions known to analyse a simple motorcycle model. Ghosh & Mukhopadhyay found that applying braking force was seriously affected on motorcyle stability and also increasing braking force can decrease to some extent of the peak amplitude of roll. The settle of roll oscillation seem to come to the rest faster even braking force increased and appropriated torque on the handle bar applied. Moreover, (Salvador & Fabris, 2004), who conducted the road test and laboratory test with a scooter, substantiated the claim that wobble mode damping imprement which promote vehicle stability is strongly influenced by characteristics of front tire inflation stiffness chassis, front frame inertia about steering axis and sideslip stiffness of front tire. It has been clearly established that, Seiniger, Schröter & Gail’s findings appeared to similar behaviours that of Ghosh & Mukhopadhyay, while Salvador & Fabris results presented more influencing parameters on motorcycle stability. This could be because Salvador & Fabris attented to only driving stability behaviour do not focused on braking stability behaviour of motorcycle.

2.4.1 Straight Line Testing

(Sharp & Limebeer, 2004) obtained the understanding for steering wobble oscillations by simulating a manoeuvering motorcycle and rider. They also determined the rider upper body and arm structural parameters associated with a forced motion of the steering wheel. Sharp & Limebeer used the straight run simulation with a very high speed for detecting the oscillation operation. The findings indicated that steering wobble oscillations develop more dynamically as amplitude increases beyond a very small initial steer angle. Moreover, the stabilizing impact of the rider's tensing his/her muscles in response to a growing wobble problem is small.

(Salvador & Fabris, 2004) carried out a stability study of a two-wheeled vehicle by producing the full-scale physical experiments on straight running test the road and then conducting the analysis in the laboratory. Two separate parts were considered, one with the wobble mode and its time evolution, identification based on the road testing, and the other with the modal analysis of the scooter based on laboratory testing. The road testing exposed some important results. It predicted the presence of important factors influence wobble frequency and damping throughout the front frame inertia value, front tyre sideslip stiffness and chassis stiffness. Whereas front tyre inflation pressure influenced on wobble damping increasing. The laboratory testing using the modal analysis software named MESHGEN showed a complete influence on wobble frequency of the scooter structure in a low-frequency band (12.6 Hz). The torsion of the front and rear structure is very flexible. These confirmed that wobble mode could be precarious for this kind of two-wheeled vehicles.

(Evangelou, Limebeer, Sharp, & Smith, 2007) used mechanical steering compensators which are mechanical networks consisting of springs, dampers, and inertia to improve the dynamic behaviour of high-performance motorcycles (the Suzuki GSX-R1000). The study focused on the role of the wobble and weave mode of primary oscillatory in maintaining dynamic stability properties. The computer simulations were conducted to synthesise the networks of the inertia and the passive circuit. The straight-running test which is the condition of the three translational and three rotational freedoms of the main frame, a steering freedom associated with the rotation of the front frame relative to the main frame, and the influences of spinning road wheels were produced in the motorcycle model named AUTOSIM. The study's results show that a possibility of the use of active steering compensation was a practical advantage.

The study by (Gail, Funke, Seiniger, & Westerkamp, 2009) showed the examination of the safety potential of Anti-Lock Braking Systems (ABSs) and Vehicle Stability Control (VSC) for motorcycles. Accident analysis, driving test and technical assessment of these systems were acquired from braking tasks in straight and in-curve path. The driving tests were done for five different brake systems each tasks measuring the stopping distance of the vehicle, stress and strain on the riders. The heart rate of test persons who performed the test without ABS was higher than with ABS. ABS helps both prevent rider and motorcycle from the critical riding situation and bring down the mental strain while riding and braking. A cost-benefit analysis of ABS was found to be economically reasonable. Pointing to explain the potential of VSC, Gail et al. included the estimation of VSC ability to prevent or detect the accident. For VSC behaviour study, Gail et al. conducted the real-world experiments of simulated accidents using a test motorcycle and computer simulation with the simulation package VI/Motorcycle, resulting from these sources was then derived by using a mathematical model. The results suggested that the future dynamic control systems cannot be recommended at today's motorcycles because it was estimated at very low potential. Accordingly the system is highly economically sensible with above four times and motorcycle accidents influenced by this system are only a subgroup of the mentioned 4 to 8 % of all accidents.

(Marumo & Katayama 2009) tried to point out the existence of effects of structural flexibility on motorcycle straight running stability. A linearized four-degree-of-freedom model proposed by Sharp (Sharp R. , 1971) included six aspects of structural flexibility: lateral bending of front fork, lateral bending of main frame, lateral bending of rear swing arm, torsion of main frame, torsion of main frame and torsion of rear swing arm: were used to compare the effect straight running stability. The dynamic variable as lateral velocity, yawing angle, rolling angle and steering angle were provided by means of an external force acting on each degree of freedom. Marumo and Katayama also benchmarked the velocity vectors as an energy flow and gave the assumption that the negative of the X component of vector diagram expresses the stabilize motion and vice versa as shown in Figure 2.5. The model responses for a medium-sized motorcycle (250 cc) with a speed of 180 km/h (50 m/s) showed a large term in the external force (front tyre side force, yaw rate force, rear tyre side force and rolling acceleration force) affecting the lateral motion. It was clear that for structural flexibility affecting wobble mode stability, the external force due to the frame bending and torsion velocity changes, stabilized the wobble mode. While the torsion of the front fork and lateral bending of the rear swing arm affected the weave mode stability at high speed but have no impact on the wobble mode stability.

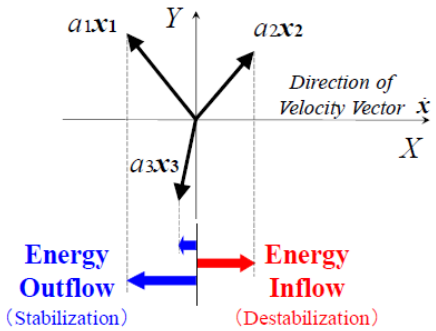


Figure 2.5 Vector Diagram (Marumo & Katayama, 2009)

(Ooms, 2011) conducted the 11 degree of freedom motorcycle model for predicting motorcycle behaviour at extreme driving conditions. The equations of motion that borrowed from robot modelling has been implemented and proved. In the validation process, the linearized model, the model of Koenen (Koenen C. , 1983) and the nonlinear model using SimMechanics (Matlab/Simulink) were created. The two straight lines and two arcs virtual track were done with two input signals: steering torque in time and wheel torque. By this simulation the speed was kept to be 20 meter per second in order to simplify of the model analysis. The results proposed that the model is comprehensive and compact enough to be carried out and simulated real time. Moreover, it provided an adequate accuracy for predicting the complete configuration of the motorcycle as a function of time.

The typical straight running test for motorcycle stability has been shown in many research studies concerning achieved the dynamic ability of the vehicle to dampen various disturbances introduced by road environments or rider behaviors. When studying the response frequency and oscillations effected at the stability level of motorcycle (Salvador & Fabris 2004) have finally claimed that increasing front tire inflation, stiffness chassis, and front frame inertia about steering axis and decreasing the front tire sideslip stiffness of the front tire, wobble mode damping is improved, promoting vehicle stability. In terms of stiffness chassis and front frame inertia which are parts of motorcycle structure, the claims by (Marumo & Katayama 2009) were similarity presented. They pointed out that the effect of structural flexibility on motorcycle wobble mode stability depended on the change of the frame lateral bending and torsion velocity which denoted the external applied forces. For all of other variables tests, the influence which the torsion of the front fork and lateral bending of the rear swing arm have on weave mode stability occurred at high speed but could not happened on wobble mode stability. In addition, an exclusive study of (Gail et al. 2009) and (Boubezoul et al. 2013) focused on Anti-Lock Braking Systems (ABSs) performance and a low-complexity fall detection algorithm, respectively. The application of straight running seems to be preferable to combine with the physical experiments of safety devices. As a matter of fact that, the preferable of Salvador and Fabris, Marumo and Katayama on using the straight running assumptions regarding the motorcycle stability study appeared to similarly of an adaptive of Gail et al. and Boubezoul et al., this could be because straight running test can be allowed an easy methodology and appropriate results.

2.4.2 Non Straight Line Testing

Bougard, Moussay, & Davenne 2008, investigated time of day and sleep deprivation impacts on motorcycling performance. The tests were set into two main sessions of laboratory test and motorcycling test (slalom) with eight subjected participants. The different sessions were planned at 06:00 and 18:00 hour after a normal night's sleep and after a night of total sleep deprivation for assessing key variables of a principal riding task, such as reaction time, motor coordination and vigilance. It has been clearly established that the evaluation results of which laboratory test and motorcycling test involved reaction time, motor coordination and vigilance varied as a function of time of day by a direct consequence of a normal night's sleep. By the same token, the type of test used (motorcycling or laboratory) has an influence on a noxious effect of sleep deprivation condition.

Creaser, Ward, Rakauskas, Shankwitz, & Boer 2009, observed the impairing effects of alcohol on riding skills. There were five riding test course included two slalom tasks, hazard avoidance, curve circuit and emergency stop conducting with twenty four male motorcycle riders. Two important experimental apparatuses were considered, firstly the instrumented motorcycle 2000 Honda Shadow VT1100 furnished with outriggers and sensors equipment and lastly the Draeger Alcotest 7410Plus Breathalyzer for collecting data. A blood alcohol content (BAC) was ranged in four conditions of 0.00, 0.02, 0.05 and 0.08%. The measurement data were then analyzed using an analysis of covariance (ANCOVA). The independent variables of model were consisted of baseline riding performance, years of riding experience, and also the number of reported drinks per week. At this point it became apparent that the 0.08 BAC affected most riding skill especially the slalom task (offset weave) and hazard avoidance which demanded high skill, whereas some were assessed at the lower 0.05% BAC and the curve circuit were constrained.

Cossalter, Lot, & Rota 2010, examined slalom, lane change and steady turning test to point out the method of evaluation the Department of Innovation in Mechanics and Management (DIMEG) simulator of Padua University. In order to enhance suitable motorcycle riding simulator, Cossalter et al. selected the objective and subjective evaluation method. The objective evaluation consists of riding tasks of slalom, lane change and steady turning, in which the UNIPD instrumented motorcycle was used as a measurement. Several riding conditions were performed for measuring the most relevant parameters; the roll rate, the yaw rate, steer torque, steer angle; and were then compared with the simulator's output and concluded that the ratio between the roll rate and the steering torque was more meaningful to describe the vehicle behaviour and the steering torque also significant representative of the rider action. The subjective evaluation methodology was used for assessing the riding sensation (visuals, acoustics and motion cues) using the complex questionnaires technical questions and perception and cognitive questions involved. There were consistent results of all evaluation points from expert rider with a lower score of DIMEG riding simulator.

Until recently in 2013, (Boubezoul, Espie, Larnaudie, & Bouaziz, 2013) evaluated a low-complexity fall detection algorithm of such passive safety system for motorcycle. By analysing the selected fall accident arrangements, the main causation factors were obtained and then repeated by a stuntman using an instrumented motorcycle. The experimental motorcycle a Honda CBF1000 were installed with the sensors of three-accelerometers, three-gyroscopes, ABS hall-effect sensor, relative optical encoder, brake contact, linear potentiometer and turn contact. The dynamic parameters such as the linear accelerations, angular velocities (roll, yaw, and pitch rates), longitudinal displacement, steering angle and acceleration demand were recorded. There were four selected scenarios; fall in a curve, fall on a slippery straight road section, fall with leaning of the motorcycle and fall in a roundabout; that usually represent the accident situation carried out to understanding the factors, the fall and the near-fall signature. The valuable experimental data of yaw gyroscope signal was used for comparing the performance of three filtering techniques consisted of Low-pass Butterworth filter (LPF), Median filter (MF) and Wavelet filter (WF). With the intention of developing an algorithm, the MF algorithm was selected because it is simple and easy to implement. After validation the presented fall algorithm detection, the finding presented that the time elapsed between the triggering of the algorithm and the fall occurring was a sufficient time for air bag jacket inflation with between 0.2 s and 0.4 s which longer than typical time duration of 100 ms. It may be indicated that using simple norms of the accelerometers and gyroscopes can provided a robust and effective algorithm that detected fall events accurately and can be developed by industrial and financial constraints.

2.5 Tyre Characteristics

Many research works put more efforts on studying the important of tyre characteristics to gain access to the performance optimization about vehicle safety, handling capabilities and riding comfort. A model for motorcycle tyre based on the experimental data was implemented by Lot (Lot, 2004). The tyre deformability and others actual physical characteristics such as the shape of tyre carcass and the positon of the contact point were taken into account. The simulated longitudinal slip, sideslip angles, tyre forces and torques which are functions of velocity of the contact point provided a successful validity in comparison with the experimental data.

A numerical motorcycle model developed by Cossalter et al. to study the influence of speed on motorcycle tyre and verified its reliability with a straight running test (Cossalter, Lot, & Maggio, 2004). In this tyre model, the geometry of tyre tread, tyre deformation, and camber angle, an elasticity of the carcass and the position of the contact point consisted in. For validating the tyre model, the instrumented sports motorcycle that equipped with sensors was used for collecting all real signals which purposed to compare with a model output. The findings showed that the measured damping ratios were rather different from the simulation results; this was because the real motorcycle had strong non-linear behaviours. Many parameters such as tyre properties were assumed as linear condition for the modelling.

Tyre-road friction directly affects a vehicle dynamic control system that plays an important role in vehicle stabilization, vehicle capability and riding comfort. Knowledge of tyre-road friction is essential and beneficial for improving vehicle safety. According to the study of (Li, Yang, Jia, Ran, Song, & Han, 2015) that estimated the tire-road friction coefficient on three different manoeuvering condition included braking, driving and steering condition using signal fusion method. The experiments were conducted on three road surface included dry asphalt, packed-snow and ice road. The basic dynamic characteristics of a tyre such as resistance force and vehicle such as longitudinal and vertical force of the tested vehicle were used for determining the utilize road friction and slip ratio of the wheel. The relation between input characteristics and slip ratio and slip angle were then obtained that can directly affect the accuracy of the estimated road friction.

The effect of tyre contact length which is one of substantial tyre characteristics on controllability of the vehicle was studied by (Matilainen & Tuononen, 2015). The subjective of this study were the influences of tyre pressure, driving velocity, tread depth on dry and wet asphalts on the contact length. Measuring the inner linear accelerations with a three-axial accelerometer that mounted inside a new (run-in) tyre and a worn tyre with 2 mm tread depth can provide direct data from the tyre-road contact and yielded a minimal effect on the stiffness and inertial characteristics of the tyre on the longitudinal acceleration signal. The waveform of longitudinal acceleration can be exploited the contact length and presented the constant figures on dry asphalt regardless of an increasing driving speed. The increasing of contact length presented inversely relation to tyre pressure. The new tyre was found a considerable longer contact length than a worn tyre on dry asphalt.

Tyre characteristics are essential parameters that contribute in motorcycling. With apparent and effective physical properties of motorcycle tyre such as material, tyre tread, tyre shape and the contact length combined with speeds and others environmental conditions could be evaluated the complicated robust influence on vehicle dynamic behaviours. Tyre friction force, slip angle, camber angle and self-aligning torque and moment in three directions (longitudinal, lateral and vertical) were taken into account vehicle safety, handling behaviours and comfort. To gain more knowledge about tyre characteristics, a mathematic model and experiment were normally used. The typical proposes of many studies also need to be addressed and linked to all angles of tyre characteristics and its dynamic behaviours to improve a better safety vehicle.

2.6 Summary of Key Literatures Reviews

This section provided a summary of related literature reviews of this study. The motivation of this study was to find out the cause of motorcycle single vehicle crash such as a slippy crash that may be caused by motorcycle defects. This kind of motorcycle crash was reported by the studies of (Kasantikul, 2001a) and (Kasantikul, 2001b) and also reported by (WHO, 2013) and (WHO, 2015). The basic theories of motorcycle stability were adapted from Cossalter (Cossalter V. , 2006) and Cocco (Cocco, 2013) who are motorcycle experts. An overview is presented with respect to identification motorcycle stability influenced by varying tyre widths using the full-scale experimental riding test as in many studies including (Cossalter V. , Doria , Basso, & Fabris, 2004), (Salvador & Fabris, 2004), (Cheli, Pezzola, Leo, Ibrahim, & Saita, 2010), (Seiniger, Schröter, & Gail, 2010), and (Jamieson, Frith, Lester, & Dravitzki, 2013). The reasons behind this methodology were that tyre was anisotropic objects, therefore, a physical test could more likely deliver actual behaviours. Straight running test which is a basic method for identifying stability behaviour of a vehicle was selected to examine motorcycle dynamic responses on steady rectilinear condition. Slalom test which is one of a common method used for describing handling ability of vehicle was chosen. These tests can explain the cornering behaviour affected by tyre characteristics of the tested motorcycle as the study of Bougard et al., Creaser et al. and Cossalter et al. have shown (Bougard, Moussay, & Davenne, 2008), (Creaser, Ward, Rakauskas, Shankwitz, & Boer, 2009) and (Cossalter, Lot, & Rota, 2010). Furthermore, the tyre forces that related to vehicle responses and the rider control action can ordinarily be associated in these tests. Other relevant elements to research structures such as methodology, research tools and independent variables are shown in Table 2.3.

Table 2.3 Summary of Related Literature Reviews

Research Structures	Authors	Title
Motivation on examining contribution factors of motorcycle single vehicle crash		
	• (Kasantikul, 2001a)	• Motorcycle Accident Causation and Identification of Coutermeasures in Thailand Volume I: Bangkok Study
	• (Kasantikul, 2001b)	• Motorcycle Accident Causation and Identification of Countermeasures in Thailand Volume II: Upcountry Study
	• (WHO, 2013)	• Global Status Report on Road Safety 2013
	• (WHO, 2015)	• Global Status Report on Road Safety 2015
Theories/Thems		
	• (Cossalter V. , 2006)	• Motorcycle Dynamics
	• (Cocco, 2013)	• Motorcycle Design and Technology

Table 2.3 (continued)

Research Structures	Authors	Title
Methodology • Experimental Research	• (Cossalter V. , Doria , Basso, & Fabris, 2004) • (Salvador & Fabris, 2004) • (Evangelou, Limebeer, Sharp, & Smith, 2007) • (Cheli, Pezzola, Leo, Ibrahim, & Saita, 2010) • (Seiniger, Schröter, & Gail, Perspectives for Motorcycle Stability Control Systems, 2010) • (Seiniger, Schroter, & Gail, 2012) • (Jamieson, Frith, Lester, & Dravitzki, 2013)	• Experimental Analysis of out-of-plane Structural Vibrations of Two-Whelled Vehicles • Study of stability of a two wheeled vehicle through experiments on the road and in laboratory • Mechanical Steering Compensators for High-Performance Motorcycles • Motorcycle Dynamic Stability Monitoring During Standard Riding Conditions • Perspectives for Motorcycle Stability Control Systems • Perspectives for Motorcycle Stability Control Systems • Stability of motorcycles on audio tactile profiled (ATP) roadmarkings
Research Tools/ • Smartphone	• (Astarita, Bertini, d'Elia , & Guido, 2006) • (Astarita, et al., 2012) • (Douangphachanh & Oneyama , 2013) • (Douangphachanh & Oneyama, 2014) • (Ferrer & Ruiza, 2014) • (Sekine, 2014)	• Motorway traffic parameter estimation from mobile phone counts • A Mobile Application for Road Surface Quality Control: UNIquALroad • A Study on the Use of Smartphones for Road Roughness Condition Estimation • A Study on the use of Smartphones under Realistic Settings to Estimate Road Roughness Conditions • Travel behavior characterization using raw accelerometer data collected from smartphones • Utilization of Probe Powered Two-Wheeler Vehicles to Realize a Safe Mobile Society
• Sensors and Acquisition System	• (Cheli, Pezzola, Leo, Ibrahim, & Saita, 2010) • (Cossalter, Lot, & Rota, 2010) • (Boubezoul, Espie, Larnaudie, & Bouaziz, 2013)	• Motorcycle Dynamic Stability Monitoring During Standard Riding Conditions • Objective and subjective evaluation of an advanced motorcycle riding simulator • A Simple Fall Detection Algorithm for Powered Two-Wheelers
Instrument Calibration • Smartphone Calibration	• (Automation, 2015)	• Calibration Principles

Table 2.3 (continued)

Research Structures	Authors	Title
Riding Test • Straight Run Test	• (Koenen, 1983) • (Sharp & Limebeer, 2004) • (Salvador & Fabris, 2004) • (Gail, Funke, Seiniger, & Westerkamp, 2009) • (Marumo & Katayama, 2009) • (Ooms, 2011)	• The Dynamic Behaviour of a Motorcycle when running straight ahead and when cornering • On steering wobble oscillations of motorcycles • Study of stability of a two wheeled vehicle through experiments on the road and in laboratory • Anti Lock Braking and Vehicle Stability Control for Motorcycles – Why or Why Not? • Effects of Structural Flexibility on Motorcycle Straight Running Stability by using Energy Flow Method • Motorcycle Modeling and Control
• Slalom Test	• (Bougard, Moussay, & Davenne, 2008) • (Creaser, Ward, Rakauskas, Shankwitz, & Boer, 2009) • (Cossalter, Lot, & Rota, 2010)	• An assessment of the relevance of laboratory and motorcycling tests for investigating time of day and sleep deprivation influences on motorcycling performance • Effects of alcohol impairment on motorcycle riding skills • Objective and subjective evaluation of an advanced motorcycle riding simulator
Specification of Measured Responses Signals • Vibration Analysis, Average Value, Root Mean Square (RMS) • Roll to Yaw Rate	• (Thomson , 1993) • (Inman, 2001) • (Cossalter, Lot, & Rota, 2010)	• Theory of Vibration with Applications • Engineering Vibration • Objective and subjective evaluation of an advanced motorcycle riding simulator
Hypothesis Testing • ANOVA	• (Chen, Chen, Liu, Chen, & Pan, 2009) • (Symeonidis, Kavadarli, Erich, Graw, & Peldschus, 2012) • (Levulis, DeLucia, & Jupe, 2015) • (Creaser, Ward, Rakauskas, Shankwitz, & Boer, 2009)	• Whole-body vibration exposure experienced by motorcycle riders – An evaluation according to ISO 2631-1 and ISO 2631-5 standards • Analysis of the stability of PTW riders in autonomous braking scenarios • Effects of oncoming vehicle size on overtaking judgments • Effects of alcohol impairment on motorcycle riding skills

CHAPTER 3
METHODOLOGY

This chapter presents the research methodology and apparatuses. In addition, the details of the study framework, the experimental design and calibration of a smartphone are also described.

3.1 Framework of the Study

The explanation of motorcycle driving stability was mentioned in chapter 2 and was also given in several sources as example of Cossalter (Cossalter V. , 2006) and Cocco (Cocco, 2013). This section provided an overall account of the study framework as shown in Figure 3.1. The research question was developed from the literature reviews related to motorcycle single vehicle crash. To find out what factors contribute to the supposed effect, thus vehicle defect was dedicated. In terms of a vehicle defect, stability was the most relevant to motorcycle crash research studies. The key factors influencing motorcycle stability can be described into two groups of static factors and dynamic factors. For static factors, there are contribution factors of vehicle geometry, frame compliance, mass distribution and suspension characteristics. For dynamic factors, there are vehicle speed, longitudinal acceleration and lean angle (or bank or roll angle) that put on motorcycle driving stability. The special factor is tyre characteristics that involved in both static and dynamic factors.

As a consequence of the research question and the developed theoretical framework, tyre width which is one of tyre characteristics was justified as a key subject of this study. Additionally, vehicle speeds were specified as independent variables. The hypotheses connected to research questions were then created. In the research fixed designs, the design of experiment was used to study the influence of different tyre widths and vehicle speeds. There are two road tests which are straight running test and slalom test. Before examining the road test the instrument calibration was conducted to ensure its accuracy. And then the nine dynamics vibration responses signals were gained from the road tests. The methods used for specification the responses signals for the straight running test are time waveform plots, the average value and root mean square. For slalom test, the ratio of roll to yaw rate ratio was used as a key specifying factor as in the study of Cossalter et al. (Cossalter, Lot, & Rota, 2010). Then, the ANOVA tests were conducted for testing the research hypotheses. Lastly, all findings were summarized to explain the relationships between key variables and research question, followed by a conclusion and recommendation.

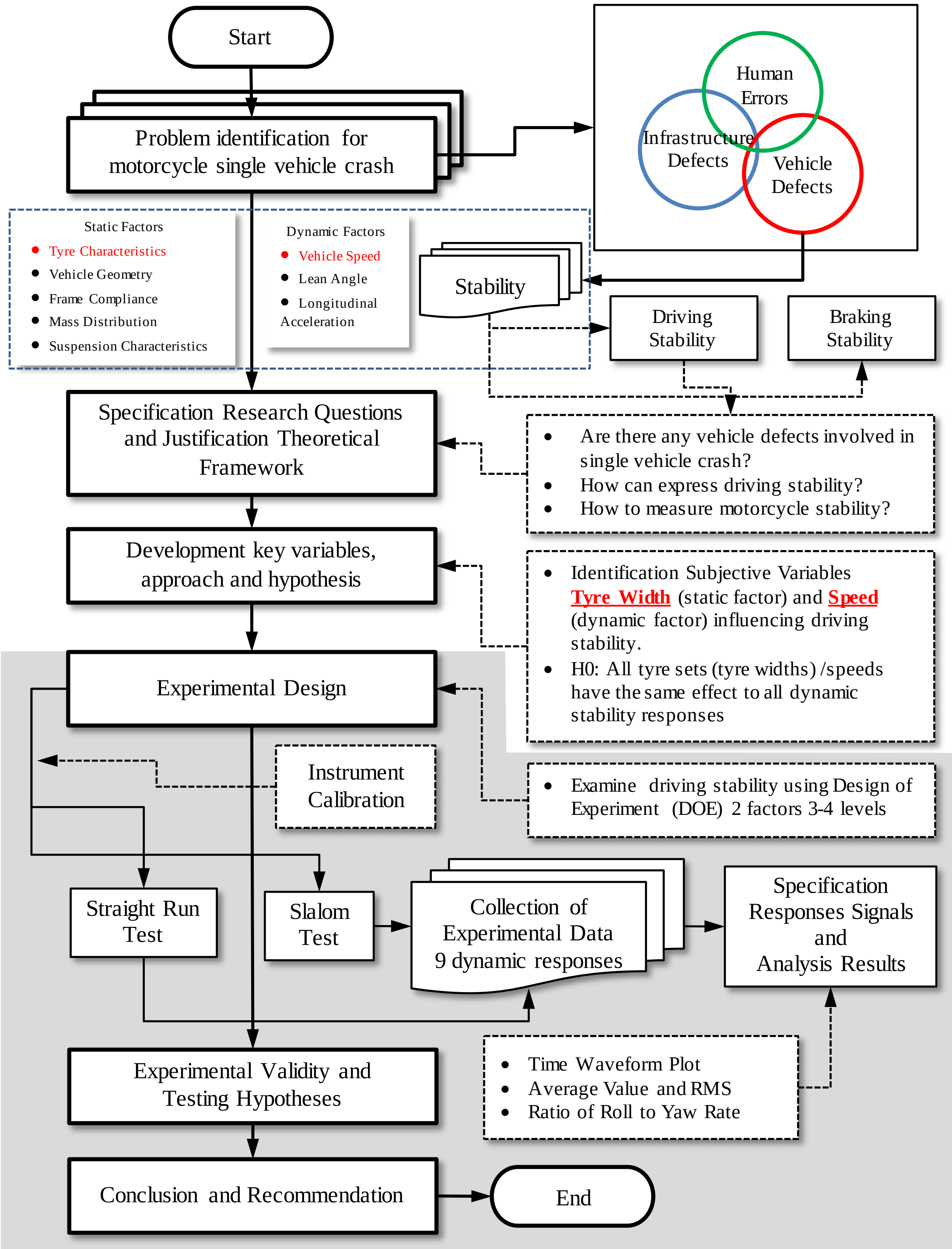


Figure 3.1 Research Framework

3.2 Methods and Apparatuses

3.2.1 Participant

To achieve a good dynamic behaviour data of the motorcycle while riding with steering freedom of straight running, and extreme riding path of slalom, a skilled male rider took part in this study as a participant. With an eight year experience as professional riding instructor, his expertise was an important factor to consider to avoid risk or accident that might have had happened in the experiment (Boubezoul, Espie, Larnaudie, & Bouaziz, A simple fall detection algorithm for powered two wheelers, 2013). The objective of this study consists of a comparison between the dynamic behaviors of the four tyre sizes during the same riding conditions, thus the same rider performed all tests to omit the expertise riding level.

3.2.2 Motorcycle

The selected motorcycle was a typical lightweight motorcycle SUZUKI Skydrive 125 with a displacement 124 cm^3 (see Figure 3.2). The body of this model was designed with overall length of 1885 mm, width of 665 mm, height of 1050 mm, and a wheel base of 1260 mm. The maximum steering angle was 45 degrees and the caster angle trail was 25.6 degrees. The frame type was steel tube under bone with the telescope oil damped type of front suspension and the swing arm oil damped type of that rear. The standard configuration front tyres were 70/90-14 M/C 34P and the rear tyres was 80/90-14 M/C 40P, these were attached with spoked rims. For the front tyre markings 70/90-14 M/C 34 P, it could be explained that nominal section width was 70 mm, aspect ratio (or section height or sidewall height) was 90 mm, and motorcycle (M/C) wheel diameter was 14 inch. The marking “34” denoted load index, the maximum load carrying capacity was 118 kg. The marking “P” presented speed symbol, the maximum speed for which tyre was 150 km/h (or 95 mph). For the rear tyre markings 80/90-14 M/C 40 P, could be explained that nominal section width was 80 mm, aspect ratio was 90 mm, and motorcycle (M/C) wheel diameter was 14 inch. The marking “40” represented load index, the maximum load carrying capacity was 140 kg. The marking “P” represented speed symbol, the maximum speed for which tyre was 150 km/h (or 95 mph). The load index and speed symbols were given in Appendix A.

In this study the judgmental sampling technique was preferred based on nonprobability sampling. Since the majority of motorcycles registration in Thailand (DLT, 2015) was the model with engine capacity between 101 to 125cc what can be said as a population interest, thus SUZUKI Skydrive 125 was an appropriate sample. An understanding of the impact of tyre width on stability of this model could be a presentation of motorcycles with engine size capacity of 101 to 125cc.

3.2.3 Data Acquisition System

Smartphone Samsung Galaxy Note 3 was used throughout as instrument calibration method and straight running test. It was integrated with various sensors such as accelerometer, gyroscope, compass, barometer, thermometer, humidity, gesture, and Global Positioning System (GPS). With complex performance of such sensors like sensing non gravitational acceleration, sensing orientation, and detecting location, it was employed to collect dynamic behaviors of a moving motorcycle. Modern smartphone has grown in popularity as an accurate measurement device because it provides features which are easy to use, inexpensive, and give reliable output. A number of studies using smartphone, including the works of Douangphachanh & Oneyama (2013) and Douangphachanh & Oneyama (2014) utilized on road roughness conditions and (Sekine, 2014) examined the possibility of realizing safe mobility of powered two-wheeler vehicle.

A smartphone software application named AndroSensor and Bubble Level 360 (Google Play, 2014) were pre-installed into the smartphone. The AndroSensor was used to record key data such as 3-axis accelerations, 3-axis angular velocities, and vehicle speeds. The recording interval was done at 20 Hz frequency or 0.05 seconds. All information from the sensors was recorded into a CSV file. The box housing the smartphone was positioned on level plane under the rider seat as shown in Figure 3.3. The application, Bubble Level 360 was used to accurately position the smartphone.

The necessary measurement instruments have been adapted to specify measure and record motorcycle movement for slalom test. Three control units of sensors, GPS and an Inertial Measurement Unit (IMU) and data-logger system were equipped on the experimental motorcycle (see Table 3.1). These systems allowed acquiring and recording riding data. The use of front/rear wheel speed sensors monitors the motorcycle velocity, while a handlebar rotating angle data come from steering angle sensor. GPS antenna used for reference measurement system together with an IMU used in these experiments consists of 3-axis gyroscope sensor and 3-axis accelerometer. The data-logger system recorded the data from sensors, GPS and IMU. The model Raspberry Pi RS232 was employed because of the advantage of Linux operating system, I/O CPU 400 mHz, Ram 255 and with the effective data processing and transferring of wireless router.

Table 3.1 Measured Technology Selected

Parameter quantity	Transducer	Model
Steering angle	Hall-effect sensor	
Rotational velocity	3-axis gyroscope sensor	GY-86
Roll rate (ω_x)		
Pitch rate (ω_y)		
Yaw rate (ω_z)		
Angular acceleration	3-axis accelerometer	
longitudinal acceleration (α_x)		
lateral acceleration (α_y)		
vertical acceleration (α_z)		
Forward speed	Proximity transducer	TURNIGY
Front/Rear speed	Speed sensor	
Data logger		Raspberry Pi RS232
Wireless router		Link sys dd-wrt

3.3 Experimental Design and Procedure

3.3.1 Design of Experiments

Dynamic behaviors of motorcycle were taken from various factors. The mechanism for stabilizing motorcycling was composed of static and dynamic factors. It is worth highlighting that tyre property is a key influence on motorcycle stability, maneuverability and handling as mentioned by many previous studies of (Bortoluzzi, Lot, & Ruffo, 2001), (LOT, 2004) and (Hejtmánek, Čavoj, & Porteš, 2013). Thus aiming to investigate the effect of tyre width on motorcycle stability seems to involve several various related factors.

Suppose that vibration of moving motorcycle comprises q_i static factors such as vehicle geometry, mass distribution, frame compliance, suspension characteristics, and tyre properties, and x_i represents speed level that interrelated to main dynamic factors such as longitudinal acceleration, lateral acceleration and roll angle. It is safe to assume that static factors except tyre properties are controllable fixed factors. In the light of the stability study, tyre width one of tyre properties which impacted on friction and posed consequently to centrifugal force becomes controllable factors. The levels of vehicle speed contributed to different behaviors of those dynamic factors, as a result vehicle speeds were set as controllable factors. It makes more sense to take dynamic factors which normally used for expressing motorcycle vibration characteristics as uncontrollable factors. Using control system fundamental, the responses variable of interest in vibration analysis are the proportion of different controllable factors. The minimum average of amplitude was utilized in identifying a stability of motorcycle system.

Figure 3.2 Experimental Apparatus

Figure 3.3 Software Applications

With a complicated and a large number of factors, General Full-Factorial Design (Anderson & Whitcomb, 2007) was an appropriate technique for this study. Using two-level factorial can produce estimates of main effects of tyre widths and interactions among speed levels factors in different riding scenarios.

This experiment comprised of two riding test courses that conducted to test the tyre width effects on motorcycle dynamic behaviour. The first was a straight running test measurement of dynamic parameters produced by free steering rotation. The second was slalom running test involved quantifiable cornering stability as a function of handling. Table 3.2 lists all independent variables (or factors) and level of combinations. Three sets of tyre width set were considered consisting of tyre set A which had 70 mm tyre width and 80 mm section height for the front wheel and 80 mm tyre width and 90 mm section height for the rear wheel. Tyre set B had the same width of both wheels of 90 mm tyre width and 90 mm section height. The larger tyre named Tyre set C expressed its width of 110 mm and 70 mm section height for the front wheel and 120 mm tyre width/ 70 mm section height for the rear. A noticeable standard configuration of the SUZUKI Skydrive125 tyre showed as Tyre set A (see Figure 3.4). Wider tyre width of set B and set C were selected as a subjective of the riding test. Totally there are three selected tyre sets that are available in Thailand. This is because the fact that a commercial lightweight motorcycle model with the same engine capacity widely used in developed countries as United Kingdom has a wider tyre width than Thai model. The minimum tyre width of UK model was 100 mm (see Appendix A). Obviously, out coming results from road test would delivered advantages of using wider tyre width. These tyre width set used throughout two riding test. Initially, speed levels were set into four levels of 30 km/h, 40 km/h, 50 km/h and 60 km/h. The specified speed was then completed with identifying combinations of selected better treatments. As consequently presented in Table 3.3, three speed levels as 20 km/h, 40 km/h and 60 km/h were approved for the slalom test. The experiment was replicated ten times. Therefore, there were 4×3×10=120 runs for straight running test and 3×3×10=90 runs for slalom test. To avoid expertise riding level effects associated with difficulty and replication of testing, the experiments were performed by the same rider.

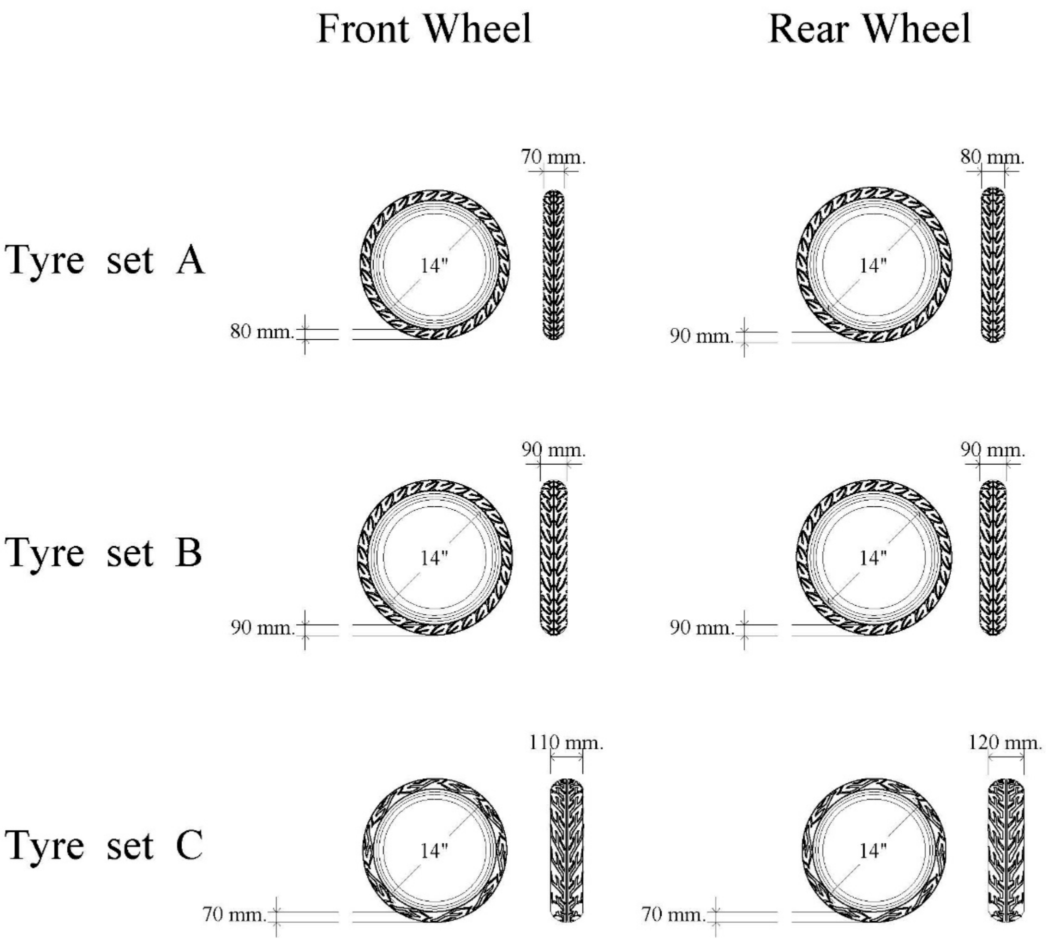


Figure 3.4 Tyre Dimensions

Table 3.2 General Full-Factorial Design of Two Controllable Factors for Straight Running Test

Factors	Level	Number of Replications	Details			Remark
			Name	Front Wheel	Rear Wheel	
Tyre Size, x_1	1	10	Tyre set A	70/80-14 M/C 34P	80/90-14 M/C 40P	* Standard Configuration (OEM)
	2	10	Tyre set B	90/90-14 M/C 46P	90/90-14 M/C 46P	
	3	10	Tyre set C	110/70-14 M/C 56P	120/70-14 M/C 61P	
Speed, x_2	1	10	30 km/h			
	2	10	40 km/h			
	3	10	50 km/h			
	4	10	60 km/h			

Table 3.3 General Full-Factorial Design of Two Controllable Factors for Slalom Test

Factors	Level	Number of Replications	Details			Remark
			Description	Front Wheel	Rear Wheel	
Tyre Size, x_1	1	10	Tyre set A	70/80-14 M/C 34P	80/90-14 M/C 40P	* Standard Configuration (OEM)
	2	10	Tyre set B	90/90-14 M/C 46P	90/90-14 M/C 46P	
	3	10	Tyre set C	110/70-14 M/C 56P	120/70-14 M/C 61P	
Speed, x_2	1	10	20 km/h			
	2	10	40 km/h			
	3	10	60 km/h			
Cone Spacing	1		14.00 m			
Track Width	1		2.60 m			

3.3.2 Instrument Calibration Method

Accordingly, smartphone has been a data collection device since the early 21st century. It was widely adopted to estimate traffic parameters (Astarita, Bertini, d'Elia , & Guido, 2006), estimate road roughness (Astarita, et al., 2012), (Douangphachanh & Oneyama , 2013), and (Douangphachanh & Oneyama, 2014) and classify travel behavior (Ferrer & Ruiza, Travel behavior characterization using raw accelerometer data collected from smartphones, 2014). Before the critical riding test was carried out, instrument calibration was an essential requirement to establish the reliability of smartphone. The calibration in this study was based on comparison technique by forming the working curve from smartphone and motorcycle speedometer measurement. A graph of motion which is a curve of velocity-time as in Figure 3.5 was applied in this study. The procedure started with riding the motorcycle with a constant gradient velocity from 10 km/h at time 10 seconds to 60 km/h at time of 60 seconds with time step 10 seconds and velocity step 10 km/h. Then the motorcycle kept moving with a constant velocity for a minute (60 seconds). After 120 seconds, the velocity was slightly reduced along with time step and velocity step condition until the motorcycle stopped. The measures of velocity and time on motorcycle's speedometer recording by a video camera as shown in Figure 3.6 were then analyzed.

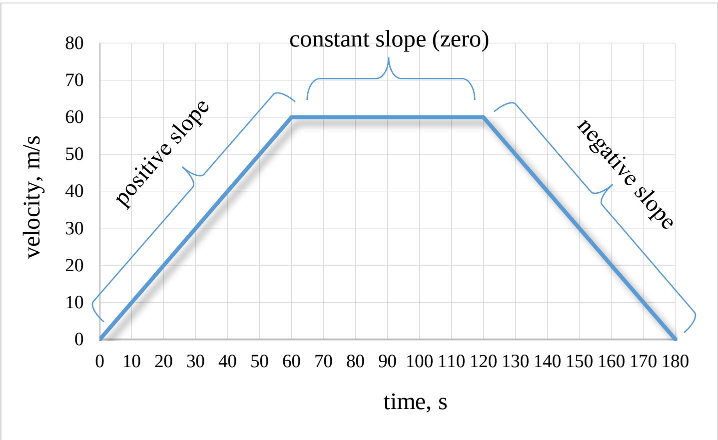


Figure 3.5 Working Graph of Motion

The reliance of orientation of smartphone was calibrated using a granite surface plate. The smartphone was fixed with a v-box tool surface (lay flat) and then rotated to the designed angle 45 and 90 degree (standard horizontal and vertical) as shown in Figure 3.7. Each direction of a smartphone was test individually. The data of smartphone orientation was recorded in form of roll and pitch angle. To summarize the experimental results of this calibration, the mean and sample standard deviation was then calculated.

Figure 3.6 Motorcycle Speedometer on Instrument Calibration
(a) at starting time 0 sec, (b) at time 60 sec, (c) at time 120 sec, and (d) at time 180 sec

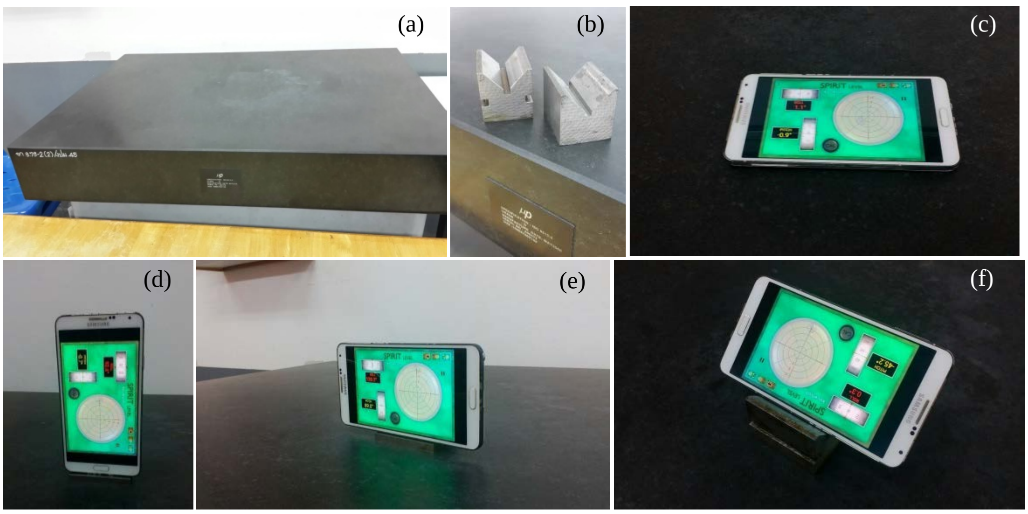


Figure 3.7 Orientation Calibration Tools and Procedures
(a) a granite surface plate, (b) a v-box, (c)-(f) smartphone orientation directions

3.3.3 Procedure

Prior to testing, the participant was requested to have a usual sleep to avoid time of day and sleep deprivation influences on motorcycling performance (Bougard, Moussay, & Davenne, 2008) and error-free performance on the course (Creaser, Ward, Rakauskas, Shankwitz, & Boer, 2009). The participant completed a general introduction and was instructed on the outline of the instrument calibration and two riding test courses. At the same time, the motorcycle components such tyres, inflation pressure, control, brake response, lights, seat, mirror, helmet and other relevant factors were inspected. For best comparability, each tyre inflation pressure was carried out on the same 30 psi for the front wheel and 32 psi for the rear wheel as shown in Table 3.4. Also for this reason, the same test route was used. After the tested vehicle had been completely checked, the rider was allowed to perform practice drive to familiarize the tested motorcycle and road path during a pre-experimental session.

The experiment was divided into six successive sessions (see Figure 3.8). First was the participant and vehicle preparation as previously mentioned. The second session was instrument (smartphone) calibration to establish the reliability of it. Followed by instruction dissemination and then the straight running tests performed in ten replications for 12 treatments. Before conducting the slalom test, the fourth session of screening analysis was examined to obtain a proper speed level of the association of the riding test. The control speeds for slalom test were selected systematically using the previous straight running results. Among the four speed levels (see Table 3.3), only three speed levels of 20 km/h, 40 km/h, and 60 km/h were practiced in the slalom test. The fifth phase was slalom test preformation with 3×3 treatments and ten replications each. Finally, analysis of data and conclusion were carried out.

The smartphone calibration test, straight running experiments were performed on the road with general grade within Songkhla municipality, Thailand (see Figure 3.9) while slalom test was performed on the Institute of Disaster Prevention and Mitigation, Disaster Prevention and Mitigation Center 12 Songkhla (DPMC12) as shown in Figure 3.10. All test programs were conducted in clear weather condition and dry road surface. These allow efficient maneuverability and clear visibility. By employing the same rider for each test, it is reasonable to assume that the rider behaviors should not create any biased interference on the output.

There were two general categories of riding test course that relate to this study. The first was a straight running test and the second was slalom running test. The straight running test aims to study a given influence of tyre width on driving stabilizing performance of motorcycle under free steering control along straight path.

The straight running task assessed motorcycle behaviours in terms of self-stabilization without rider controlling the handle bar which some named as steering system. During the free rotation of steering of moving motorcycle, the kinematic and dynamic treatments of vehicle and rider were deliberated as a rigid control system. Therefore, amplitude of vibration and oscillation of this test could indicate the stabilization of that system. The various dynamic response frequency signals (roll, pitch and yaw) of free rotation of steering system and the period of time during the motorcycle stop weaving could be reflected associated forces and all complicated dynamic behaviours created by a given tyre. For protection of the rider, the free handle bar could be stopped by the rider anytime when the tested motorcycle becomes unstable.

The slalom task assessed motorcycle behaviors in terms of ease and confidence for handling. This test course was examined based on the previous development of (Cossalter V. , 2006) with cone spacing at 14 meters as shown in Figure 3.11. The designed track width was 2.60 meters. The roughness (friction) coefficient of experimental road based on information of (Baker, 1975) were raged 0.60-0.80 for speed less than 30 mph (48.3 km/h) and 0.55-0.70 for speed over 30 mph as shown in Table 3.6. The rider was asked to ride the motorcycle around the cones with a designed constant speed (see Figure 3.12). Description of riding test course is shown in Table 3.5.

Table 3.4 Tyre Inflation Pressure

		Description	Inflate tyre pressure kPa (psi)
Tyre set A	Front	70/80-14 M/C 34P	206.8 (30)
	Rear	80/90-14 M/C 40P	220.6 (32)
Tyre set B	Front	90/90-14 M/C 46P	206.8 (30)
	Rear	90/90-14 M/C 46P	220.6 (32)
Tyre set C	Front	110/70-14 M/C 56P	206.8 (30)
	Rear	120/70-14 M/C 61P	220.6 (32)

Table 3.5 Description of Riding Test Course

Riding Test Course	Description	Parameter Tests
Straight run	Consistent speed ride along straight path with free steering head control and without braking	(1) Minimum deviation of roll, yaw and pitch angle (2) Minimum period of time stop weaving
Slalom run	Consistent speed ride around 14.0 m segment with cones without touching cones and braking	(1) Minimum ratio of roll to yaw rate

Table 3.6 Coefficient of Friction of Various Roadway Surfaces (Baker, 1975)

Description of Road Surface	Coefficient of Friction of Various Roadway Surfaces			
	Dry		Wet	
	-30 mph	+30 mph	-30 mph	+30 mph
Portland Cement				
New/Sharp	0.80-1.20	0.70-1.00	0.50-0.80	0.40-0.75
Traveled	0.60-0.80	0.60-075	0.45-0.70	0.45-0.65
Traveled Polished	0.55-0.75	0.50-0.60	0.45-0.65	0.45-0.60
Asphalt / Tar				
New/Sharp	0.80-1.20	0.65-0.10	0.50-0.80	0.45-0.75
Traveled	0.60-0.80	0.55-0.70	0.45-0.70	0.40-0.65
Traveled Polished	0.55-0.75	0.45-0.65	0.45-0.65	0.40-0.60
Excess Tar	0.50-0.60	0.35-0.60	0.30-0.60	0.25-0.55
Gravel				
Packed/Oiled	0.55-0.85	0.50-0.80	0.40-0.80	0.40-0.60
Loose	0.40-0.70	0.40-0.70	0.45-0.75	0.40-0.75
Cinders				
Packed	0.50-0.70	0.50-0.70	0.65-0.75	0.65-0.75
Rock				
Crushed	0.55-0.75	0.55-0.75	0.55-0.75	0.55-0.75
Ice				
Smooth	0.10-0.25	0.07-.020	0.05-0.10	0.05-0.10
Snow				
Packed	0.30-0.55	0.35-0.55	0.30-0.60	0.30-0.60
Loose	0.10-0.25	0.10-0.20	0.30-0.60	0.30-0.60

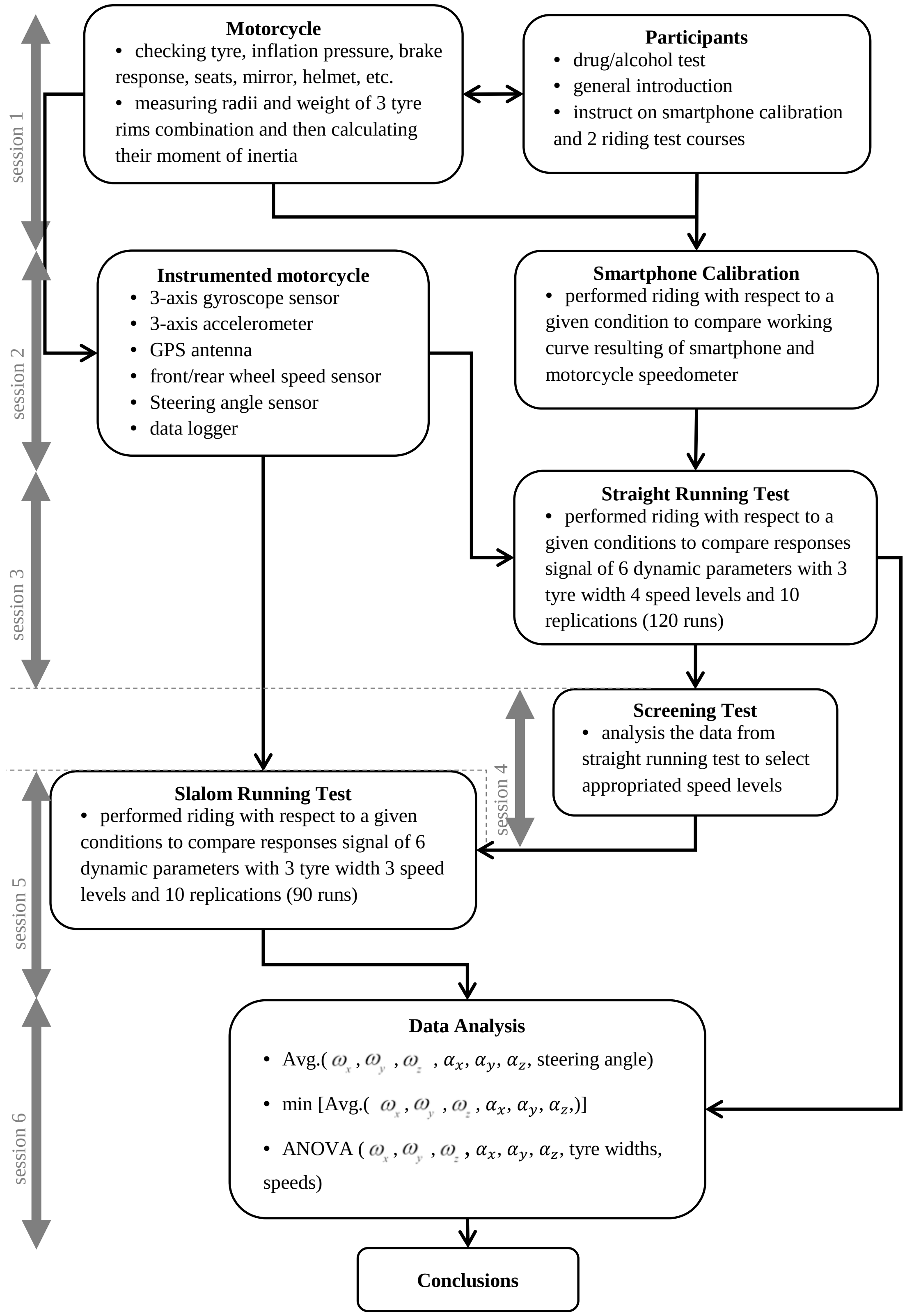


Figure 3.8 Experimental Flow Chart

Figure 3.9 Route of Straight Run Road Test (Google maps, 2015)

Figure 3.10 Location for Slalom Test (Google maps, 2015)

Figure 3.11 Cone Spacing and Track Width

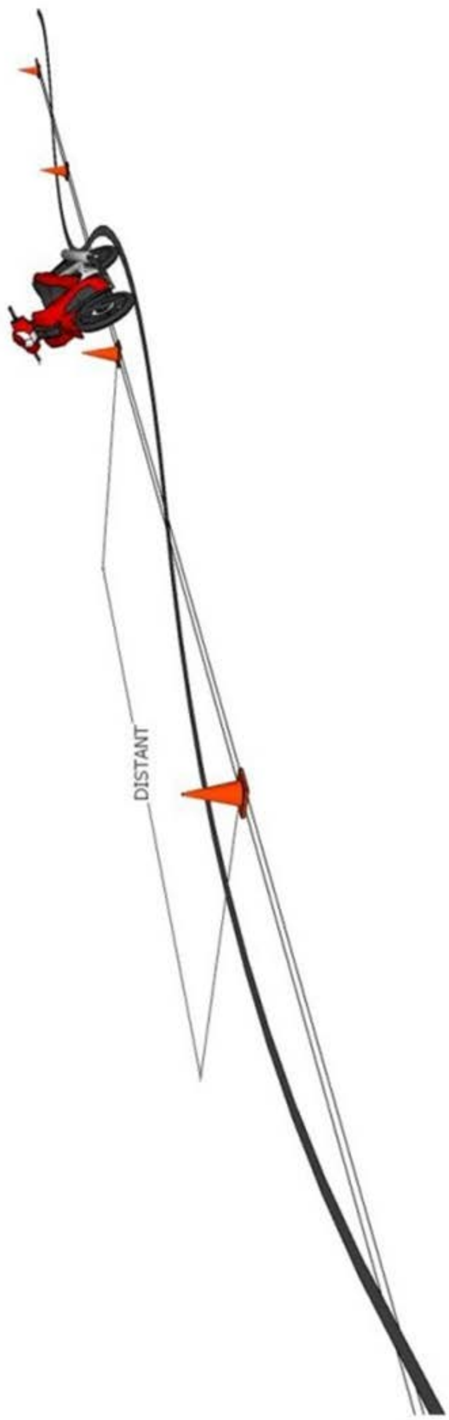


Figure 3.12 Slalom Riding Test

3.4 Statistical Analysis

For the instrument calibration method, the five positive and negative slopes of the working graphs of motion (see Figure 3.4) from the speedometer and the smartphone were analyzed using an analysis of variance (ANOVA) using SPSS Statistic Bass 17.0 for Windows EDU S/N 5065845 (see the letter of permission in Appendix A), of two instruments. This statistical test was based on the assumption that, a random sample from each instrument has a normal distribution, and all samples have the same variance. To validate the assumptions, the normality test using Kolmogorov-Smirnov Test was first conducted. Then the Levene's test for equality of variances was used to exam the variances of the five slopes each. To answer the main question "Do all of the populations have the same mean?", the independent sample t-test was conducted. The null hypothesis assumed that the means differences of two measurements (smartphone and motorcycle speedometer) is equal to zero $(H_o : \mu_1 = \mu_2)$, whereas the alternative hypothesis H_1 argue that the mean of these differences is not equal to zero ($H_1 : \mu_1 \neq \mu_2$). The tests gathered with level of significance of 0.01. The results of the test illustrate a significant reliability of using smartphone for assessing the dynamic parameters of tested motorcycle.

For screening test and analyzing the influence of tyre characteristics (tyre width) on the response dynamic variables, the analysis of variance (ANOVA, using SPSS Statistic Version 17) and multiple comparison procedures (MCP) were met. These analyses provided an understanding of subgroup differences among the different experimental and control groups. There were three subgroups of tyre width and four different experimental speed levels. To produce the effectiveness and improve the significance of this experimental result, each treatment was performed with ten replications. With this intention, a comparison between the all possible pairs of those would results in 120 statistical tests. The tyre sets and speeds were used as control variables whereas the six dynamic behaviors which are composed of roll rate, pitch rate, yaw rate, longitudinal acceleration (x-axis), lateral acceleration (y-axis) and vertical acceleration (z-axis) were set as response variables. Several methods such as Tukey, Scheffe, Duncan and S-N-K were used to test comparing pairs of subgroup to find some differences in order to be statistically significant. These statistical tests used a significance level of 0.05.

CHAPTER 4
EXPERIMENTAL RESULTS

In the present chapter an attempt is made to evaluate the dynamics behaviours of motorcycles under straight running and slalom study. The main focus is on the impact of tyre width on motorcycle stability and vibration characteristics of motion motorcycle.

4.1 Properties of Tyres

Once all motorcycle tyre and rim parameters have been measured and calculated. Six measurements each were made to assess the best accuracy. The values of the geometry properties can be found in the Table 4.1. For a given inflation pressure, tyre set A which is an original equipment manufacturer (OEM) tyres have a moment of inertia about wheel axis of 0.3200 kg×m^2 for the front and 0.4095 kg×m^2 for the rear wheel. Furthermore, these quantities presented on tyre set B with 0425 kg×m^2 of the front wheel and 0.4787 kg×m^2 for the rear one. To highlight that, the different amount of radius of 0.2583 m and 0.2598 m for the front and the rear with a different inflation pressure, respectively shown in tyre set B, even for the same tyre dimension and rims. As previously emphasized by (Sakai, Kanaya, & Iijima, 1979) and (Otto, 1980) that tyre inflation pressure is one of the vital parameters that influence behaviours of motorcycle at high speed. Thus, to avoid the impact of this parameter on the experimental result, it was embedded as a controllable variable in this study. The moment of inertia about wheel axis of tyre set C met the highest value interrelated to their largest width with 0.4540 kg×m^2 and 0.5550 kg×m^2.

Table 4.1 Tyres Properties

		Description	Inflate tyre pressure (kPa (psi))	Weight (kg)	Radius (m)	Moment of inertia about wheel axis (kg×m^2)
Tyre set A	Front	70/80-14 M/C 34P	206.8 (30)	5.5	0.2403	0.3200
	Rear	80/90-14 M/C 40P	220.6 (32)	6.7	0.2475	0.4095
Tyre set B	Front	90/90-14 M/C 46P	206.8 (30)	6.4	0.2583	0.4255
	Rear	90/90-14 M/C 46P	220.6 (32)	7.1	0.2598	0.4787
Tyre set C	Front	110/70-14 M/C 56P	206.8 (30)	6.9	0.2564	0.4540
	Rear	120/70-14 M/C 61P	220.6 (32)	8.0	0.2634	0.5550

One of the controllable parameters of riding tests was using the same original equipment manufacturer spoke rim diameter of wheel. The contact patches of the specified three tyre sets were then measures after the complete the road tests based on the vertical angle of motorcycle body and steering head. As provided in Table 4.2, the mean contact area of the front wheel of tyre set A which is OEM was 23.60 cm^2 slightly larger than that of tyre set B with 21.88 cm^2. Tyre set C presented the largest contact area of the front wheel with 31.85 cm^2. For the rear wheel, tyre set B exposed the smallest contact area with 28.45 cm^2. Whereas, tyre set A showed an incredible size of 36.95 cm^2 more likely larger than tyre set C with 31.66 cm^2. The front and rear wheel of tyre set B smaller than tyre set A by 7% and 23%, respectively. Furthermore, even the contact patch of the front wheel of tyre set C was greater than that of tyre set A by 35% but the consequence of the rear wheel was unbelievably smaller percentage of 14%.

Table 4.2 Contact Area of Tyre Sets

Run no.	Contact Area of Front Wheel (cm^2)			Contact Area of Rear Wheel (cm^2)		
	Tyre set A	Tyre set B	Tyre set C	Tyre set A	Tyre set B	Tyre set C
1	23.34	20.20	32.15	37.27	28.54	31.95
2	23.83	23.20	33.07	37.00	28.13	32.22
3	24.11	22.42	31.24	37.28	28.52	30.10
4	23.82	21.50	30.95	36.41	28.52	30.56
5	22.93	22.06	-	36.80	28.52	33.49
Average	23.60	21.88	31.85	36.95	28.45	31.66
% different from OEM (tyre set A)	0	-7	35	0	-23	-14

4.2 Analysis of Instrument Calibration

The following graphs in Figure 4.1 show the results of five replications smartphone calibration. Each plot represents the working graph of motion fitted for smartphone measured data and motorcycle speedometer data. The graphs are divided into two parts to present the measured data, one is in the blue symbol and the other one is in red fitted line. The positive and negative slopes of fitted line were estimated to evaluate the reliability of smartphone.

Figure 4.1 shows that in a smartphone calibration based on vehicle speed, the graphs of motion have a parallel figure. Their positive slope and negative slope of velocity-time plot from observed value were fitted. The significance of those was simply indicated using the value of the coefficient of determination, r^2. This statistical measure is commonly used for explaining how close observed data are to fitted trend line. The statistical data, significant positive and negative slope, for all test runs are presented in Table 4.3. In all cases, the r^2 was found to be better fitted for measured data with a higher r^2. This is expected as comparison working graph of motion exist extensively in a simple instrument calibration. The test run number four of smartphone is found to be superior to other test runs based on both r^2 with 0.9929 and 0.9863. Whereas the highest r^2 of vehicle speedometer presented on test run number five.

After ensuring slope value of experimental data, the independent sample t-test was conducted to test the means of two measurements. The null hypothesis assumed that the mean differences of two measurements (smartphone and motorcycle speedometer) are equal to zero $(H_o : \mu_1 = \mu_2)$, whereas the alternative hypothesis H_1 argued that the mean of these differences is not equal to zero $(H_1 : \mu_1 \neq \mu_2)$. The tests gathered a level of significance of 0.01. As presented in Table 4.4, it was found that the difference of positive slope of velocity-time measured by smartphone and vehicle speedometer is equal to zero with *p-value* 0.021 (p-value > 0.01). The different means of negative slope of two measurements presented the same result as the positive one with *p-value* 0.138 (*p-value* > 0.01). These seem to be a guaranty that smartphone capacity could provide a reliability observation for measuring dynamical data.

Table 4.3 Observation Data Fitted Criteria

Test run	Smartphone		Vehicle Speedometer		Constant	Smartphone		Vehicle Speedometer	
	Positive slope	r^2	Positive slope	r^2	Slope	Negative slope	r^2	Negative slope	r^2
1	0.2004	0.9824	0.2551	0.9912	0	-0.3203	0.9288	-0.4167	0.9698
2	0.2206	0.9580	0.2560	0.9690	0	-0.2100	0.9559	-0.2748	0.9646
3	0.1817	0.9921	0.2466	0.9666	0	-0.2453	0.9507	-0.3333	0.9730
4	0.1854	0.9929	0.2278	0.9863	0	-0.2451	0.9506	-0.3310	0.9854
5	0.2058	0.9890	0.2827	0.9930	0	-0.2058	0.9671	-0.2051	0.9891

Table 4.4 Independent Sample Test

		Levene's Test for Equeality of Variance		t-test for Equality of Means				
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std.Error Difference
P-slope	Equal Variances assumed	0.977	0.352	-2.870	8	0.021	-0.0323800	0.0112820
	Equal Variances not assumed			-2.870	7.049	0.024	0.0323800	0.0112820
N-slope	Equal Variances assumed	1.306	0.286	1.646	8	0.138	0.0668800	0.0406322
	Equal Variances not assumed			1.646	0.6455	0.147	0.6688000	0.0406322

* P-slope = Positive slope
* N-slope = Negative slope

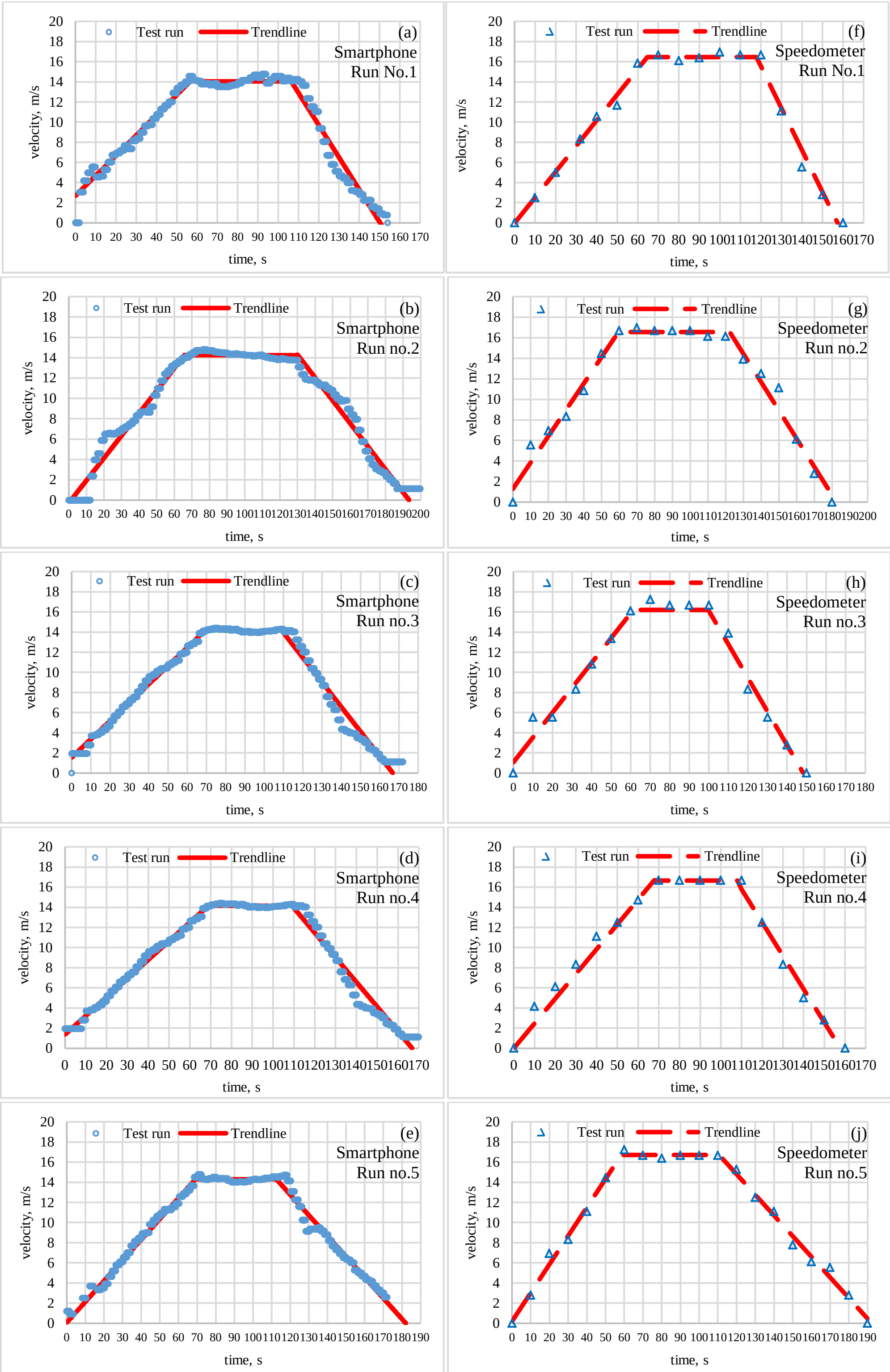


Figure 4.1 Subset of Experimental Velocity-Time Relationship (a)-(e) Smartphone Test Run No.1-5 (f)-(j) Motorcycle Speedometer Test Run No.1-5

For the calibration of orientation of smartphone, the measured roll and pitch angle of seven orientation directions were summarized in Table 4.5 using the commercial application Spirit Level. Each orientation direction was tested with five replications and the schematics provided in Figure 4.2. For lay flat direction, the mean of and standard deviation of roll angle and pitch angle were 0.3 0.1 and -0.3 and 0.1, respectively. For horizontal (left and right) direction, the standard deviation of roll varied in rage of 0.7-0.8 and that of pitch angle were 0.1-0.2. It is underlining that, the standard deviation of roll and pitch angle of all orientation direction present very low value.

Table 4.5 Mean and Standard Deviation of Measured Data for Orientation Calibration of Smartphone

	Run no.	Orientation Direction						
		Lay Flat	Horizontal (Left)	Horizontal (Right)	Vertical (Down)	Vertical (Up)	45 degree (Left)	45 degree (Right)
Roll	1	0.4	177.0	181.5	92.2	-91.5	0.1	0.5
	2	0.3	177.2	181.2	92.8	-92.2	0.6	0.5
	3	0.2	176.7	181.9	92.4	-92.2	0.4	0.4
	4	0.2	177.8	180.5	92.7	-91.8	0.2	0.3
	5	0.2	178.7	180.2	92.1	-92.0	0.4	0.2
	Mean	0.3	177.5	181.1	92.4	-91.9	0.3	0.4
	S.D.	0.1	0.8	0.7	0.3	0.3	0.2	0.1
Pitch	1	-0.2	-87.4	89.7	-0.7	-0.7	-45.9	45.2
	2	-0.2	-87.6	89.9	-0.7	-0.7	-45.4	45.2
	3	-0.3	-87.5	90.0	-0.7	-0.5	-45.8	45.2
	4	-0.4	-87.1	90.1	-0.7	-0.7	-44.6	45.1
	5	-0.4	-87.1	89.9	-0.7	-0.6	-45.0	44.8
	Mean	-0.3	-87.3	89.9	-0.7	-0.6	-45.3	45.1
	S.D.	0.1	0.2	0.1	0.0	0.1	0.5	0.2

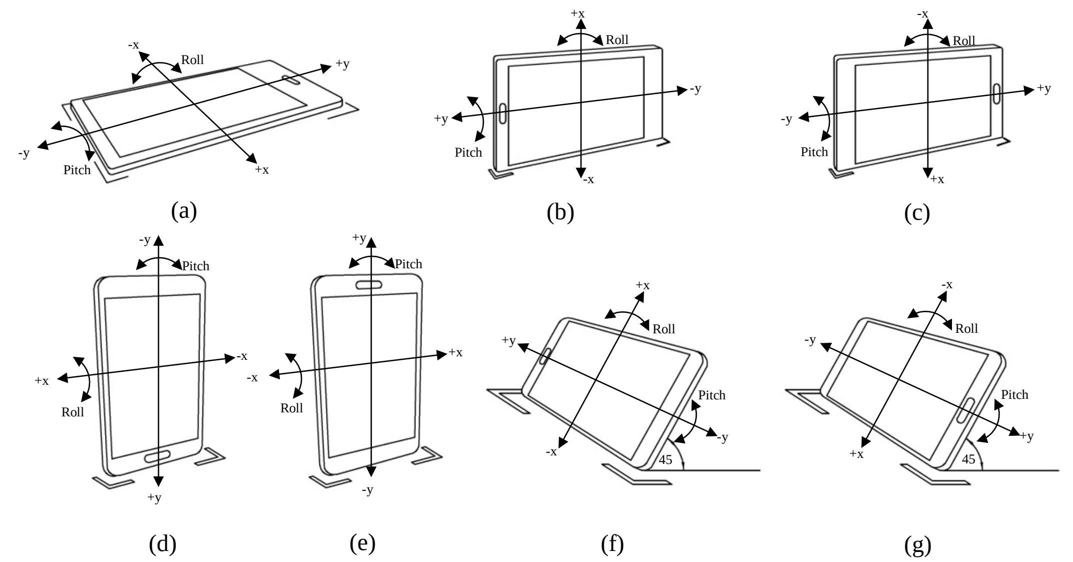


Figure 4.2 Orientation Direction of the Calibrated Smartphone
(a) Lay Flat, (b) Horizontal (Left), (c) Horizontal (Right), (d) Vertical (Down),
(e) Vertical (Up), (f) 45° (Left), and (g) 45° (Right)

4.3 Analysis of Straight Run Test

In this section the data measurement in the road test will be presented. All the measures were achieved considering classified speed level to compare the stability range of three tyre sets. In this study, the attention was focused on the minimum range of rotating roll angle with respect to vertical plane of the tested vehicle in free handle bar controlled condition.

4.3.1 Experimental Observations of Tyre Set A, B and C

The straight run procedure was used to investigate dynamic parameters of motion motorcycle in the form of sensors vibration signals. These devices produced time histories of positions, velocity and accelerations in three global coordinate systems. The data sets of response signals were extracted from 10 replications of the road test. The mean ($\bar{x}$) and standard deviation ($S.D$) of the duration of each data sets were computed to specify the lower limit ($\bar{x} - S.D$). The mean ($\bar{x}$) of duration for all tyre sets is 18.99 seconds and the standard deviation ($S.D$) is 13.56 seconds. Thus, the data sets that have duration less than the lower limit of 5.43 seconds were disregarded for the statistical analysis.

The examples of common plot of time history for the hand-off condition of tyre set A are shown in Figure 4.3-4.5 and the others were shown in Appendix B. In this test the speed was held constant at 7 m/s (24-26 km/h) to 16 m/s (60-62 km/h) as shown in the graphs. The waveform of vehicle roll angle and yaw angle raged from -1 to 1 degree whereas the pitch angle presented a higher range of -2 to 2 degree. The yaw angle was clearly recognizable with the smallest variation followed by roll angle and pitch angle, respectively. The angular velocity in y-axis presented the highest value in comparison with x-axis and z-axis. All waveforms obtained as a random excitation without any periodic function above and below the zero line. These can be expressed that the response signal appeared a stable system.

For tyre set B, and tyre set C the waveform plots are also provided in Appendix B. There were similar patterns of a non-symmetrical waveform as occurred in tyre set A. All responses vibration signals varied below and above the zero axis without any out-of-balance figures. In these case therefore it can be expressed that, the signals of the free motion of steering system of motorcycle driving in a straight path with the given tyre set B is stable.

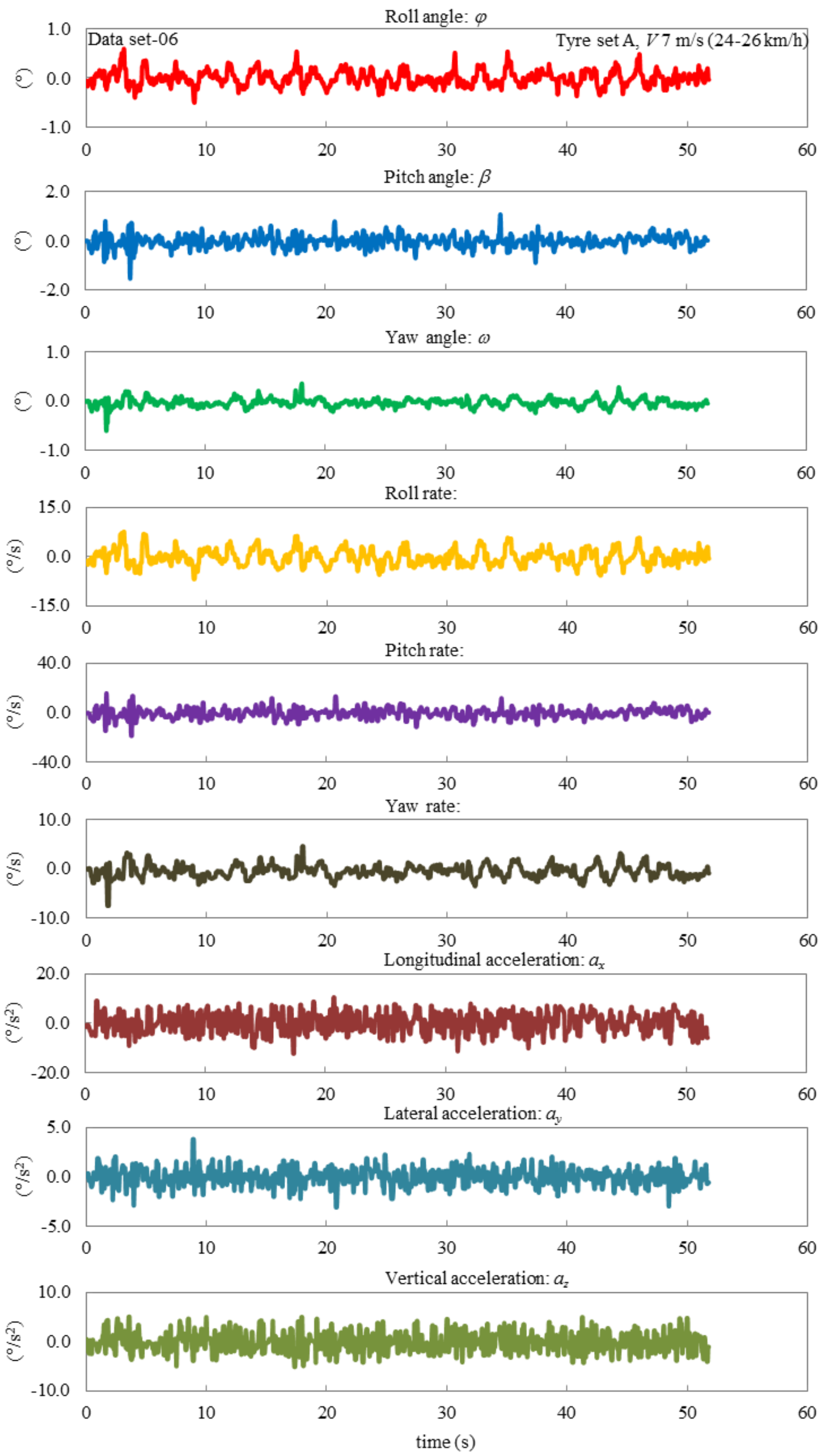


Figure 4.3 Dynamics Response Signals from Straight Run Test of Tyre Set A at Speed 7 m/s (24-26 km/h), Data Set 06

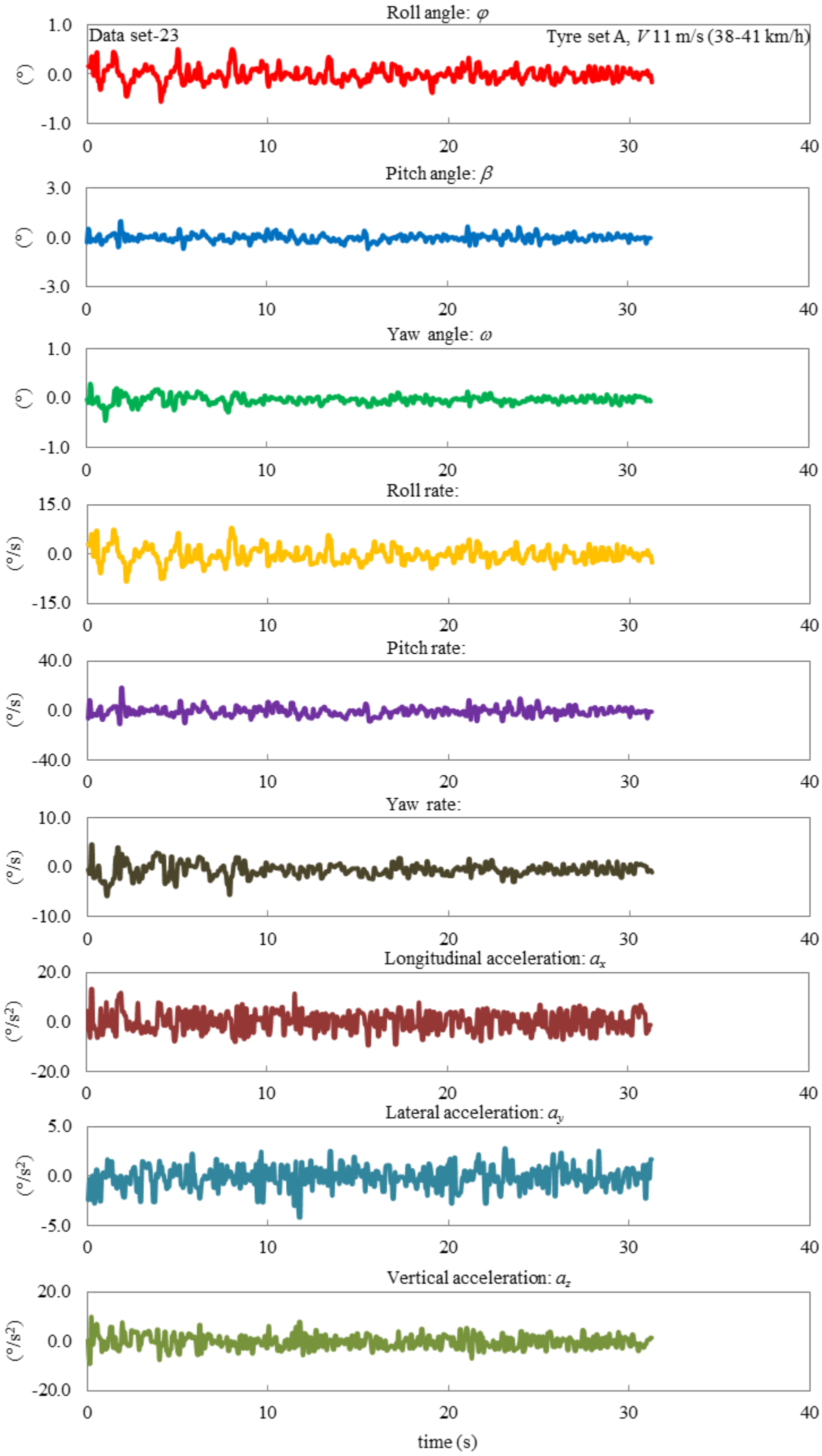


Figure 4.4 Dynamics Response Signals from Straight Run Test of Tyre Set A at Speed 11 m/s (38-41 km/h), Data Set 23

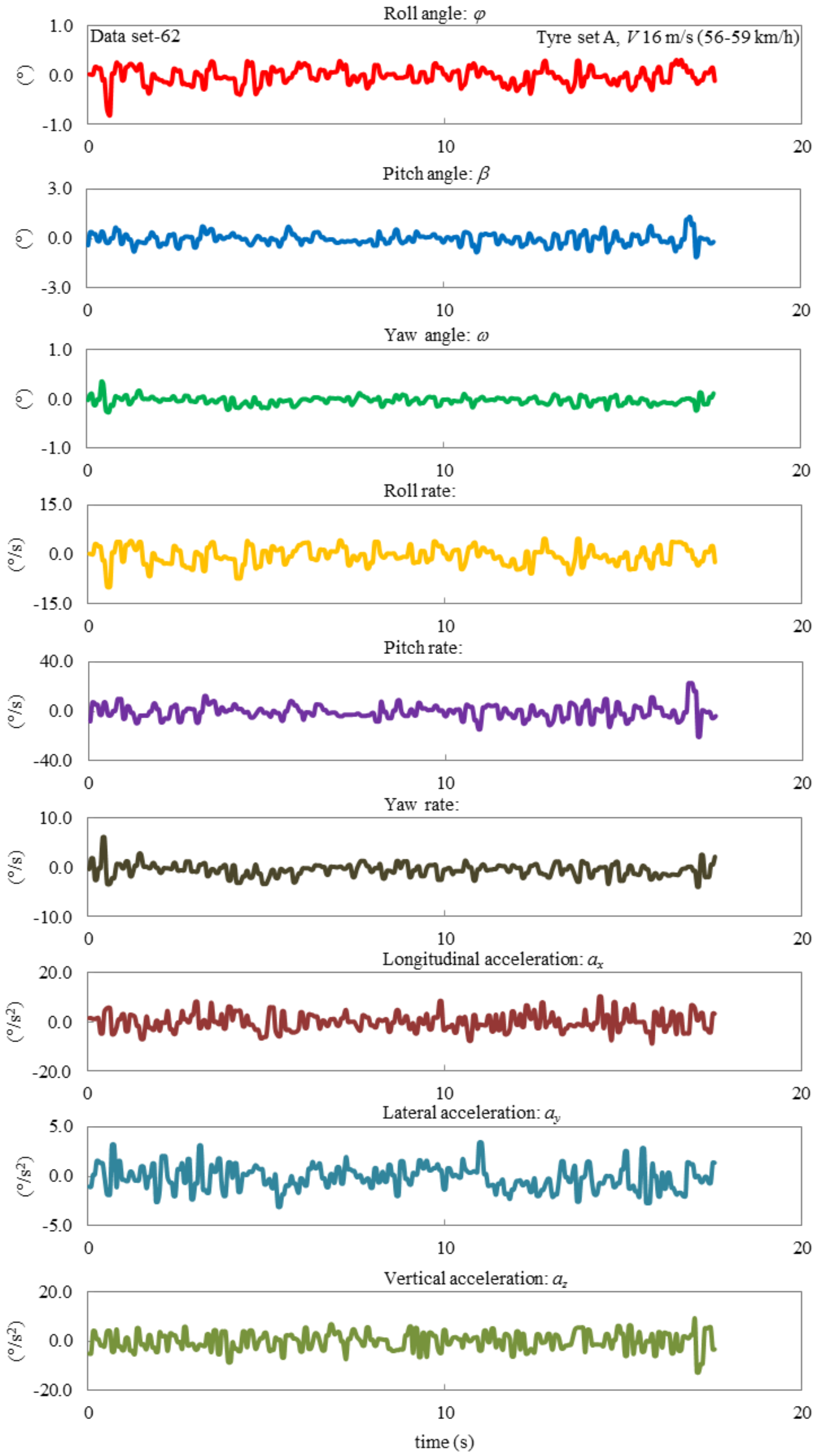


Figure 4.5 Dynamics Response Signals from Straight Run Test of Tyre Set A at Speed 16 m/s (56-59 km/h), Data Set 62

4.3.2 Vibration Signals Specification

This section features a brief statistical observation of proposed experimental measurements. A detailed optimization analysis of the vision methods will be introduced to show what the parameters indicate vehicle stability conditions. Following the optimization analysis, a concise comparison of the presented approaches will be shown how the tyre width highlights the appropriated driving stability in straight path. To this purpose, the free steering control of measured data was firstly synchronized with riding video files. For each corresponding experiment data, the average acceleration (α), orientation ($roll\,angle$, $pitch\,angle$ and $yaw\,angle$), were individually calculated and classified by running speed. In particular, the driving stability of motorcycle system was identified based on responses vibration analysis. The equation (4.1) below means the average of acceleration.

$$\alpha = \sqrt{\alpha_x^2 + \alpha_y^2 + \alpha_z^2} \tag{4.1}$$

Where α = average of angular acceleration in 3-axis
α_x, α_y, α_z = angular acceleration in x-axis, y-axis and z-axis

The “average value” or some called “average level” of common ten dynamic parameters was basically used to define vibration characterization. In this case the average level of vehicle’s position ($roll\,angle$, $pitch\,angle$ and $yaw\,angle$), rotation velocity (ω_x, ω_y and ω_z) and angular acceleration (lateral acceleration α_x, longitudinal acceleration α_y, vertical acceleration α_z and average acceleration α) were computed using equation 4.2.

$$average\ value = \frac{1}{n}\sum_{i=1}^{n}|x_i| \tag{4.2}$$

Where x_i = responses signals
n = sample sizes

Among the minimum based approach, for tyre set A in Table 4.6 the mean average value of roll angle (x-axis), pitch angle (y-axis) and yaw angle were ranged from 0.103 to 0.138 degree, 0.162 to 0.256 degree and 0.062 to 0.083 degree, respectively. At the speed level 7 m/s (24-26 km/h) appeared the smallest value of roll angle and pitch angle. While at the speed level 15 m/s (53-55 km/h) displayed the smallest value of yaw angle. The proposed orientation of vehicle in between the road plane and the front/rear damping (y-axis) and the twisting angle with respect to vertical direction (z-axis) reached a similar figure of those parameters (see Figure 4.6). With regard to vehicle’s vibration responses in vehicle reference system at the same speed, for example at 15 m/s, the mean average of yaw angle showed their smallest value of 0.062 degree. The median result displayed on the roll angle with 0.112 degree. While the degree of pitch angle obtained the highest 0.256 degree for speed 15 m/s (53-55 km/h). The nearly zero variation in the vehicle orientation can be demonstrated that the driving forces and moments were in equilibrium conditions

The graphs in Figure 4.7 show the mean of average value of nine dynamics responses signals from straight running tests. In the graphs (a)-(c) the overall figures of the mean of average value of the acceleration in x, y and z directions were totally different. The quantity of average value of acceleration in x direction (α_x) presented a varying figure. Besides the trend of acceleration in y direction (α_y) showed the almost level off. Whereas there was a steady increased pattern of α_z depending on increasing vehicle speeds. Among acceleration in three directions, the value of acceleration in lateral direction α_y gained the smallest numbers where the longitudinal acceleration α_x presented the highest value. The slight decrease in longitudinal acceleration (α_x) were from low speed of 7 m/s (24-26 km/h) to 10 m/s (35-37 km/h) and then reached a peak of 11 m/s (38-41 km/h) speed followed by steady decreased until high speed at 16 m/s. The maximum mean of average value of angular acceleration was observed during 11 m/s (38-41 km/h) speed level in x-axis with 3.724 deg/s^2 and the minimum was found at 7 m/s (24-26 km/h) speed level in y-axis with 0.681 deg/s^2.

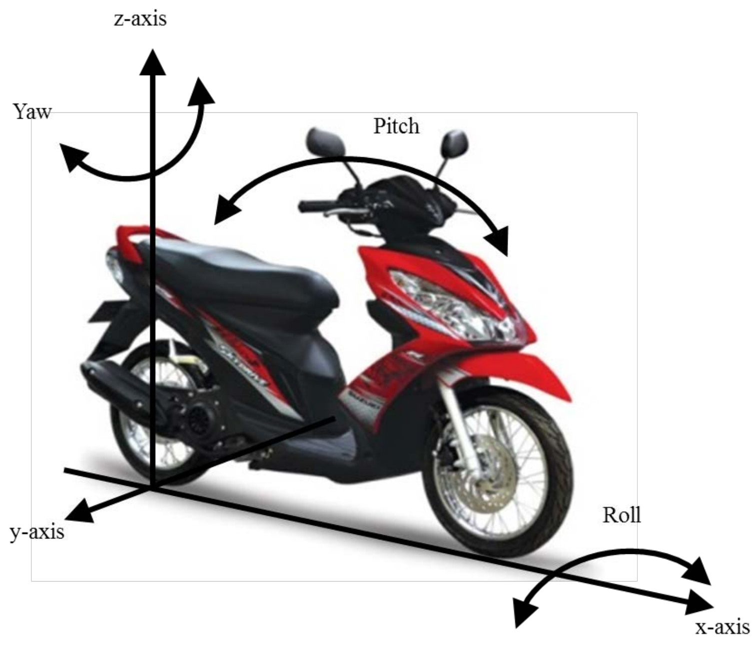


Figure 4.6 Motorcycle Rotational Direction Schematics

For the following ten speed levels in Figure 4.7 (d)-(f) the general pattern of the average value of angular velocity can be obtained with two groups of level off patterns for angular velocity in x-axis (ω_x) and in z-axis (ω_z) and grow up pattern for y-axis (ω_y). The trends of angular velocity displayed the highest value in y direction, the middle value in x direction and the lowest value in z direction. For longitudinal direction as it illustrated by the graph, the angular velocity gently ranged in between 1.748 deg/s to 2.385 deg/s. On the other hand, the rise of lateral velocity ω_y was at low speed of 7 m/s (24-26 km/h) to high speed of 16 m/s (56-59 km/h) when it rose by almost 61%. During the tested speed levels, the vertical velocity ω_z remained fairly unchanged.

From the graphs of the average value of rotational angle in Figure 4.7 (g)-(i) it is clear that the overall patterns were similar to the patterns of angular velocity. There was an increasing trend of rotational angle ($pitch\, angle$) in y-axis depending on speed level. By contrast, the trend of rotational angle in x-axis and in z-axis, $roll\, angle$ and $yaw\, angle$, showed the level off style. The $roll\, angle$ remained stable about 0.12 degree for the following ten speed levels. The $pitch\, angle$ went up to about nearly 60% with the maximum value of 2.56 degree at speed 15 m/s (53-55 km/h). The smallest rotation angle in the vertical direction stayed roughly constant with 0.07 degree.

For tyre set B, as shown in Table 4.7 the statistics of the mean average value of dynamic responses parameters were presented. Overall, it can be seen that the quantity of angular acceleration in x-axis was far higher than in y-axis and z-axis. While the angular velocity and rotational angle in y-axis presented the higher quantity comparing with another axis. The angular acceleration in x-axis, y-axis and z-axis were ranged from 2.196 to 3.971, 0.597 to 1.062 and 1.170 to 3.308, respectively. The highest value of acceleration in longitudinal direction observed at speed 11 m/s with 3.971 deg/s^2. For the average acceleration (α), the smallest value was found at low speed of 7 m/s with 2.92 deg/s^2 although the highest value was found at speed 14 m/s (49-52 km/h) with 5.46 deg/s^2. As observed in tyre set A's output, the average value of nine responses signals of tyre set B presented a similarity style in the speed range of 8 m/s (27-30 km/h) to 16 m/s (56-59 km/h).

In Figure 4.8 (a)-(c) used three angular acceleration to show the dynamic responses character of straight running motorcycle. The rose of α_x were from a low speed of 7 m/s (24-26 km/h) to 10 m/s (35-37 km/h) and then reached a peak at 11 m/s (38-41 km/h) speed after that gradually went down until 17 m/s (60-62 km/h). This pattern was similar as that of tyre set A. The acceleration in lateral α_y had a gentle trend around 0.86 deg/s^2. The value of acceleration in vertical axis α_z presented a significant trend. Between low to high speed level, the value of α_z shot up dramatically from 1.34 deg/s^2 to 3.3 deg/s^2.

The graphs in Figure 4.8 (d)-(f) shows the angular velocity where in (g)-(i) illustrated the angular rotation. It can be clearly seen that, there were similar patterns of the three variables for each axis. The angular velocity in x-axis (ω_x) presented a slightly stable during speed level 14 m/s (49-52 km/h) to 17 m/s (60-62 km/h). The value of angular velocity in y-axis (ω_y) was a far higher than another with an oscillated increasing trend. For vertical direction the angular velocity (ω_z) was continuously unchanged after speed of 8 m/s (27-30 km/h).

The overall value of $roll\, angle$ (x-axis), $pitch\, angle$ (y-axis) and $yaw\, angle$ in Figures 4.8 (g)-(i) were around 0.12 degree, 0.21 degree and 0.07 degree, respectively. At the low speed level of 9 m/s (31-34 km/h) there was an appearance of the smallest value of $roll\, angle$. During the speed of 13 m/s (45-48 km/h) to 17 m/s (60-62 km/h), the unchanged figure of $roll\, angle$ can be observed significantly. Likewise the $yaw\, angle$ at the speed level of 8 m/s (27-30 km/h) to 17 m/s (60-62 km/h) gained a similar result. On the contrary, the minimum value of $pitch\, angle$ occurred at the speed of 8 m/s (27-30 km/h) and then rapidly went up to 0.270 degree at speed 17 m/s (60-62 km/h). This characteristic was rather similar to the output of tyre set A.

For tyre set C, the mean average value of dynamic responses parameters is shown in Table 4.8. By comparing the overall experimental results of tyre set A and tyre set B, it can be seen that the highest quantity of most responses dynamics parameters were far higher than other tyre sets except the value of ω_x, ω_z and $yaw\, angle$. Similarly, the angular velocity and rotational angle in y-axis presented the higher quantity in both tyre set A and tyre set B. The angular acceleration in x-axis, y-axis and z-axis ranged from 1.725 to 4.699, 0.680 to 1.162 and 1.273 to 5.231, respectively. The highest value of acceleration in longitudinal direction (α_x) was observed at speed 14 m/s (49-52 km/h) with 4.699 deg/s^2. The α_x and α_z of tyre set C were higher than those of tyre set A and tyre set B with about 20 percent, 15 percent, 43 percent and 36 percent, respectively. From very low speed to high speed, the increasing percentage of $pitch\, angle$ showed the remarkable figure with around 100 percent. In the same way, the $roll\, angle$ went up by roughly 60 percent from 0.103 degree to 0.116 degree. By nearly 20 percent increase, the $yaw\, angle$ could be supposed as a stable pattern.

As given in Figure 4.9 (a)-(c), the average values of acceleration in the three main directions were displayed. There was a rapid up trend of longitudinal direction (α_x) from very low speed with 1.725 deg/s^2 to the peak of 4.699 deg/s^2 at 14 m/s speed level which was roughly stable. However the trend of acceleration in lateral direction represented the notable level off. The pattern of average value of acceleration in vertical direction displayed a considerable rising pattern. These characters were similar to those of tyre set A and B.

Figure 4.9 (d)-(f) displays the average value of angular velocity and in (g)-(i) are the average value of rotational angle of tyre set C's outputs. It is important to consider that the similarity in pattern of parameters in three main axes is very noticeable. The varying velocity and rotation in vertical axis represented the smallest value compared to other axes. From low to high speed, there was a steady upward trend of velocity and rotational angle in x-axis. In the same manner, the patterns of velocity and rotational in y-axis displayed a sharp rise by almost 2 times.

Table 4.6 Mean of Average Value of the Straight Running Test of Tyre Set A

Average Speed (m/s)	Average Value									
	α_x	α_y	α_z	α	ω_x	ω_y	ω_z	*roll*	*pitch*	*yaw*
7	3.082	0.681	1.644	3.843	1.748	2.743	1.138	0.103	0.162	0.066
8	3.051	0.772	1.388	3.758	1.994	2.906	1.286	0.117	0.171	0.076
9	2.957	0.835	1.602	3.855	1.937	3.059	1.323	0.115	0.183	0.079
10	2.864	0.875	1.934	3.965	2.385	2.972	1.427	0.138	0.170	0.083
11	3.724	0.918	2.539	5.037	2.040	3.113	1.208	0.120	0.183	0.071
12	3.595	0.907	2.759	5.086	2.069	3.924	1.156	0.118	0.225	0.066
13	3.582	0.893	2.766	5.089	2.171	3.921	1.108	0.124	0.224	0.064
14	3.278	1.014	2.971	5.028	2.028	3.727	1.091	0.115	0.213	0.063
15	3.191	1.198	2.719	4.845	1.932	4.420	1.049	0.112	0.256	0.062
16	2.754	1.029	2.805	4.543	2.025	4.190	1.122	0.118	0.243	0.066

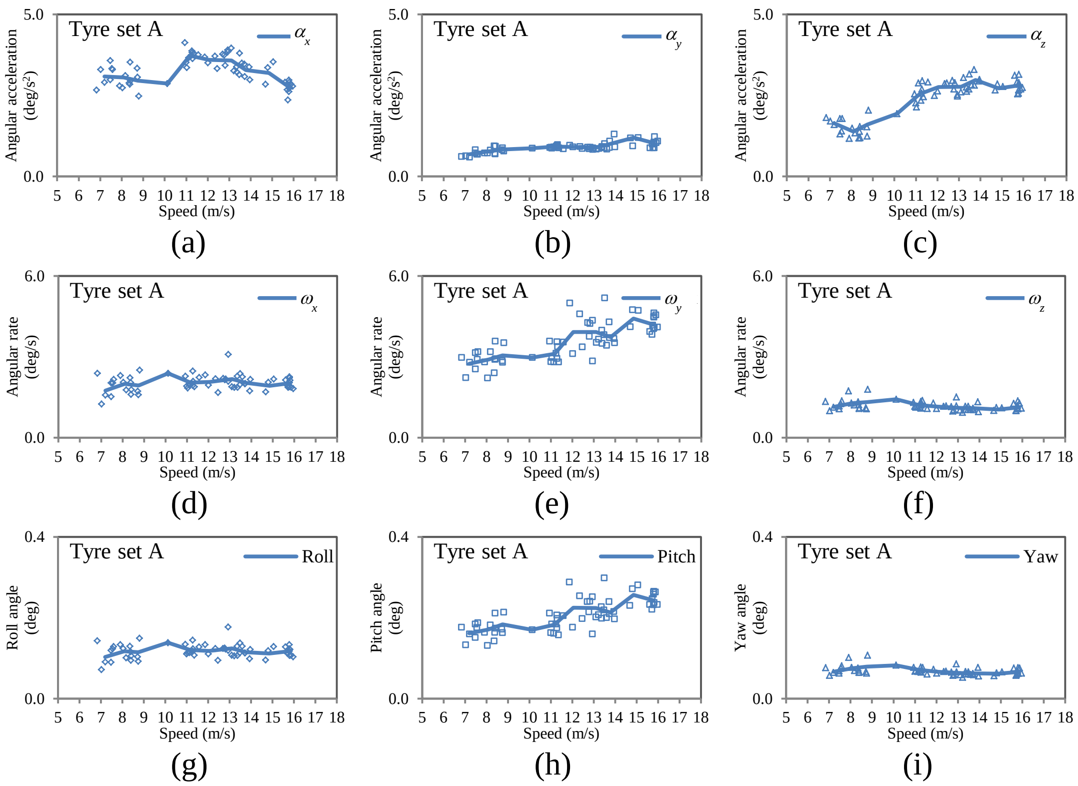


Figure 4.7 The Mean of Average Value of 9 Dynamic Parameters of Tyre Set A

Table 4.7 Mean of Average Value of the Straight Running Test of Tyre Set B

Average Speed (m/s)	Average Value									
	α_x	α_y	α_z	α	ω_x	ω_y	ω_z	*roll*	*pitch*	*yaw*
7	2.196	0.639	1.342	2.924	2.806	3.571	2.571	0.159	0.202	0.146
8	2.409	0.597	1.170	3.402	1.700	2.581	1.069	0.097	0.150	0.062
9	2.910	0.678	1.306	3.549	1.579	3.110	1.056	0.088	0.176	0.060
10	3.253	0.700	1.562	3.945	1.914	2.738	1.036	0.108	0.154	0.059
11	3.971	0.879	2.641	5.261	2.532	3.249	1.240	0.146	0.188	0.072
12	3.889	0.861	2.818	5.335	2.435	4.177	1.153	0.140	0.239	0.067
13	3.816	0.861	2.768	5.177	2.008	3.272	0.958	0.116	0.191	0.055
14	3.588	1.050	3.292	5.465	2.059	4.399	1.030	0.119	0.254	0.060
15	3.474	1.062	3.220	5.332	2.073	4.193	1.116	0.121	0.243	0.066
16	3.405	1.061	3.308	5.354	2.104	4.444	1.128	0.122	0.255	0.067
17	2.987	0.941	3.233	4.978	2.183	4.646	1.185	0.127	0.270	0.069

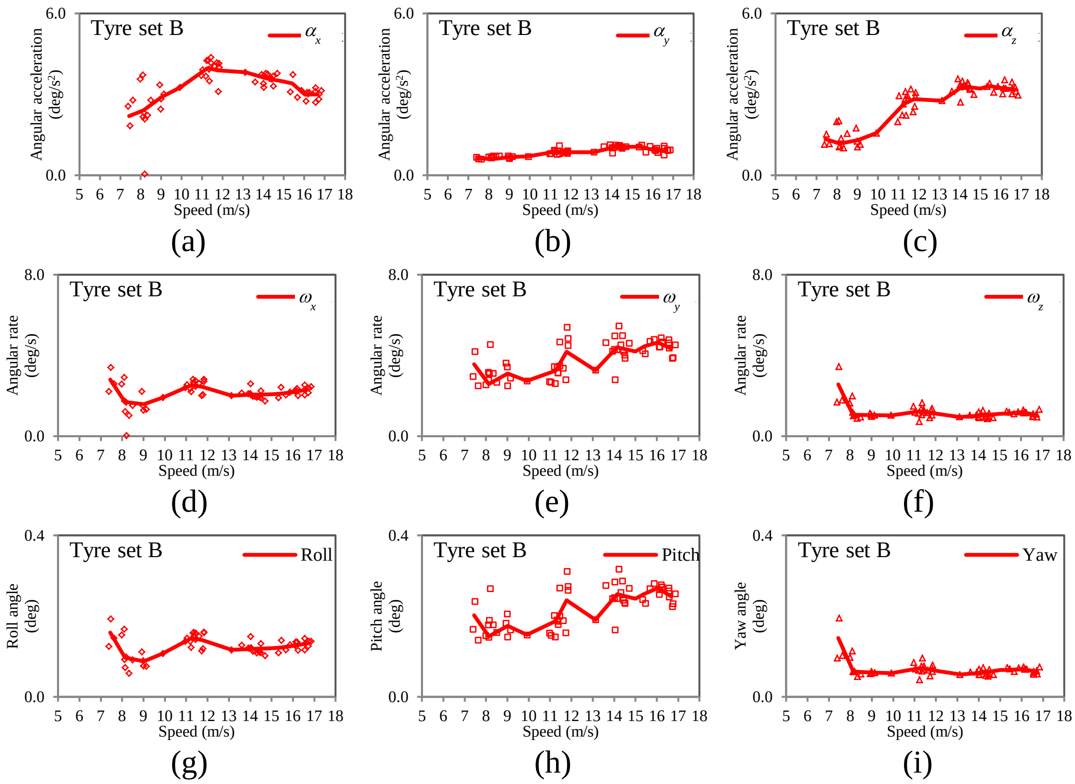


Figure 4.8 The Mean of Average Value of 9 Dynamic Parameters of Tyre Set B

Table 4.8 Mean of Average Level of the Straight Running Test of Tyre Set C

Average Speed (m/s)	Average Value									
	α_x	α_y	α_z	α	ω_x	ω_y	ω_z	*roll*	*pitch*	*yaw*
8	1.725	0.680	1.273	2.538	1.745	2.825	1.411	0.103	0.168	0.084
10	2.596	0.922	1.406	3.419	1.974	3.119	1.314	0.118	0.187	0.079
11	3.026	0.914	1.779	4.007	1.900	3.138	1.159	0.117	0.192	0.071
13	4.581	0.976	4.081	6.695	2.377	3.891	1.271	0.146	0.240	0.078
14	4.699	0.989	4.003	6.745	2.486	3.920	1.211	0.152	0.242	0.075
16	4.558	1.162	5.231	7.601	2.696	5.537	1.326	0.166	0.338	0.081

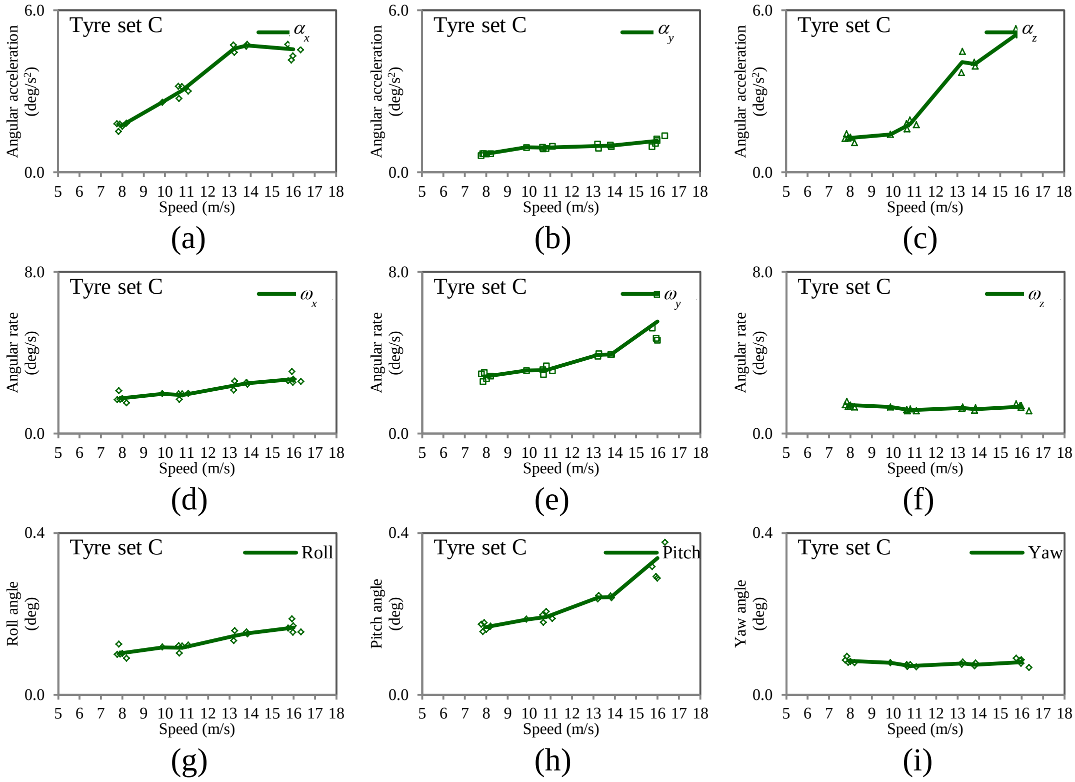


Figure 4.9 The Mean of Average Value of 9 Dynamic Parameters of Tyre Set C

It is worth stressing the importance of a root mean square (*RMS*) which is a time analysis feature of vibration signals that measure the power content in the vibration characteristics (Sabin, 2006) (Yang, Mathew, & Ma, 2003) (Lebold, McClintic, Campbell, Byington, & Maynard, 2000). The equation below (4.3) is used to calculate the root mean square value of vibration responses data, $f(t)$ over the period of the waveform.

$$RMS = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} f(t)^2\,dt} \tag{4.3}$$

Where $f(t)$ = responses signals at time t_i
T = the period (one complete cycle) of the waveform

RMS analyses have proved to be useful in detecting changes and a major out-of-balance of vibration signals. Additionally, as in previous works of (Lebold, McClintic, Campbell, Byington, & Maynard, 2000) (Yang, Mathew, & Ma, 2003) (Chen, Chen, Liu, Chen, & Pan, 2009) (Cheli, Mazzoleni, Pezzola, Ruspini, & Zappa, 2013), the determination of the root mean square (RMS) of the average acceleration could be applied to complete dynamics of a vehicle. Table 4.9-4.11 presents the determined value of the mean of RMS of the ten dynamic parameters for tyre set A, tyre set B and tyre set C for straight road test at different running speeds.

Table 4.9 contains the mean of RMS ten major dynamic responses signal of motorcycle vibration in terms of angular acceleration, velocity and rotation of tyre set A. In the case of roll angle (x-axis), pitch angle (y-axis) and yaw angle, they ranged from 0.50 to 0.62 degree, 0.74 to 1.16 degree and 0.27 to 0.38 degree, respectively. At the speed level 7 m/s (24-26 km/h) appeared the smallest value of roll angle and pitch angle. While at the speed level 15 m/s (53-55 km/h) displayed the smallest value of yaw angle. With regard to vehicle’s vibration responses in vehicle reference system at the same speed, for example at 15 m/s (53-55 km/h), the mean average of yaw angle showed their smallest value of 0.31 degree. The middling result was displayed on the roll angle with 0.55 degree. While the degree of pitch angle obtained with the highest of 1.16 degree for speed 15 m/s (53-55 km/h).

The graphs in Figure 4.10 provide the mean of RMS of nine dynamics responses signals from straight running tests. In the graphs (a)-(c) the overall figures of the mean of average value of the acceleration in x, y and z directions were completely different. The quantity of RMS of acceleration in x direction (α_x) presented a varying figure. On the other hand, the trend of acceleration in y direction (α_y) showed mostly unchanged. Whereas a steady increased pattern of α_z was observed depending on increasing speeds. These RMS characters had similar feature as of the average value. Among acceleration in three directions, the RMS value of acceleration in lateral direction α_y appeared to have the smallest numbers while the longitudinal acceleration α_x presented the highest value. The minute increase in longitudinal acceleration (α_x) were at the speed of 7 m/s (24-26 km/h) until it reached a first peak at 10 m/s (38-41 km/h) speed. After that, a small valley occurred between speed 11 m/s to 13 m/s followed by a second peak at 14 m/s. Then the RMS of α_x continuously decreased to 16.37 deg/s^2 at speed 16 m/s. The minimum mean of RMS value of angular acceleration was observed at speed 7 m/s in lateral axis with 3.42 deg/s^2 and the maximum was found at 7 m/s (24-26 km/h) speed level in longitudinal axis with 23.52 deg/s^2.

For the following ten speed levels in Figure 4.10 (d)-(f) the general pattern of the average value of angular velocity can be obtained with three style of fluctuated decrease patterns for angular velocity in x-axis (ω_x), fluctuated trend in z-axis (ω_z) and level off pattern for y-axis (ω_y). Overall, the angular velocity displayed the highest value in y direction, the middle value in x direction and the lowest value in z direction. For longitudinal direction as illustrated by the graph, the angular velocity ranged between 3.28 deg/s to 11.88 deg/s. On the other hand, the oscillated lateral velocity ω_y was from 7.29 deg/s to 21.40 deg/s where its variance provided by almost 200%. During the tested speed levels, the vertical velocity ω_z remained fairly unchanged.

From the graphs of the RMS of rotational angle in Figure 4.10 (g)-(i) it is clear that the overall patterns were similar to the patterns of angular velocity. There was an increasing trend of rotational angle ($pitch\,angle$) in y-axis depending on speed level. By contrast, the RMS trend of rotational angle in x-axis and in z-axis; $roll\,angle$ and $yaw\,angle$; showed a closely stable style. The $roll\,angle$ remained stable at about 0.55 degree for the following ten speed levels. The $pitch\,angle$ went up to almost 56% with the maximum value of 1.16 degree at speed 15 m/s (53-55 km/h). The smallest RMS of rotation angle in the vertical direction stayed roughly constant with 0.31 degree.

As shown in Table 4.10 the statistics of the mean of RMS of dynamic responses parameters of tyre set B were presented. Inclusive, it can be seen that the quantity of angular acceleration in x-axis was far higher than in y-axis and z-axis. While the angular velocity and rotational angle in y-axis presented the higher quantity comparing with another axis. The angular acceleration in x-axis, y-axis and z-axis ranged from 10.70 to 19.58, 3.35 to 5.35 and 5.25 to 16.02, respectively. The highest value RMS of acceleration in longitudinal direction was observed at speed 11 m/s with 19.58 deg/s^2. For the average acceleration (α), the smallest value was found at low speed of 7 m/s with 12.35 deg/s^2 although the highest value was found at speed 14 m/s (49-52 km/h) with 24.70 deg/s^2.

Figure 4.11 (a)-(c) shows three angular acceleration of the dynamic responses character of straight running motorcycle. The RMS of α_x sharply rose at lower speed to peak at speed 11 m/s and later tumbled when the value was cut by almost 30%. This pattern was unlike to that of tyre set A. Whereas the acceleration in lateral α_y had a gentle unchanged trend with a small value of 4.29 deg/s^2. The upward 46% acceleration in vertical axis α_z where the speed was lower than 11 m/s before it gently climbed up 20% to the topmost value at a speed of 16m/s.

The graphs in Figure 4.11 (d)-(f) shows the RMS of angular velocity where (g)-(i) illustrates the angular rotation. It can be clearly seen that, there were similar patterns of that velocity and rotation angle. The angular velocity in x-axis (ω_x) swung during speed 7m/s-13 m/s before it slightly went up to 11.26 deg/s. The value of angular velocity in y-axis (ω_y) was a far higher than others with an oscillated increasing trend. For vertical direction the angular velocity (ω_z) had a three times lower value than v_y which was continuously unchanged after speed 9 m/s.

Figures 4.11 (g)-(i) the overall average value RMS of $roll\,angle$ (x-axis), $pitch\,angle$ (y-axis) and $yaw\,angle$ were around 0.58 degree, 0.98 degree and 0.33 degree, respectively. At low speed level of 9 m/s (31-34 km/h) there was an appearance of the smallest value of $roll\,angle$ followed by swinging form 0.41 degree to 0.68 degree finally ending with the value of 0.61 degrees. During low to high speed, the varying figure of $pitch\,angle$ can be significantly observed. In comparison with the output of $pitch\,angle$, the contrast result happened with the minimum value of $yaw\,angle$. After speed 9 m/s forward, there was an insignificant 15% increase. This characteristic was fairly parallel to the output of tyre set A.

For tyre set C, the mean of RMS value of dynamic responses parameters is shown in Table 4.11. By comparing the overall experimental results to another two reference axes, it can be seen that the RMS value of angular acceleration in longitudinal direction was greater than in lateral and vertical direction. The angular velocity and rotation angle in lateral direction, whereas, had a higher value than the other directions. The angular acceleration in x-axis, y-axis and z-axis ranged from 838 to 21.86, 3.26 to 5.92 and 6.08 to 23.27, respectively. The highest value of acceleration in longitudinal direction (α_x) was observed at speed 16 m/s (56-59 km/h) with 21.86 deg/s^2. For the average acceleration (α), the smallest value was found at a low speed of 8 m/s with 11.96 deg/s^2 albeit the highest value was found at speed 16 m/s (56-59 km/h) with 33.92 deg/s^2.From very low speed to high speed, the increasing percentage of $pitch\,angle$ showed the remarkable figure of around 120 percent. In the same way, the $roll\,angle$ went up by roughly 60 percent from 0.47 degree to 0.77 degree. By nearly 15 percent increase, the $yaw\,angle$ could be supposed as a stable pattern.

As given in Figure 4.12 (a)-(c), the RMS of acceleration in the three main directions were displayed. There was a rapid climbed up trend of longitudinal direction (α_x) from very low speed with 8.38 deg/s^2 to 21.36 deg/s^2 at 14 m/s speed level and then roughly stable until 16 m/s. In contrast the trend of acceleration in lateral direction represented a notable level off. The pattern of RMS of acceleration in vertical direction displayed a considerable increasing form. These characters were similar to those of tyre set A and B.

It was clear that, there were similar patterns in velocity and rotation angle. The angular velocity in x-axis (ω_x) swung during speed 7m/s-13 m/s before it slightly went up to 11.26 deg/s. The value of angular velocity in y-axis (ω_y) was a far higher than another with an oscillated increasing trend. For vertical direction, the angular velocity (ω_z) had a three times lower value than ω_y, which was continuously unchanged after speed 9 m/s.

In Figure 4.12 (d)-(f) shows the mean of RMS of angular velocity. Apparently there were similar patterns in velocity and rotation angle. The angular velocity in x-axis (ω_x) slightly increased from 7.97 deg/s to 12.28 deg/s. The value of angular velocity in y-axis (ω_y) was far higher than others with a sharp increasing trend. But the near constant value came from the RMS value of angular velocity in vertical direction.

The overall mean of RMS of $roll\,angle$ (x-axis), $pitch\,angle$ (y-axis) and $yaw\,angle$ as shown in the Figures 4.12 (g)-(i) were around 0.62 degree, 1.05 degree and 0.33 degree, respectively. At low speed level of 8 m/s (27-30 km/h) there was an appearance of mild rising style of $roll\,angle$ by 0.47 degree to finally end with the value of 0.77 degree. On the other hand, a remarkable jump in the number of $pitch\,angle$ can be significantly observed. In comparison with the output of $pitch\,angle$, the contrast result happened with the minimum constant value of $yaw\,angle$. This characteristic was fairly parallel to the output of tyre set A and B.

Table 4.9 Mean of RMS of Response Dynamic Parameters of Road Tests for Tyre Set A

Measured Parameter	x-axis			y-axis			z-axis			avg. α
	roll	α_x	ω_x	*pitch*	α_y	ω_y	*yaw*	α_z	ω_z	
Average Speed (m/s)	(deg)	(deg/s^2)	(deg/s)	(deg)	(deg/s^2)	(deg/s)	(deg)	(deg/s^2)	(deg/s)	(deg/s^2)
7	0.50	14.05	10.11	0.74	3.42	7.29	0.30	7.57	2.68	17.22
8	0.54	15.76	8.97	0.78	3.85	14.33	0.33	6.98	5.55	17.24
9	0.51	14.74	8.89	0.85	4.14	15.25	0.35	9.11	6.23	17.98
10	0.62	20.22	11.88	0.78	4.38	15.03	0.38	9.21	7.06	17.90
11	0.56	17.61	7.25	0.83	4.83	9.88	0.31	12.20	4.12	22.30
12	0.56	17.78	8.93	1.06	7.17	18.55	0.29	13.70	4.82	22.74
13	0.58	19.59	8.50	1.07	4.62	15.10	0.28	14.00	3.05	23.26
14	0.51	23.52	4.74	0.95	5.17	21.40	0.29	10.84	3.10	21.74
15	0.54	18.89	3.28	1.16	5.48	8.23	0.27	13.08	3.26	21.91
16	0.55	16.37	7.48	1.13	5.15	16.93	0.30	13.40	3.79	20.26

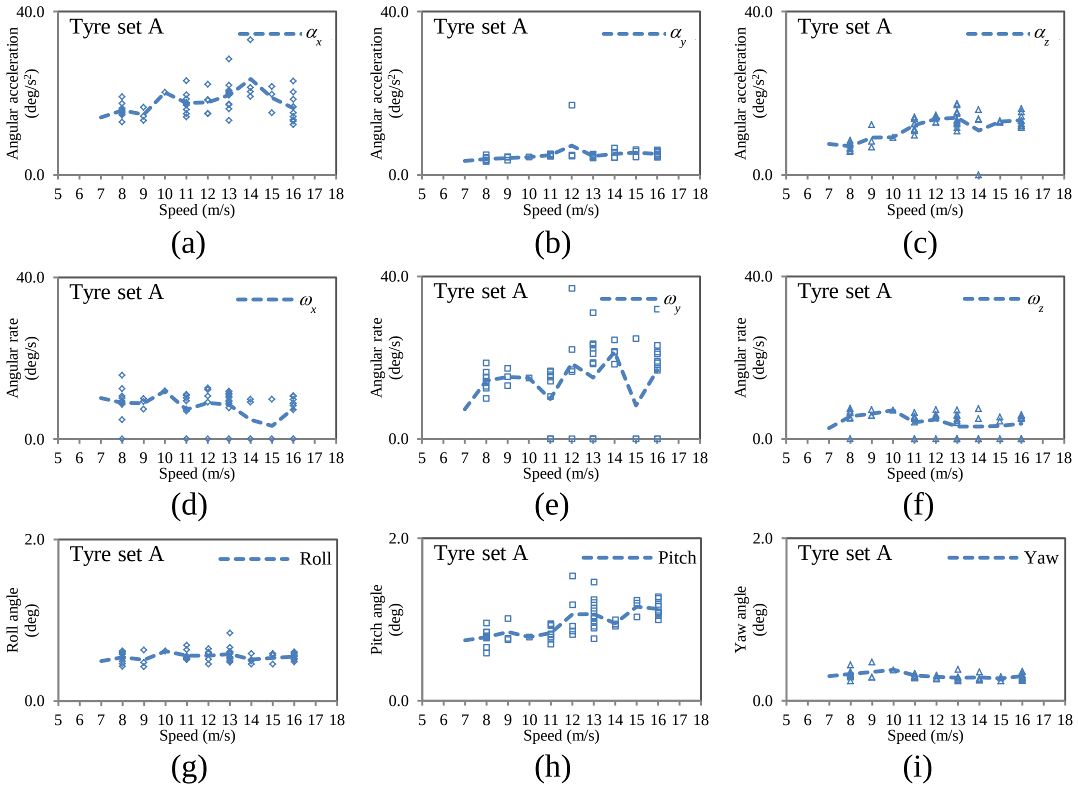


Figure 4.10 The Mean of Root Mean Square of 9 Dynamic Parameters of Tyre Set A

Table 4.10 Mean of RMS of Response Dynamic Parameters of Road Tests for Tyre Set B

	x-axis			y-axis			z-axis			
Measured Parameter	*roll*	α_x	ω_x	*pitch*	α_y	ω_y	*yaw*	α_z	ω_z	avg. α
Average Speed (m/s)	(deg)	(deg/s^2)	(deg/s)	(deg)	(deg/s^2)	(deg/s)	(deg)	(deg/s^2)	(deg/s)	(deg/s^2)
7	0.74	10.70	12.80	0.92	3.35	18.37	0.61	6.80	9.56	12.35
8	0.52	13.33	9.20	0.82	3.41	15.05	0.36	6.76	6.13	14.81
9	0.41	14.18	7.84	0.81	3.57	15.36	0.27	6.42	5.04	17.79
10	0.48	13.27	9.36	0.72	3.35	14.12	0.26	5.25	4.95	14.86
11	0.68	19.58	11.66	0.86	4.58	17.01	0.31	12.66	5.63	24.37
12	0.65	18.67	11.50	1.14	4.26	23.13	0.30	14.13	5.48	23.85
13	0.57	18.49	9.81	0.88	4.32	17.71	0.24	13.42	4.99	22.73
14	0.55	17.39	9.95	1.15	5.25	22.68	0.26	15.83	4.94	24.70
15	0.55	16.79	9.98	1.15	5.35	22.31	0.45	15.06	5.72	23.63
16	0.59	14.74	10.74	1.23	5.10	21.82	0.30	16.02	5.33	22.76
17	0.61	14.32	11.26	1.16	4.62	21.10	0.28	14.17	5.67	21.34

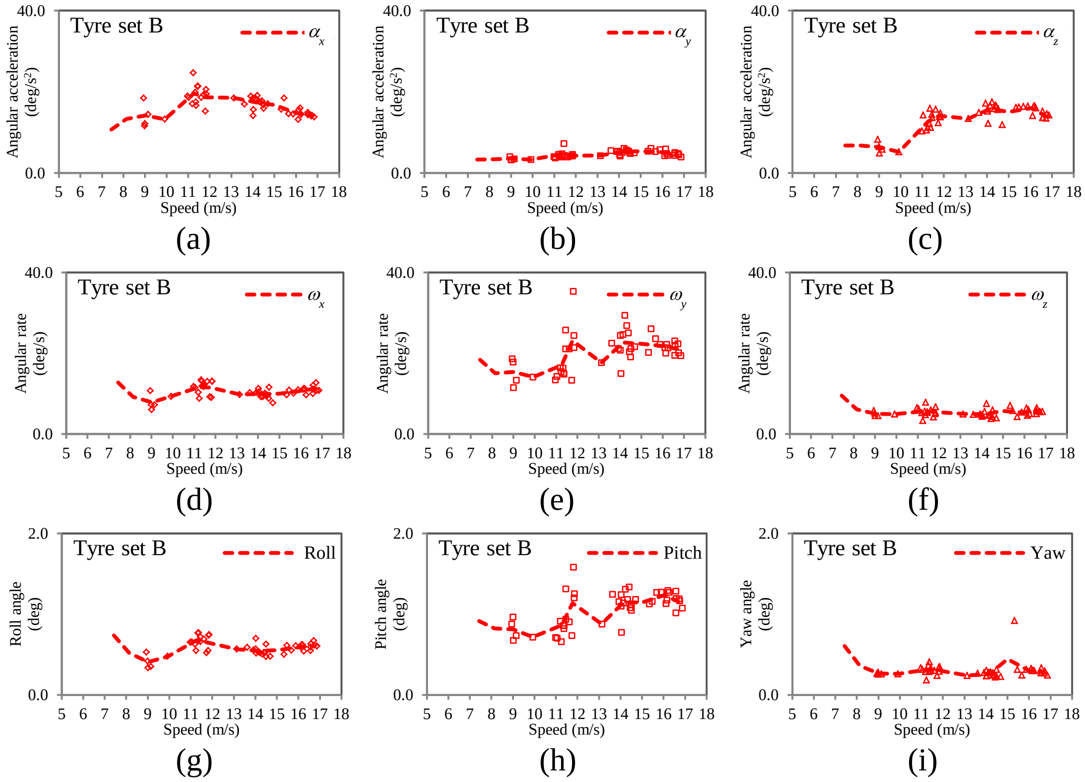


Figure 4.11 The Mean of Root Mean Square of 9 Dynamic Parameters of Tyre Set B

Table 4.11 Mean of RMS of Response Dynamic Parameters of Road Tests for Tyre Set C

Measured Parameter	x-axis			y-axis			z-axis			avg. α
	roll	α_x	ω_x	*pitch*	α_y	ω_y	*yaw*	α_z	ω_z	
Average Speed (m/s)	(deg)	(deg/s^2)	(deg/s)	(deg)	(deg/s^2)	(deg/s)	(deg)	(deg/s^2)	(deg/s)	(deg/s^2)
8	0.47	8.38	7.97	0.77	3.26	13.35	0.34	6.08	5.79	11.96
10	0.54	13.29	8.88	0.84	4.42	13.92	0.33	7.08	5.52	16.51
11	0.54	14.15	9.03	0.87	4.40	14.43	0.31	8.45	5.19	18.39
13	0.67	20.68	10.87	1.08	4.89	18.35	0.33	18.80	5.47	30.55
14	0.72	21.36	11.62	1.10	4.91	18.86	0.32	18.89	5.38	30.60
16	0.77	21.86	12.28	1.68	5.92	26.58	0.36	23.27	5.90	33.92

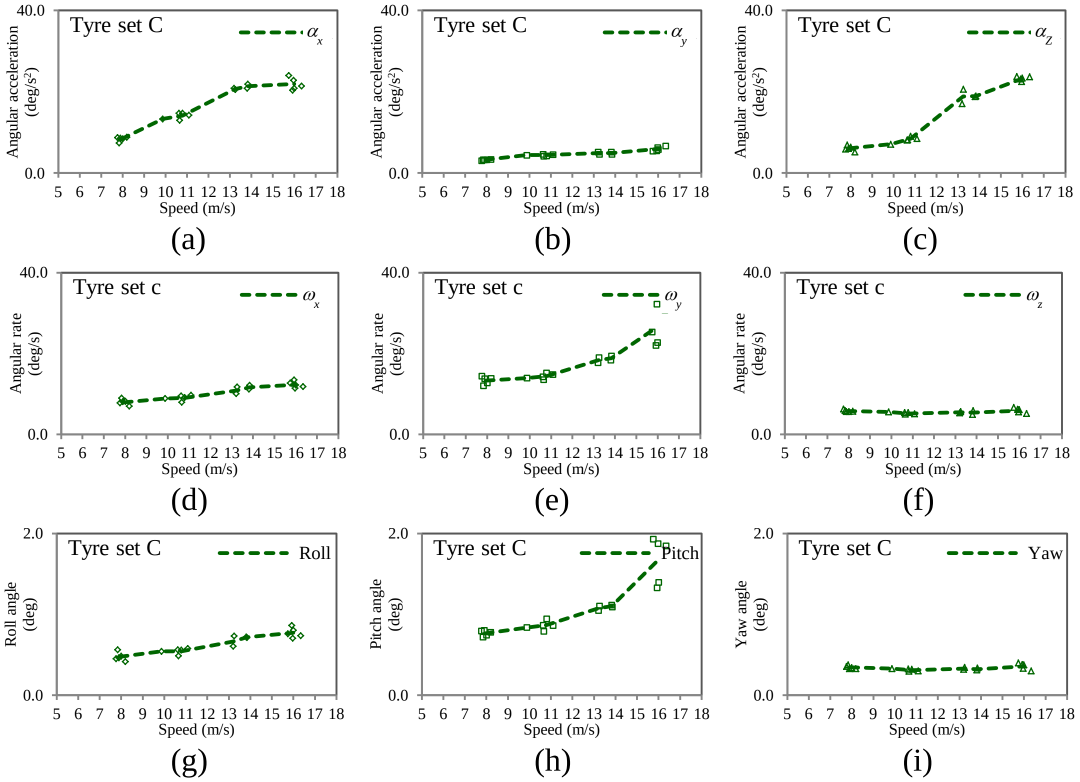


Figure 4.12 The Mean of Root Mean Square of 9 Dynamic Parameters of Tyre Set C

4.3.3 Statistical Analysis

The statistical analysis was performed using SPSS Statistics Version 17 for Windows. Group differences between the mean of average value and RMS of ten measured dynamic parameters were assessed by the analysis of variance ANOVA. In particular, the focus was on determining the association between tyre sets, speed levels and interrelated dynamic stability parameters such as acceleration, velocity and displacement. Under the null hypothesis of no association between the mentioned tyre sets and driving stability parameters, the tyre sets and speed levels were used as the within-subjects factors to evaluate its effect to motorcycle stability when running along the straight route. A significant level of *p-value* was regarded as 0.05.

Table 4.12 contains the output from Kolmogorov-Smirnov test. This statistic particularly used for testing the normality assumption of variables. No significant results in average value of ten dynamic responses signals were observed among the three tyre sets and eleven speed levels. The test statistics were 0.072, 0.089, 0.100, 0.103, 0.084, 0.076, 0.171, 0.070, 0.077 and 0.174 for α_x, α_y, α_z, α, ω_x, ω_y, ω_z, $roll$, $pitch$ and yaw, respectively which are greater than alpha 0.05. This indicated that the dynamic responses signals variable have a normal distribution.

As shown in Table 4.13 the results of Kolmogorov-Smirnov test provided the values 0.045, 0.150, 0.082, 0.090, 0.186, 0.129, 0.210, 0.082, 0.078 and 0.202, respectively. The results of most variables were greater than the significant level 0.05. While α_x presented the smaller value than significant level 0.05.

To account for these potential groups which were tyre sets and dynamic responses vibration signals association, the One-Way Analysis of Variance was conducted. A Tukey test was used to indicate which groups may be responsible for a significant effect. This is because there were no equal sample sizes of speed levels and it was more powerful for three factors. Table 4.14 shows the results of the analysis of the mean of average value of ten key dynamic responses signals affecting by differences of tyre sets. The total of sum of square presented a wide range of 0.049-158.225. The *p-value* for all variables was greater than significant level 0.05. Therefore, the null hypothesis was accepted. It is worth highlighting that there were no significant differences in behaviour among three groups of tyre to responses dynamic signals.

In the case of speed within-subjective factor as shown in Table 4.15, most of dynamic responses variables were significant as affected by variation in speed levels except the angular velocity (ω_z) and the rotational displacement in vertical direction (yaw). Therefore the null hypothesis of v_z and yaw were accepted. These denote that speed level had significant influence on the mean average value of ω_z and yaw.

Table 4.12 Mean (S.D.) and Kolmogorov-Smirnov Test of Average Value of Response Dynamic Parameters of Road Tests

Parameter	α_x	α_y	α_z	α	ω_x	ω_y	ω_z	*roll*	*pitch*	*yaw*
Mean	3.283	0.890	2.545	4.728	2.095	3.685	1.185	0.122	0.215	0.069
S.D.	0.718	0.177	0.976	1.075	0.423	0.948	0.329	0.025	0.055	0.019
Sample size (N)	138	138	138	138	138	138	138	138	138	138
One-Sample Kolmogorov-Smirnov Test Statistic	0.072	0.089	0.100	0.103	0.084	0.076	0.171	0.070	0.077	0.017

* Sig < 0.05

Table 4.13 Mean (S.D.) and Kolmogorov-Smirnov Test of Root Mean Square of Response Dynamic Parameters of Road Tests

Parameter	α_x	α_y	α_z	α	ω_x	ω_y	ω_z	*roll*	*pitch*	*yaw*
Mean	16.746	4.628	12.190	21.302	9.271	16.992	4.921	0.571	1.002	0.315
S.D.	3.958	1.370	4.471	4.882	3.430	7.616	2.189	0.109	0.250	0.084
Sample size (N)	138	138	138	138	138	138	138	138	138	138
One-Sample Kolmogorov-Smirnov Test Statistic	0.045**	0.150	0.082	0.090	0.186	0.129	0.210	0.082	0.078	0.202

** Sig < 0.01

Table 4.14 One-Way ANOVA for Average Value of Dynamic Responses with Tyre Set as the Within-Subjects Factors

Average Value of Variables	Total Sum of Squares	df	F-Statistic	*p-value*
α_x	70.706	137	0.308	0.735
α_y	4.268	137	1.177	0.311
α_z	130.528	137	3.022	0.052
α	158.255	137	1.628	0.200
ω_x	24.515	137	1.528	0.221
ω_y	123.153	137	0.961	0.385
ω_z	14.822	137	1.272	0.284
roll	0.087	137	2.826	0.063
pitch	0.421	137	1.847	0.162
yaw	0.049	137	2.848	0.061

* Sig < 0.05

Table 4.16 provides the results of ANOVA of the RMS of ten key dynamic responses signals affected by difference of tyre sets. The total of sum of square presented an extremely wide range of 0.973-7947.009. The *p-value* of most variables was greater than significant level 0.05 consisting of three angular accelerations, average acceleration and three rotational displacements. It is worth mentioning that there were no significant differences of these behaviours among three groups of tyre to responses dynamic signals. In contrast, the *p-value* of three angular velocities revealed a smaller value than the overall alpha level. By these results, rejecting the null hypothesis was done. These indicate that three different tyre sets contributed to three different axes angular velocity of tested motorcycle.

Significant in most measured dynamic responses variables were obtained for the case of speed within-subjective factor as shown in Table 4.17. The opposite results can be observed in the angular velocity in x-axis (ω_x) and z-axis (ω_z). For that reason the null hypotheses of ω_x, ω_z and yaw were accepted. These signify denoted that speed level had no significant power on the RMS value.

Table 4.15 One-Way ANOVA for Average Value of Dynamic Responses with Speed as the Within-Subjects Factors

Average Value of Variables	Total Sum of Squares	df	F-Statistic	*p-value*
α_x	70.706	137	8.290	0.000*
α_y	4.268	137	18.670	0.000*
α_z	130.528	137	29.617	0.000*
α	158.255	137	17.936	0.000*
ω_x	24.515	137	2.439	0.011*
ω_y	123.153	137	13.948	0.000*
ω_z	14.822	137	1.379	0.197
roll	0.087	137	2.411	0.012*
pitch	0.421	137	13.434	0.000*
yaw	0.049	137	1.390	0.192

* Sig < 0.05

Table 4.16 One-Way ANOVA for Root Mean Square of Dynamic Responses with Tyre Set as the Within-Subjects Factors

Average Value of Variables	Total Sum of Squares	df	F-Statistic	*p-value*
α_x	2145.922	137	2.597	0.078
α_y	257.021	137	0.785	0.458
α_z	2738.039	137	2.172	0.118
α	3265.634	137	2.027	0.136
ω_x	1611.398	137	9.009	0.000*
ω_y	7947.009	137	8.091	0.000*
ω_z	656.646	137	9.812	0.000*
roll	1.635	137	3.051	0.051
pitch	8.592	137	2.658	0.074
yaw	0.973	137	1.181	0.310

* Sig < 0.05

Table 4.17 One-Way ANOVA for Root Mean Square of Dynamic Responses with Speed as the Within-Subjects Factors

Average Value of Variables	Total Sum of Squares	df	F-Statistic	*p-value*
α_x	2145.922	137	6.886	0.000*
α_y	257.021	137	5.179	0.000*
α_z	2738.039	137	23.686	0.000*
α	3265.634	137	16.058	0.000*
ω_x	1611.398	137	0.861	0.571
ω_y	7947.009	137	3.491	0.000*
ω_z	656.646	137	1.338	0.218
roll	1.635	137	2.479	0.010*
pitch	8.592	137	13.745	0.000*
yaw	0.973	137	2.049	0.033*

* Sig < 0.05

4.4 Results of Slalom Test

4.4.1 Characterization of Experimental Data

The slalom test was used to investigate motorcycle dynamics behaviours in cornering conditions by means of vibration signal responses. The importance of vehicle dynamics parameters responses from road tests were measured using useful sensors, Global Positioning System (GPS), an Inertial Measurement Unit (IMU) and data-logger system. The designs of experiment were used to study an influence of three tyre sets (set A, set B and C) on cornering stability of three vehicle designed speeds 20, 40 and 60 km/h with 14 cone spacing as the study of (Cossalter, Lot, & Rota, 2010). Each treatment was tested with 10 runs. Since misfortune occurred with steering sensor during the tests, the output of steering angle could not use for analyzing at this stage. Therefore, there were vehicle speeds, rotational velocity in 3-axis (ω_x, ω_y, ω_z) and angular accelerations in 3-axis (α_x, α_y, α_z) data involved in the analysis of slalom test.

After completed the riding tests, the first analysis verified that extracted the filed data to identify the slalom riding durations and all associated dynamic responses signals from data logger. The plots of dynamics responses signals as delivered in Figure 4.13 was used to characterize the motorcycle reaction in actual motion through the vehicle roll rate and yaw rate. In particular, the yaw rate was used for representing the force that motorcycle rider control the steering system. Moreover, in cornering condition the rotation of steering head caused the transformation of moment that generated by the vertical and lateral reaction force of the tyre. These strongly related to a torque at the handlebar that can initiate more difficult in motorcycling for some inexperience riders and finally contributing to slipping out.

The first result of tyre set A shown in Figure 4.13-4.15, is a set of roll rate and yaw rate plots for 10 runs tests. The design speed was increased from 20 km/h (6 m/s) to 60 km/h (17 m/s). It can be noted that the magnitude of roll rate of high speed motorcycle was far greater than the low speed. The amplitude of roll rate at designed speed 20 km/h (6 m/s) varied at about 30 to -30 ADC/s. ADC value is voltage form of accelerometer and gyroscope sensor output. While at proposed speed 40 km/h (11 m/s) the roll rate oscillated in between 80 to -80 ADC/s. For the proposed speed 60 km/h (17 m/s) the roll rate presented the highest oscillated figure with almost 120 to -120 ADC/s. The values of roll rate for all speed were higher than the yaw rate. An inference can be drawn that higher different of roll rate and depend on an increasing vehicle speed. By considering the peak value, it is clear from the chart that at low speed of 20 km/h the peak of yaw rate occurred nearly the same time with roll rate. At the 40 km/h and 60 km/h the peak of yaw rate can observed at a time lag before that of roll rate.

Cross plots of roll rate and yaw rate by speed level in Figure 4.16 shows that the majority of high amplitude of the roll rate and yaw rate presented in proposed speed level 60 km/h (17 m/s), followed by the middle figure of proposed speed 40 km/h (11 m/s). For the lowest amplitude of roll rate and yaw rate, it resulted in the low speed 20 km/h (6 m/s) for all runs. In comparison between roll rate to yaw rate, it was clear that at the same speed the value of roll rate was greater than yaw rate. Thus the ratio of roll to yaw rate tends to a steady rise pattern. The overall figures compared among three speed levels, it can be obtained that an increase in vehicle speed from 40 km/h (11 m/s) to 60 km/h (17 m/s) roughly remained the yaw rate variations. The increasing of different proportion of maximum roll rate to maximum yaw rate as provided in Table 4.18 were 5%, 74% and 234% for speed 20 km/h, 40 km/h and 60 km/h, respectively. The similar pattern can be found for minimum roll rate to yaw rate. These clearly confirmed that for the same tyre set the ratio of roll to yaw rater has a tendency to increase as speed increases. A large ratio of roll to yaw rate claims that there was a small friction force that contributed too little lateral force.

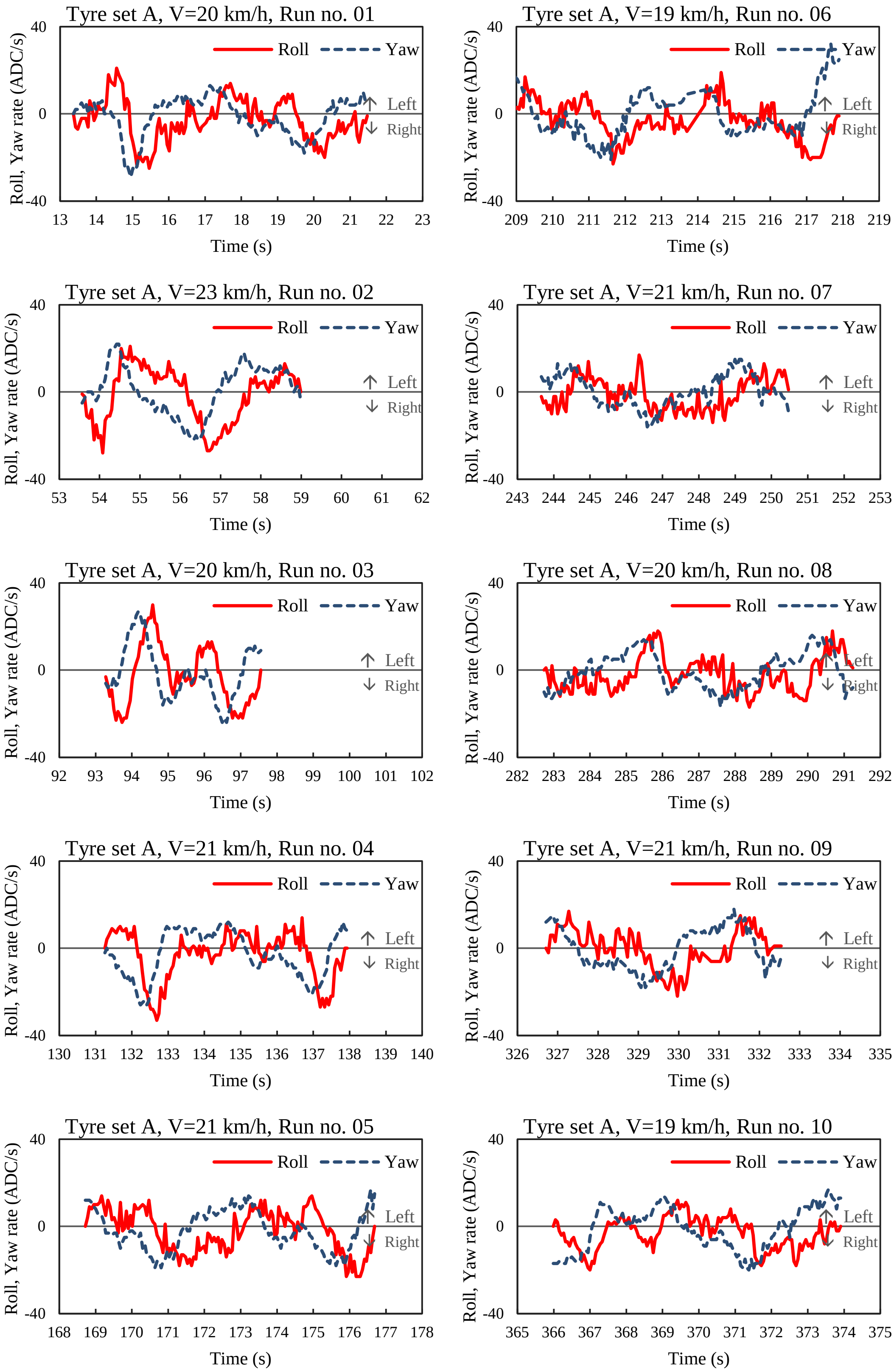


Figure 4.13 Dynamics Responses Signals from Slalom Test of Tyre Set A with Proposed Speed 20 km/h

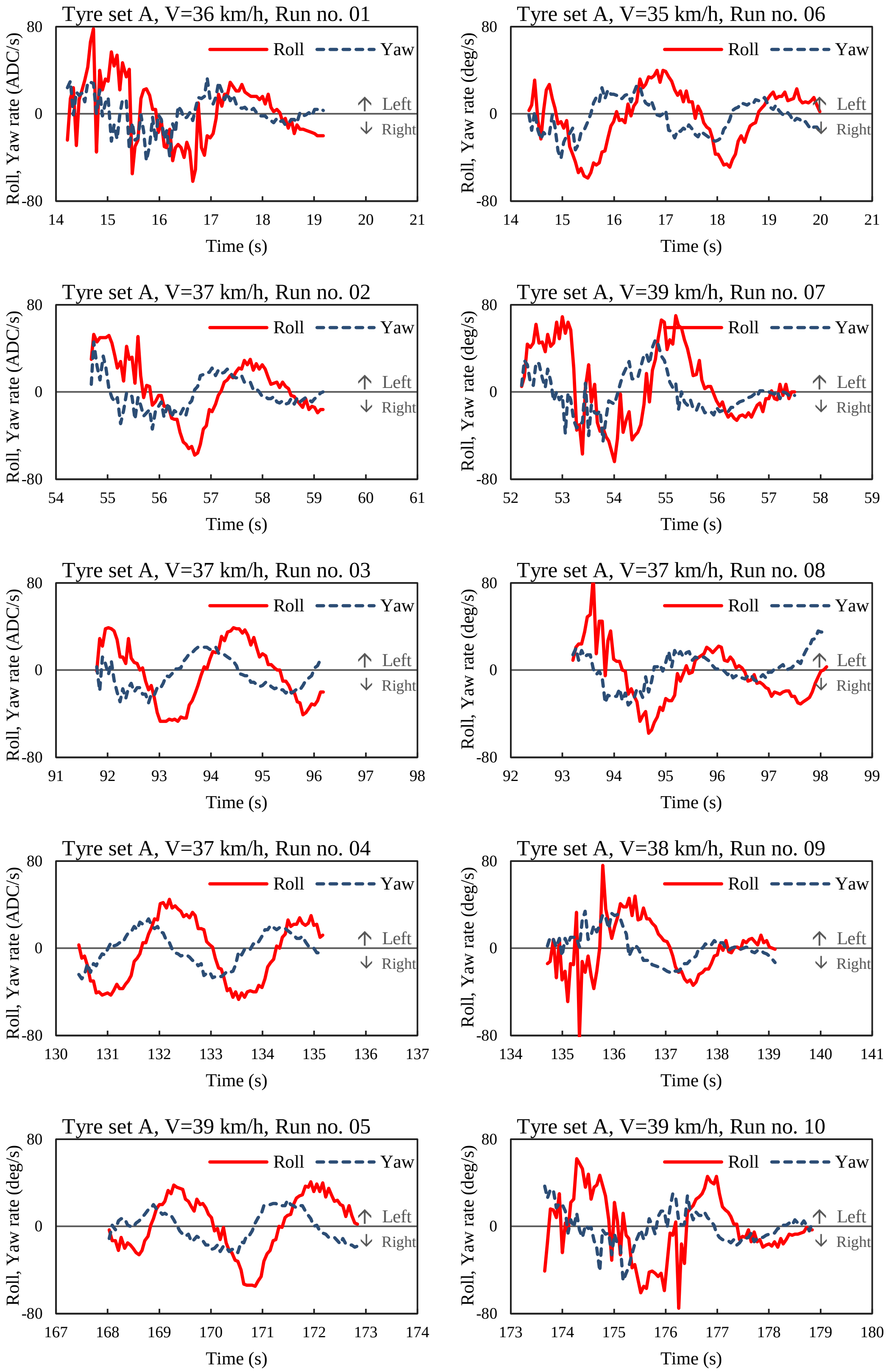


Figure 4.14 Dynamics Responses Signals from Slalom Test of Tyre Set A with Proposed Speed 40 km/h

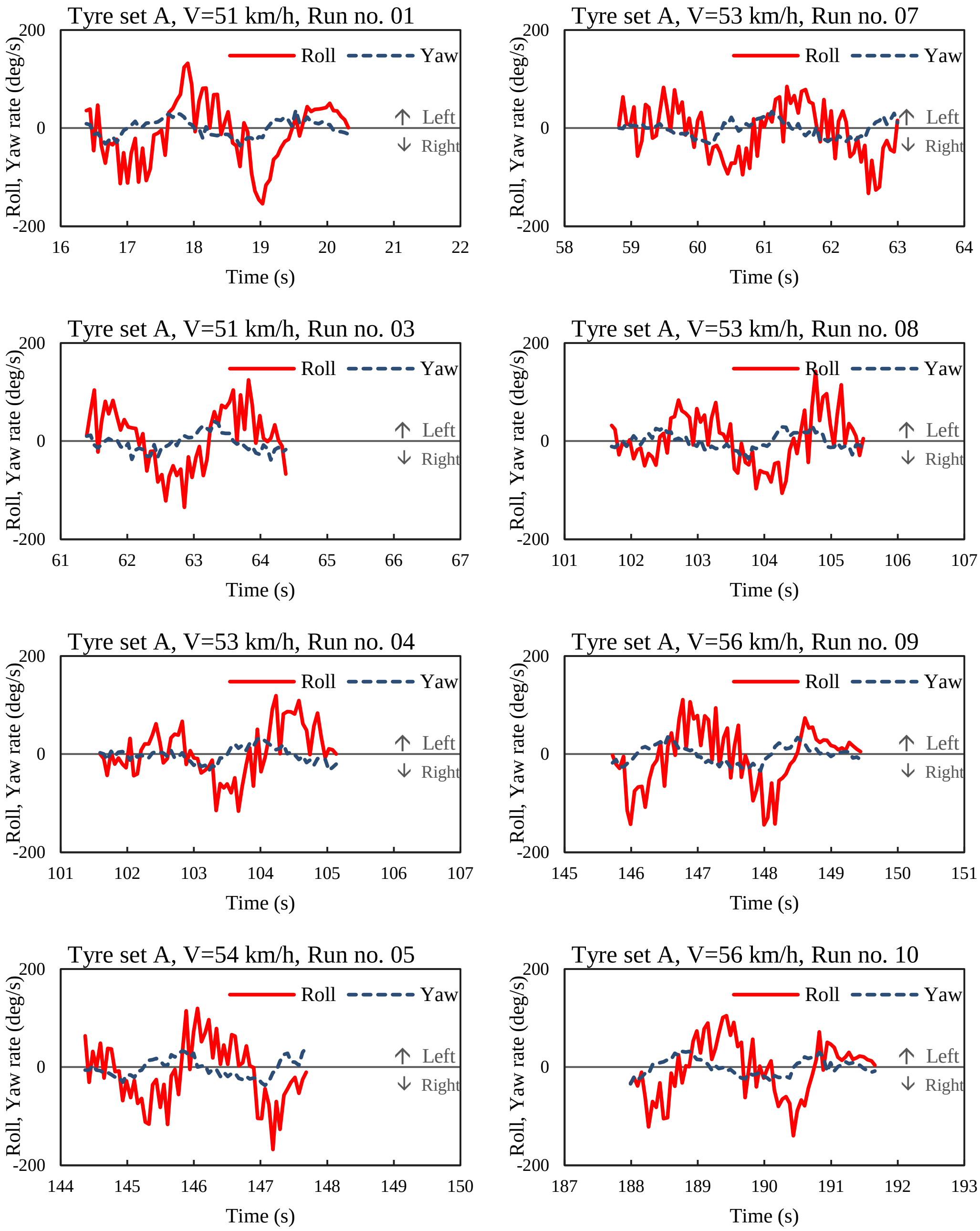


Figure 4.15 Dynamics Responses Signals from Slalom Test of Tyre Set A with Proposed Speed 60 km/h

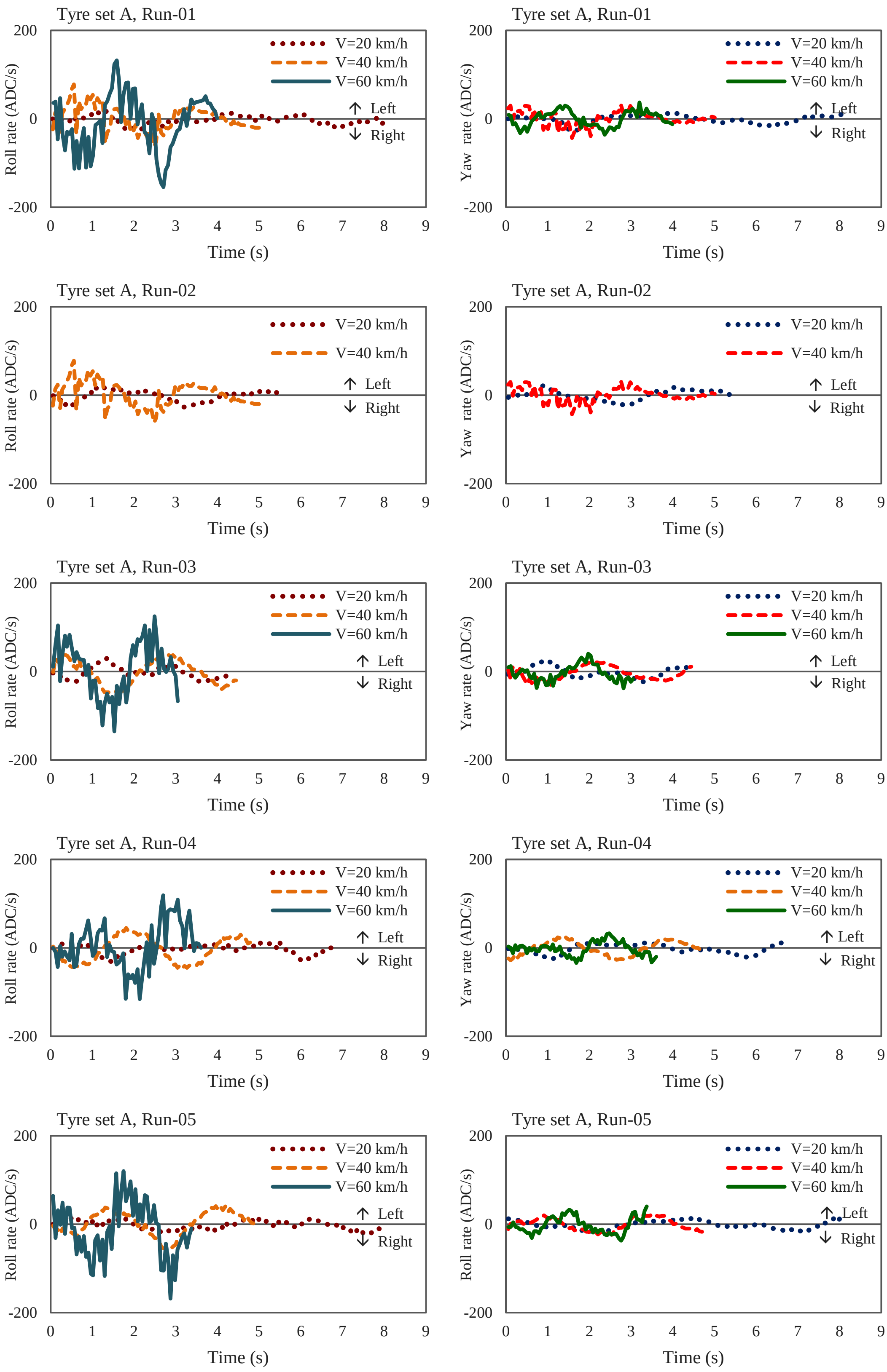


Figure 4.16 Comparison of Roll Rate and Yaw Rate from Slalom Test of Tyre Set A Run no.1-5

Table 4.18 Statistical Characteristics of the Experimental Vibration Responses Signal of Tyre Set A

Tyre Set A Treatment	Run No.	Riding Duration (s)	Average Speed (km/h)	Max. Roll Rate (ADC/s)	Min. Roll Rate (ADC/s)	Max. Yaw Rate (ADC/s)	Min. Yaw Rate (ADC/s)	Roll Rate/ Yaw Rate (ω_x / ω_z)
1	1	8.15	20	21	-25	13	-29	1.99
(Proposed	2	5.47	23	21	-28	22	-22	2.34
Speed	3	4.33	20	30	-24	27	-24	1.88
20 km/h)	4	6.73	21	14	-33	12	-26	1.50
	5	8.03	21	14	-23	17	-19	1.88
	6	8.98	19	19	-23	32	-21	1.65
	7	6.86	21	17	-14	15	-16	1.83
	8	8.57	20	18	-17	16	-17	1.65
	9	5.88	21	17	-22	18	-18	1.41
	10	7.98	19	12	-20	17	-20	1.30
	Mean	**7.10**	**21**	**18**	**-23**	**19**	**-21**	**1.74**
2	1	5.01	36	78	-62	33	-43	4.85
(Proposed	2	5.45	36	53	-58	46	-34	3.82
Speed	3	4.45	37	39	-47	21	-30	4.38
40 km/h)	4	4.78	37	45	-47	27	-28	5.36
	5	4.86	39	62	-75	37	-50	5.88
	6	5.69	35	40	-59	26	-41	3.11
	7	5.28	39	70	-64	48	-45	3.25
	8	4.97	37	86	-58	36	-32	5.83
	9	4.47	38	76	-81	34	-22	4.26
	10	5.47	39	62	-75	37	-50	5.82
	Mean	**5.04**	**37**	**61**	**-63**	**35**	**-38**	**4.66**
3	1	3.99	51	132	-154	37	-36	6.05
(Proposed	2	-	-	-	-	-	-	-
Speed	3	3.89	51	125	-135	40	-38	5.33
60 km/h)	4	4.27	53	119	-168	33	-34	8.16
	5	4.39	54	120	-168	40	-37	5.07
	6	-	-	-	-	-	-	-
	7	4.23	53	85	-133	34	-31	7.80
	8	3.83	53	142	-106	32	-36	4.67
	9	3.78	56	111	-144	35	-34	4.80
	10	3.72	56	105	-140	32	-34	8.08
	Mean	**4.01**	**53**	**117**	**-144**	**35**	**-35**	**6.24**

As it has been specified previously, the dynamic responses of the motorcycle were presented as a function of the roll rate and yaw rate. The results of tyre set B are provided in Figure 4.17-4.19. The plots of useful parameters were categorized by three speed levels that ranged from 20 km/h (6 m/s) to 60 km/h (17 m/s) with ten replications each. The key observation from Figure 4.17 is the fact that the range of roll rate was approximately similar to that of yaw rate. The damping of vibration signals of both dynamic parameters is the same to the path curvature. The lowest and highest crests of yaw rate lag occurred before those of roll rate. It is shown that in a subsequent figure (see Figure 4.18) that the oscillated characteristic of roll rate was remarkably further higher than yaw rate. However, the peak pattern at designed speed 40 km/h (11 m/s) was still the same as in low speed 20 km/h (6 m/s). In Figure 4.19 the damping of roll rate of seed 60 km/h (17 m/s) was closely similar to the quantity at speed 40 km/h (11 m/s). The change of motorcycle responses as a function of roll rate of tyre set B was fairly the same to tyre set A when the speed was increased. In case of yaw rate at high speed, it can be seen that the peak amplitude of response signals presented shift before the peak of roll rate with the greatest ratio in comparison to at low speed (20 km/h) and middle speeds (40 km/h).

In comparison between roll rate to yaw rate as shown in Figure 4.20, it was clear that at the same speed of run no.1-5 the value of roll rate was greater than yaw rate. The plots run no.6-10 were in Appendix C. Thus the ratio of roll to yaw rate tends to a steady rise pattern as similar as tyre set A. The overall figures compared among three speed levels, it can be obtained that an increase in vehicle speed from 40 km/h (11 m/s) to 60 km/h (17 m/s) roughly remained the yaw rate variations. These clearly confirmed that for the same tyre set the ratio of roll to yaw rate has a tendency to increase as speed increases. A large ratio of roll to yaw rate claims that there was a small friction force that contributed too little lateral force.

Considering the tabulation of dynamics vibration signals responses by tyre set and vehicle speed (Table 4.19) shows the approximately 13% of all runs results in the exactly proposed speed. The vast majority of 30 runs gained a lower value than a designed speed. The ratio of roll rate to yaw rate (ω_x / ω_z) which is an important parameter representing the motorcycle and rider behaviours were 1.97, 5.32 and 6.72 for low to high speed level. Low value of ω_x / ω_z indicate less difficulty in vehicle directional stabilizing. It is also interesting to note that the ratio of roll to yaw rate at speed 40 km/h was unchanged. The roll rate (in ADC/s form) for low to high speed oscillated in ranges 16 to -23, 84 to -98 and 114 to -122, respectively. While the yaw rate (in ADC/s form) for low to high speed ranged from 15 to -18, 36 to -35 and 31 to -33, respectively. There was a few difference between minimum and maximum yaw rate at speed 40 km/h and 60 km/h. These could lead to a decrease ratio of roll to yaw rate that represent less effort to follow the slalom path.

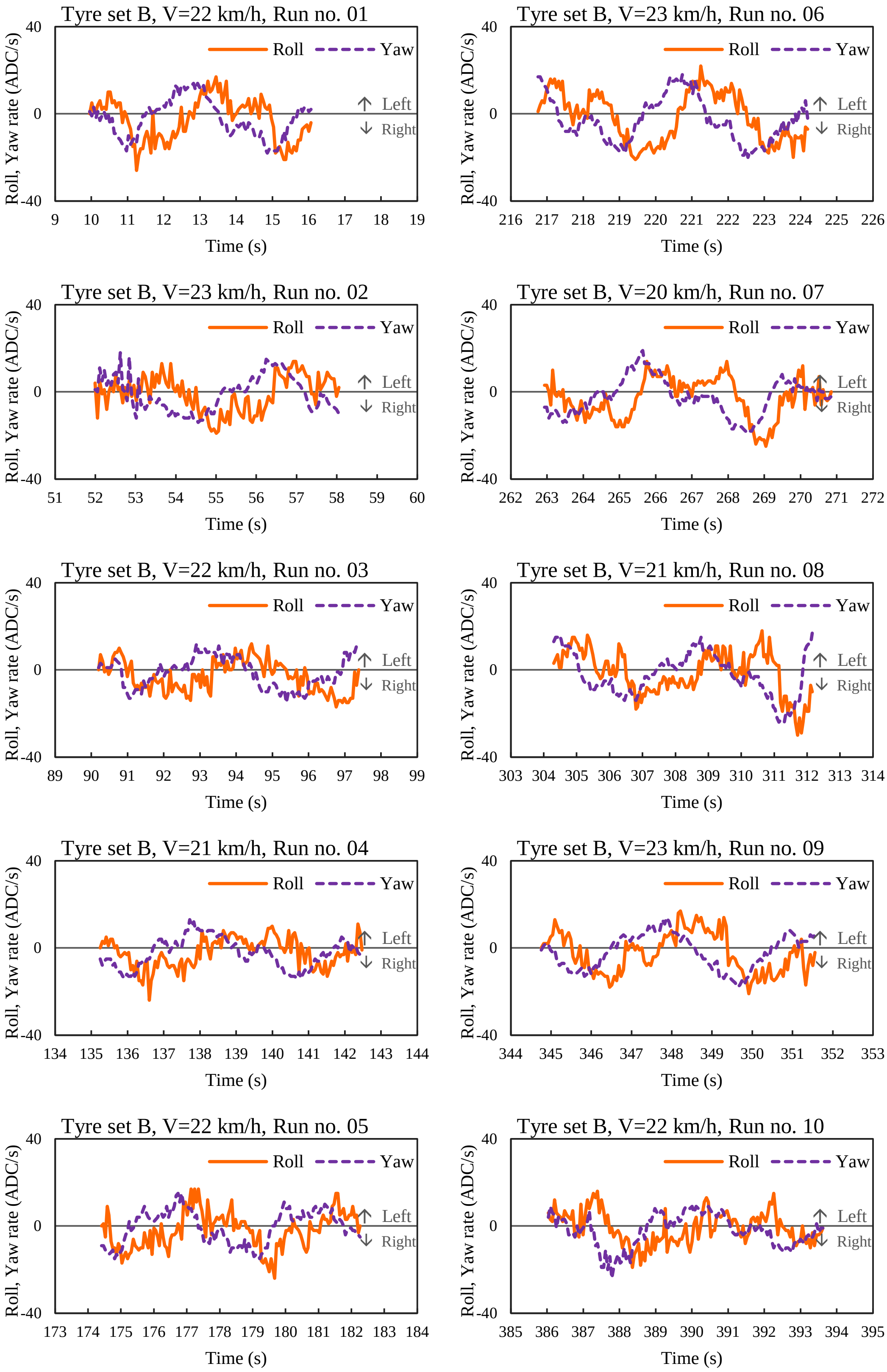


Figure 4.17 Dynamics Responses Signals from Slalom Test of Tyre Set B with Proposed Speed 20 km/h

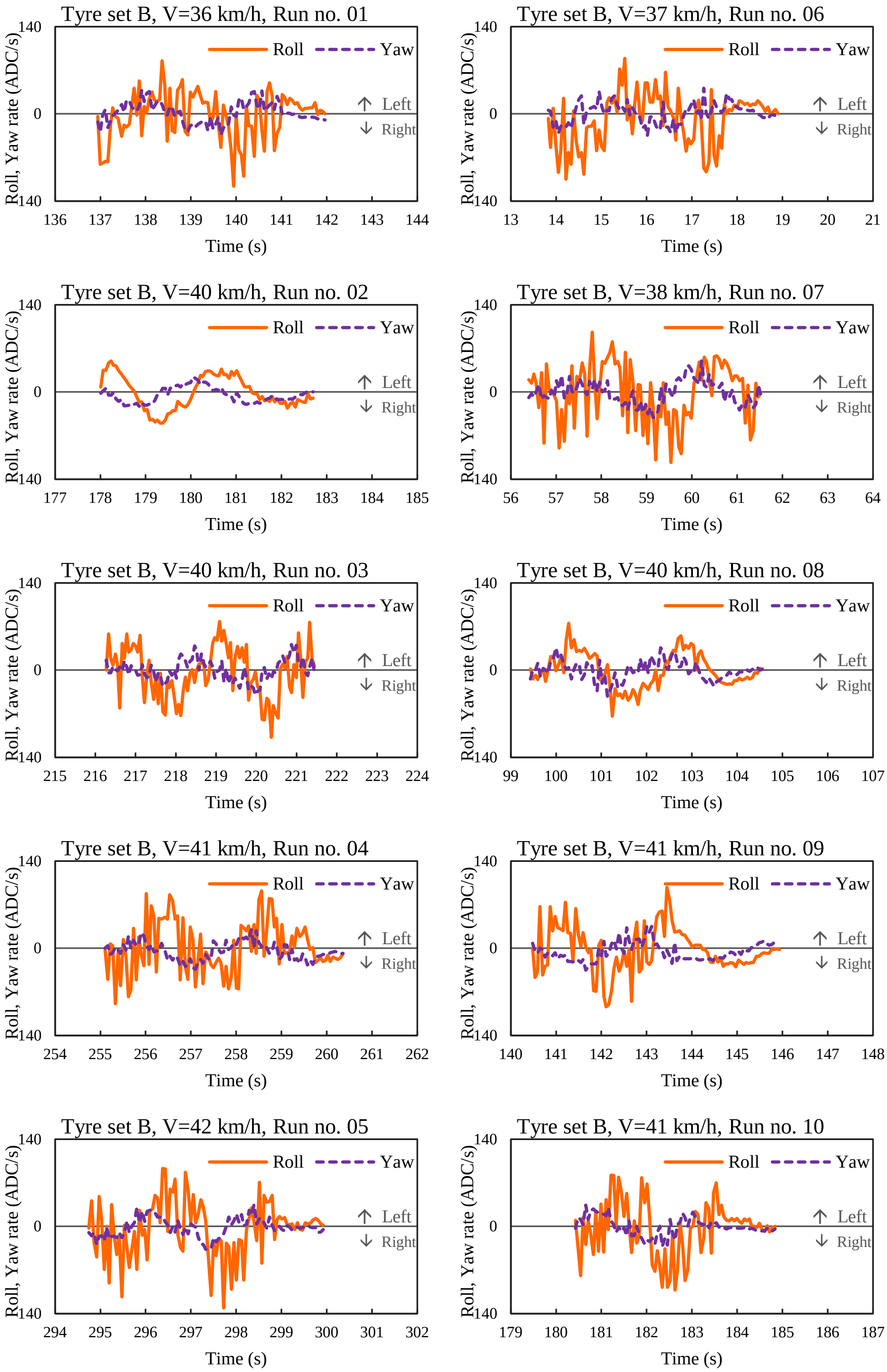


Figure 4.18 Dynamics Responses Signals from Slalom Test of Tyre Set B with Proposed Speed 40 km/h

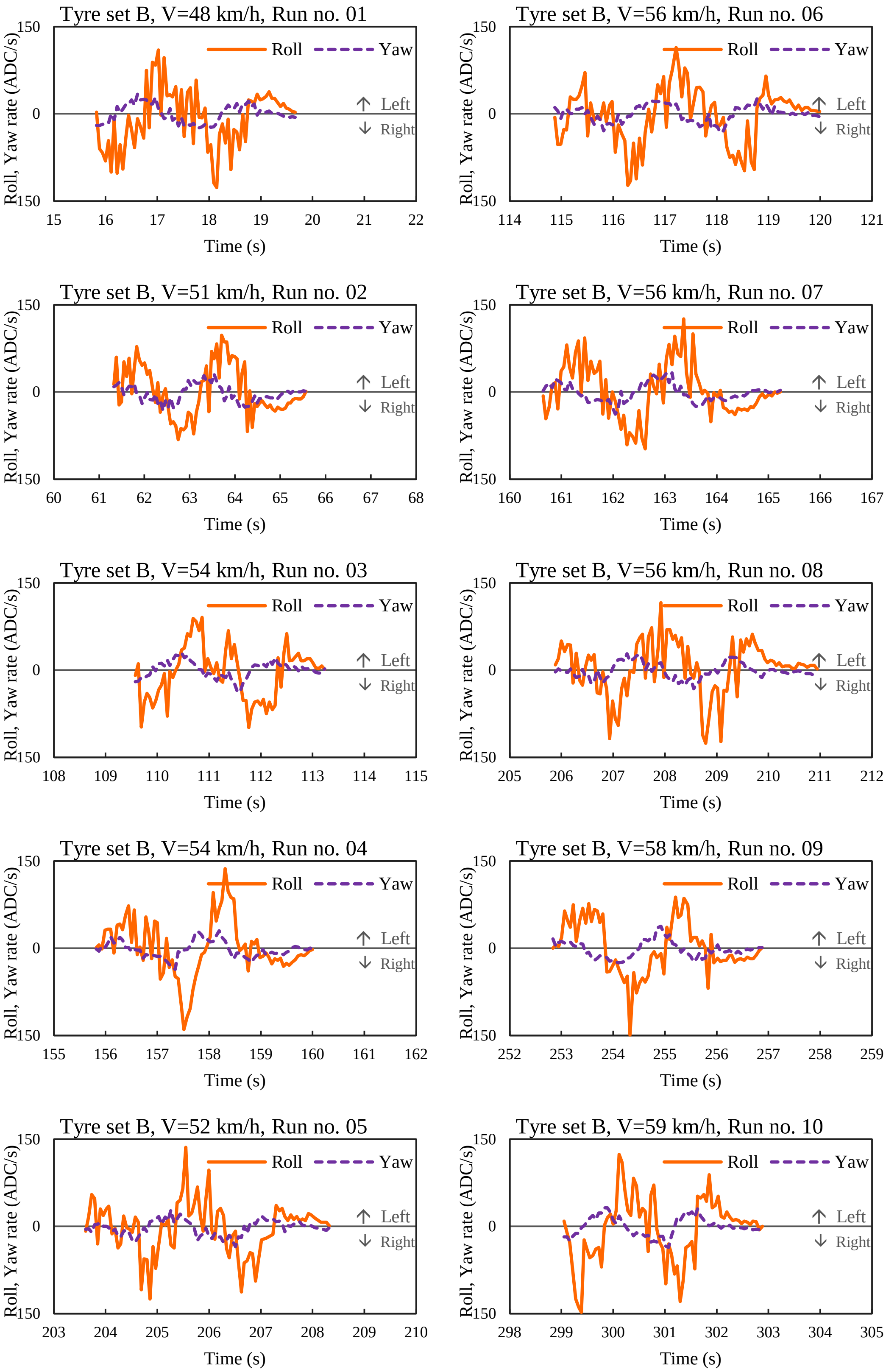


Figure 4.19 Dynamics Responses Signals from Slalom Test of Tyre Set B with Proposed Speed 60 km/h

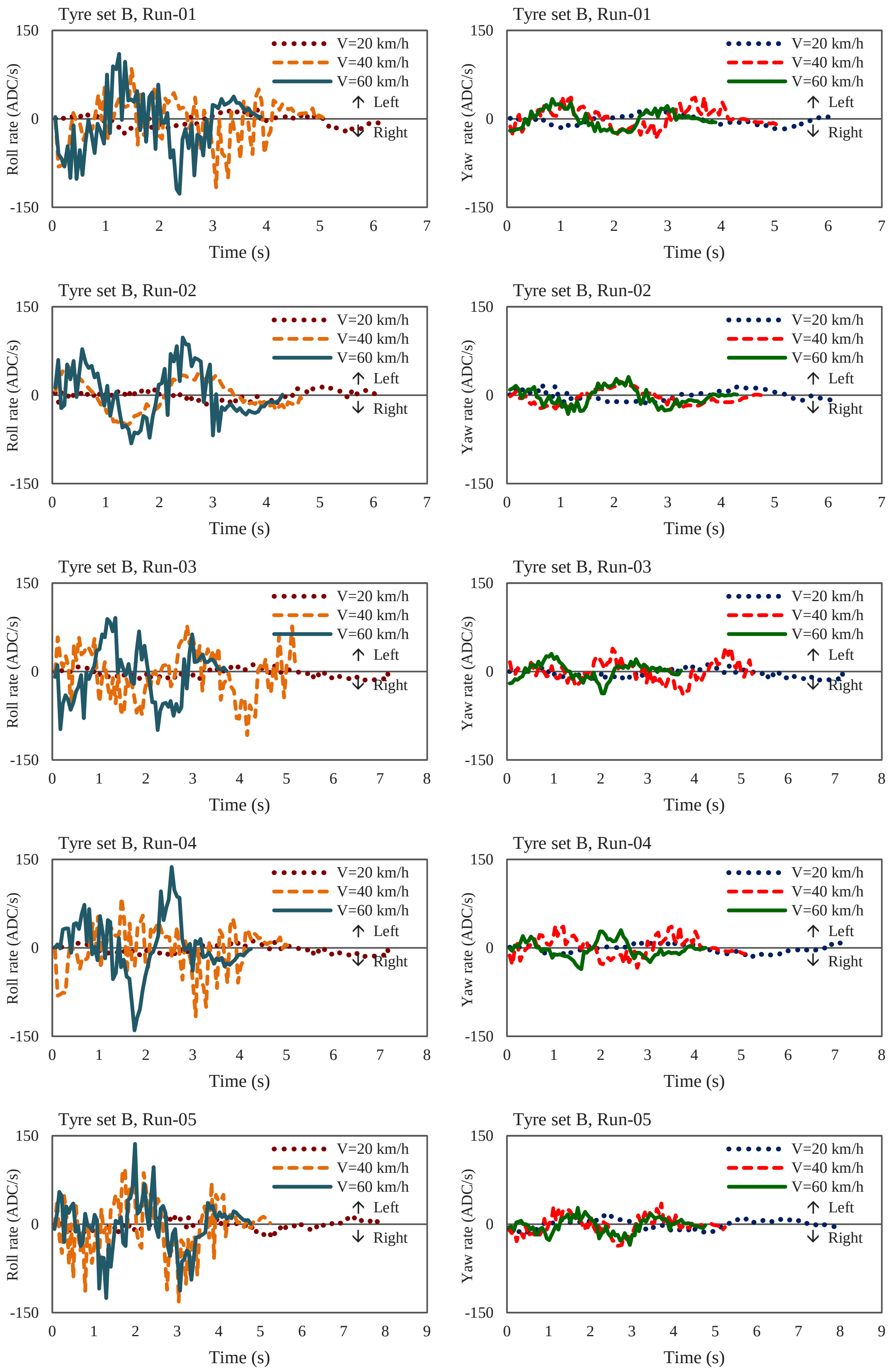


Figure 4.20 Comparison of Roll Rate and Yaw Rate from Slalom Test of Tyre Set B Run no 1-5

Table 4.19 Statistical Characteristics of the Experimental Vibration Responses Signals of Tyre Set B

Tyre Set A Treatment	Run No.	Riding Duration (s)	Average Speed (km/h)	Max. Roll Rate (ADC/s)	Min. Roll Rate (ADC/s)	Max. Yaw Rate (ADC/s)	Min. Yaw Rate (ADC/s)	Roll Rate/ Yaw Rate (ω_x / ω_z)
1 (Proposed Speed 20 km/h)	1	6.16	22	17	-26	14	-18	2.55
	2	6.11	23	14	-19	18	-14	1.76
	3	7.24	22	12	-17	12	-15	2.13
	4	7.29	21	11	-24	13	-14	1.61
	5	7.91	22	17	-24	15	-15	1.77
	6	7.50	23	22	-21	18	-20	2.08
	7	7.97	20	14	-25	19	-19	2.02
	8	7.91	21	18	-30	17	-24	1.67
	9	6.86	23	17	-21	14	-18	2.25
	10	7.63	22	16	-19	9	-24	1.88
	Mean	**7.26**	**22**	**16**	**-23**	**15**	**-18**	**1.97**
2 (Proposed Speed 40 km/h)	1	5.08	36	85	-116	38	-34	5.08
	2	4.75	40	50	-50	24	-23	4.61
	3	5.23	40	78	-108	41	-40	6.40
	4	5.31	41	92	-89	30	-34	5.96
	5	5.23	42	93	-131	35	-37	6.48
	6	5.13	37	89	-105	41	-35	4.82
	7	5.18	38	96	-113	50	-41	5.01
	8	5.18	40	75	-74	36	-42	4.63
	9	5.51	41	98	-94	35	-35	4.64
	10	4.46	41	82	-102	34	-32	5.61
	Mean	**5.11**	**40**	**84**	**-98**	**36**	**-35**	**5.32**
3 (Proposed Speed 60 km/h)	1	3.89	48	110	-127	34	-24	5.49
	2	4.30	51	98	-82	31	-32	5.93
	3	3.71	54	91	-99	30	-37	6.76
	4	4.24	54	137	-140	30	-36	8.76
	5	4.76	52	136	-125	28	-35	5.06
	6	5.17	56	114	-123	26	-32	6.31
	7	4.64	56	126	-98	33	-38	6.65
	8	0.00	56	116	-126	28	-32	7.29
	9	4.04	58	88	-149	38	-25	6.13
	10	3.89	59	124	-148	32	-36	8.86
	Mean	**3.86**	**54**	**114**	**-122**	**31**	**-33**	**6.72**

For tyre set C, only one set of experimental data showed the true behaviour of the roll rate and yaw rate from slalom test. During the experiment, data were checked by browsing through the figures. The same manner of checking and re-checking was done to tyre set A, tyre set B and tyre set C. However, during the analysis of data it was found out that only one set of experimental data from run no.1 displayed the true behaviour as shown in Figure 4.21. The rest of the runs from no.2 to no.10 showed erroneous data. The main observation from Figure 4.21 is the fact that the wavering range of roll rate was slightly similar to that of yaw rate as parallel as tyre set A and B. Fortunately, at a moderate speed (40 km/h) and high speed (60 km/h) there were any false for collecting experiment data. As displayed in Figure 4.22-4.23 it can be seen that the values of roll rate and yaw rate at speed 40 km/h (11 m/s) and 60 km/h (17 m/s) were smaller than the output of tyre set B. The quantity of roll rate (in ADC/s form) ranged from under 130 to -130. The damping of vibration signals of both dynamic parameters is same to the path curvature. The lowest and highest crests of yaw rate lag occurred before those of roll rate. It is shown that in Figure 4.22-4.23 that the oscillated characteristic of roll rate was remarkably further higher than yaw rate. However, the peak pattern of roll rate and yaw rate at designed speed 40 km/h (11 m/s) was still the same as in low speed 20 km/h (6 m/s). The change of motorcycle responses as a function of roll rate of tyre set C was fairly the same to tyre set A when the speed increasing. In case of yaw rate at high speed, it can be seen that the peak amplitude of response signals presented shift before the peak of roll rate with the greatest ratio in comparison to at low speed (20 km/h) and middle speeds (40 km/h).

Table 4.20 also shows the statistical characteristics of the experimental data of tyre set C by tyre set and vehicle speed. The table showing that there was the same average speed to a given speed for speed 40 km/h (11 m/s). For designed speed 60 km/h, the major tested speed of all runs results in the lower value. The roll rate (in ADC/s form) for low to high speed oscillated in range 19 to -20, 75 to -74 and 84 to -98, respectively. While the yaw rate (in ADC/s form) for low to high speed ranged from 24 to -22, 30 to -38 and 33 to -32, respectively. The ratio of roll rate and yaw rate (ω_x / ω_z) which is an important parameter representing the motorcycle and rider behaviours was 2.12, 4.59 and 5.62 for low to high speed level. Low value of ω_x / ω_z indicate less difficulty in handling. It is also interesting to note that the ratio of roll rate and yaw rate at speed 40 km/h and 60 km/h were lower than the results of tyre set A and B. These point out that the wider tyre width affected the ratio of ω_x / ω_z.

The increase of roll and yaw rate value of tyre set C depended on speed the same as tyre set A and B. At the same speed the value of roll rate was greater than yaw rate. Thus the ratio of roll to yaw rate was a steady rise pattern. A large ratio of roll to yaw rate meant a small friction force contributed too little lateral force and needed more effort to follow the given path. At speed 40 and 60 km/h the ratio of roll to yaw rate was smaller than that of tyre set A and B (greater friction force by wider tyre).

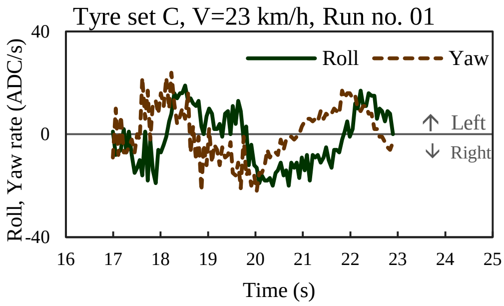


Figure 4.21 Dynamics Responses Signals from Slalom Test of Tyre Set C with Proposed Speed 20 km/h

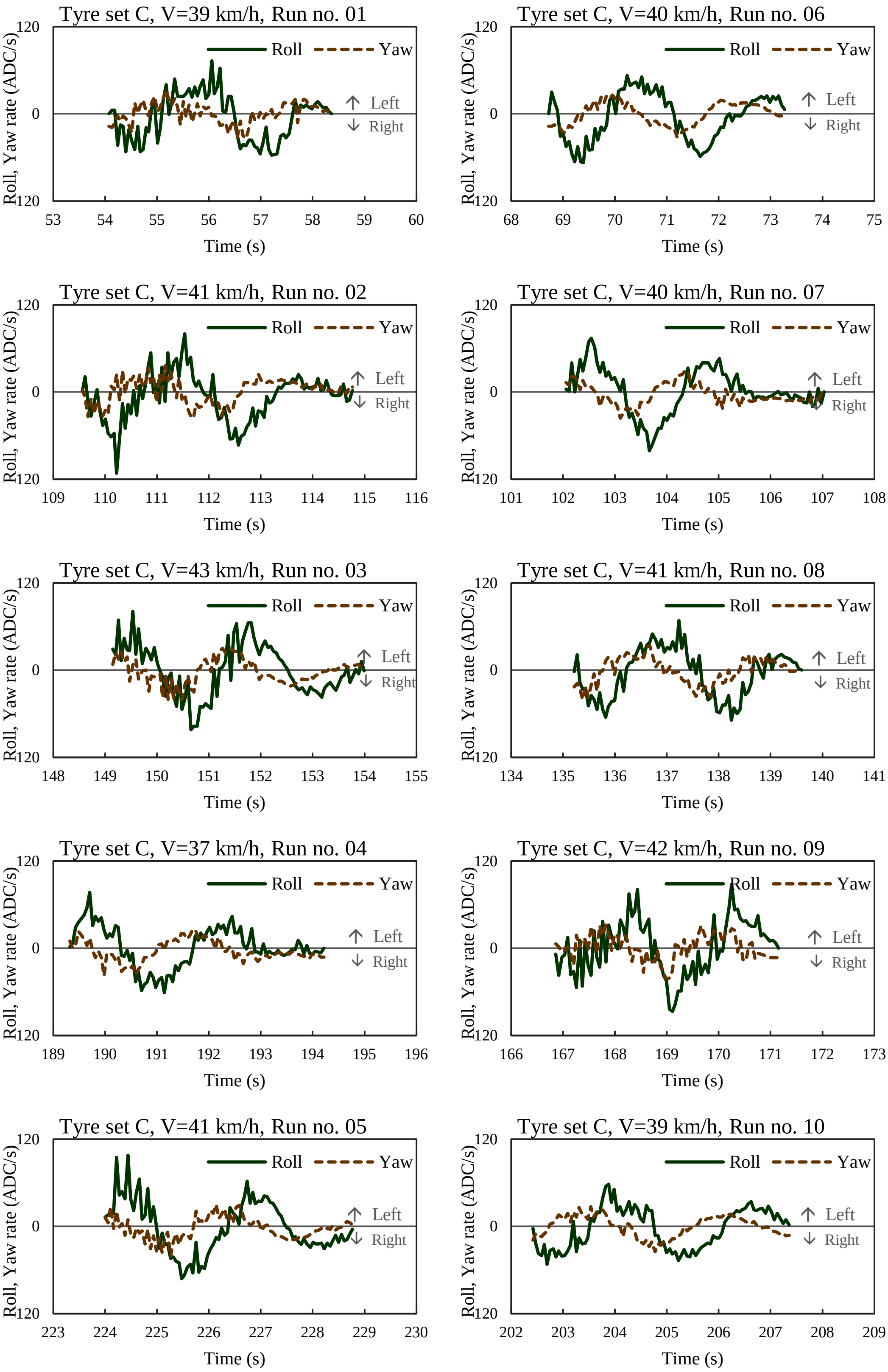


Figure 4.22 Dynamics Responses Signals from Slalom Test of Tyre Set C with Proposed Speed 40 km/h

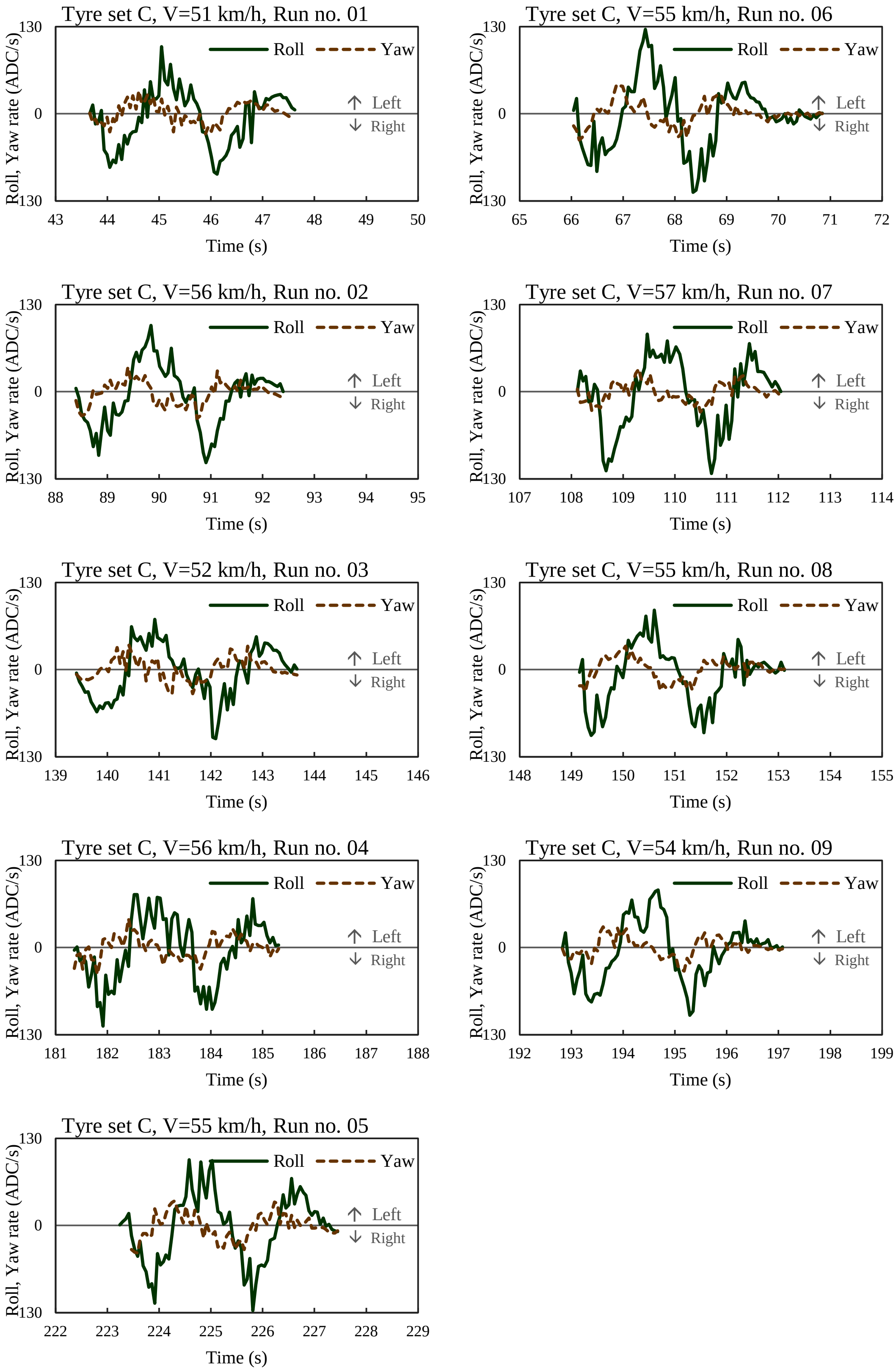


Figure 4.23 Dynamics Responses Signals from Slalom Test of Tyre Set C with Proposed Speed 60 km/h

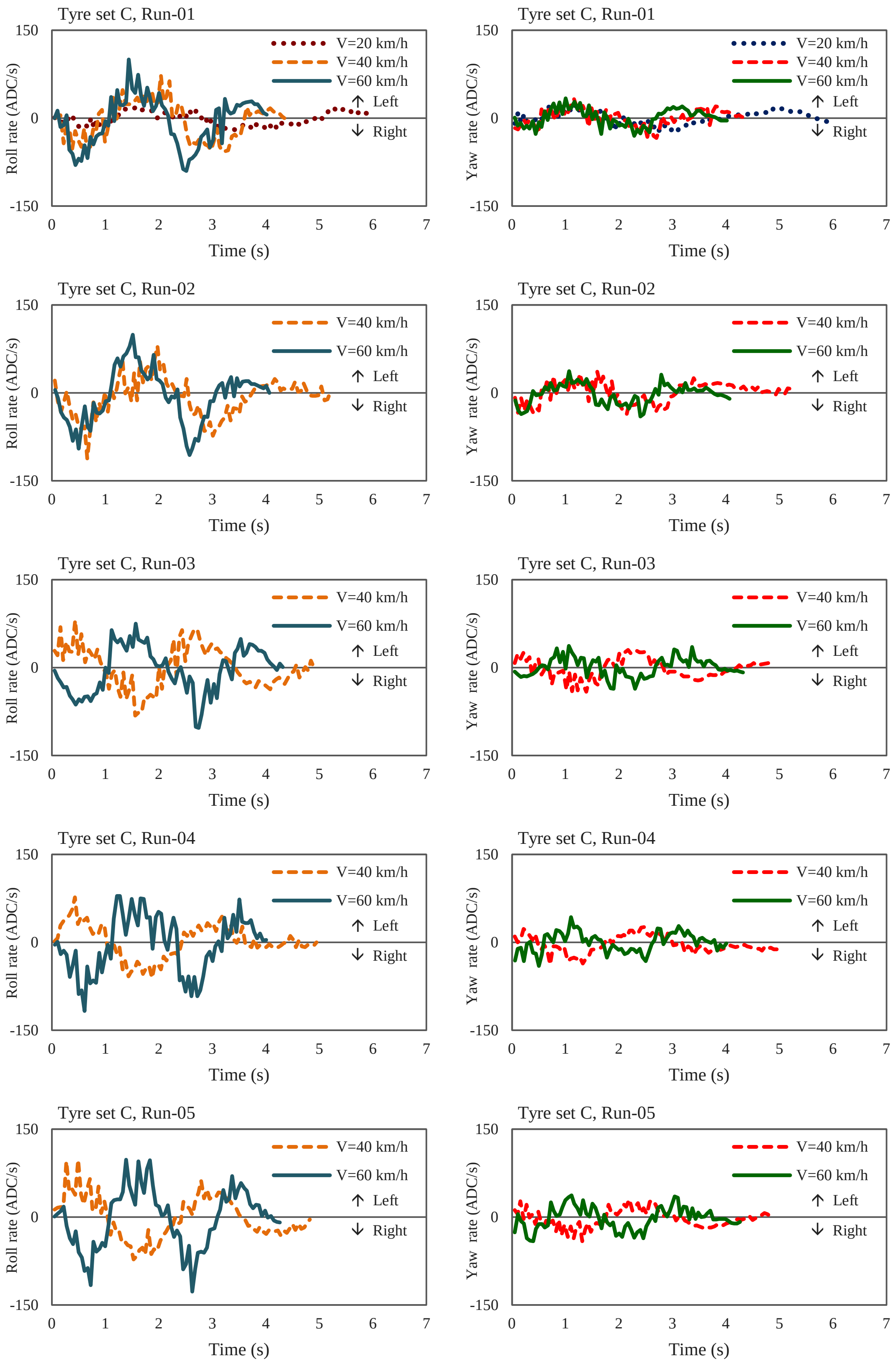


Figure 4.24 Comparison of Roll Rate and Yaw Rate from Slalom Test of Tyre Set C Run no.1-5

Table 4.20 Statistical Characteristics of the Experimental Vibration Responses Signals of Tyre Set C

Tyre Set C Treatment	Run No.	Riding Duration (s)	Average Speed (km/h)	Max. Roll Rate (ADC/s)	Min. Roll Rate (ADC/s)	Max. Yaw Rate (ADC/s)	Min. Yaw Rate (ADC/s)	Roll Rate/ Yaw Rate (ω_x / ω_z)
1 (Design Speed 20 km/h)	1	5.96	23	19	-20	24	-22	2.12
	2	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-
	4	-	-	-	-	-	-	-
	5	-	-	-	-	-	-	-
	6	-	-	-	-	-	-	-
	7	-	-	-	-	-	-	-
	8	-	-	-	-	-	-	-
	9	-	-	-	-	-	-	-
	10	-	-	-	-	-	-	-
	Mean	**5.96**	**23**	**19**	**-20**	**24**	**-22**	**2.12**
2 (Design Speed 40 km/h)	1	4.35	39	73	-57	33	-34	5.12
	2	5.21	41	80	-112	36	-36	3.66
	3	4.90	43	81	-82	30	-41	3.76
	4	4.95	37	77	-61	26	-38	3.37
	5	4.82	41	98	-72	30	-41	5.01
	6	4.61	40	53	-67	26	-32	5.14
	7	5.04	40	74	-81	29	-36	4.49
	8	4.44	41	68	-69	34	-40	4.63
	9	4.35	42	88	-87	32	-42	4.85
	10	4.99	39	58	-52	27	-35	5.84
	Mean	**4.77**	**40**	**75**	**-74**	**30**	**-38**	**4.59**
3 (Design Speed 60 km/h)	1	4.01	51	100	-90	34	-30	5.55
	2	4.06	56	99	-106	37	-40	5.36
	3	4.32	52	75	-103	37	-36	4.55
	4	4.00	56	79	-117	43	-40	6.85
	5	4.26	55	98	-127	37	-41	6.42
	6	4.86	55	126	-117	44	-39	8.20
	7	3.99	57	86	-122	34	-30	8.22
	8	4.01	55	89	-98	35	-33	5.44
	9	4.30	54	86	-101	31	-35	5.65
	10	-	-	-	-	-	-	-
	Mean	**3.78**	**49**	**84**	**-98**	**33**	**-32**	**5.62**

4.4.2 Comparison between Tyre Sets Responses Signals

Computation of the average value of the measurement results of a complete set of runs is useful to represent on measurement signals. In order to obtain the average values for many measurements a commercial program like Microsoft Excel was used to assist this task. First, for the dynamics responses signals of all tyre sets with three different speeds (20 km/h, 40 km/h and 60 km/h) 35 km/h were used to determine the riding durations, average speed, maximum roll rate, minimum roll rate, maximum yaw rate, minimum yaw rate and the ratio of roll rate and yaw rate (ω_x / ω_z) as provided in Table 4.18 to 4.20. The average values of mentioned parameters of three sets which are classified by speed level were then computed. In order to obtain the overall figure of an important variable the plots of the ratio of roll rate and yaw rate was produced.

As shown in Figure 4.25, it is worth mentioning that the value of ω_x / ω_z of all tyre sets presented an increasing figure depend on speed level. For tyre set A from low to high speed, the quantities ranged from 1.74 to 6.89. Furthermore the value of tyre set B went up from 1.97 to 6.72. Additionally, the results of tyre set C increased from 2.12 to 5.62. These results were similar to the study of (Cossalter, Lot, & Rota, 2010) as presented in Figure 4.26. When considering by speed level, at low speed 6 m/s (20 km/h) there were slight similar values of 1.74 (tyre set A), 1.97 (tyre set B) and 2.12 (tyre set C). The difference of roll to yaw rate of this speed level was nearly 10 percent. At moderate speed 11 m/s (40 km/h), the quantities of roll to yaw rate were far greater than at low speed with 4.66, 5.32 and 4.59 for tyre set A, tyre set B and tyre set C, respectively. The average percentage was 150 increasing with respect to at low speed. Inclusive, at this speed tyre set C presented the lowest value. At high speed 17 m/s (60 km/h), the key observation is that the lowest value of ω_x / ω_z spotlighting on tyre set C output with 5.62 while tyre set A gained the highest value of 6.89. These specified that for the same tyre set, the ratio of roll to yaw rate of all tyres tend to increase as speed increases. For the same speed (40 and 60 km/h) tyre set C shown the smallest ratio because larger contact patch of inclination provided more friction force (a stronger grip), it had more ability to stabilize the vehicle in cornering.

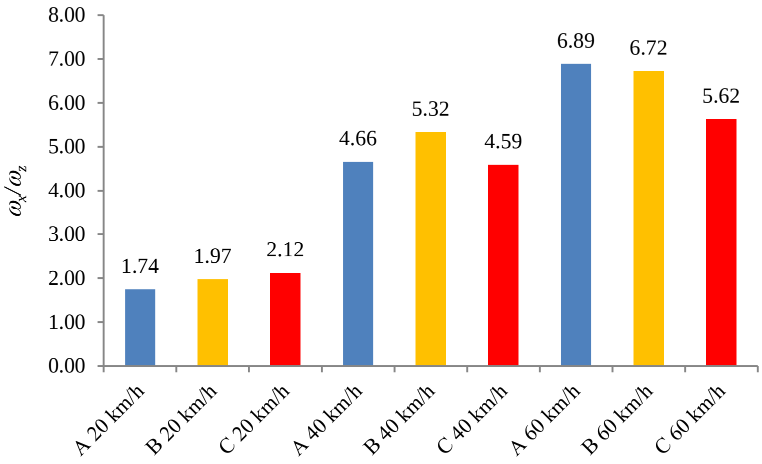


Figure 4.25 The Ratio of Roll to Yaw Rate from Slalom Test

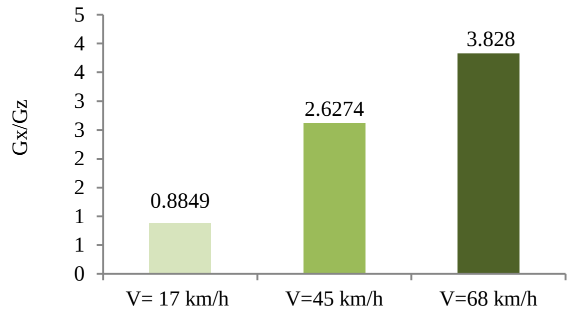


Figure 4.26 The Ratio of Roll to Yaw Rate from Slalom Test of (Cossalter, Lot, & Rota, 2010)

4.4.3 Statistical Analysis for Slalom Test Results

Group differences between the maximum and minimum value of longitudinal velocity (ω_x) and vertical velocity (ω_z) and ratio of roll rate and yaw rate of measured dynamic parameters were assessed by the analysis of variance ANOVA. In particular, the focus was on determining the association between tyre sets, speed levels and interrelated dynamic stability parameters such as acceleration, velocity and displacement. Under the null hypothesis of no association between the mentioned tyre sets and leaning stability parameters, the tyre sets and speed levels were used as the within-subjects factors to evaluate its effect to motorcycle stability when running along the straight route. A significant level of *p-value* was regarded as 0.05.

Table 4.21 contains the output from Kolmogorov-Smirnov test. This statistic particularly used for testing the normality assumption of variables. No significant results in maximum and minimum value of dynamics responses signals were observed among the three tyre sets and twenty one speed levels. The test statistics were 0.166, 0.149, 0.123, 0.125, 0.143 and 0.123 for given variables are greater than alpha 0.05. This point out that the dynamic responses signals variable contained a normal distribution.

Table 4.21 Mean (S.D.) and Kolmogorov-Smirnov Test of Dynamics Responses of Slalom Tests

Parameter	speed	$Max.\omega_x$	$Min.\omega_x$	$Max.\omega_z$	$Min.\omega_z$	ω_x/ω_z
Mean	39.500	70.205	-79.090	29.474	-31.397	4.595
S.D.	13.039	38.921	44.243	9.375	8.820	2.036
Sample size (N)	78	78	78	78	78	78
One-Sample Kolmogorov-Smirnov Test Statistic	0.166	0.149	0.123	0.125	0.143	0.123

* Sig < 0.05

To account for these potential groups which were tyre sets and dynamic responses vibration signals association, the One-Way Analysis of Variance was conducted. A Tukey test was used to indicate which groups may be responsible for a significant effect. This is because there were no equal sample sizes of speed levels and it was more powerful for three factors. Table 4.22 shows the results of the analysis of the quantity of dynamic responses signals affected by differences of tyre sets. The total of sum of square presented a wide range of 319.195 to 150722.372. The *p-value* for most variables was greater than significant level 0.05 except the minimum value of yaw rate that greater than significant level 0.01. Therefore, the null hypothesis was accepted. It is worth highlighting that there were no significant differences in behaviour among three groups of tyre to responses dynamic signals when cornering motorcycle within average speed 56 km/h.

In the case of speed within-subjective factor as shown in Table 4.23, dynamic responses variables were significant as affected by variation in speed levels. Therefore the null hypothesis was rejected or it can be supposed that the alternative hypothesis was accepted. These denote that speed level had significant influence on the roll rate and the pitch rate.

Table 4.22 One-Way Analysis of Variance for Dynamics Responses of Slalom Test with Tyre Set as the Within-Subjects Factors

Dynamic Responses Variables	Total Sum of Squares	df	F-Statistic	*p-value*
$Max.\omega_x$	116640.718	77	1.339	0.268
$Min.\omega_x$	150722.372	77	0.750	0.476
$Max.\omega_z$	6767.449	77	2.163	0.122
$Min.\omega_z$	5990.6779	77	4.615	0.013
ω_x/ω_z	319.195	77	1.914	0.155

** Sig < 0.01

Table 4.23 One-Way Analysis of Variance for Dynamics Responses of Slalom Test with Speed as the Within-Subjects Factors

Dynamic Responses Variables	Total Sum of Squares	df	F-Statistic	*p-value*
$Max.\omega_x$	116640.718	77	18.590	0.000^*
$Min.\omega_x$	150722.372	77	14.388	0.000^*
$Max.\omega_z$	6767.449	77	7.103	0.000^*
$Min.\omega_z$	5990.6779	77	8.429	0.000^*
ω_x/ω_z	319.195	77	14.308	0.000^*

* Sig < 0.05

CHAPTER 5
DISCUSSIONS AND CONCLUSIONS

This chapter provides a detail discussions on the results obtained in this study. It is also discussed on how the research objectives were achieved. Additionally, the research contributions, limitations and recommendation for future works were discussed. Therefore it is organized by discussions of results in section 5.1, conclusions in section 5.2 and further works in section 5.3.

5.1 Discussion of Results

The use of road test for perceiving the motorcycle dynamic behaviours and analyzing its responses has been demonstrated. As in this case the validation of straight running test and slalom test for studying the influence of motorcycle tyre properties especially tyre width on motorcycle behaviours was established. The subject of this study was carried out on commercial lightweight motorcycle which is 125 cc engine sizes. The influence of the three tyre sets, which were tyre set A (original equipment manufacturer with the smallest size), tyre set B (a moderate tyre size), and tyre set C (the largest tyre size), on dynamic behaviour was deeply investigated. The present study focused on answering the existing vehicle safety component especially tyre characteristics. Accordingly, dynamics behaviours of motorcycle strongly affected by tyre properties and velocity therefore the design of experiment were employed. Time waveforms of the experimental results were analyzed and statistical tested to examine their effect accounting for motorcycle stability. The findings were as follows:

5.1.1 Straight Test Results

- In most cases forces created by motorcycle tyre directly delivered to the motorcycle body. The stability condition can define using vibration signals measurement. Therefore, ten dynamics responses of vibration signals including 3-axis angular acceleration, average acceleration, 3-axis angular velocity and 3-axis angular rotation of motorcycle system. Method introduced here allowed determining driving stability behaviour of motorcycle in rectilinear motion. The results present that there are random patterns of ten major dynamic responses vibration waveforms. The non-symmetrical above and below the zero line can be precise that the signals of the free motion of steering system of motorcycle driving in a straight path is stable. To further characterize influencing tyre sets that can provide the most stability efficiency, hence, the ANOVA tests were then conducted. There were unexpected results, that led to the conclusion that there were no statistical difference in mean average value and root mean square of dynamic responses signals between tyre widths of motorcycle when driving in straight road. These answer the research questions that the original equipment manufacturer tyre set (tyre set A) can offer a suitable safe stability for commercial motorcycle when riding with speed lower than 17 m/s (60-62 km/h).

- Eleven subgroups of speed levels were validated with specified statistical test confirming power on motorcycle driving stability. The straight run test results displays that some changes of vehicle speed can affect motorcycle yaw stability but these did not occur in roll and pitch stability. However, the influence of speed levels on yaw responses signals in sequence provided little effect during straight path driving condition. Rider can subsequently performed the experiments without any danger even riding without controlling the handlebar.

- The adaptation of smartphone as vibration signals measurement was employed. The proposed system with onboard sensors devices can be configured relatively inexpensively and consequently able to measure acceleration, velocity and rotation condition of specified vehicle. The major advantage of smart phone could be permitted its use to detect other kinematic properties of vehicles or drivers. These are beneficial for research and development in less income countries.

The association of these finding could point toward that using the same original equipment manufacturer spoke rim diameter of wheel contributed to the unpredictable contact patches of the specified three tyre sets. As provided in chapter 4 (Table 4.2) , the mean contact area of the front and rear wheel of tyre set B smaller than tyre set A by 7% and 23%, respectively. Furthermore, even the contact patch of the front wheel of tyre set C was greater than that of tyre set A by 35% but the consequence of the rear wheel was unbelievably smaller percentage of 14%.

5.1.2 Slalom Test Results

In case of slalom test that investigated the motorcycle responses behaviours when cornering showed converse results compared with straight running test results. The width of tyre presented a remarkable influence on motorcycle cornering stability. The findings were as follows:

- The slalom test results show that with the same speed for all tyre sets, the value of roll rate is greater than yaw rate. Thus the ratio of roll to yaw rate tend is typically a steady rise pattern.

- For the same tyre set, the ratio of roll to yaw rate of all tyres tends to increase as speed increases. A large ratio of roll to yaw rate means a small friction force, as a direct consequence of contact area and slip angle, contributed to too little lateral force. Controlling motorcycle in this scenario need more effort to follow the given path.

- Comparison between tyre sets, for the same speed of 40 km/h and 60 km/h tyre set C shows the smallest ratio of roll to yaw rate. This is because tyre set C has a larger contact patch of inclination that provides more friction force or a stronger grip. These indicated that motorcycle with a wider tyre has more ability to stabilize the vehicle in cornering than a thinner tyre.

The riding test results showed the significance of the lateral rotation and vertical rotation of vehicle representing the responses on load and moment transfer of motorcycle tyre that must be applied to do a straight driving and cornering. The ratio of dynamic responses results pointed out some driving sensations that help to understand the dynamic behaviour of this motorcycle on three different tyre sets. Wider tyre width really affects either motorcycle handling stability while cornering, or it presented noticeable consequence on or driving in a straight pathway.

5.2 Conclusions

5.2.1 This thesis presents the results of dynamic stability test of lightweight motorcycle that contribute to road crash. The significant motivation of this study as a consequences of (Kasantikul, 2001a) (Kasantikul, 2001b) (Kasantikul, Ouellet, Smith, Sirathranont, & Panichabhongse, 2005) that mentioned the negligible figure of single vehicle accidents and other relevance. These investigations posed the question of this study, how motorcycle component especially motorcycle tyre significantly impact on the single-vehicle road crash. The analyses results imply that the tyre width of commercial motorcycle does not statistically differ by riding with speed not exceed 17 m/s (60-62 km/h) in rectilinear condition. It needs to be mentioned that this analysis did not consider contact area as a subsequence of different tyre size with the given same spoke rims diameter of wheels.

5.2.2 This slalom experiment implied aspects of several cornering motorcycling to study the influence of different motorcycle tyre width involving instrumented motorcycle. The lateral and vertical force on each wheel and also the torque reacted on the handlebar that represented by means of roll rate, and yaw rate were considered. The ratio of roll to yaw rate illustrates the vehicle behaviours and a consequence of rider controllability. The results of the riding test substantiation demonstrated that at speed exceeded 40 km/h the wider tyre width produced easier handling with the small ratio of roll to yaw rate. Motorcycle with wider tyre width provides a larger contact area between the tyre and road surface during an incline giving the rider a sense of control, confidence and a feeling of safety. However, the instability of the motorcycle with small size tyre width feature aggravated when it was controlled by motorcycle rider who has high alcohol consumption.

5.2.3 From the study, it is recommended that a wider tyre width of 110 mm for front tyre and 120 mm for rear tyre (tyre set C) should be used in a commercial lightweight Thai motorcycle.

5.2.4 The vehicle riding test in this study pioneered a vehicle (motorcycle) safety study that has been under researched in Thailand. The limitations of this study that focused on tyre width and specified speed levels should be further explored with other tyre characteristics as tread pattern, tyre rubble property and higher test speeds.

5.3 Future Works

- For Straight running test, because the proposed parameters of this study focused only on tyre width which is one feature of tyre properties and the other interesting features such as treat pattern, rolling resistance and side slip angle are omitted, the proposed study could not cover the overall characteristic of motorcycle tyres. These limitations should be considered in the further research.

- The riding speed introduced here allows a description of typical motorcycle riding behaviours. For extreme situation, the proposed experiment can be extended to investigate motorcycle stability in higher riding speed conditions, since the highest speed conducted in this study was only 60 km/h. These can help to understand characteristics of extreme motorcycling in the further work.

- The completed representation of a modern high technology of commercial smart phone should be used to measure dynamic stability of motorcycle data and compare existing information. In addition, the application of smart phone can be used to develop the dynamics measurement for other characteristics of motorcycle riding and control.

- For Slalom test, further riding experiment should be examined with different cone spacing of 7 m and 21 m as in the study conducted by Cossalter, Lot, & Rota, 2010 and correlated with already collected data. The longer spacing of cone allows higher riding speed which affects motorcycle leaning stability.

- Because the experimental results from road tests on straight line show the effect of tyre width on motorcycle stability to be insignificant; it is recommended that for future tests the contact area of the selected tyres and the pavement surface be measured before conducting the road tests. This would help in examining the physical relationship between tyre properties and motorcycle stability.

- Accordingly, the slalom tests presented a significant impact of tyre width and handling stability. Wider tyre width offered a better controllable since the larger contact area when motorcycle was in leaning condition. Therefore, the future works should be researched to investigate an influence of contact area of motorcycle tyre with respect to varying degree of the lean angle.

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APPENDIX A

Tyre Characteristics

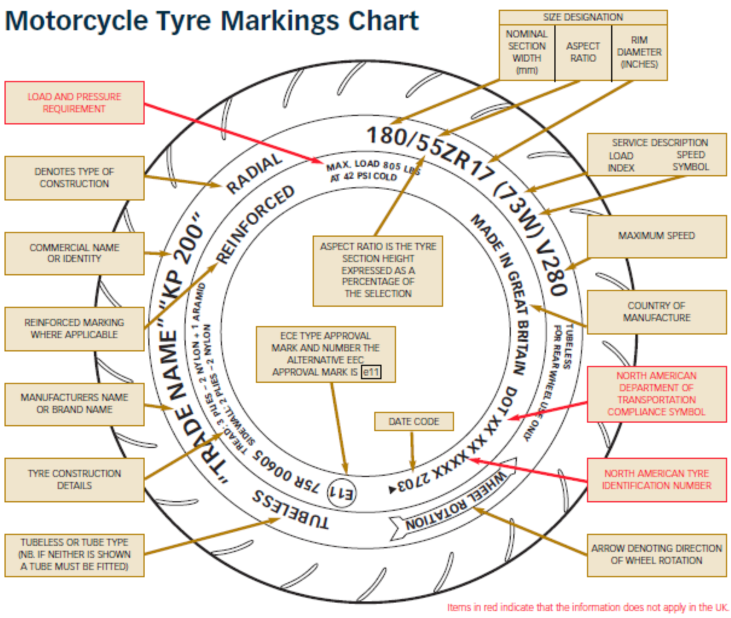


Figure A-1 Motorcycle Tyre Markings Chart
(British Tyre Manufacturer's Association, 2015)

Table A-1 Tyre Speed Marking Table (TISI, 2014)

Speed Symbol	Maximum motorcycle speed for which tyre is suitable	
	km/h	mph
Moped	50	30
J	100	62
K	110	69
L	120	75
M	130	81
P (or-)	150	95
Q	160	100
R	170	105
S	180	113
T	180	113
U	190	118
H	200	125
V*	210	130
W*	240	150
ZR	270	168

Table A-2 Tyre Load Indices & Related Maximum Loads (TISI, 2014)

Load Index	Load (kg)	Load Index	Load (kg)	Load Index	Load (kg)	Load Index	Load (kg)	Load Index	Load (kg)
20	80	35	121	50	190	65	290	80	450
21	82.5	36	125	51	195	66	300	81	465
22	85	37	128	52	200	67	307	82	475
23	87.5	38	132	53	206	68	315	83	487
24	90	39	136	54	212	69	325	84	500
25	92.5	40	140	55	218	70	335	85	515
26	95	41	145	56	224	71	145	86	530
27	97	42	150	57	230	72	355	87	545
28	100	43	155	58	236	73	365	88	560
29	103	44	160	59	243	74	375	89	580
30	106	45	165	60	250	75	387	90	600
31	109	46	170	61	257	76	400	91	615
32	112	47	175	62	265	77	412	92	630
33	115	48	180	63	272	78	425	93	650
34	118	49	185	64	280	79	437	94	670
								95	690

Table A-3 Motorcycle Tyre Specification for 125cc UK model

Model	Tyre Front	Tyre Rear
Xenter 125	110/80-16	120/80-16
BW's 125	120/70-12	130/70-12
Cygnus X	110/70-12	120/70-12
Vity	100/90-10	100/90-10
X-MAX 125	120/70-15	140/70-14
X-MAX 125 Sport	120/70-15	140/70-14
S-wing (street ahead)	110/90-13M/C (56L)	130/70-12M/C (62L)
Sh-125i	100/80-16 50P	120/80-16 60P

Table A-4 Contact Area of the Front Wheel of Tyre Set A

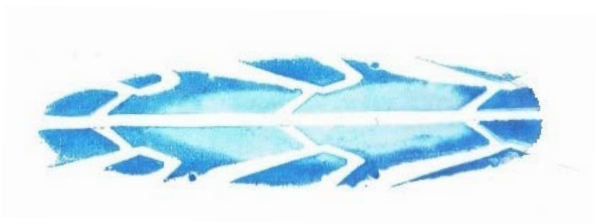
Tyre set A Front Wheel 70/80-14 M/C 34P	Run no.1	
	Run no.2	
	Run no.3	
	Run no.4	
	Run no.5	

Table A-5 Contact Area of the Rear Wheel of Tyre Set A

<table>
<tr><td rowspan="5">Tyre set A
Rear Wheel
80/90-14 M/C
34P</td><td>Run no.1</td><td></td></tr>
<tr><td>Run no.2</td><td></td></tr>
<tr><td>Run no.3</td><td></td></tr>
<tr><td>Run no.4</td><td></td></tr>
<tr><td>Run no.5</td><td></td></tr>
</table>

Table A-6 Contact Area of the Front Wheel of Tyre Set B

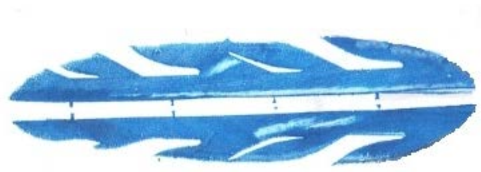
Tyre set B Front Wheel 90/90-14 M/C 90P	Run no.1	
	Run no.2	
	Run no.3	
	Run no.4	
	Run no.5	

Table A-7 Contact Area of the Rear Wheel of Tyre Set B

<table>
<tr><td rowspan="5">Tyre set B
Rear Wheel
90/90-14
M/C 46P</td><td>Run no.1</td><td></td></tr>
<tr><td>Run no.2</td><td></td></tr>
<tr><td>Run no.3</td><td></td></tr>
<tr><td>Run no.4</td><td></td></tr>
<tr><td>Run no.5</td><td></td></tr>
</table>

Table A-8 Contact Area of the Front Wheel of Tyre Set C

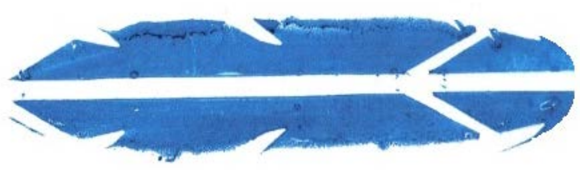
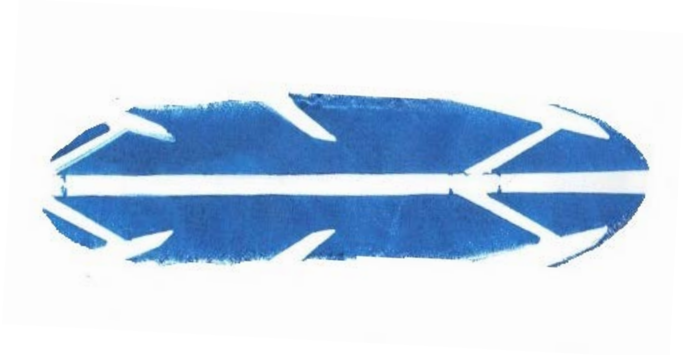
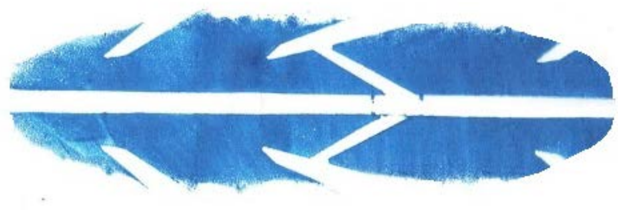
Tyre set C Front Wheel 110/70-14 M/C 56P	Run no.1	
	Run no.2	
	Run no.3	
	Run no.4	
	Run no.5	No Data

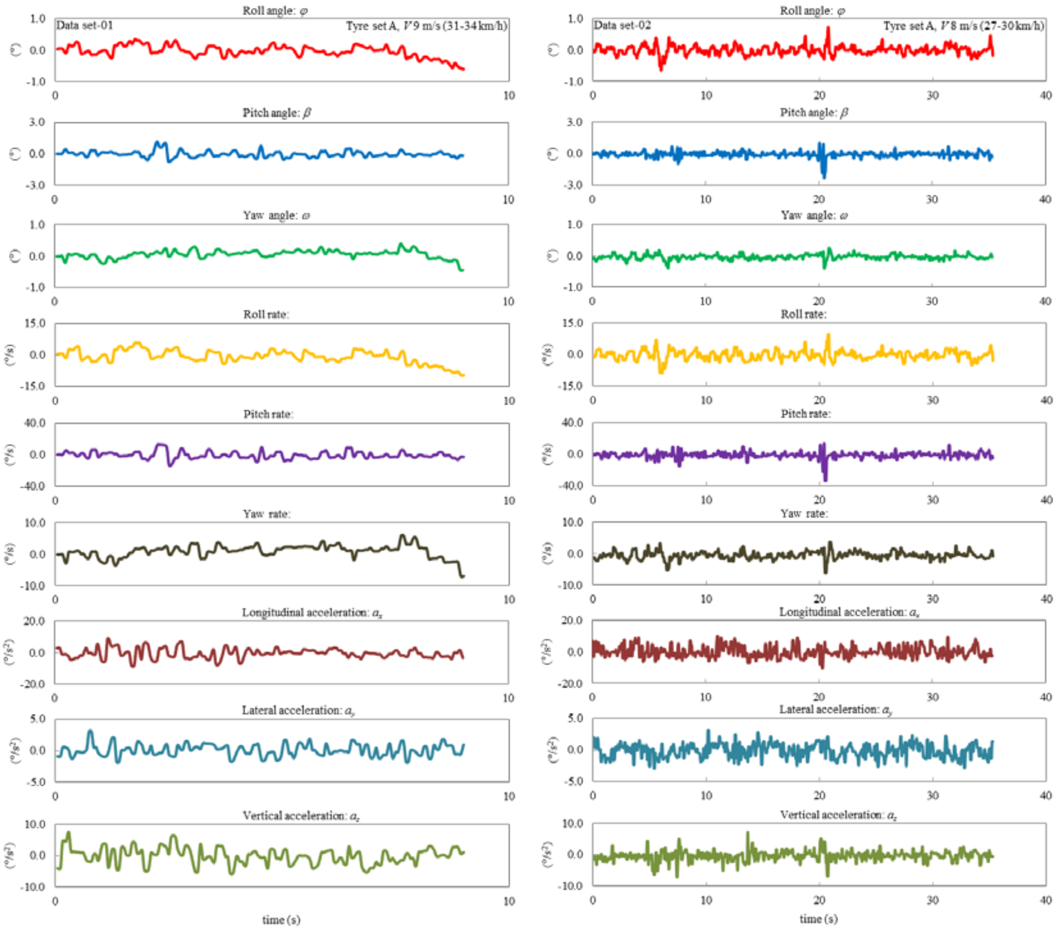
Table A-9 Contact Area of the Rear Wheel of Tyre Set C

Tyre set C Rear Wheel 120/70-14 M/C 61P	Run no.1	
	Run no.2	
	Run no.3	
	Run no.4	
	Run no.5	

APPENDIX B

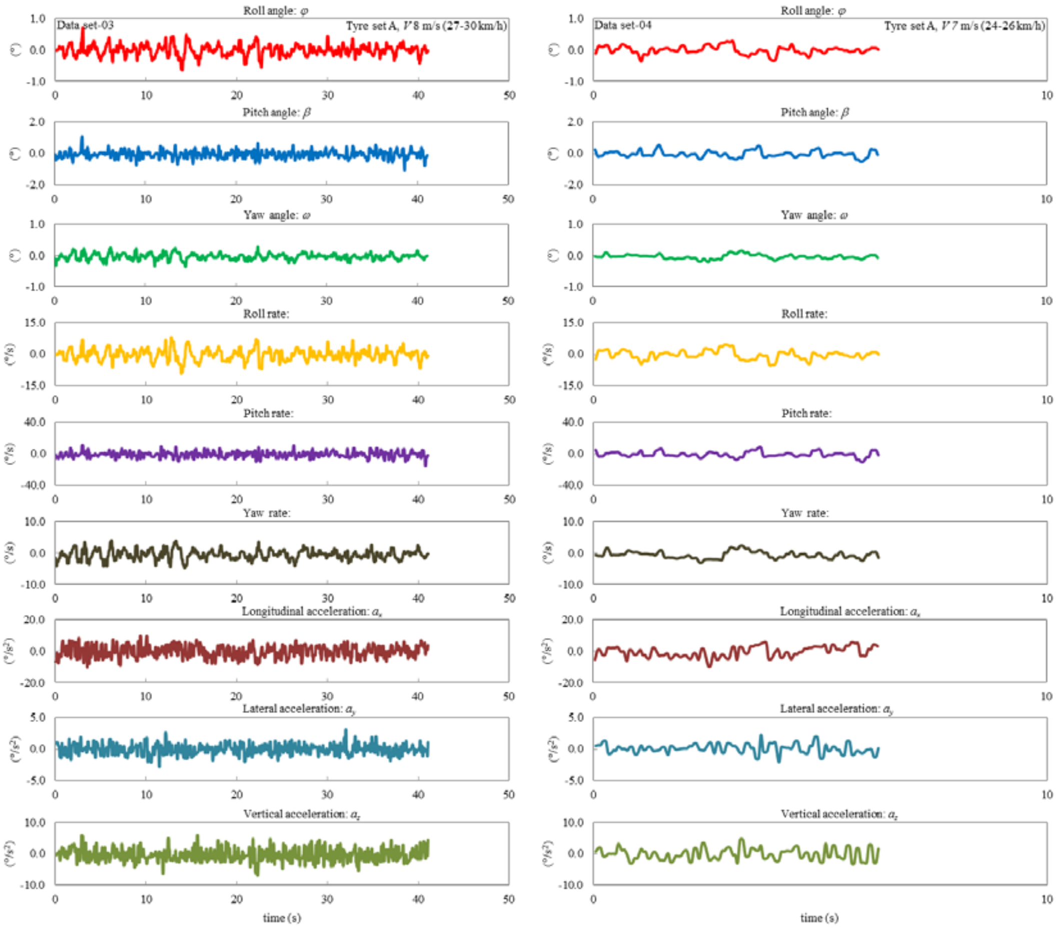
Straight Running Results

Tyre Set A



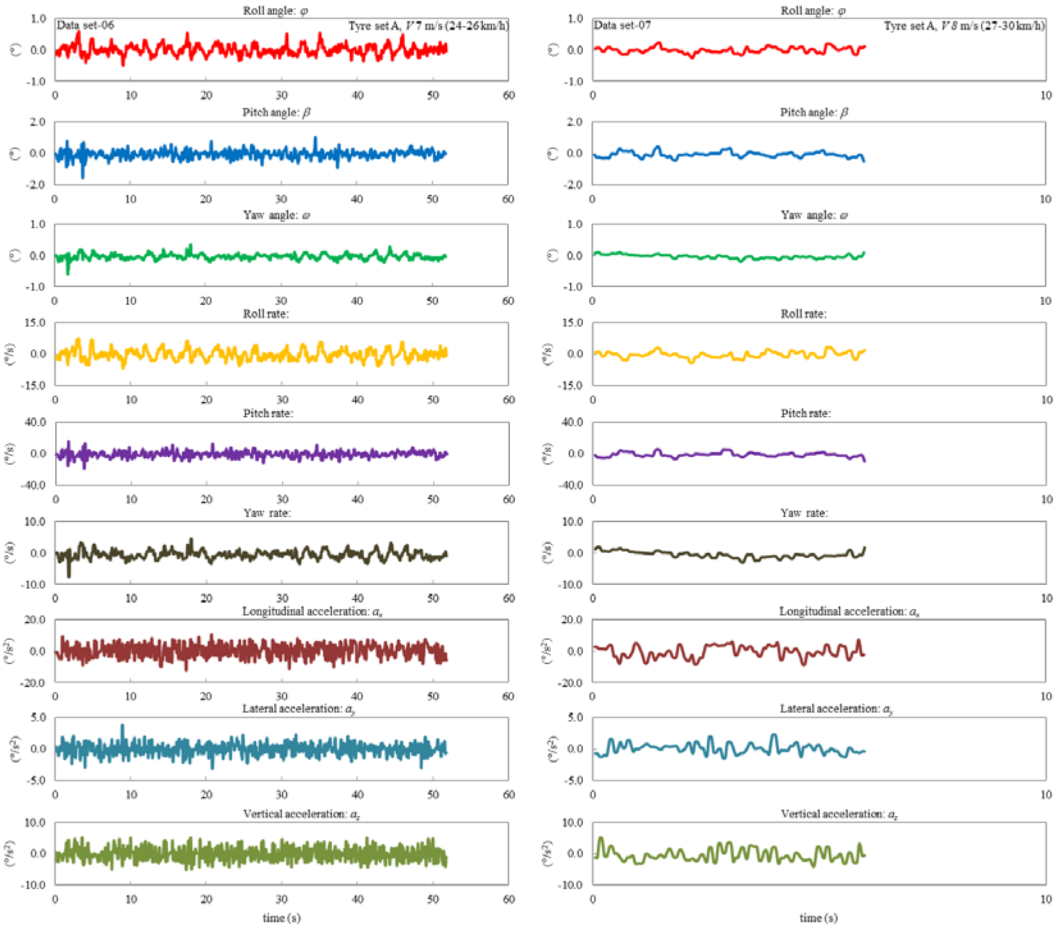
(a) (b)

Figure B-1 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 01 and (b) Data Set 02



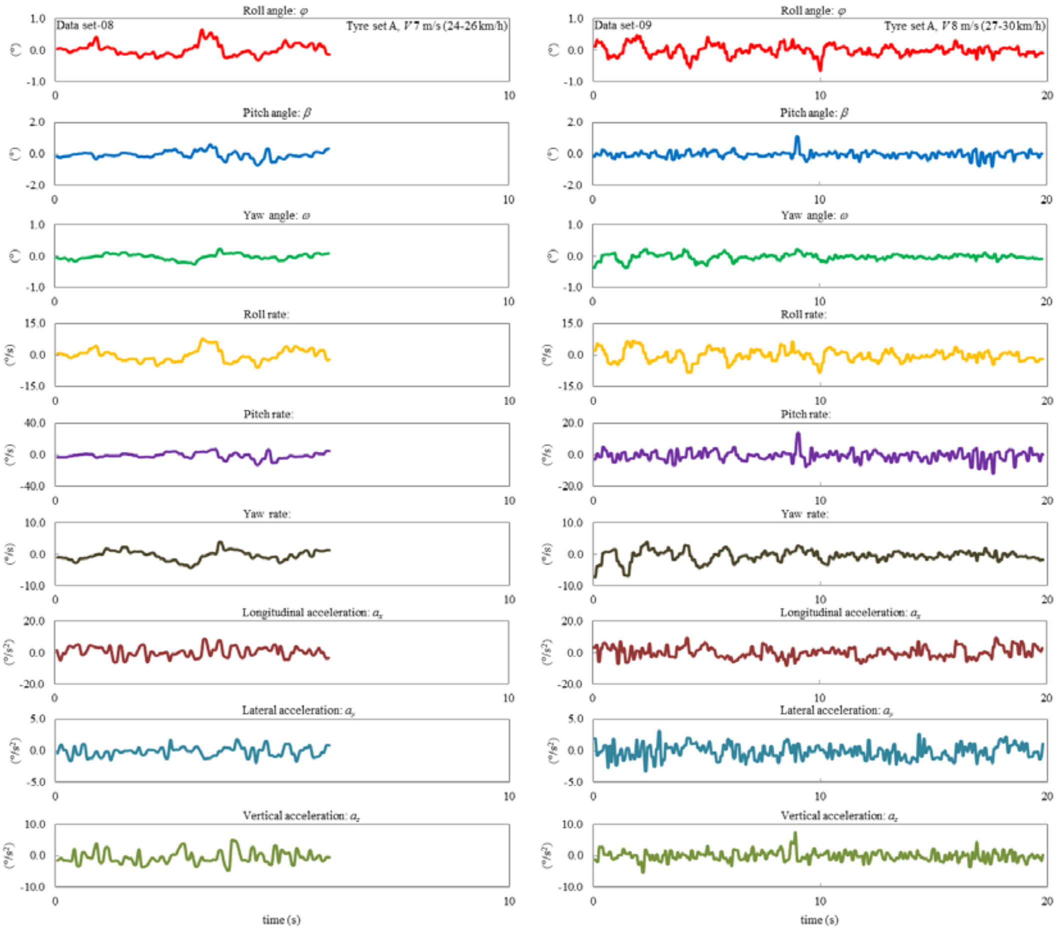
(a) (b)

Figure B-2 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 03 and (b) Data Set 04



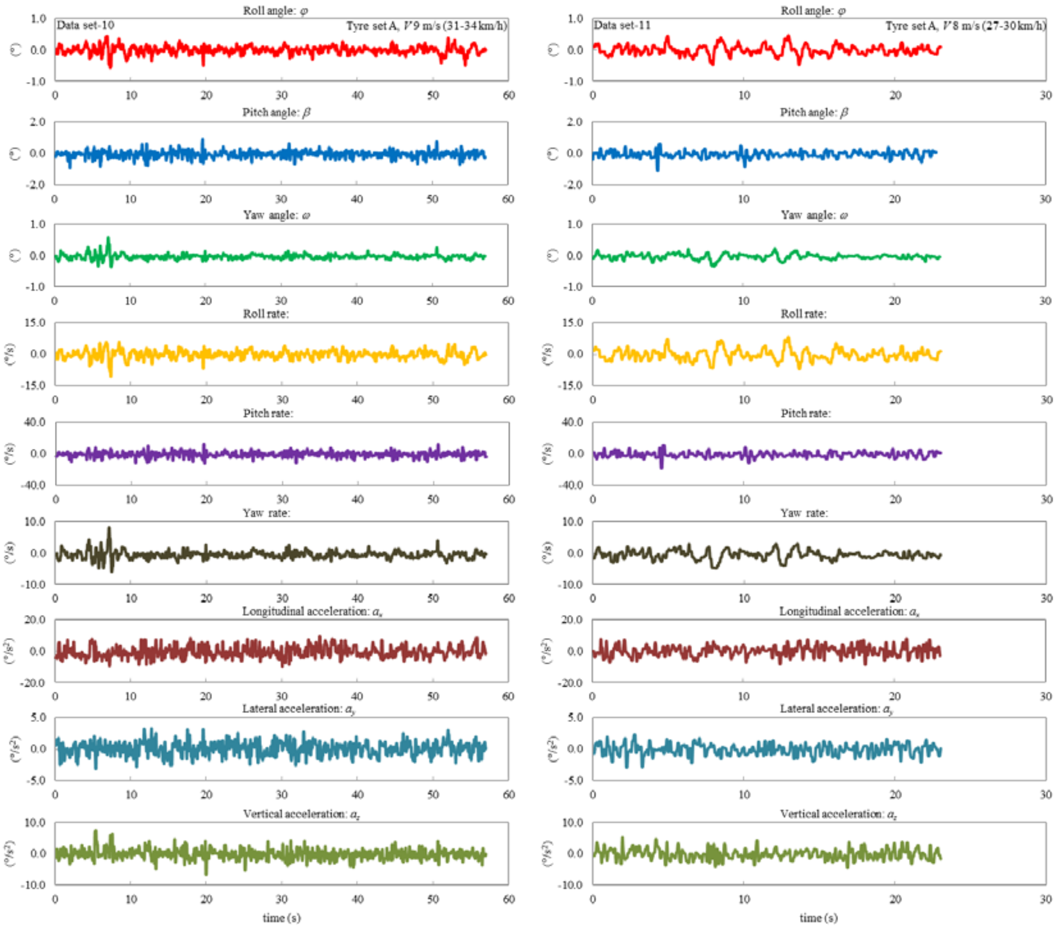
(a) (b)

Figure B-3 Dynamics Response Signals from Straight Run Test of Tyre Set A,
(a) Data Set 06 and (b) Data Set 07



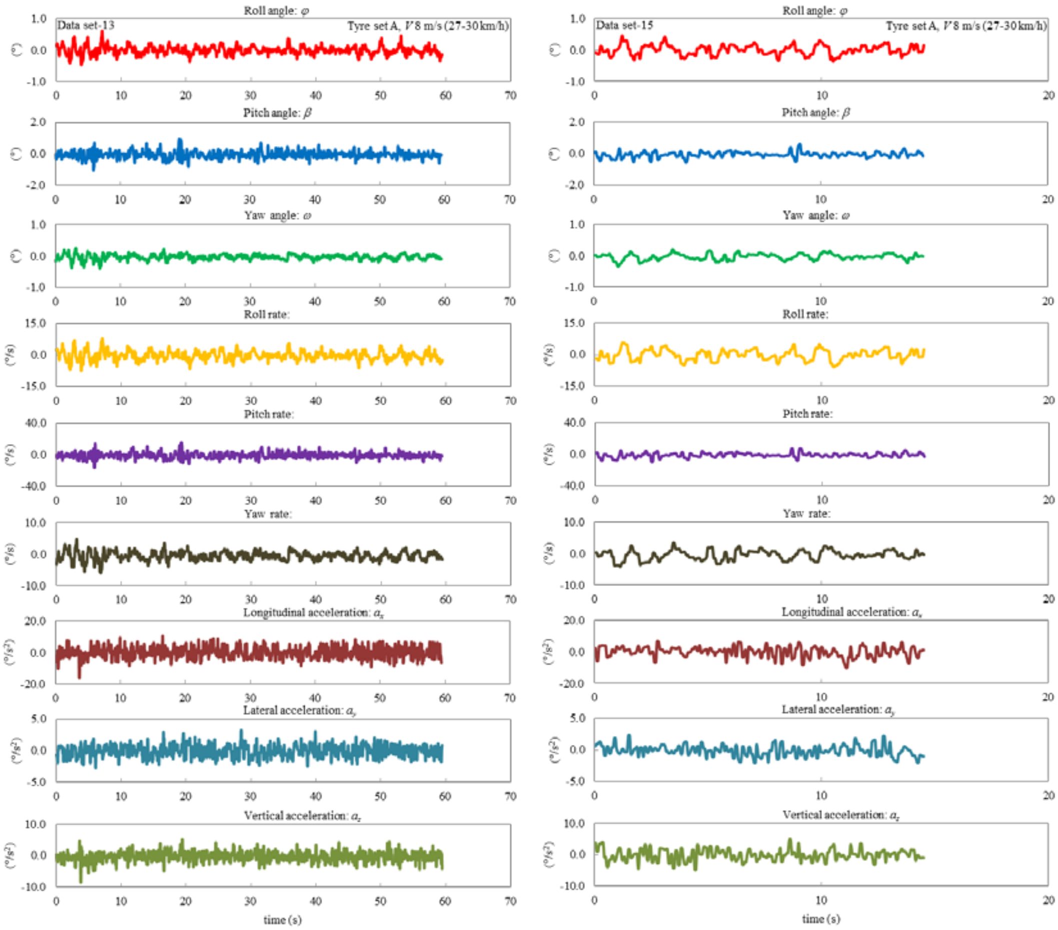
(a) (b)

Figure B-4 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 08 and (b) Data Set 09



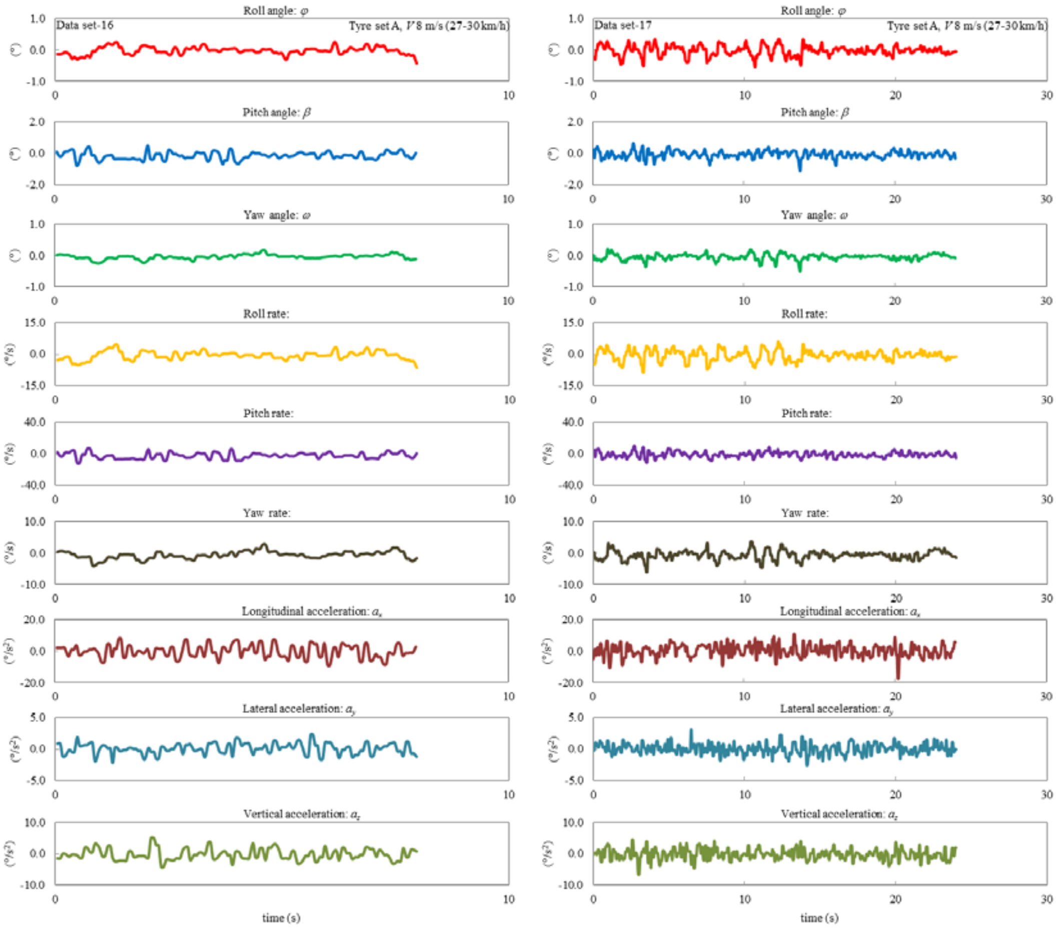
(a) (b)

Figure B-5 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 10 and (b) Data Set 11



(a) (b)

Figure B-6 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 13 and (b) Data Set 15



(a) (b)

Figure B-7 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 16 and (b) Data Set 17

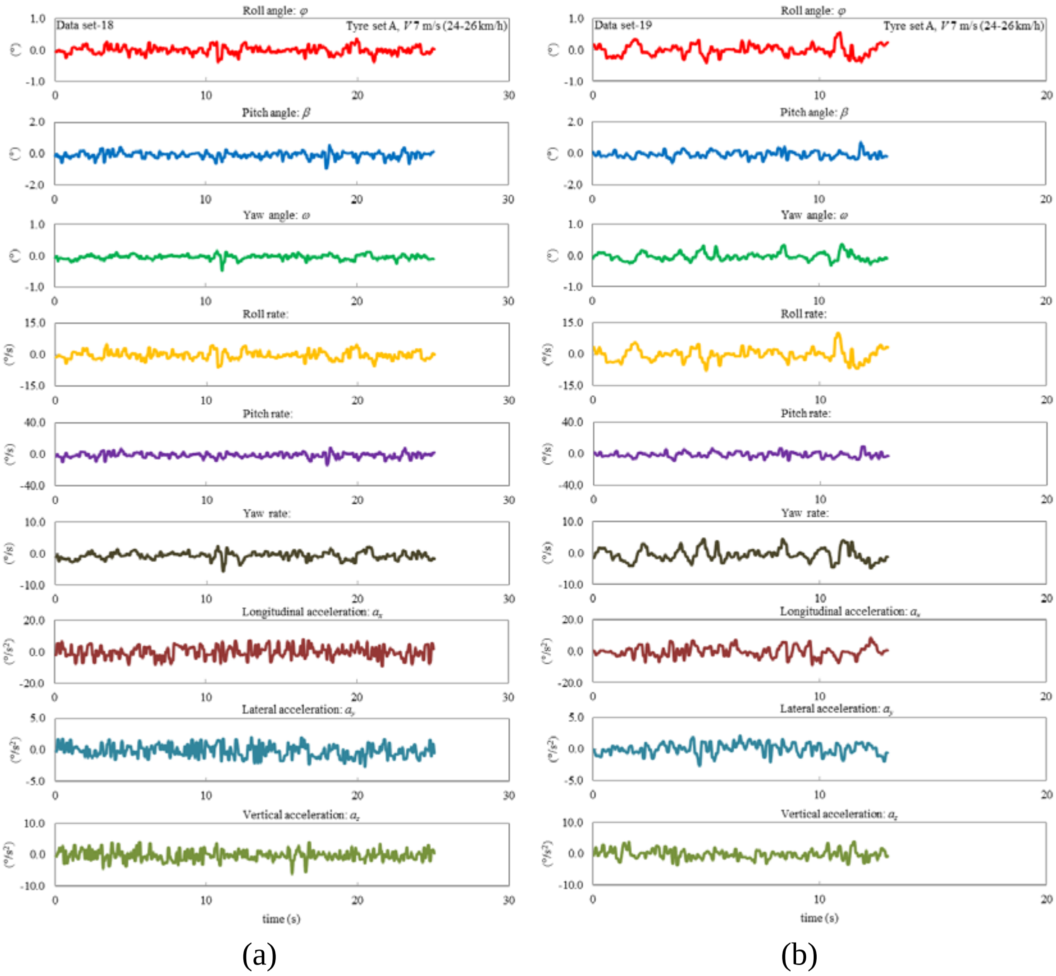
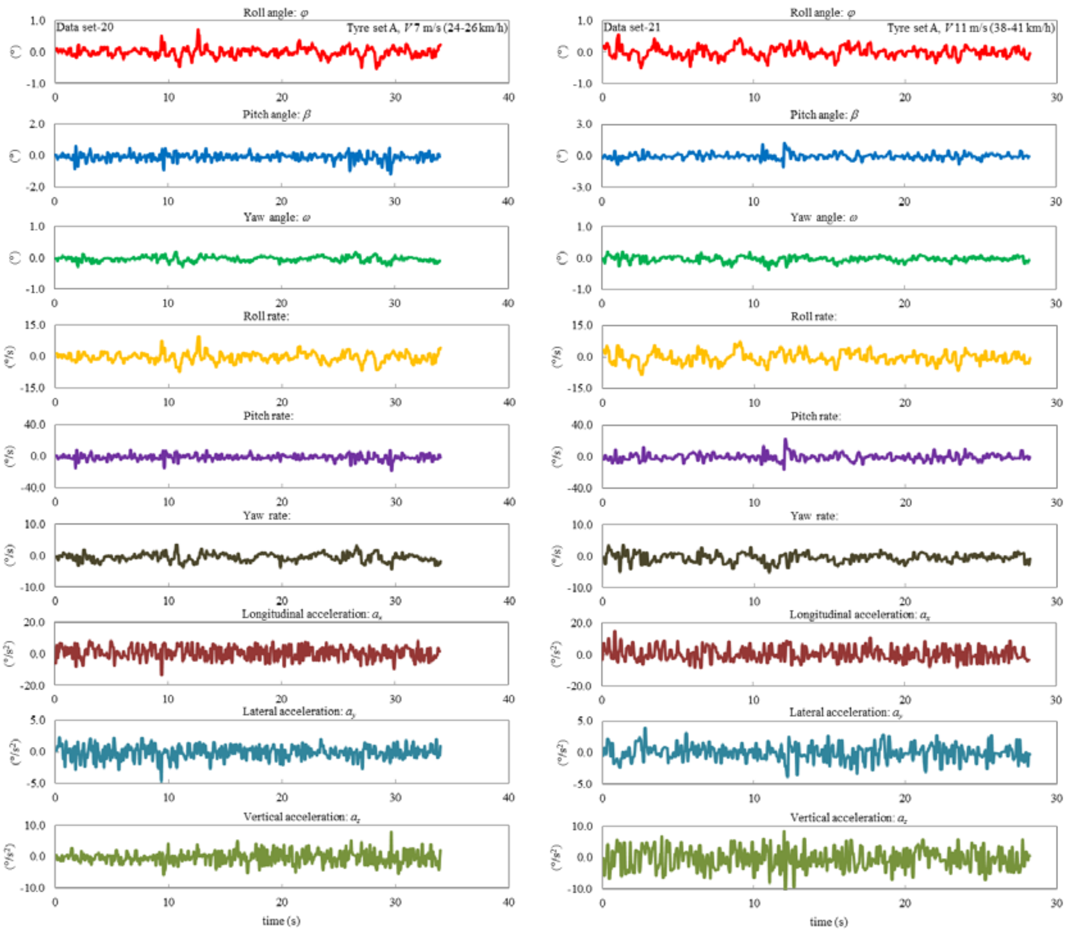
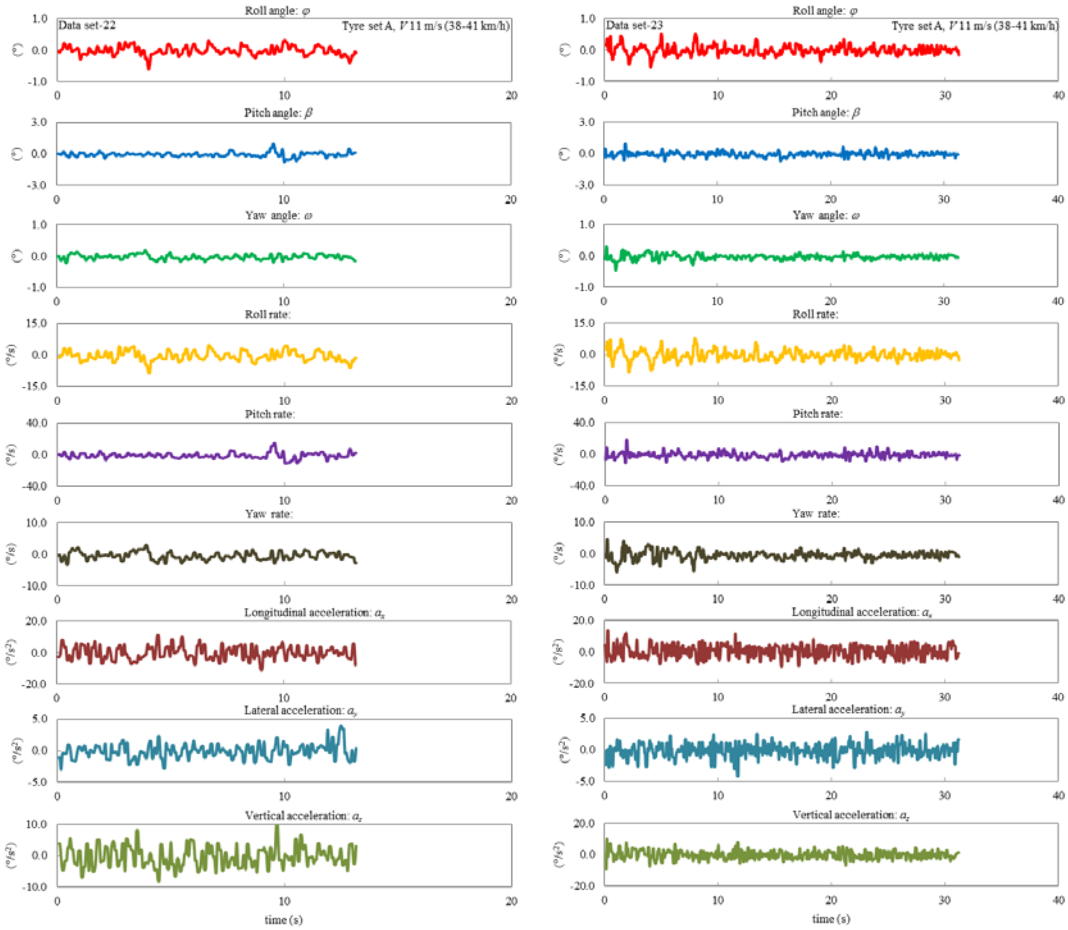


Figure B-8 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 18 and (b) Data Set 19



(a) (b)

Figure B-9 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 20 and (b) Data Set 21



(a) (b)

Figure B-10 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 22 and (b) Data Set 23

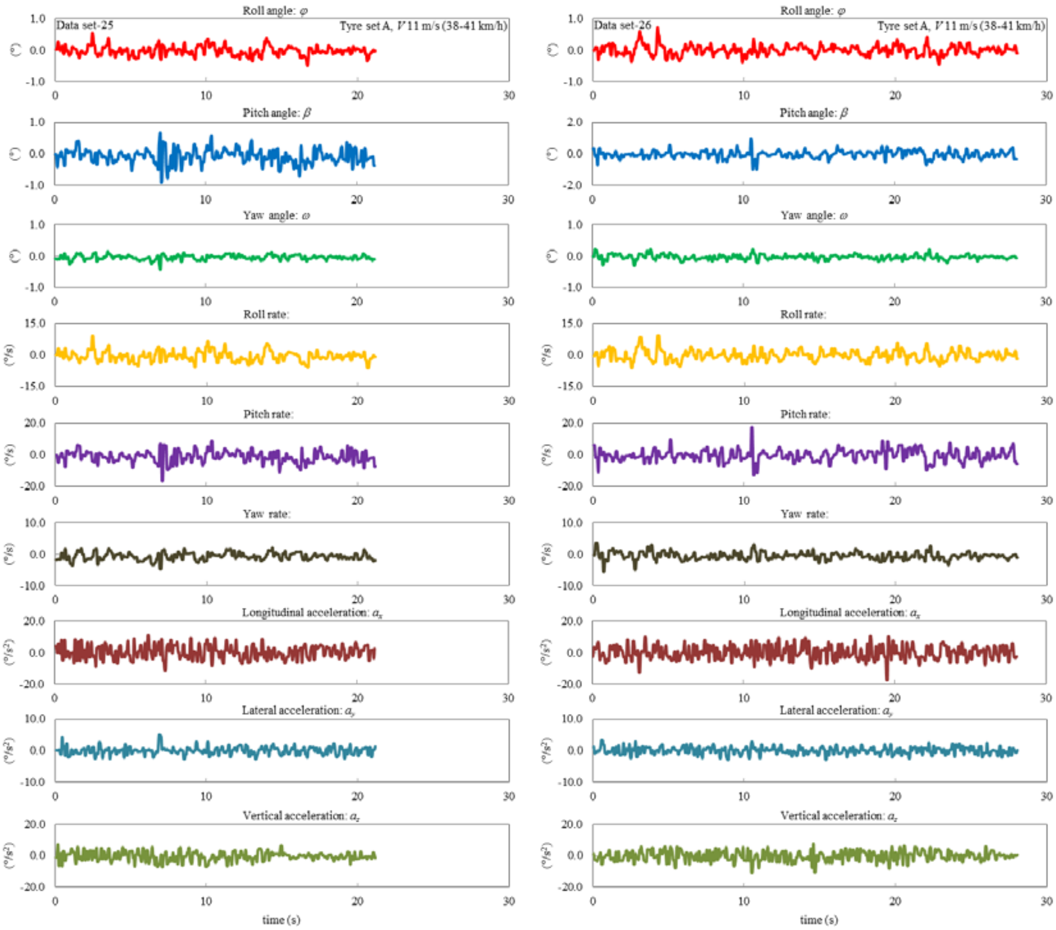


Figure B-11 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 25 and (b) Data Set 26

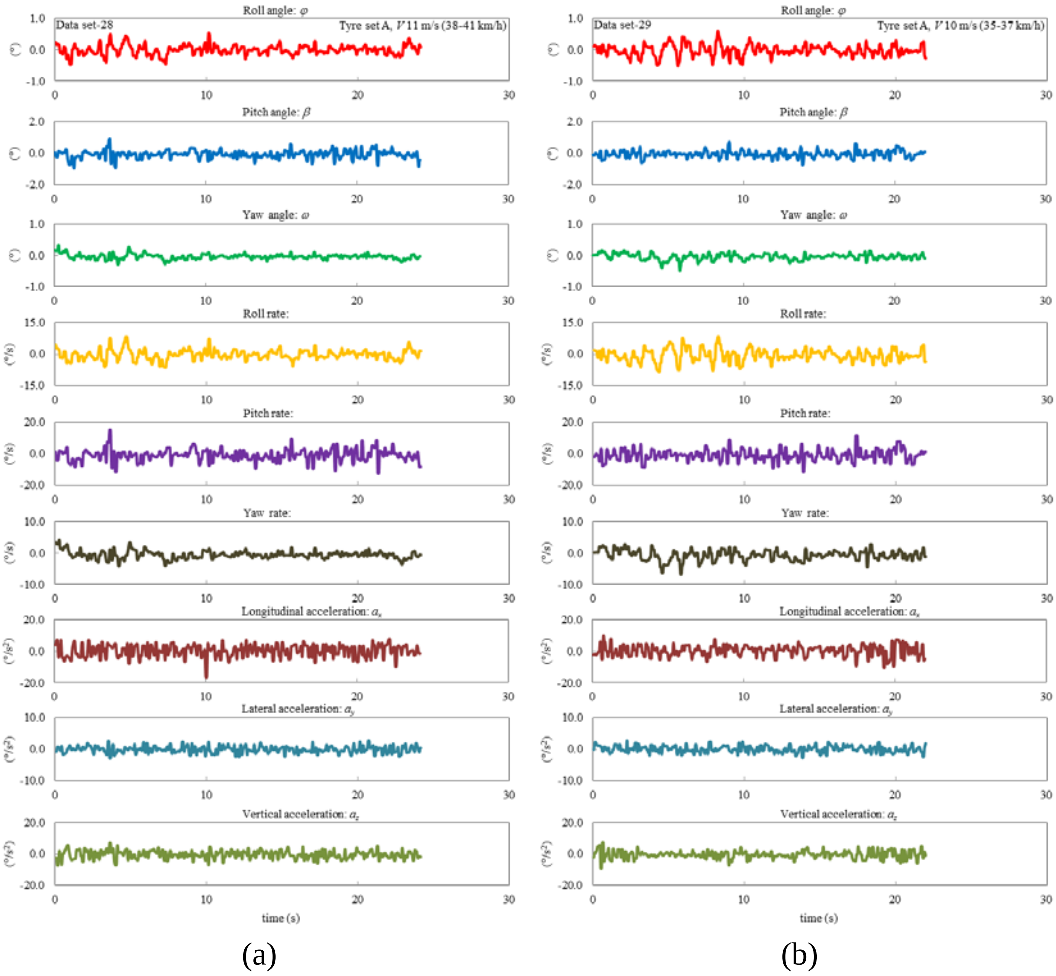


Figure B-12 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 28 and (b) Data Set 29

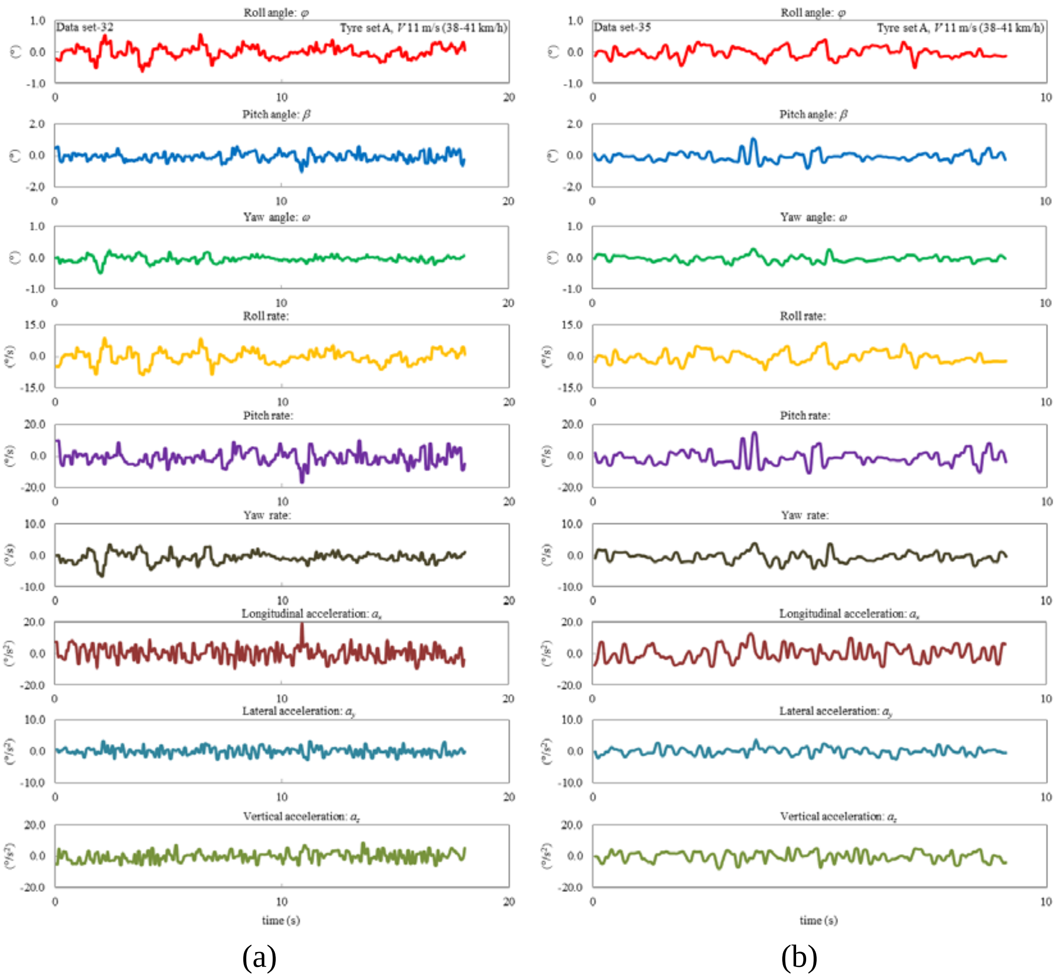
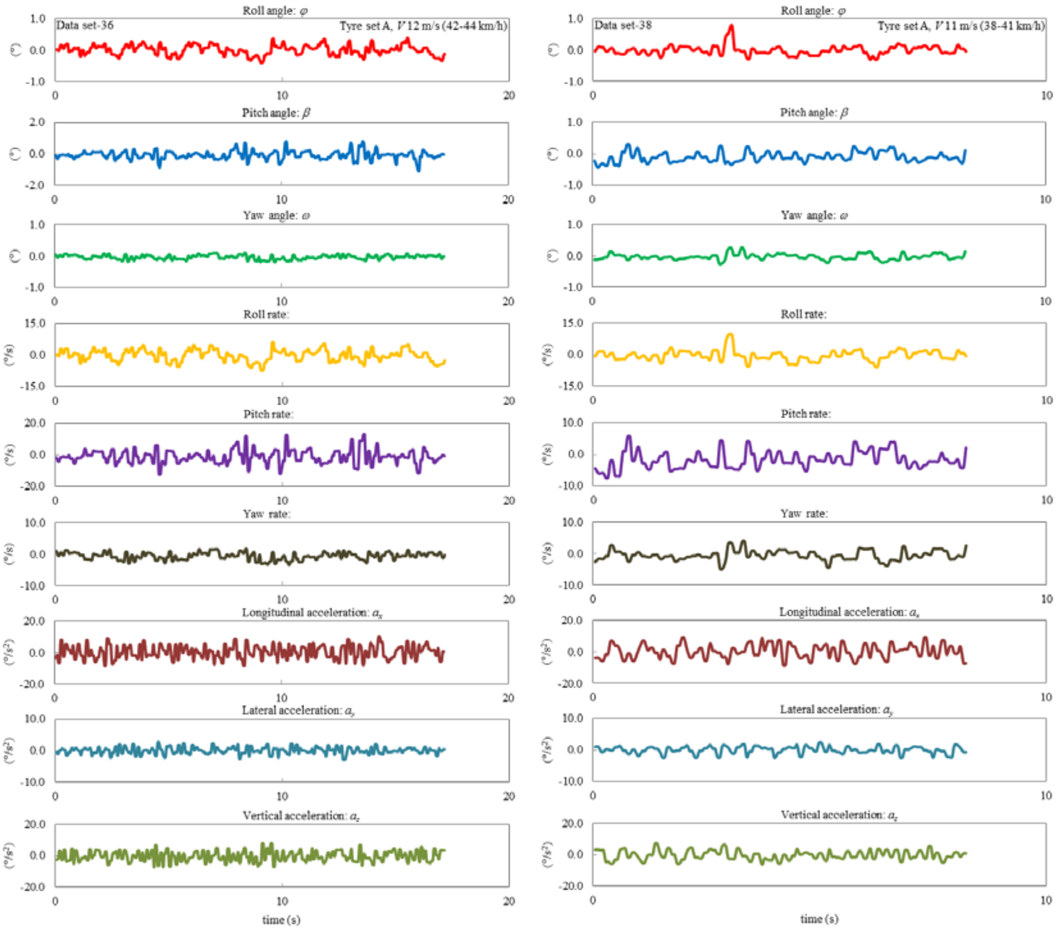
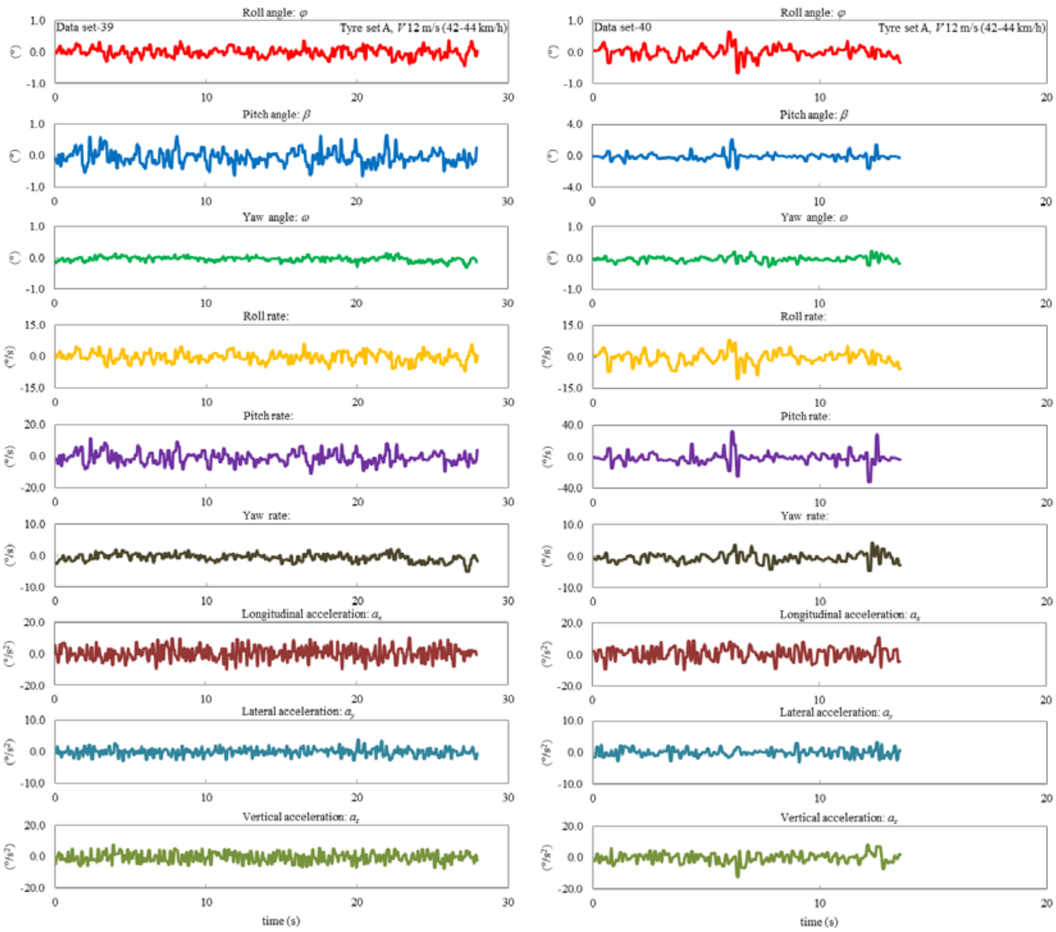


Figure B-13 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 32 and (b) Data Set 35



(a) (b)

Figure B-14 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 36 and (b) Data Set 38



(a) (b)

Figure B-15 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 39 and (b) Data Set 40

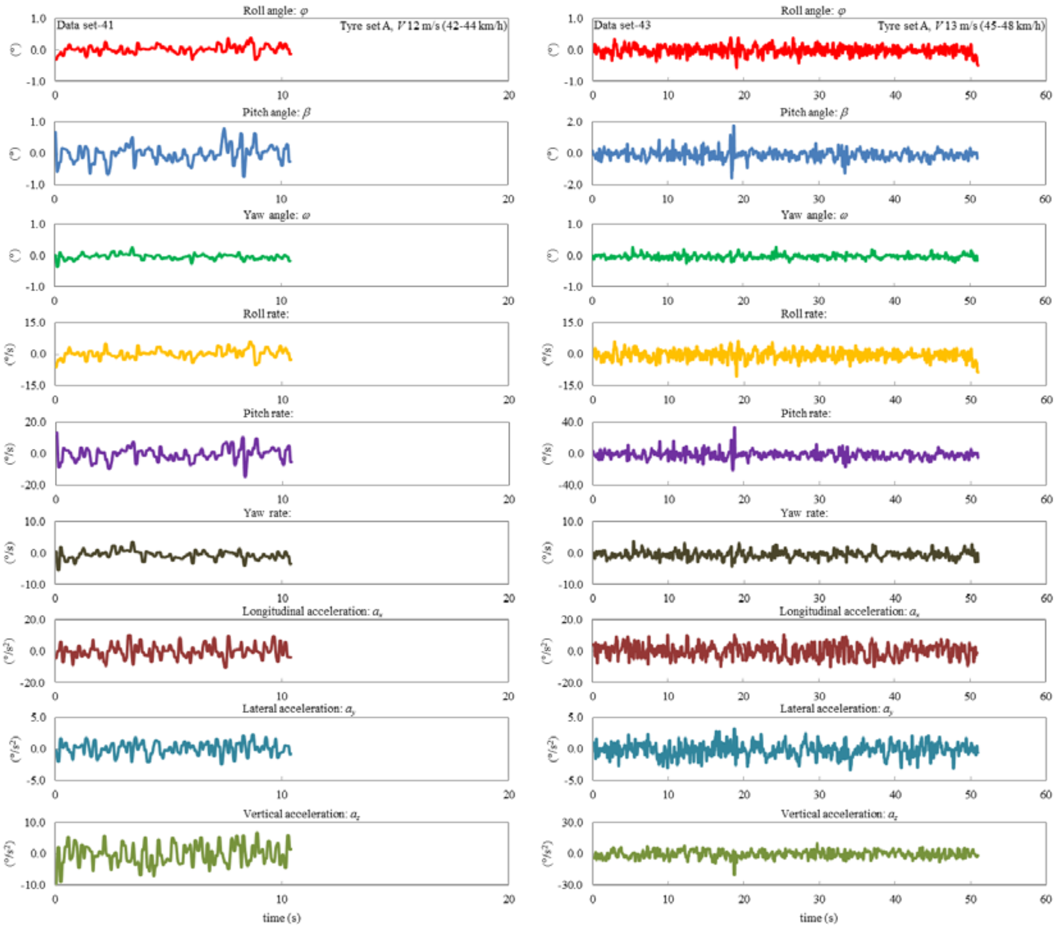


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Figure B-16 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 41 and (b) Data Set 43

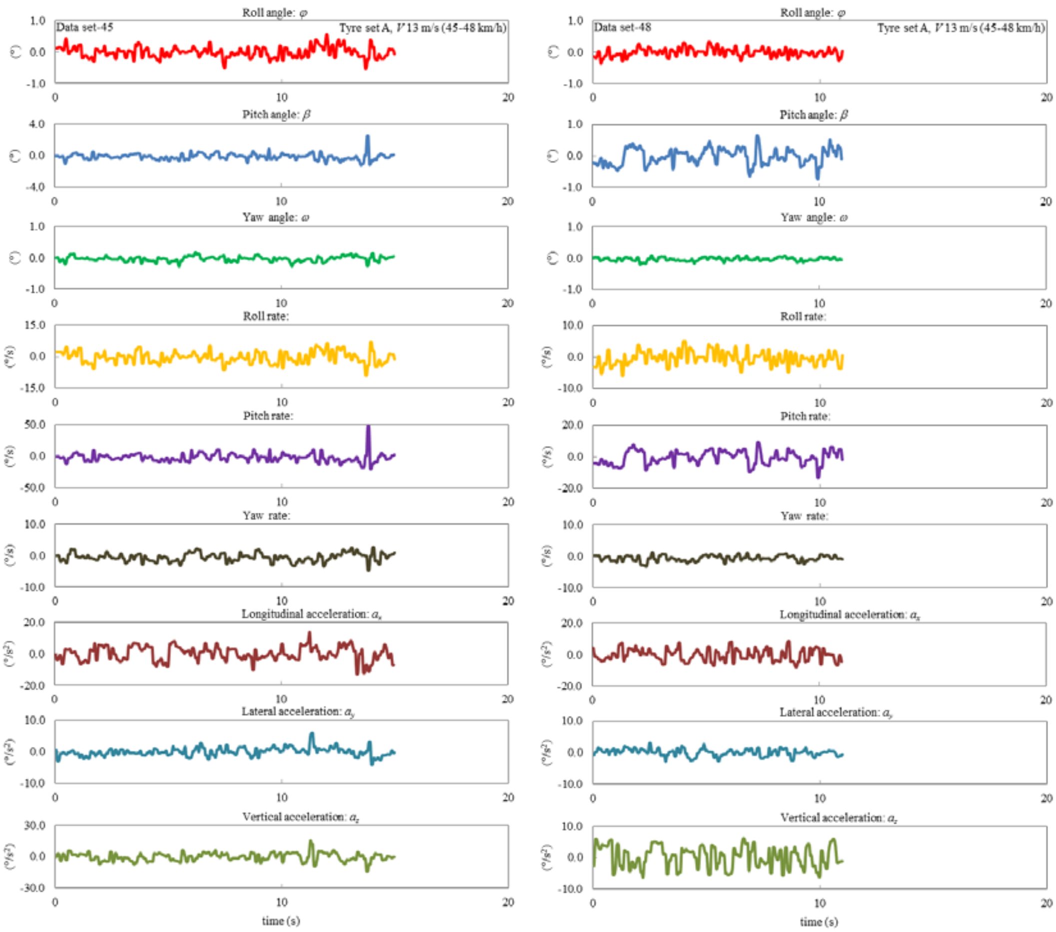

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Figure B-17 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 45 and (b) Data Set 48

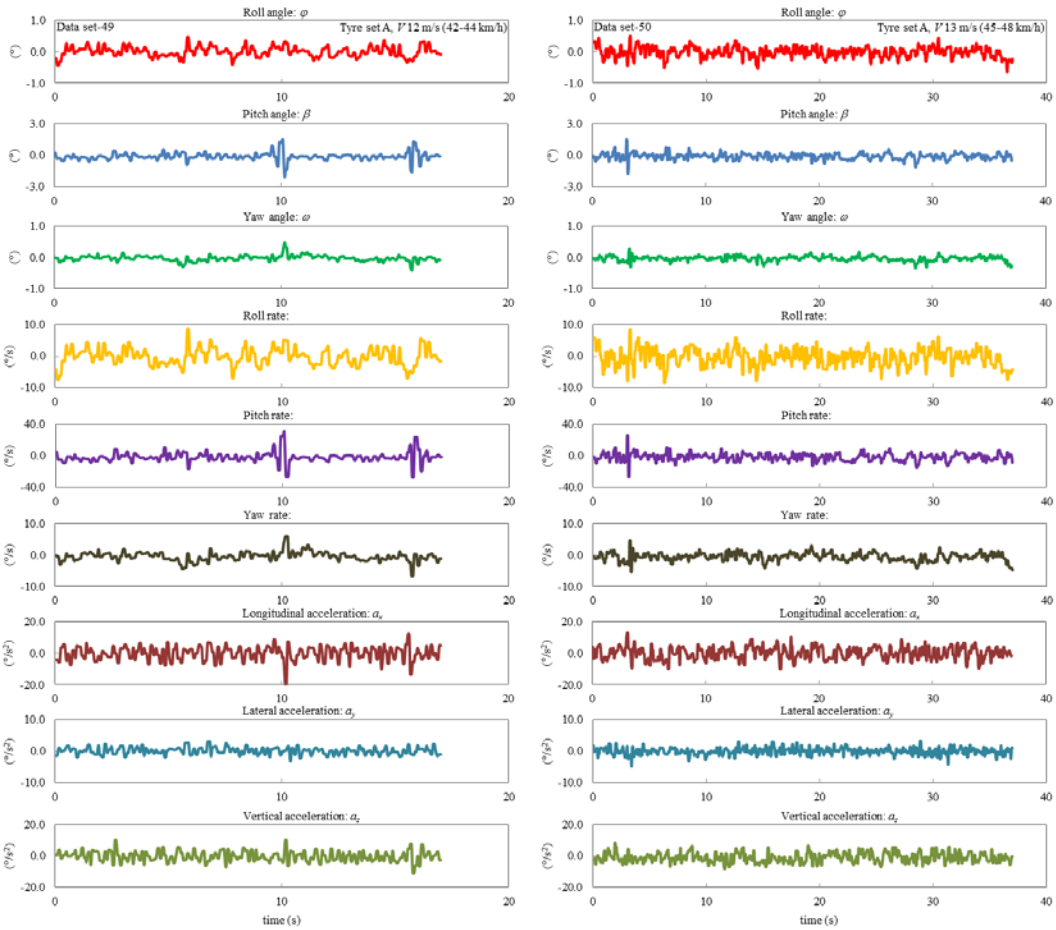

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Figure B-18 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 49 and (b) Data Set 50

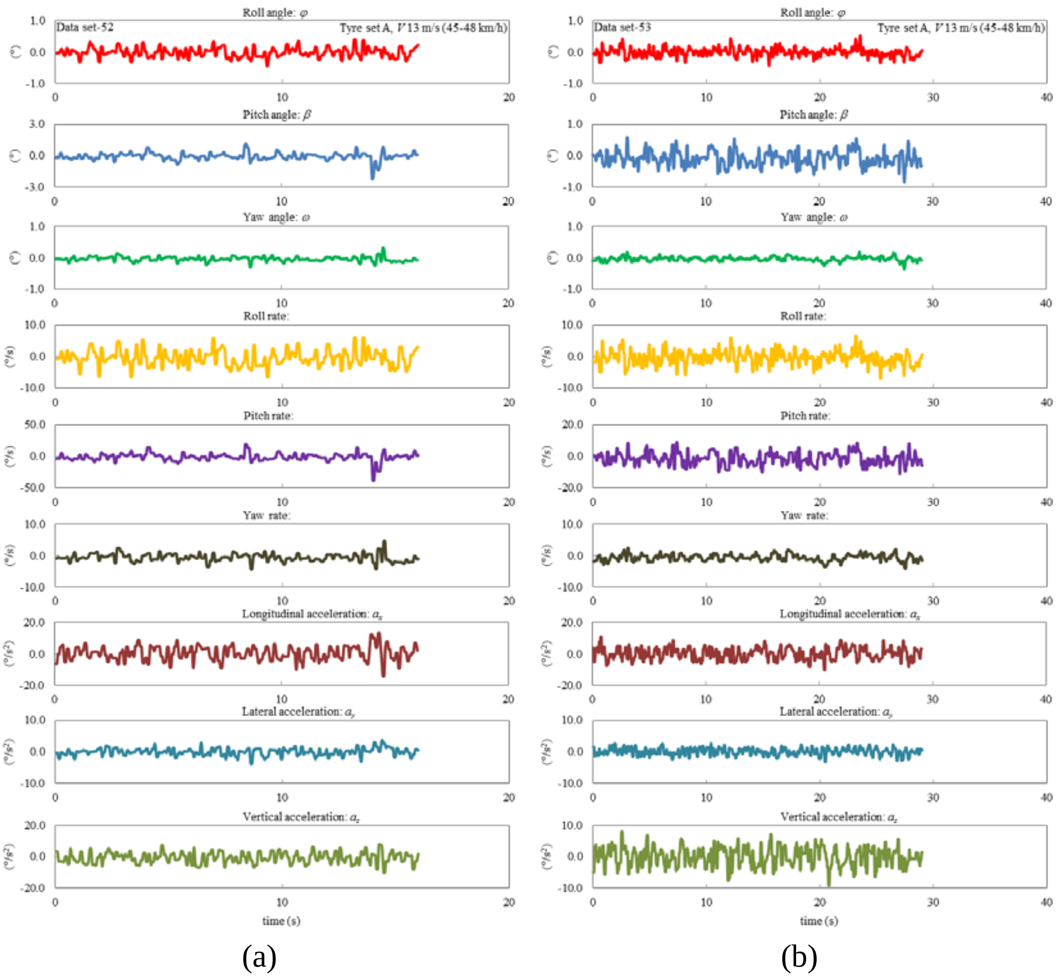

Figure B-19 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 52 and (b) Data Set 53

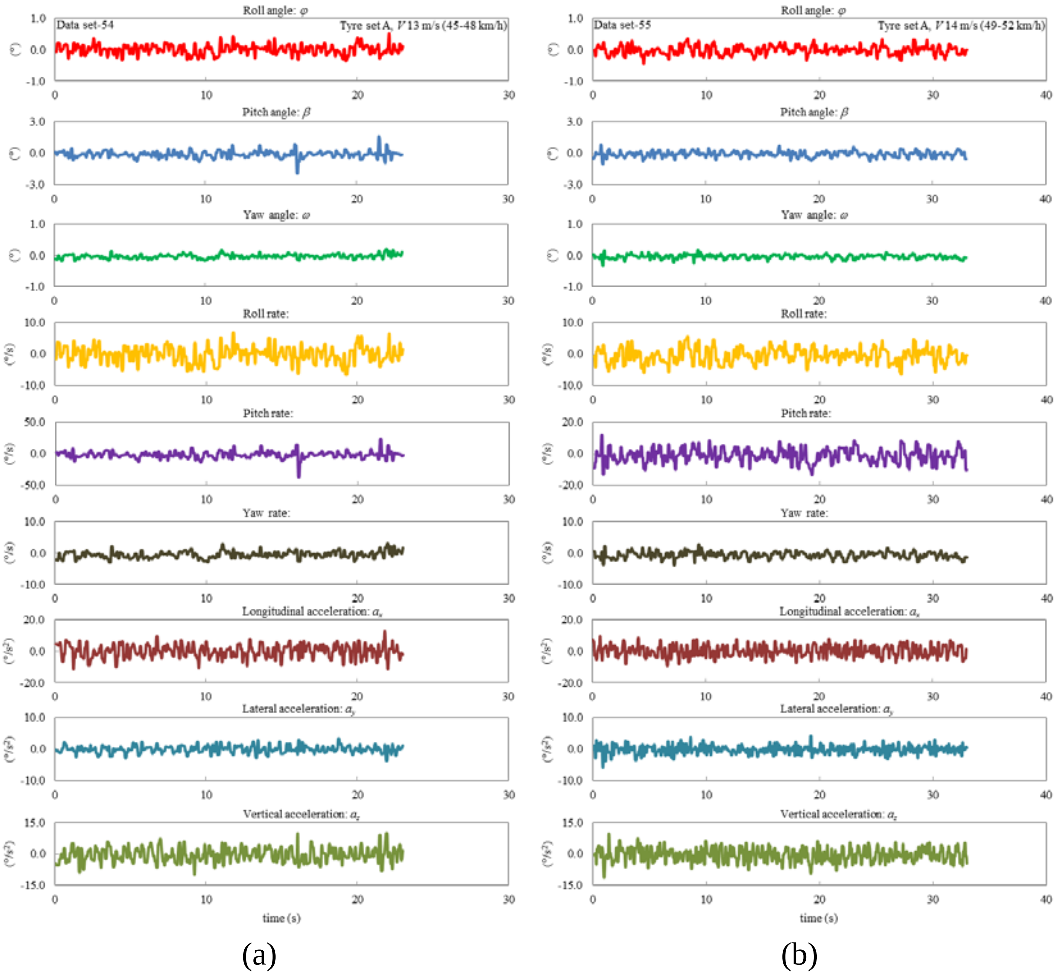

Figure B-20 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 54 and (b) Data Set 55

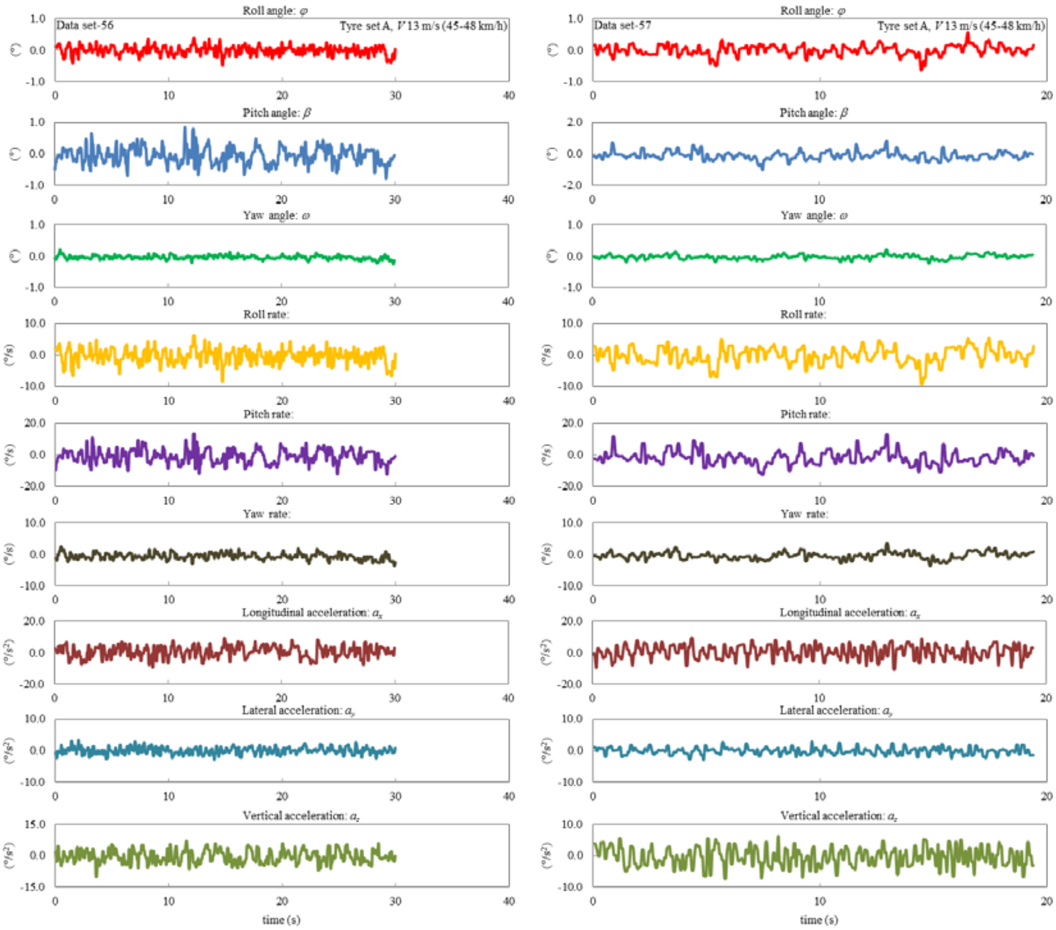

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Figure B-21 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 56 and (b) Data Set 57

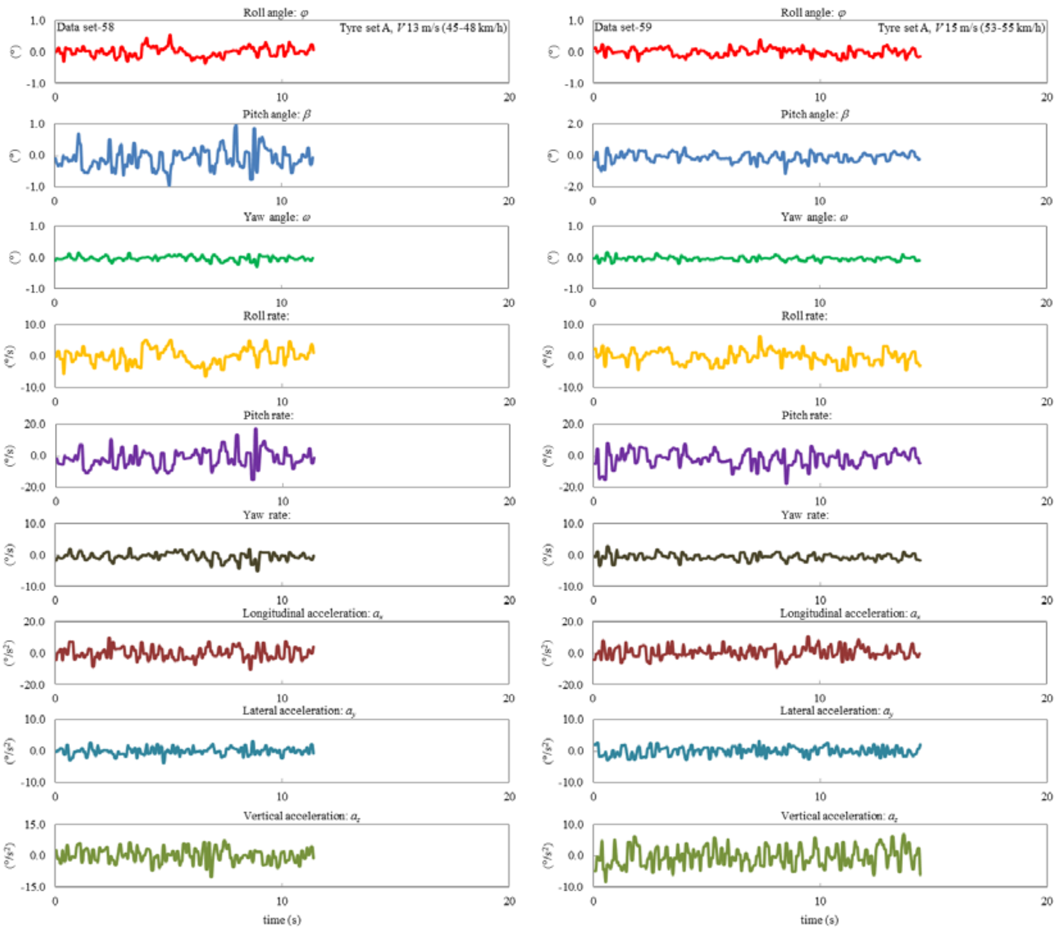

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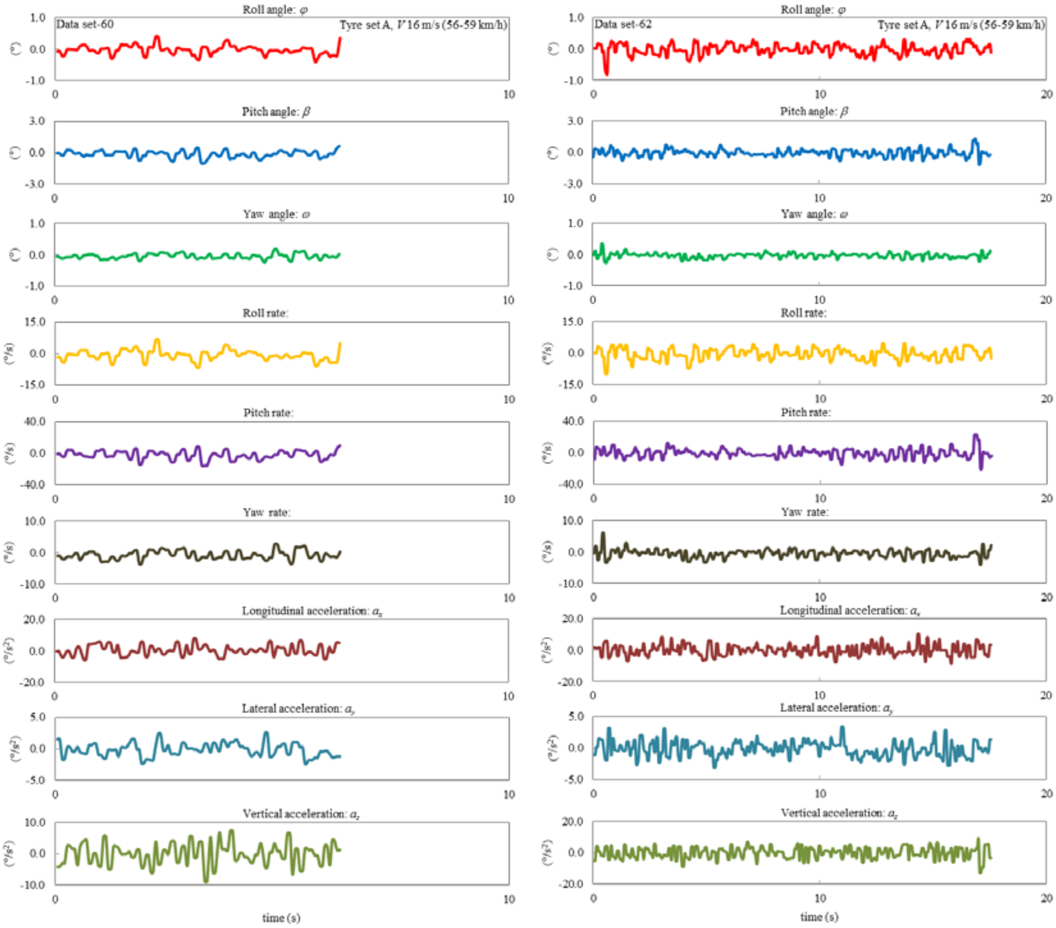
Figure B-22 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 58 and (b) Data Set 59



(a) (b)

Figure B-23 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 60 and (b) Data Set 62

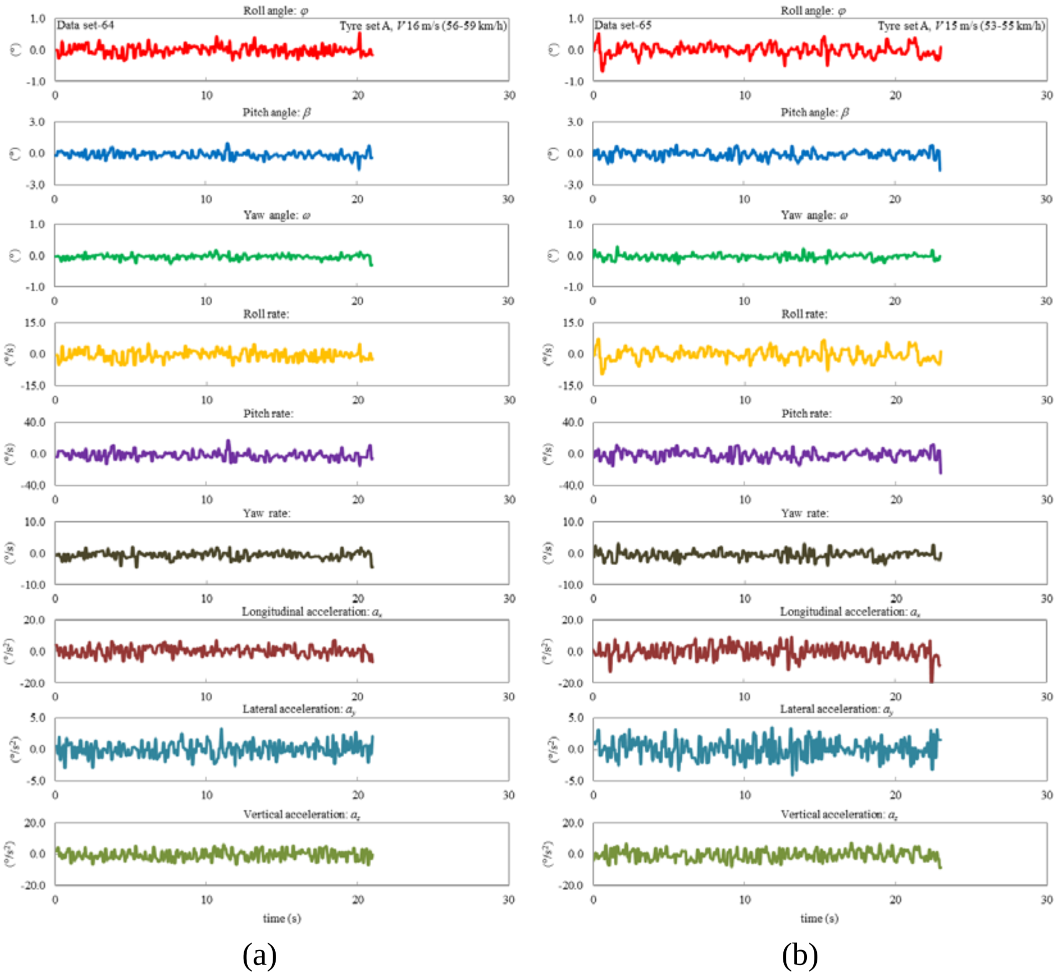


Figure B-24 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 64 and (b) Data Set 65

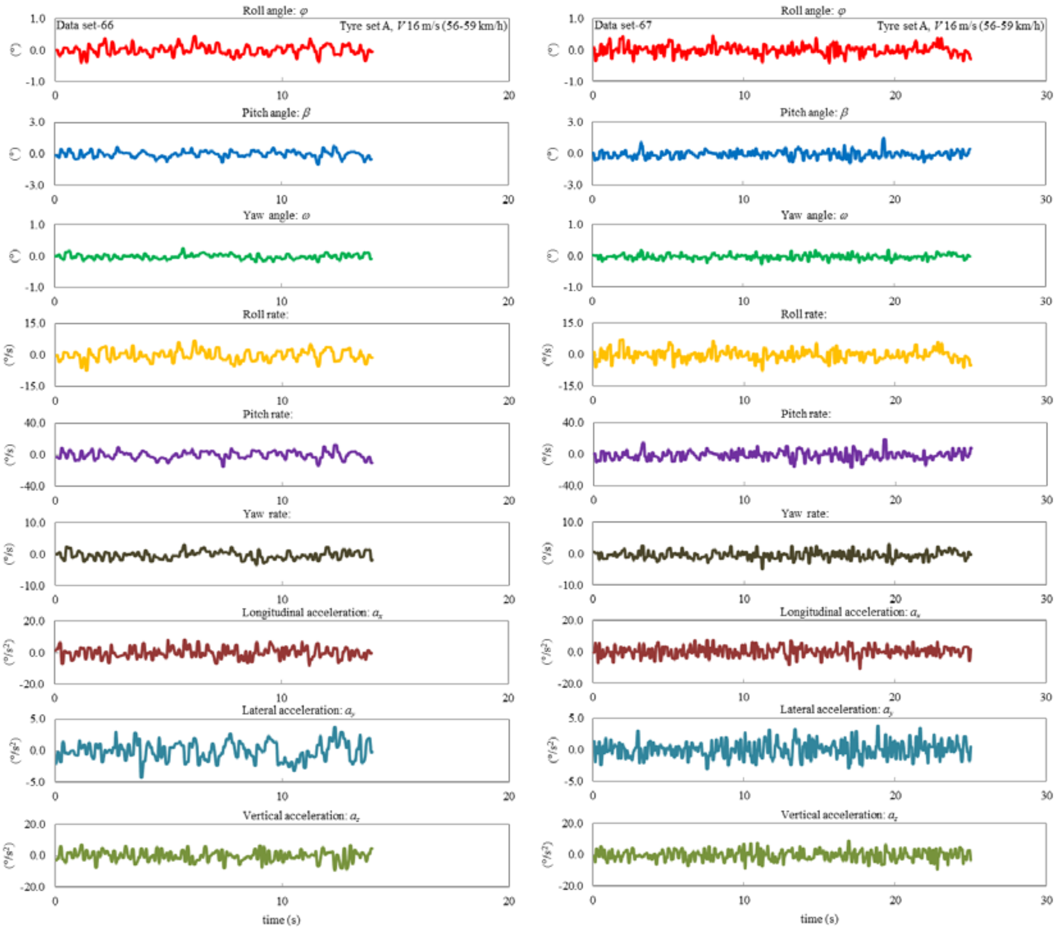


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Figure B-25 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 66 and (b) Data Set 67

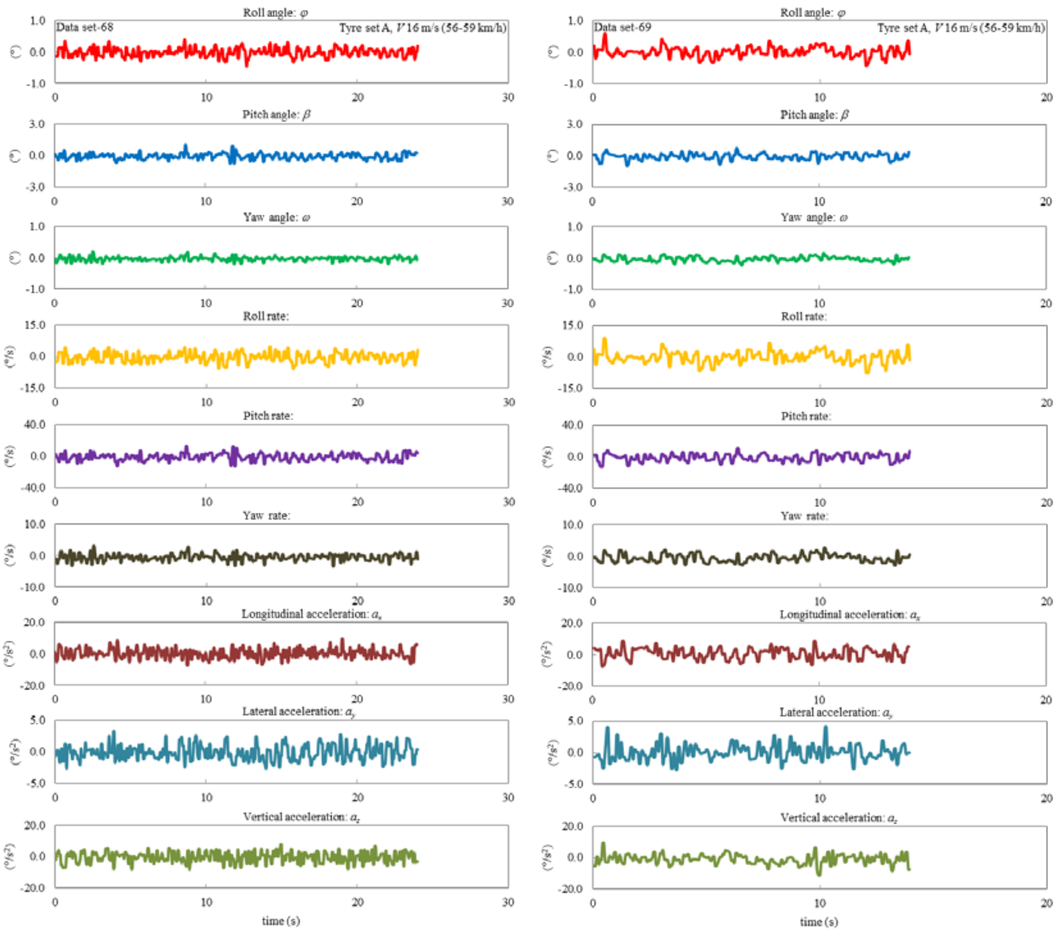

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Figure B-26 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 68 and (b) Data Set 69

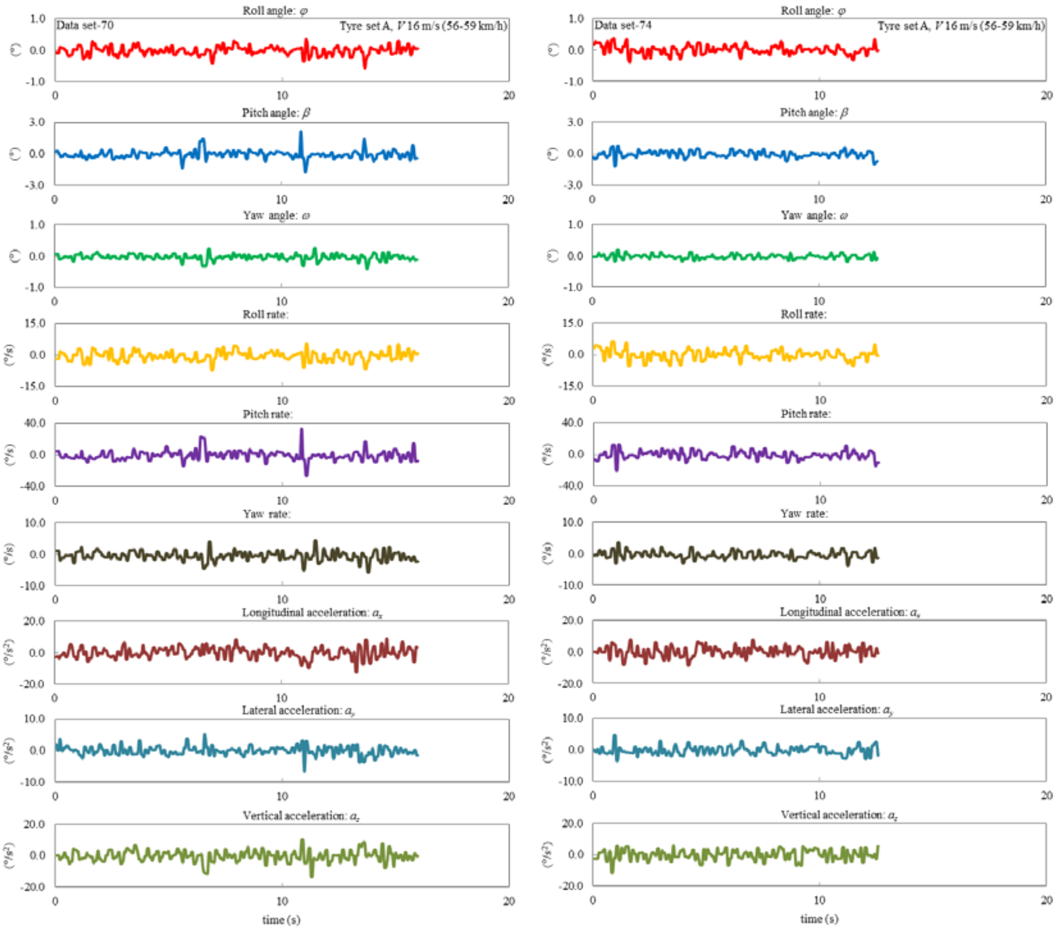

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Figure B-27 Dynamics Response Signals from Straight Run Test of Tyre Set A, (a) Data Set 70 and (b) Data Set 74

Tyre Set B

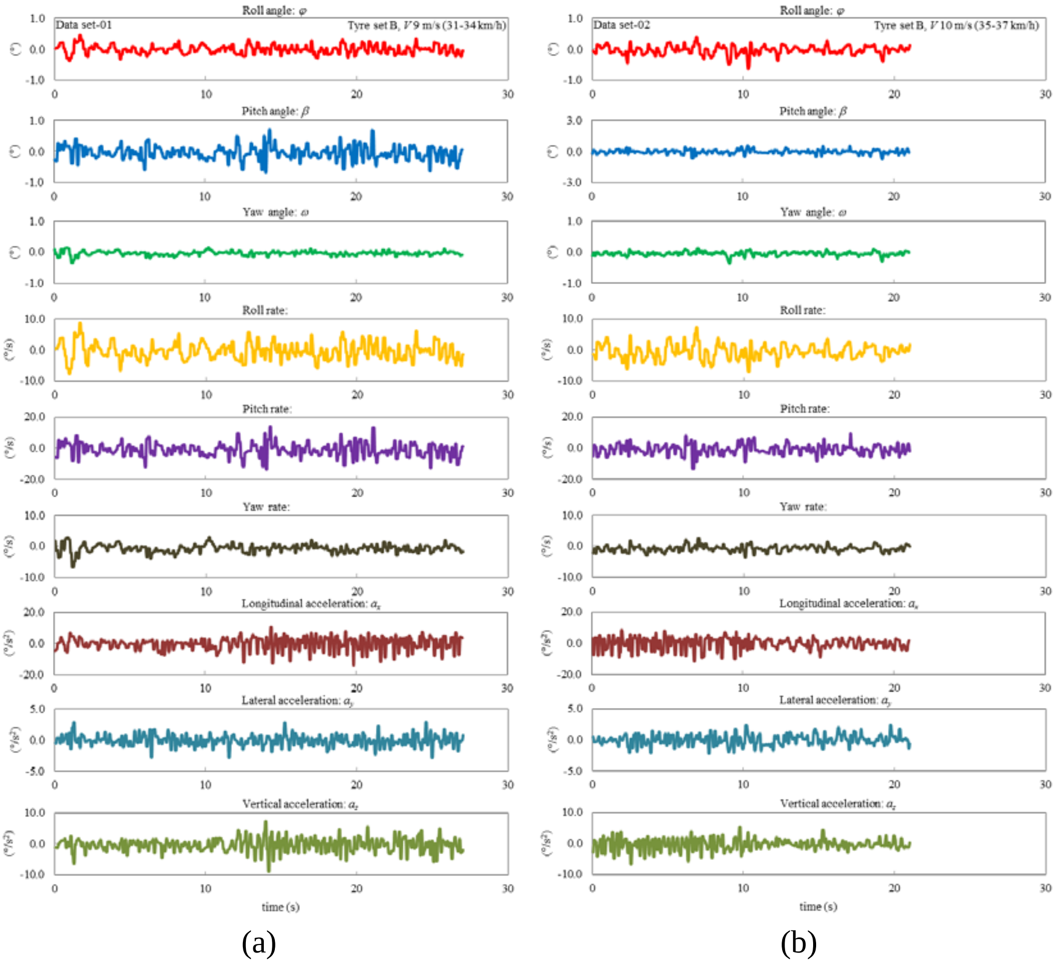

Figure B-28 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 01 and (b) Data Set 02

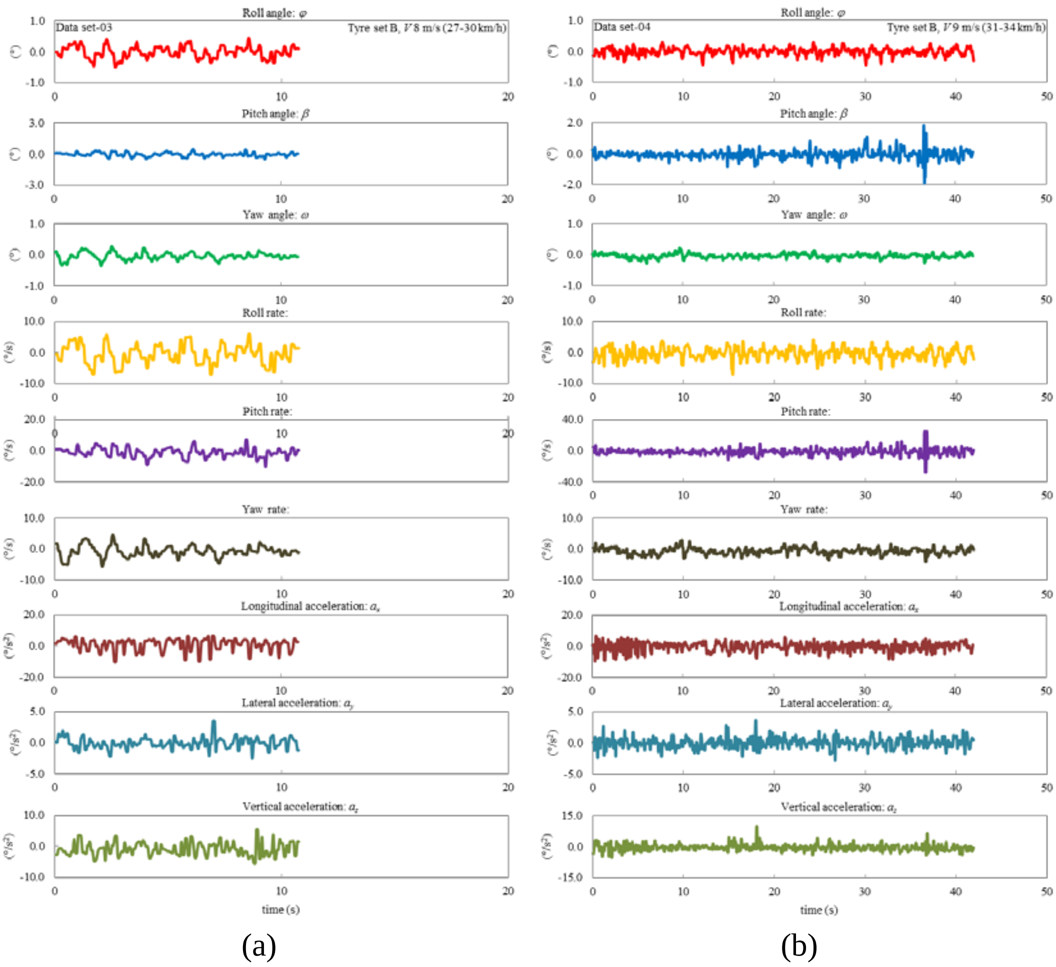

Figure B-29 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 03 and (b) Data Set 04

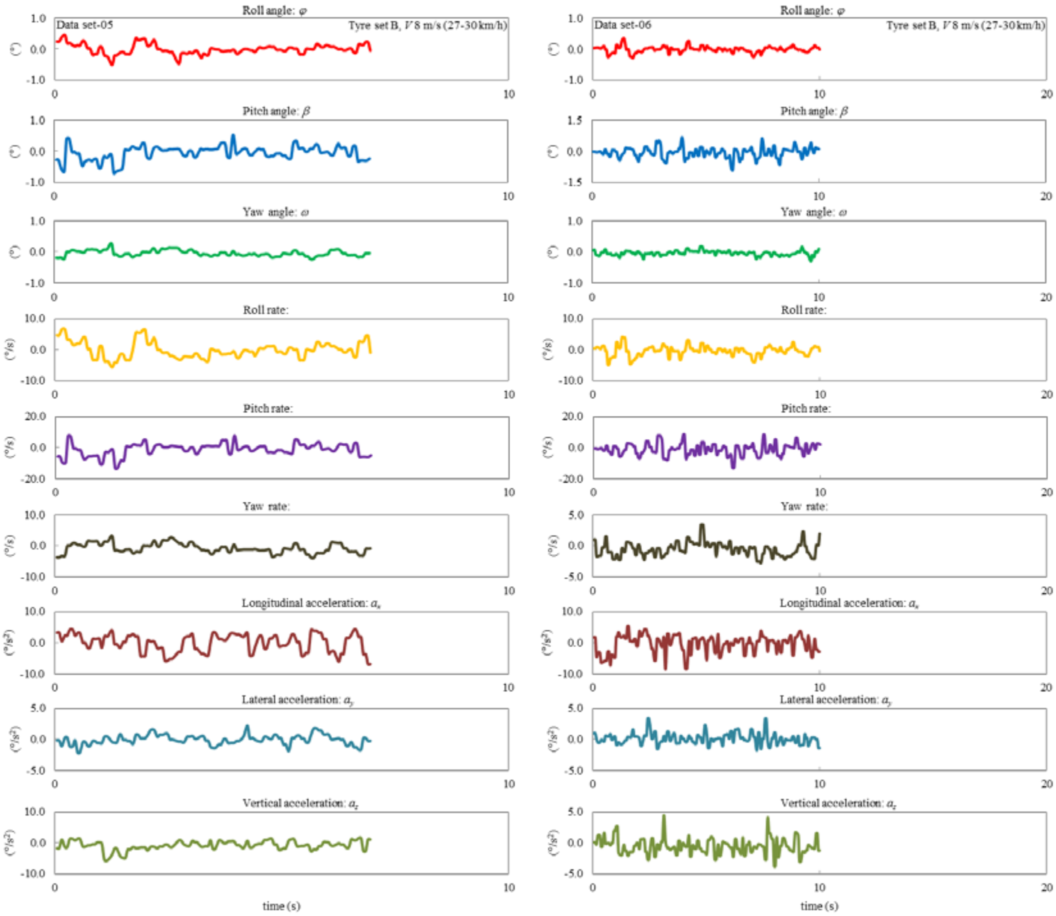

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Figure B-30 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 05 and (b) Data Set 06

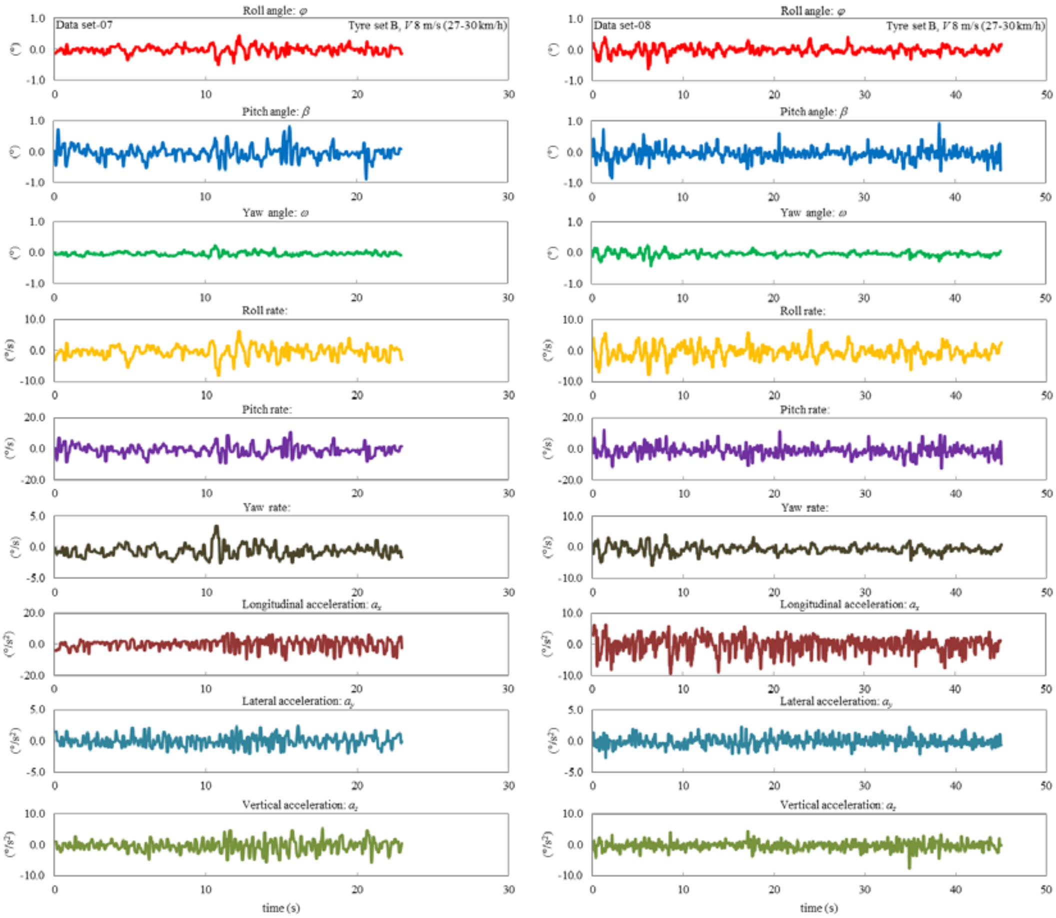

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Figure B-31 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 07 and (b) Data Set 08

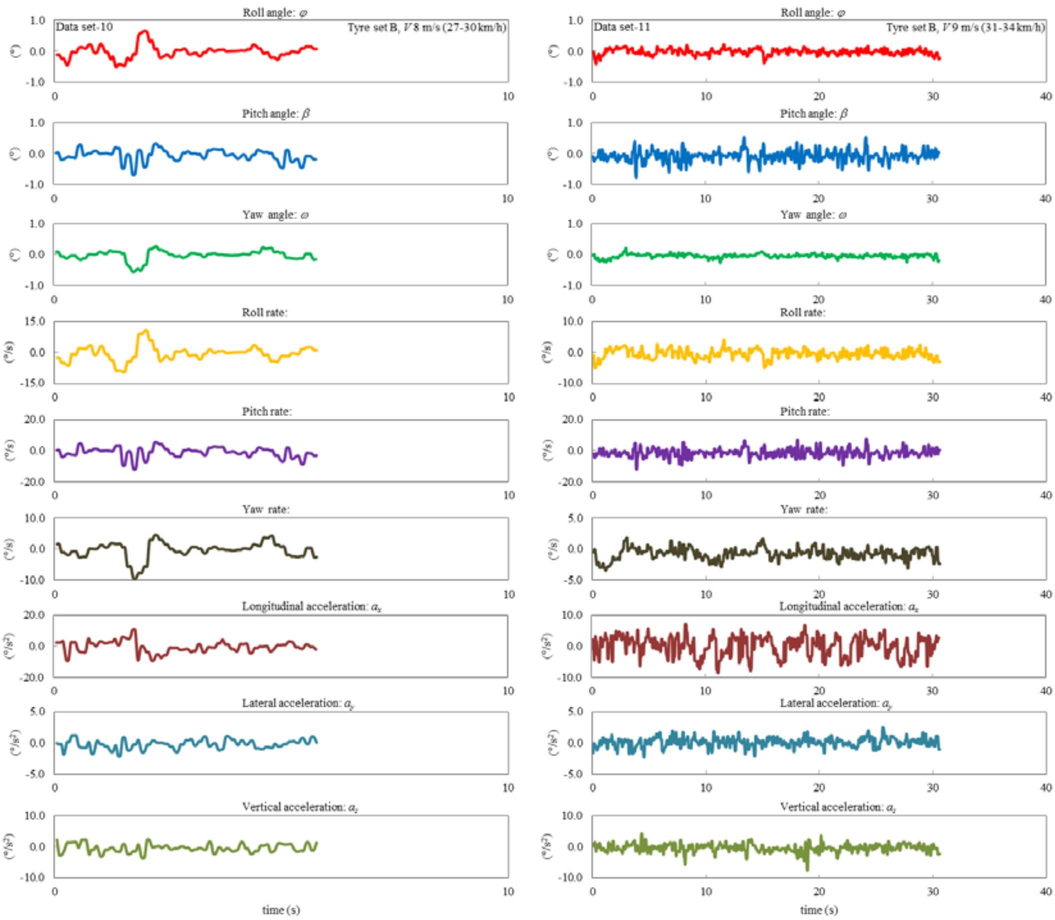

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Figure B-32 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 10 and (b) Data Set 11

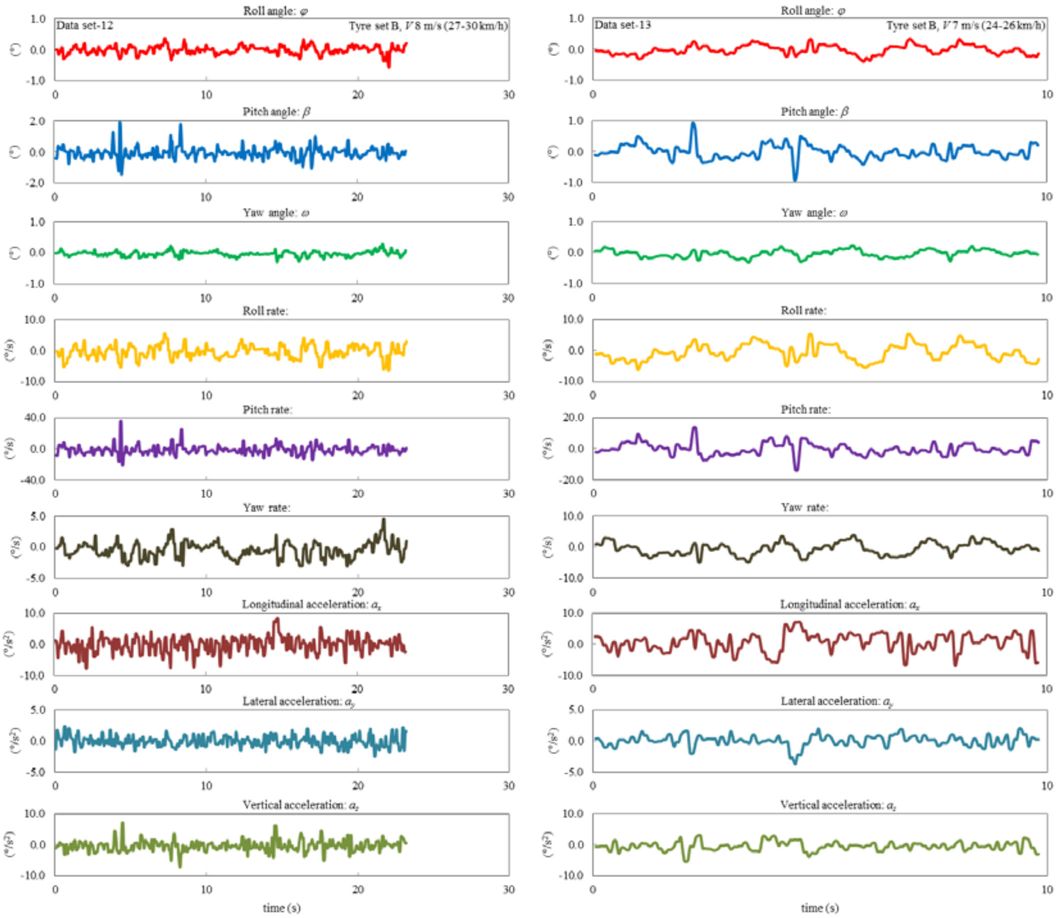

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Figure B-33 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 12 and (b) Data Set 13

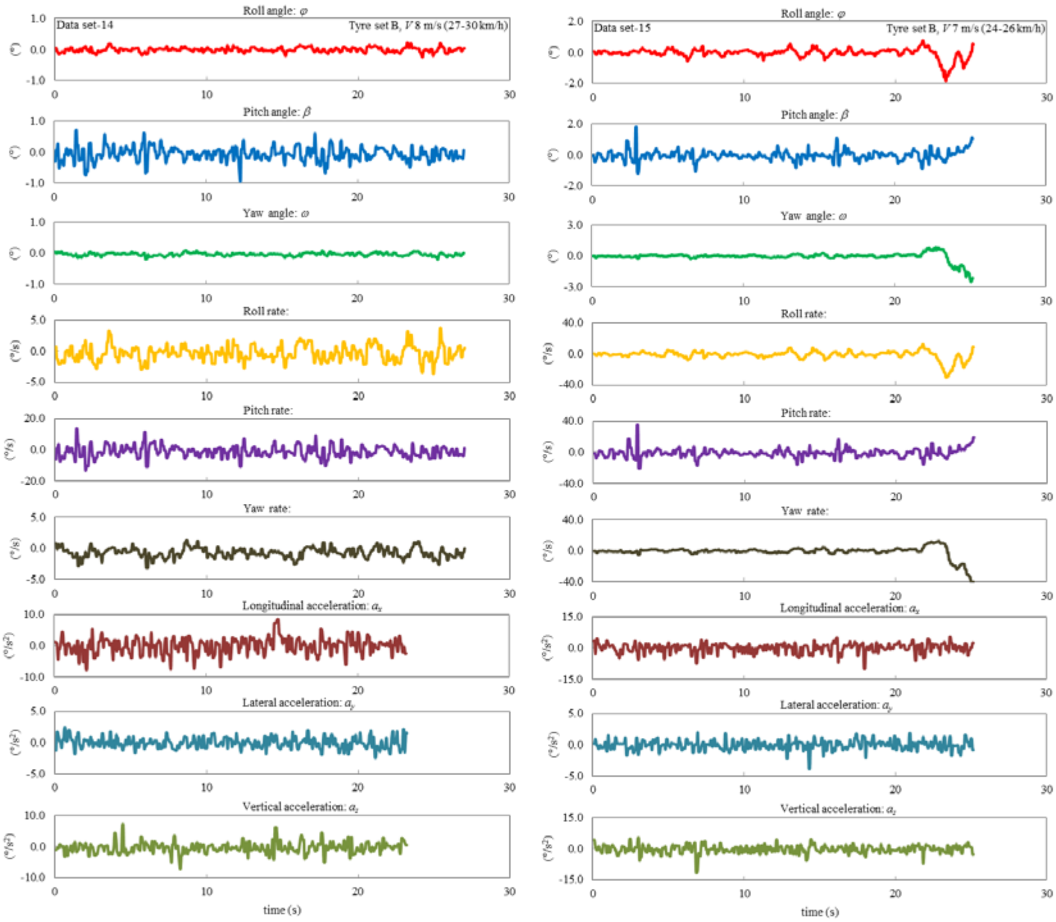

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Figure B-34 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 14 and (b) Data Set 15

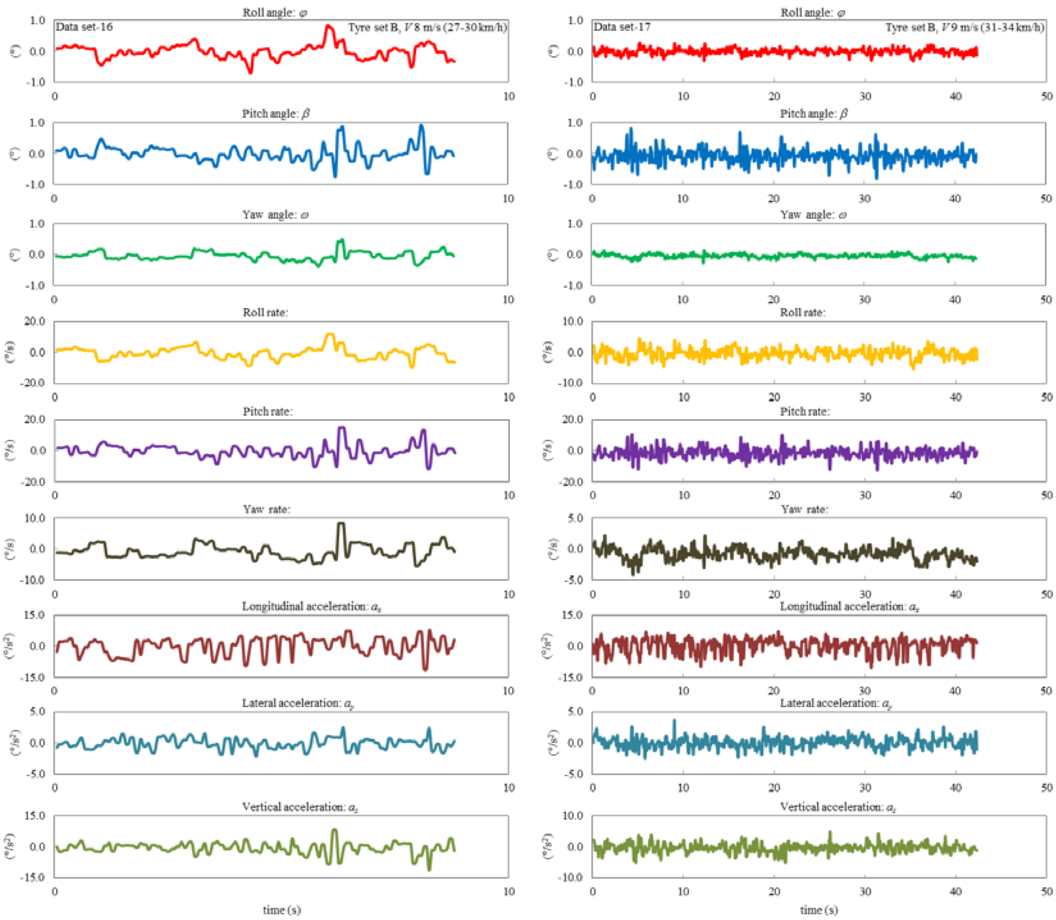

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Figure B-35 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 16 and (b) Data Set 17

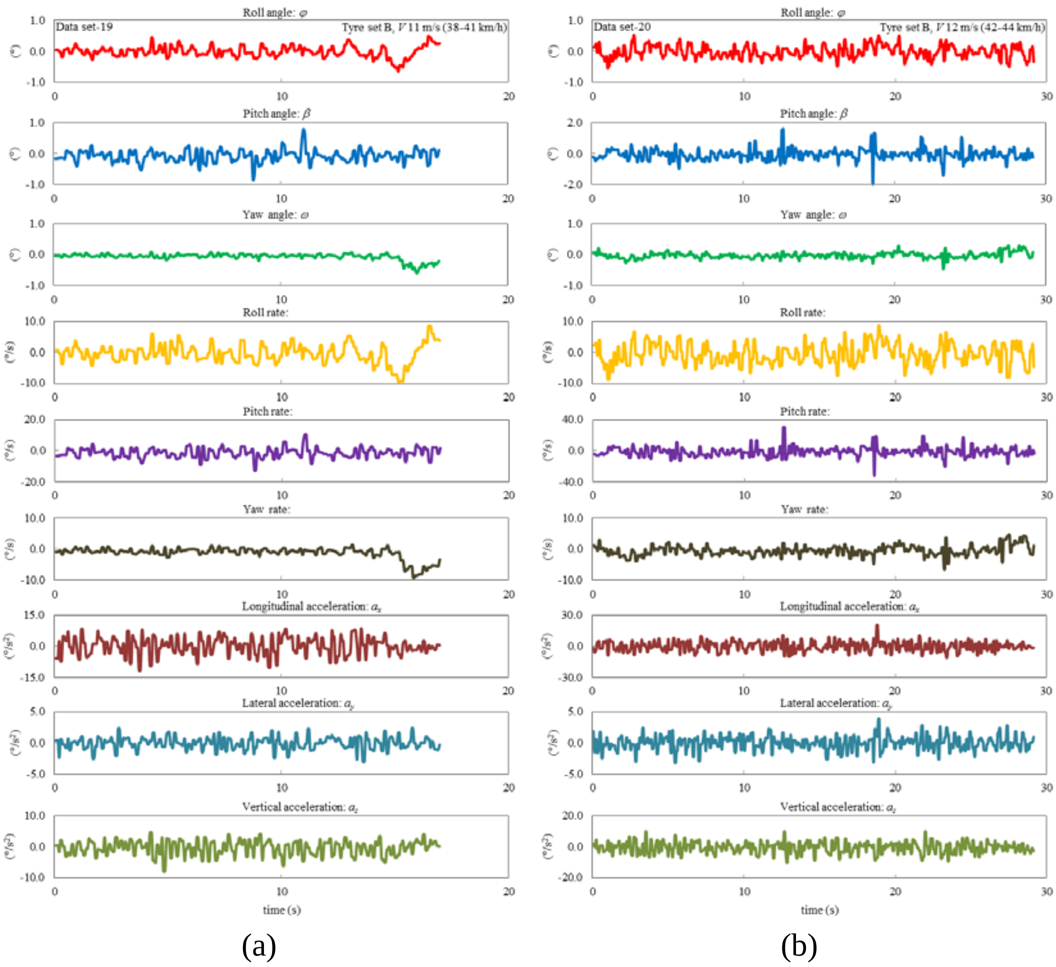

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Figure B-36 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 19 and (b) Data Set 20

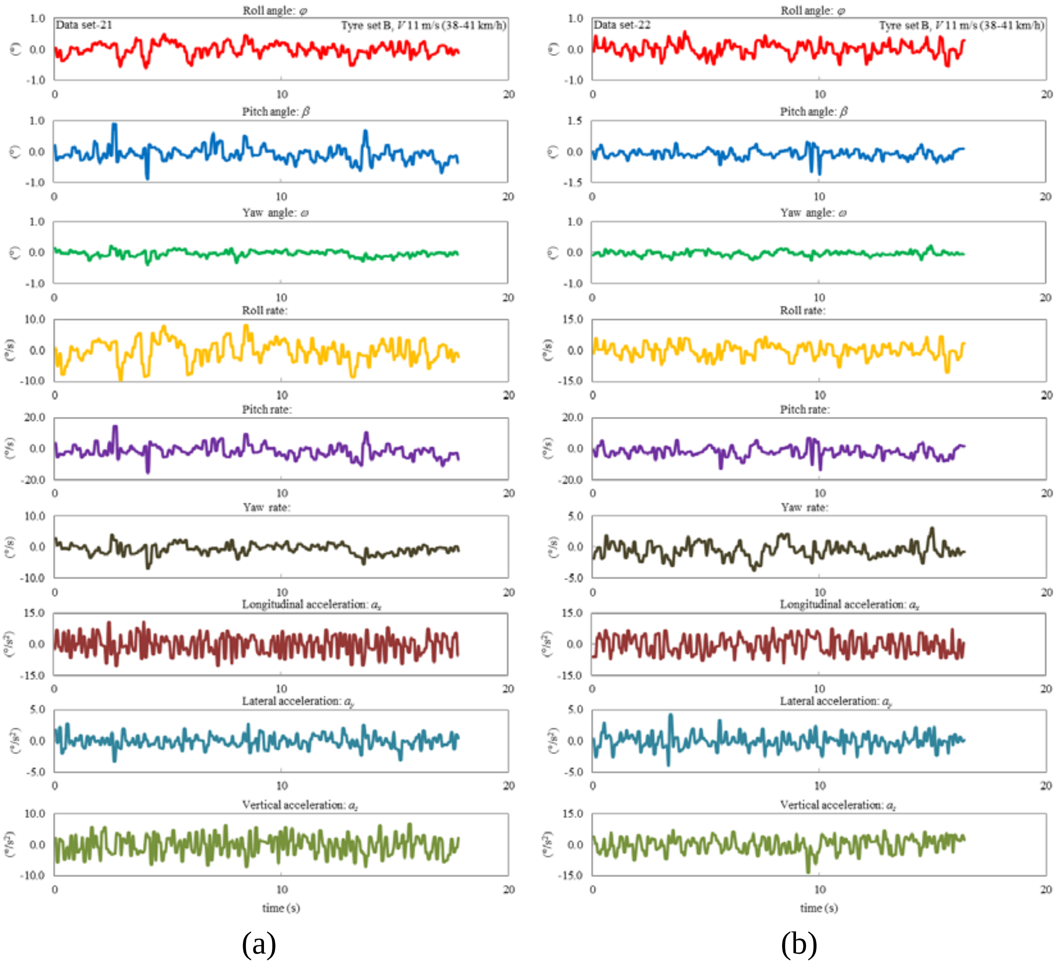

Figure B-37 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 21 and (b) Data Set 22

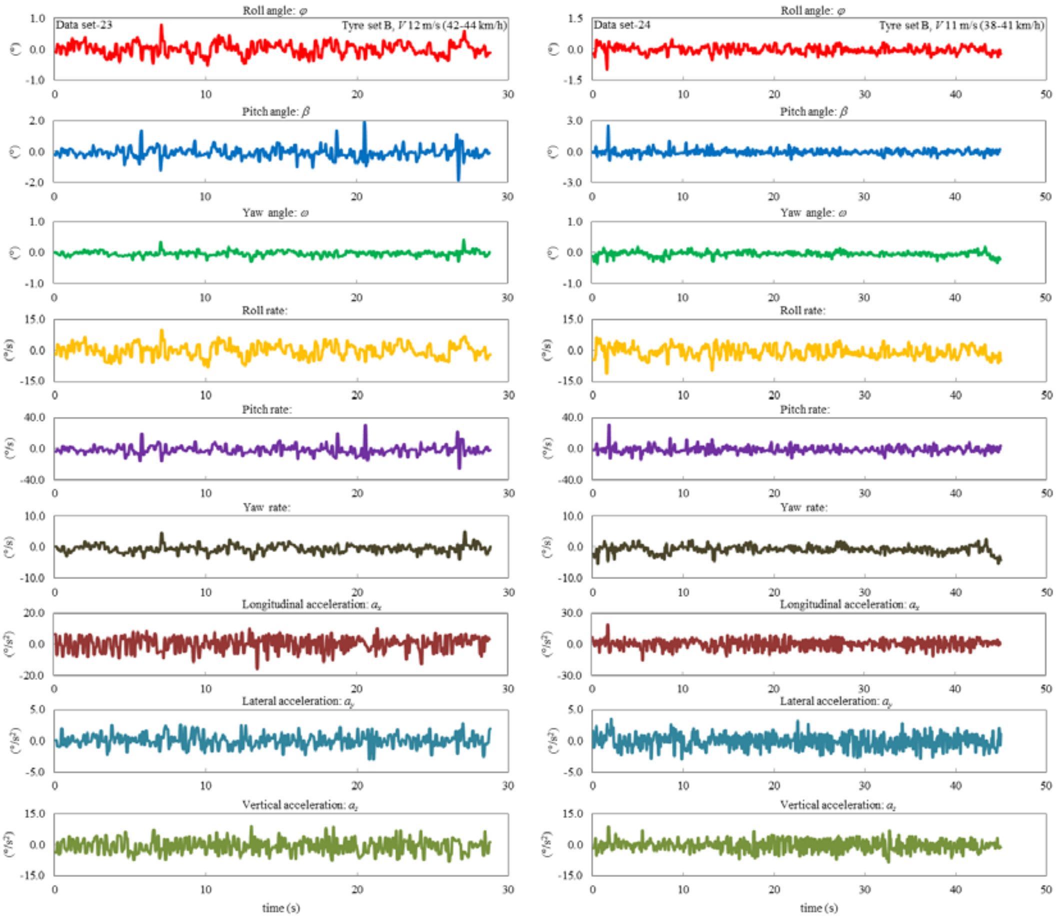

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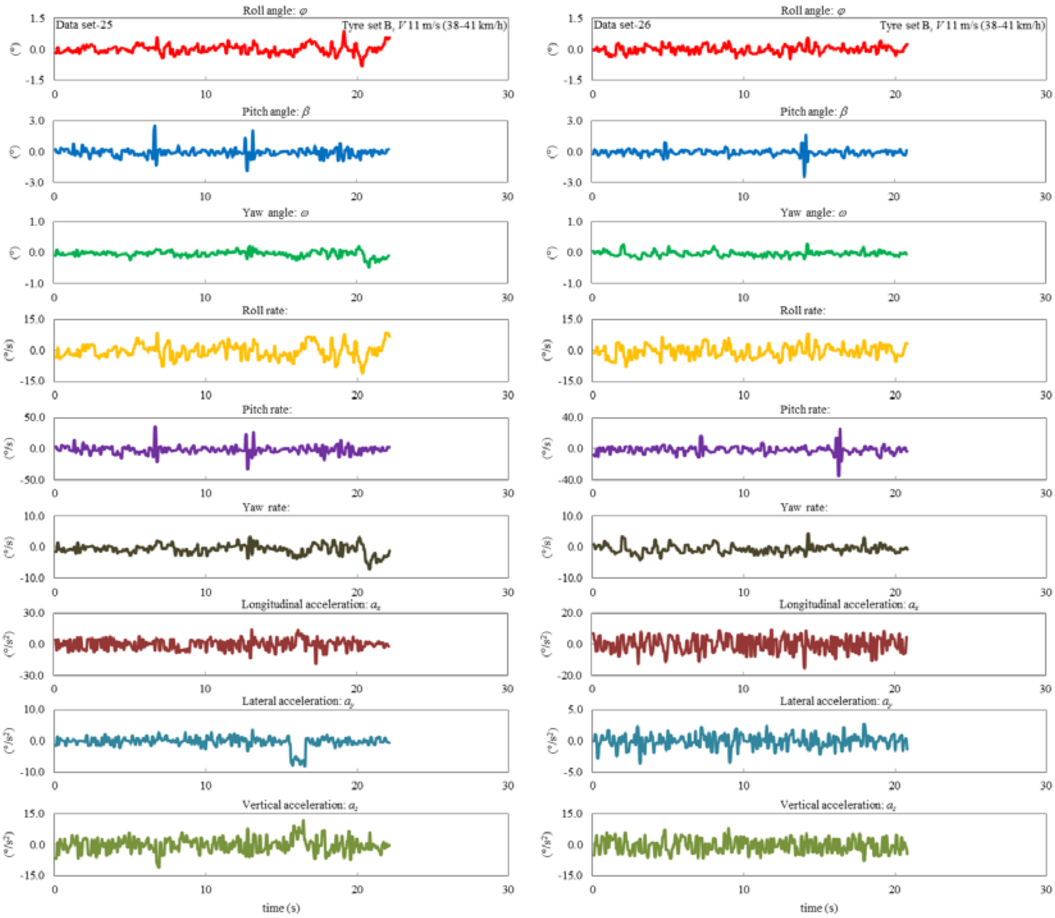
Figure B-38 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 23 and (b) Data Set 24



(a) (b)

Figure B-39 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 25 and (b) Data Set 26

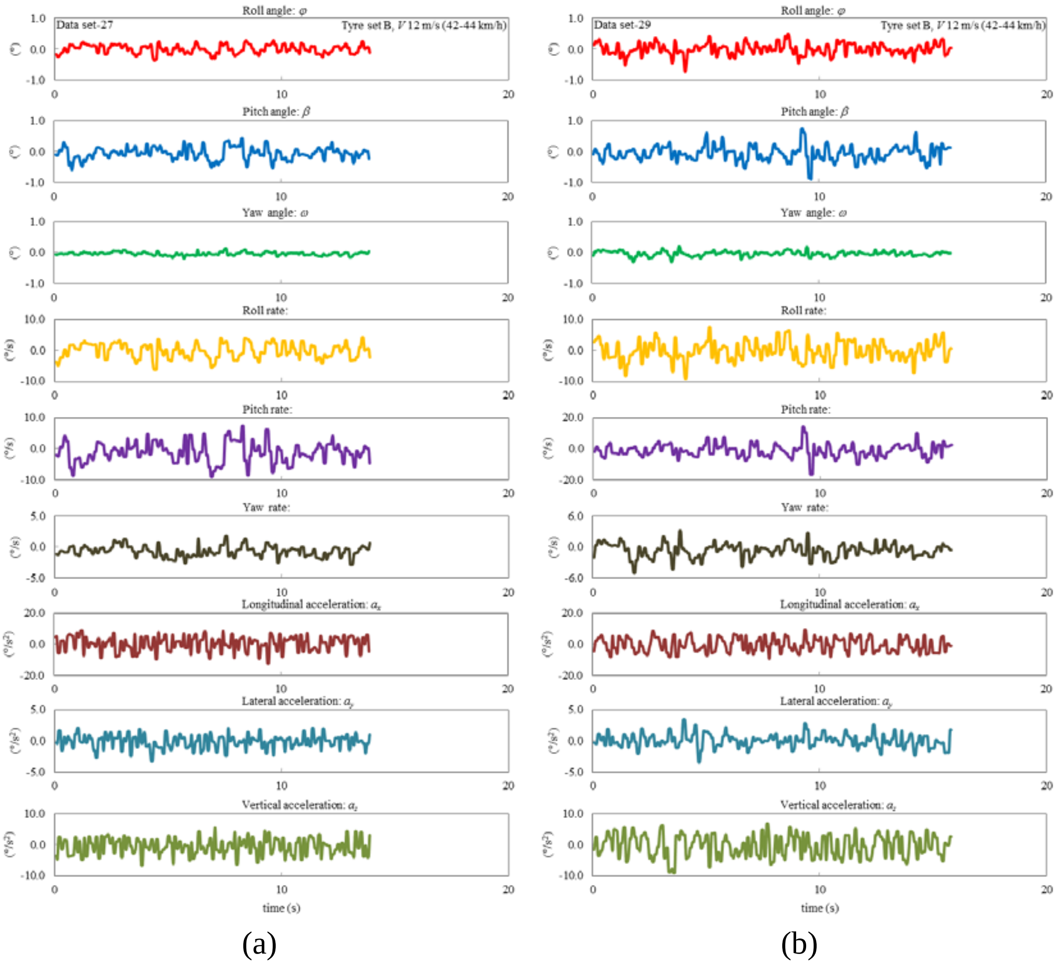


Figure B-40 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 27 and (b) Data Set 29

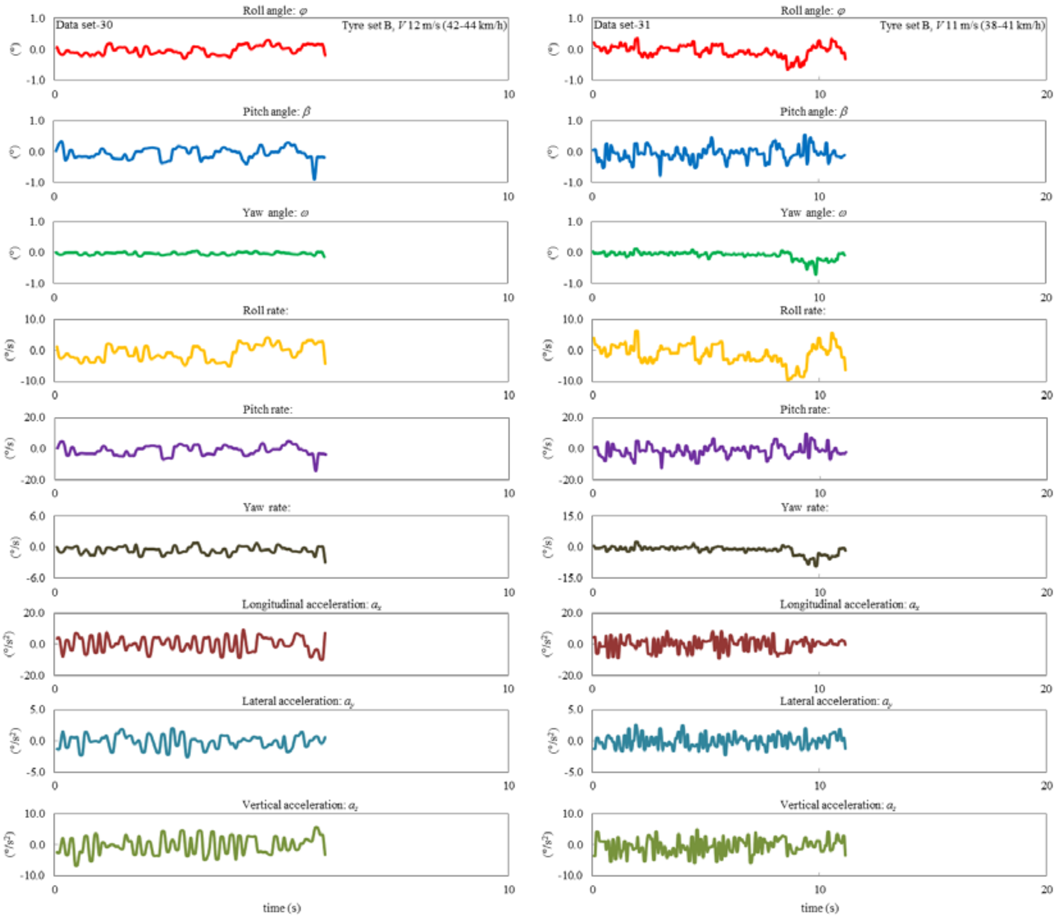


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Figure B-41 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 30 and (b) Data Set 31

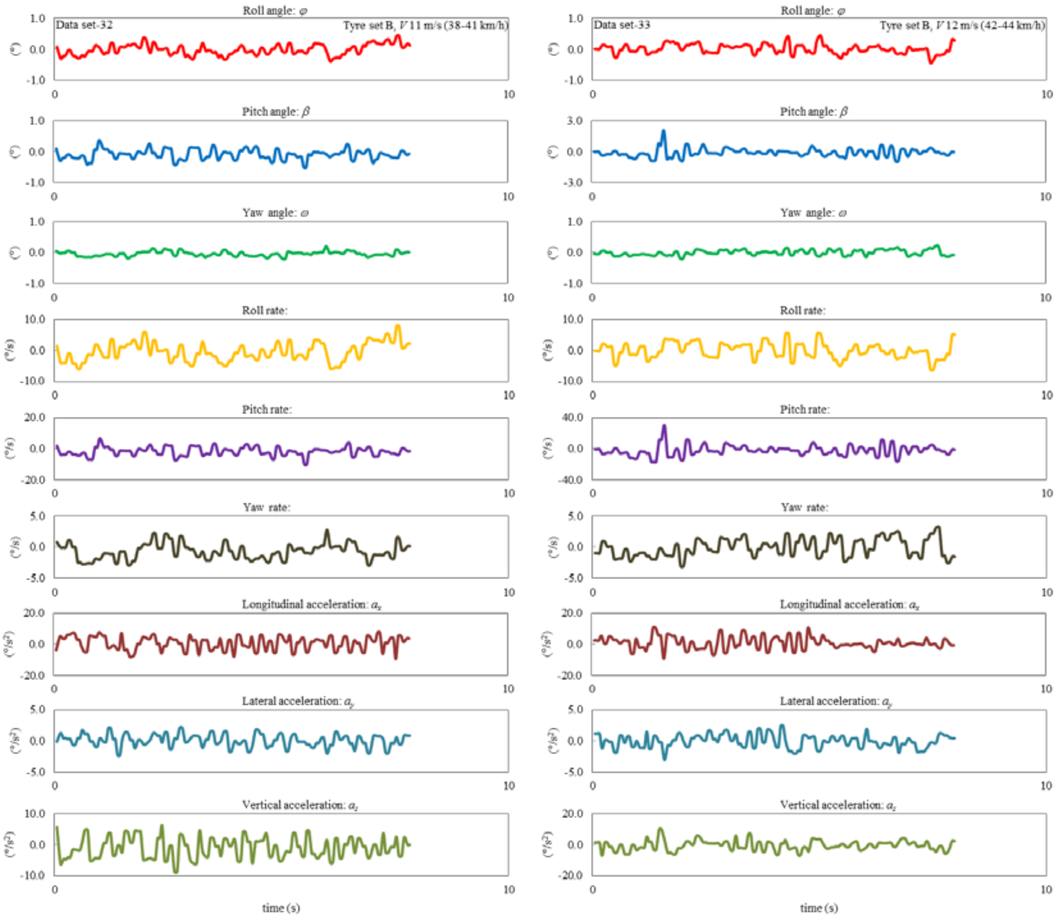

Figure B-42 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 32 and (b) Data Set 33

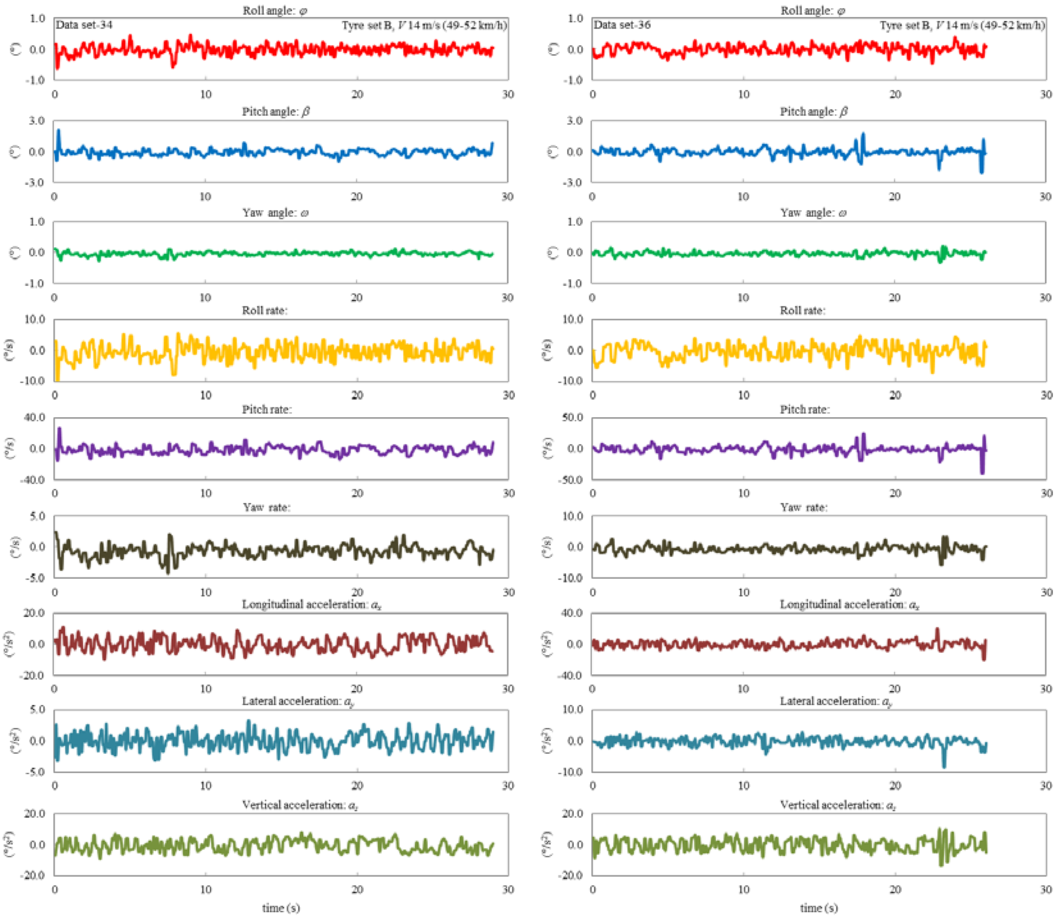

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Figure B-43 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 34 and (b) Data Set 36

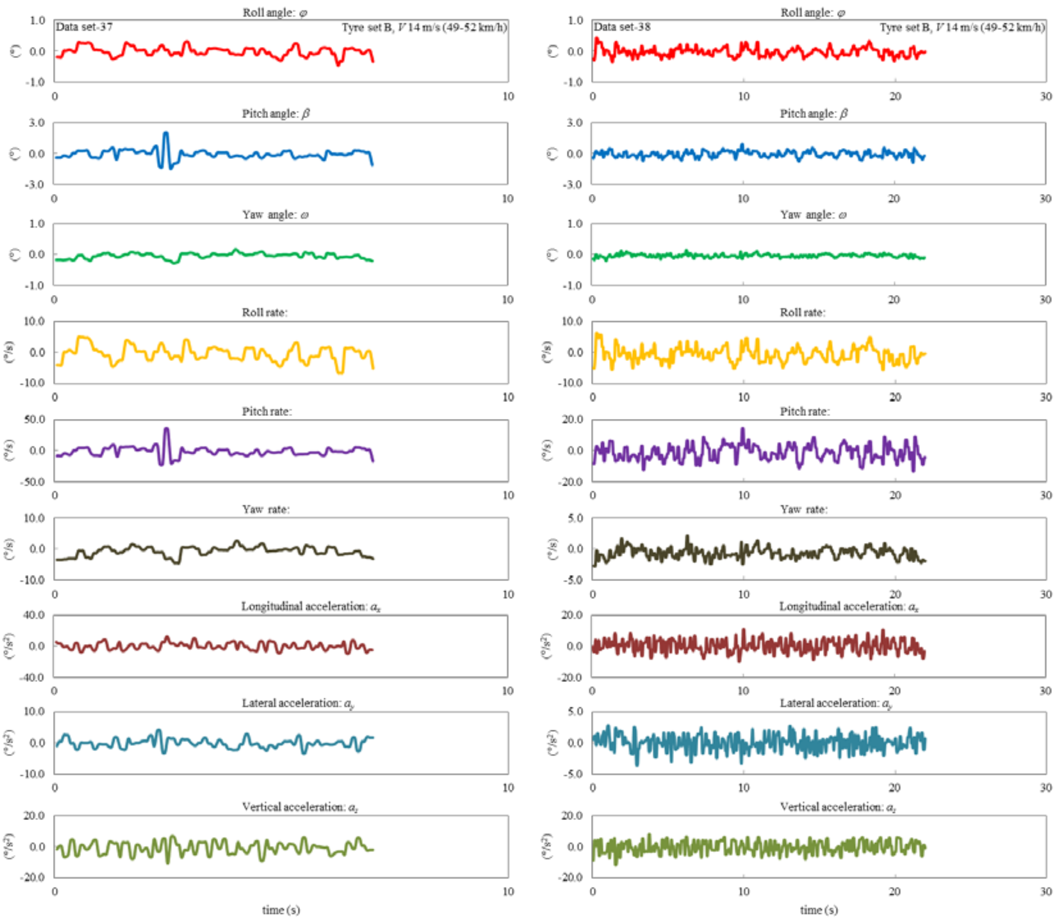

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Figure B-44 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 37 and (b) Data Set 38

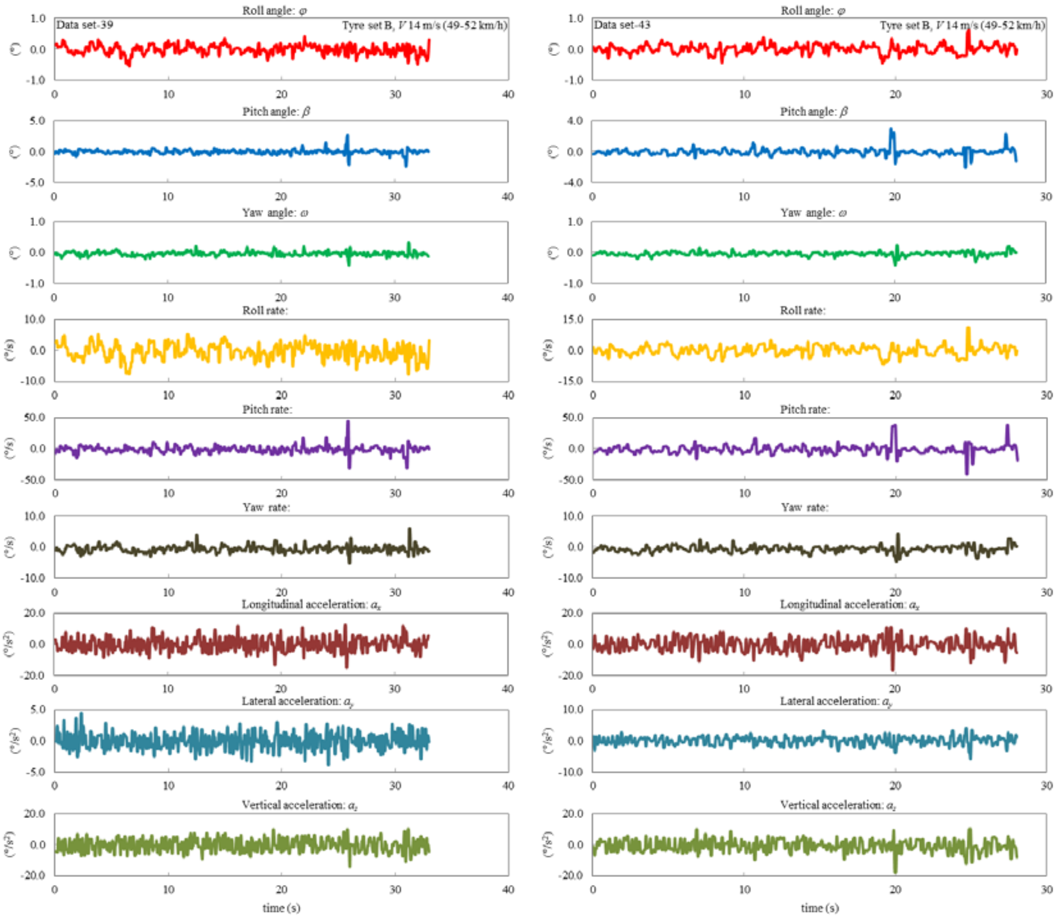

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Figure B-45 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 39 and (b) Data Set 43

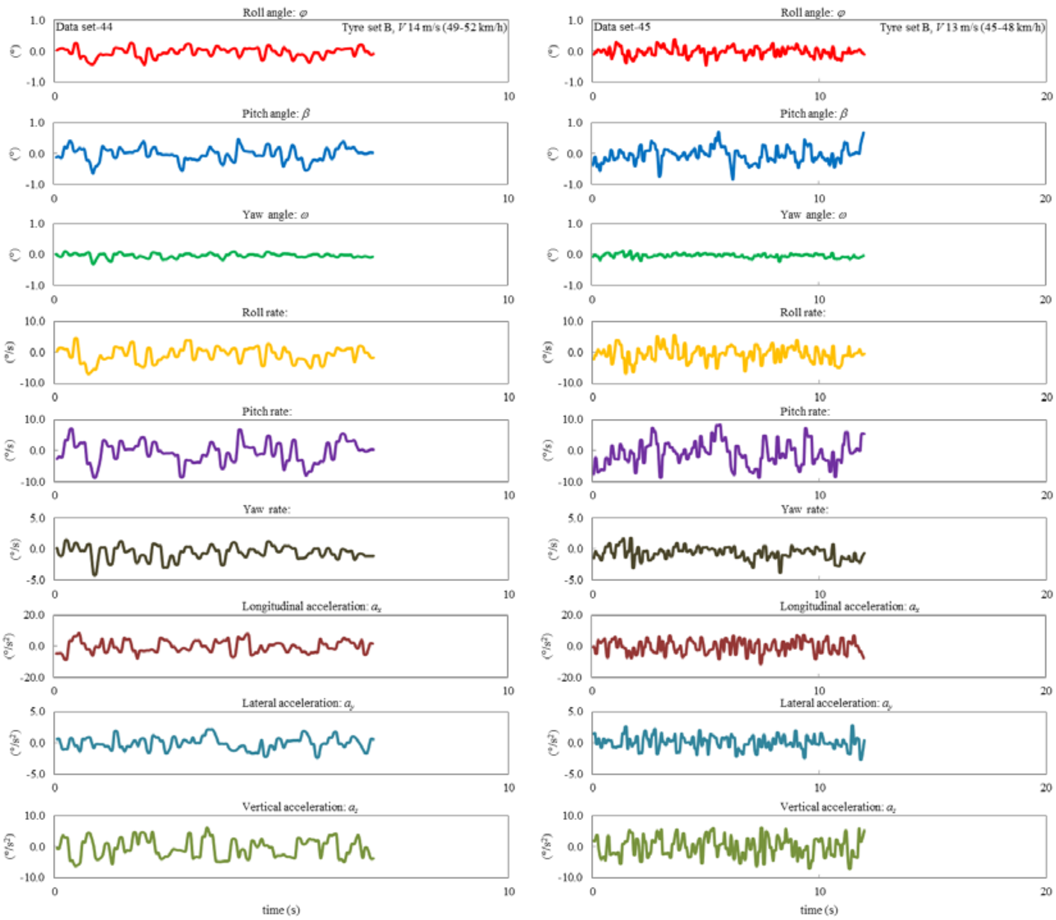

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Figure B-46 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 44 and (b) Data Set 45

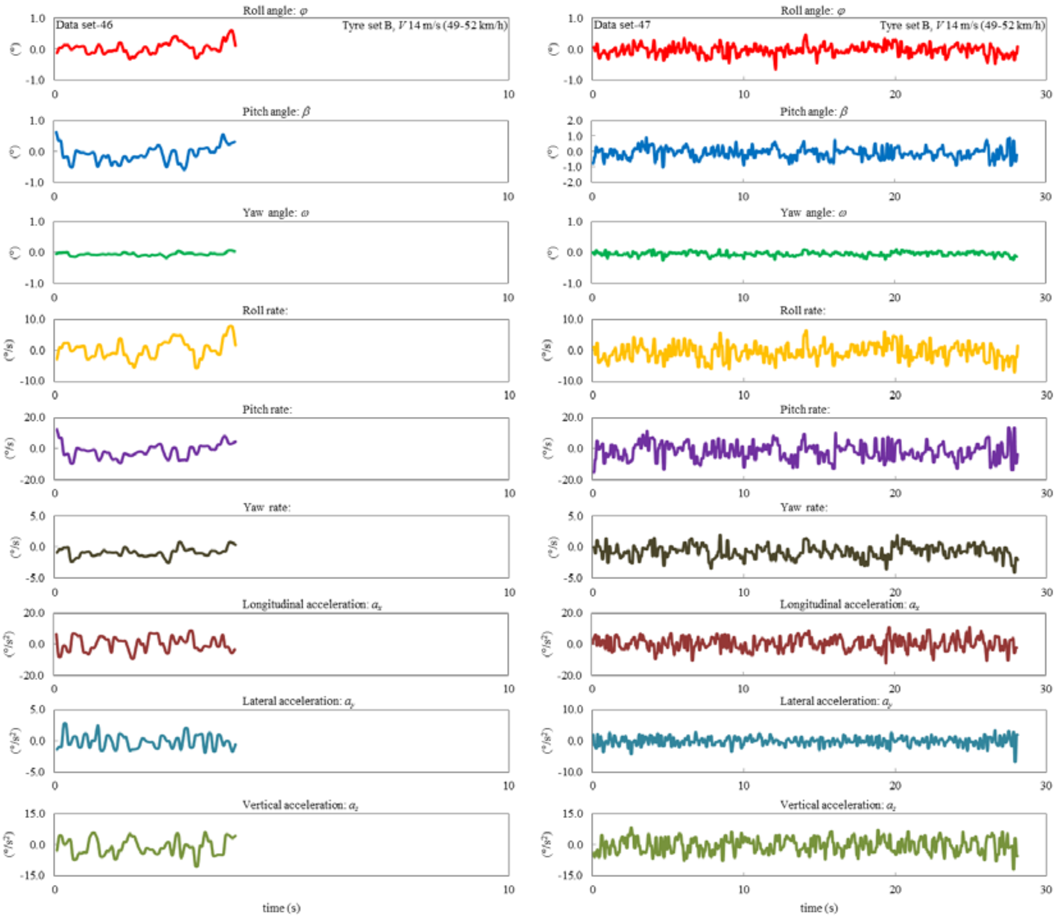

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Figure B-47 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 46 and (b) Data Set 47

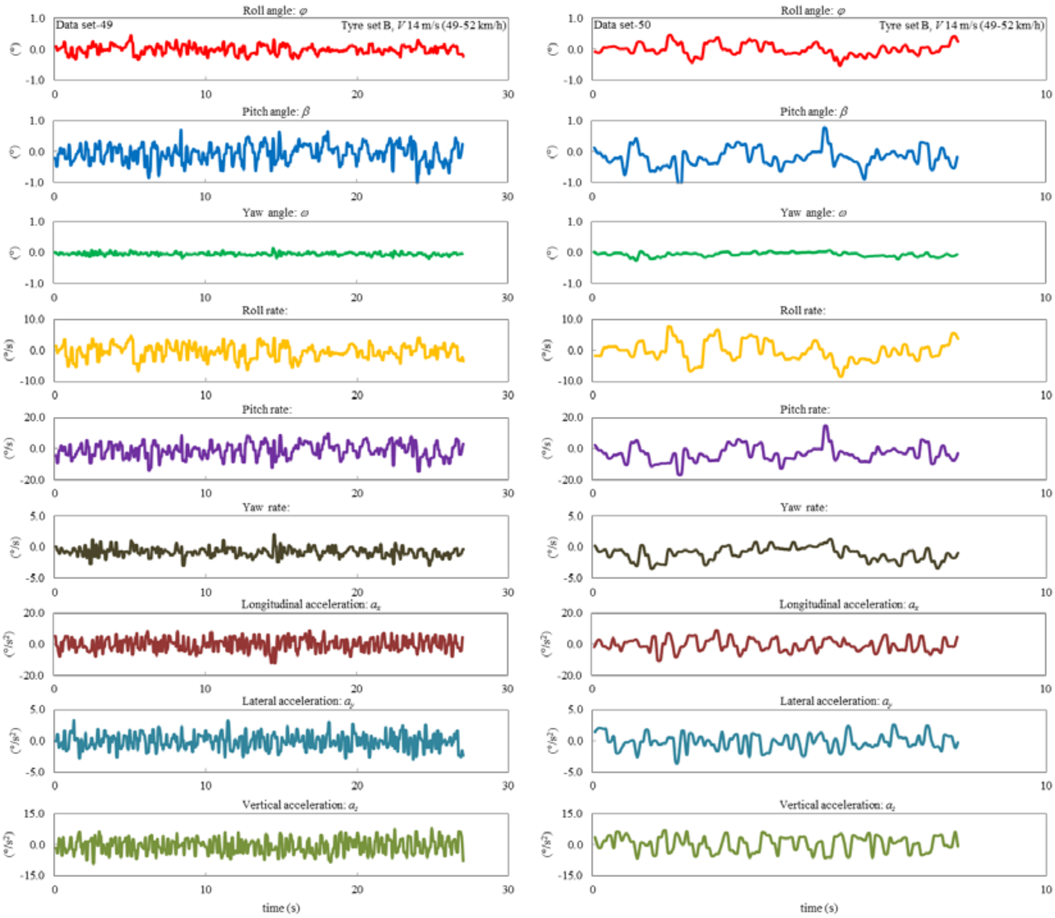

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Figure B-48 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 49 and (b) Data Set 50

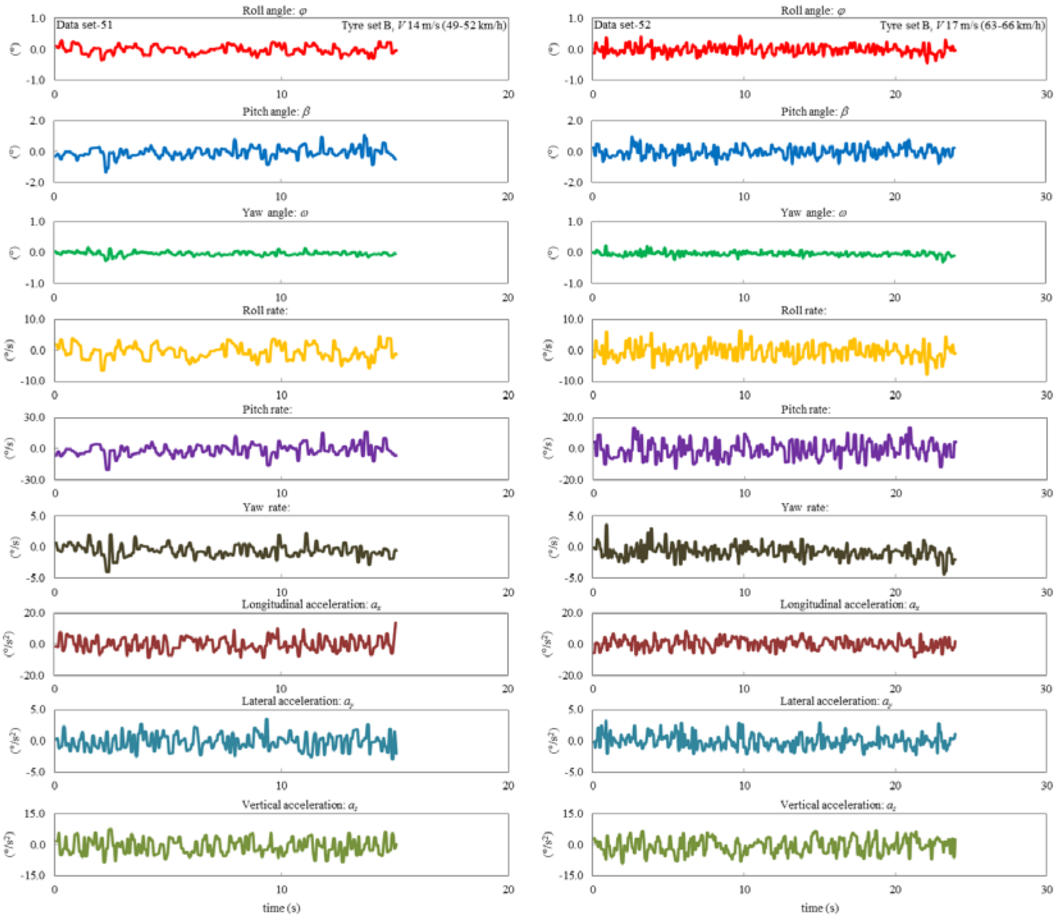

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Figure B-49 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 51 and (b) Data Set 52

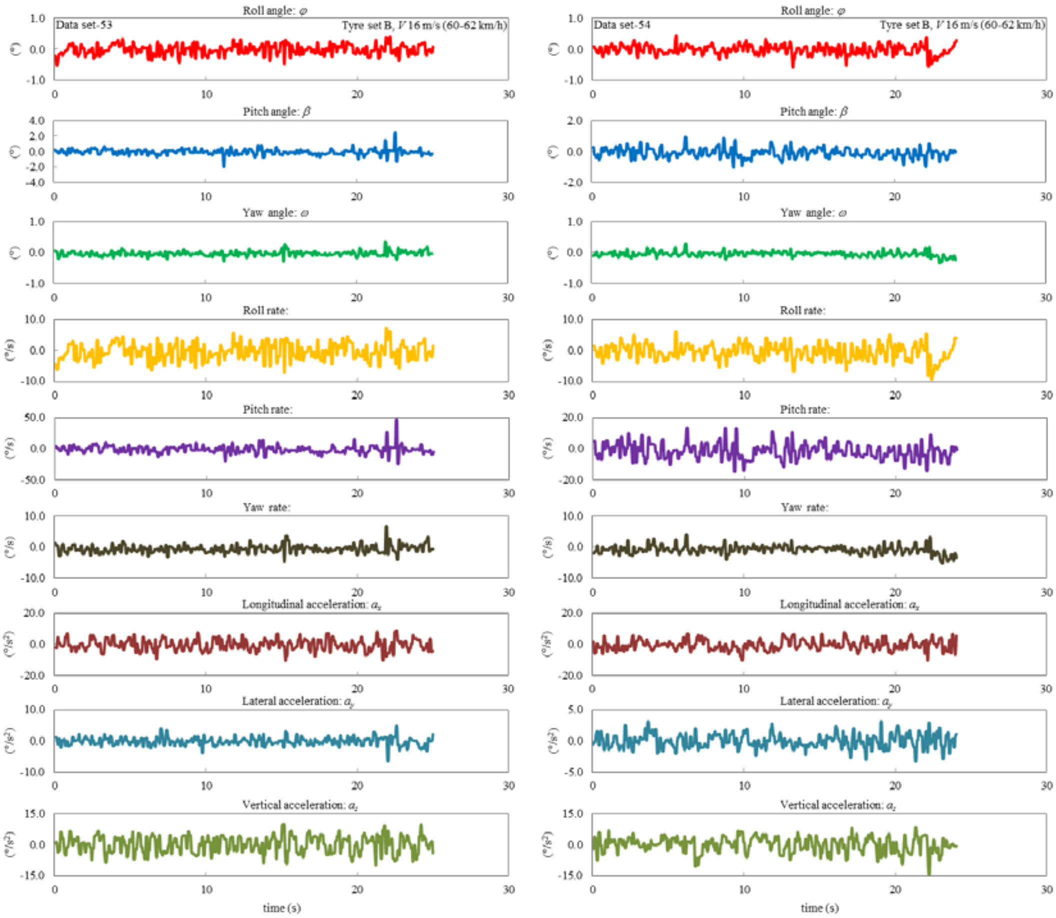

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Figure B-50 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 53 and (b) Data Set 54

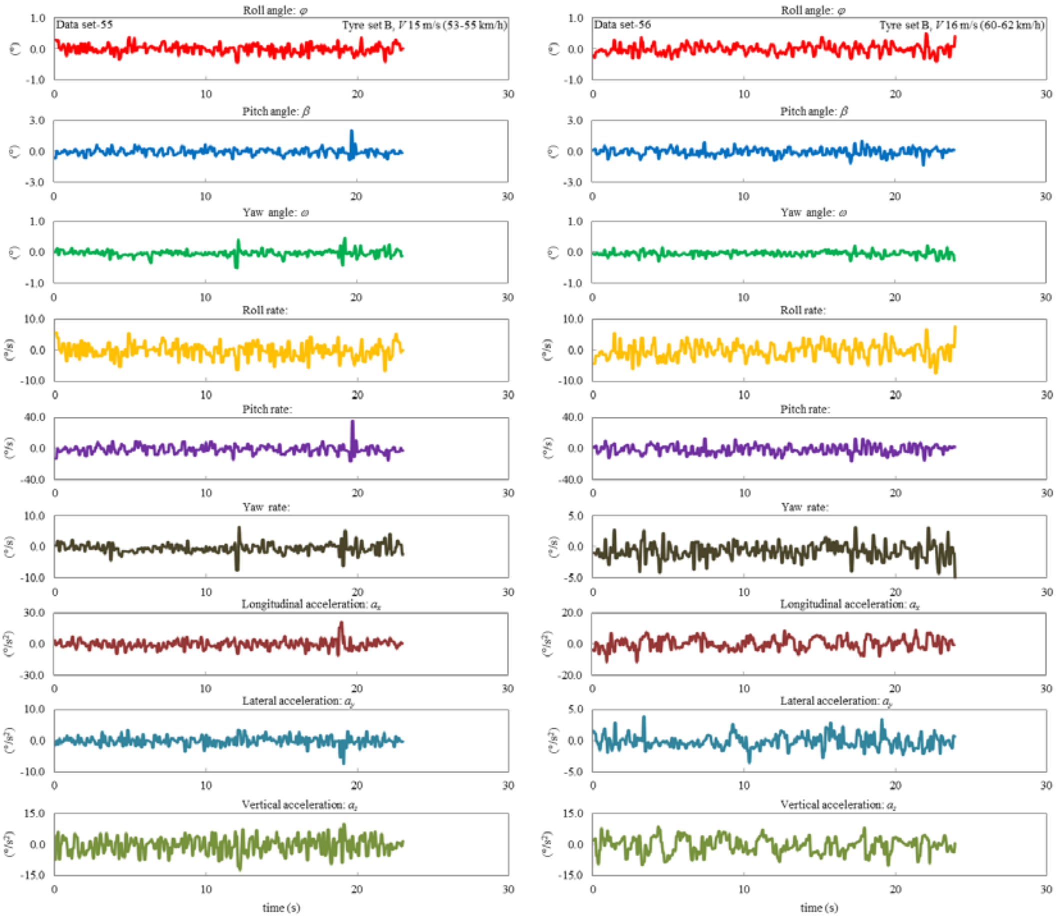

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Figure B-51 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 55 and (b) Data Set 56

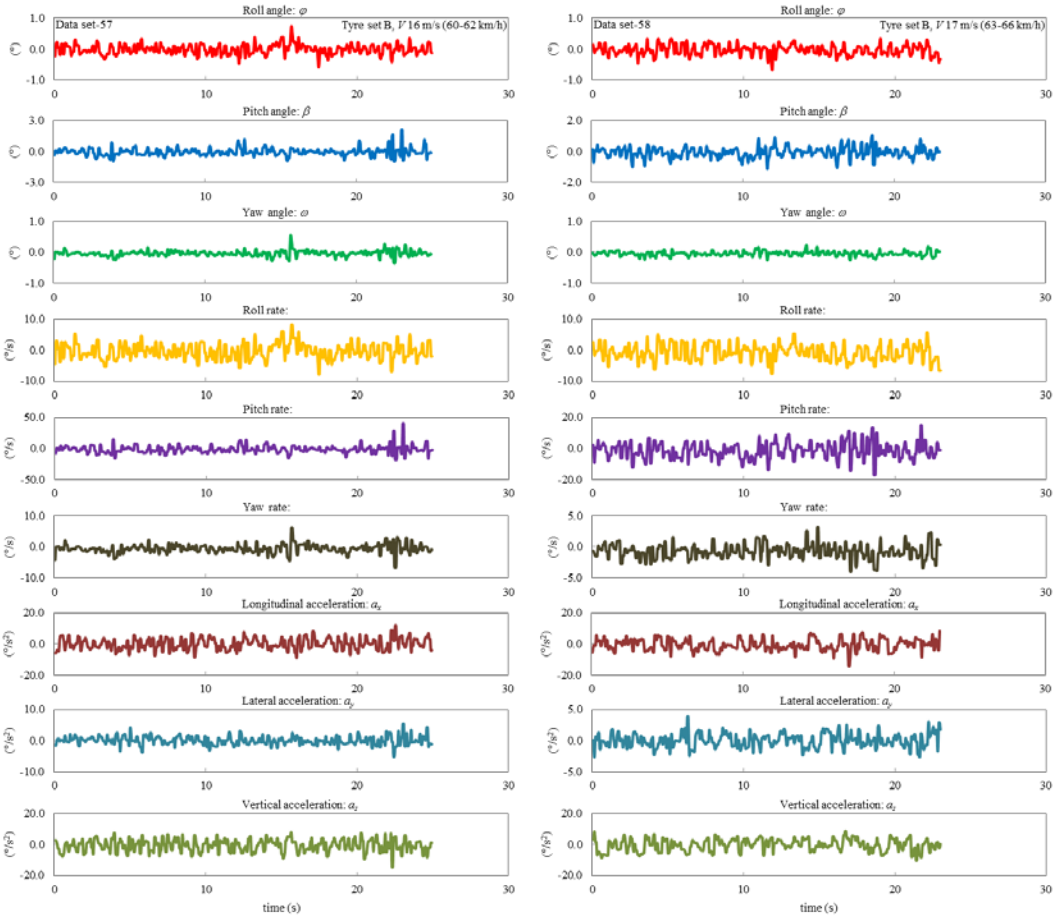

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Figure B-52 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 57 and (b) Data Set 58

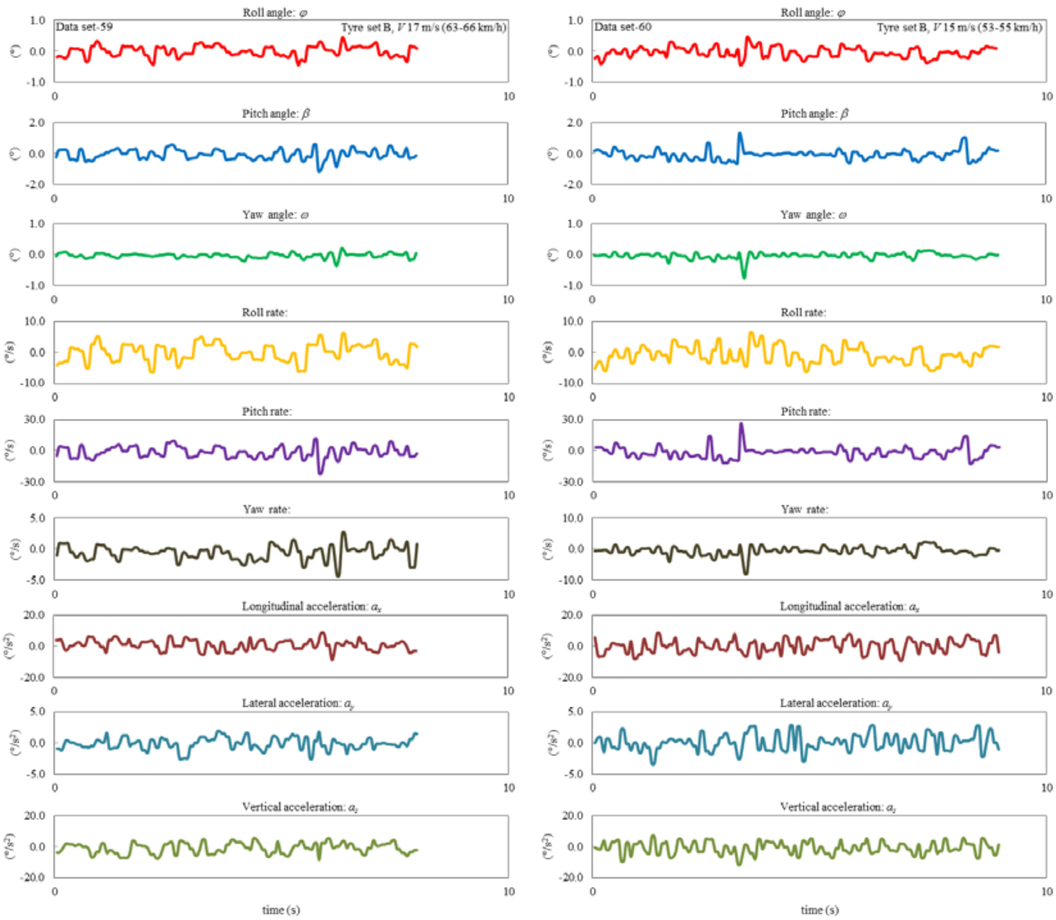

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Figure B-53 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 59 and (b) Data Set 60

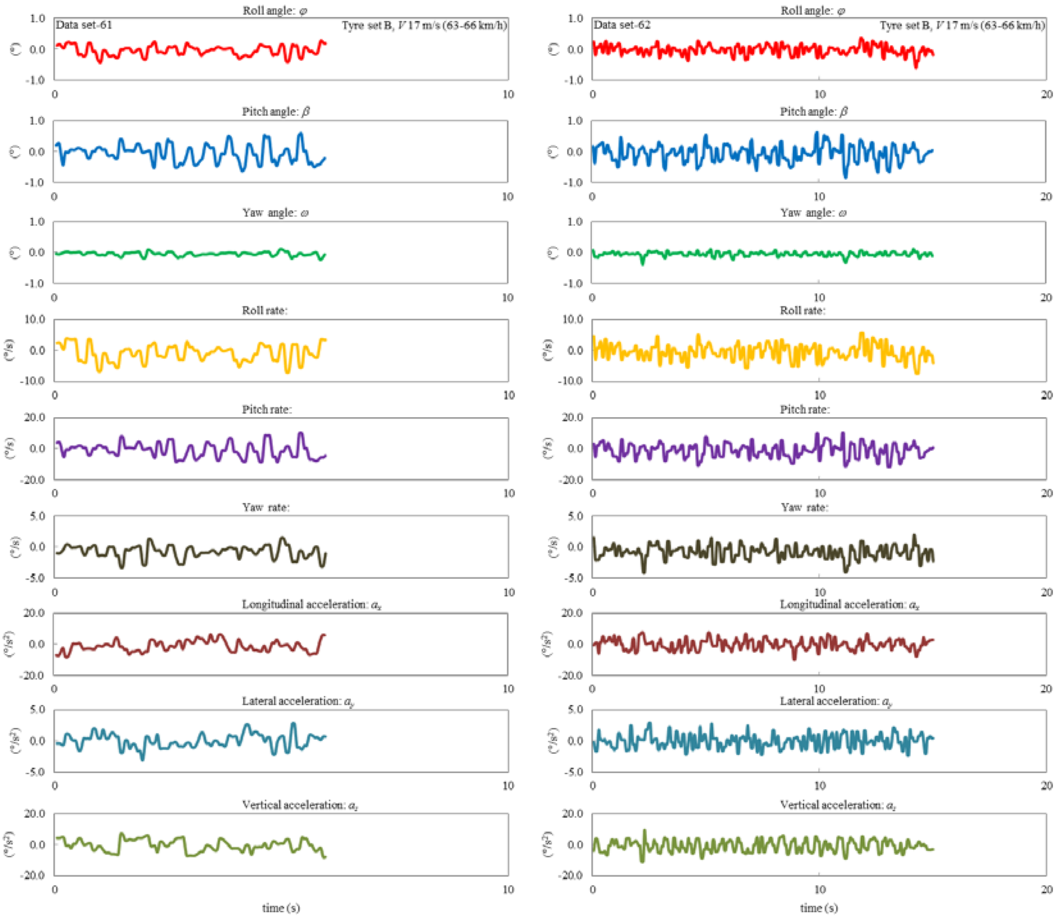

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Figure B-54 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 61 and (b) Data Set 62

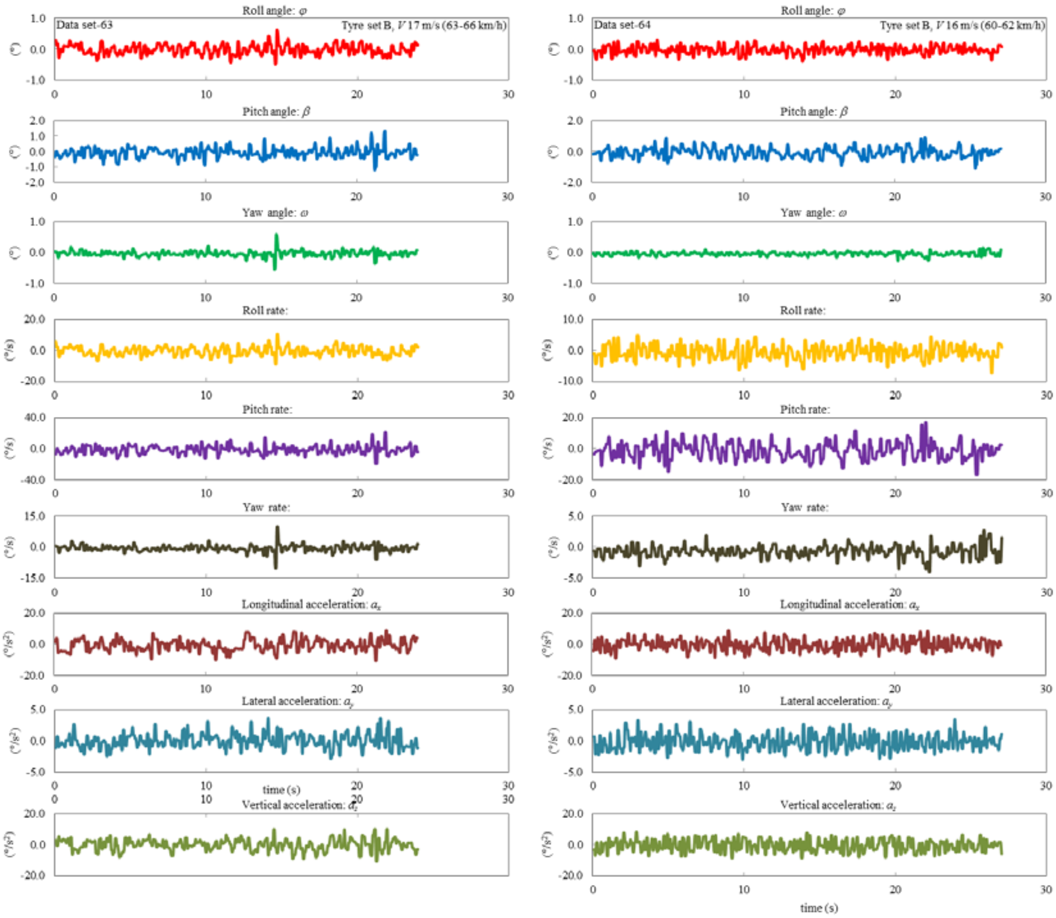

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Figure B-55 Dynamics Response Signals from Straight Run Test of Tyre Set B, (a) Data Set 63 and (b) Data Set 64

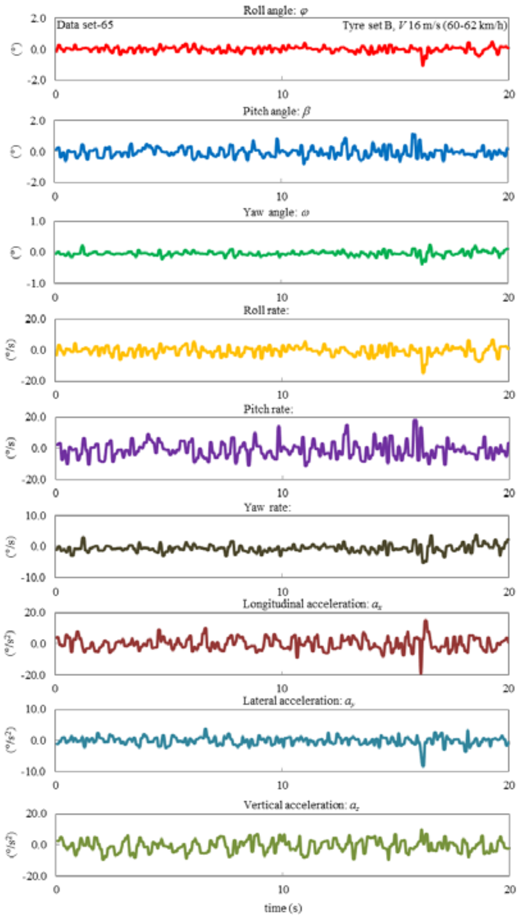
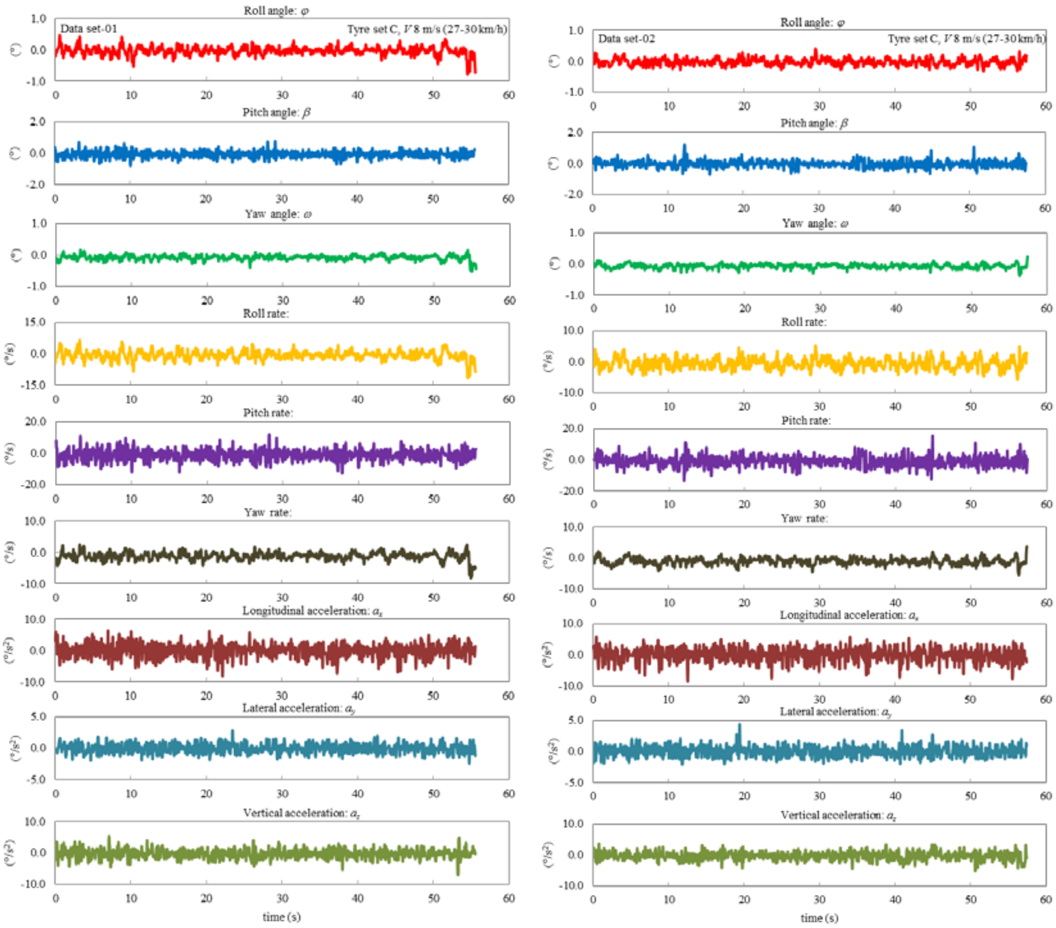


Figure B-56 Dynamics Response Signals from Straight Run Test of Tyre Set B, Data Set 65

Tyre Set C



(a) (b)

Figure B-57 Dynamics Response Signals from Straight Run Test of Tyre Set C, (a) Data Set 01 and (b) Data Set 02

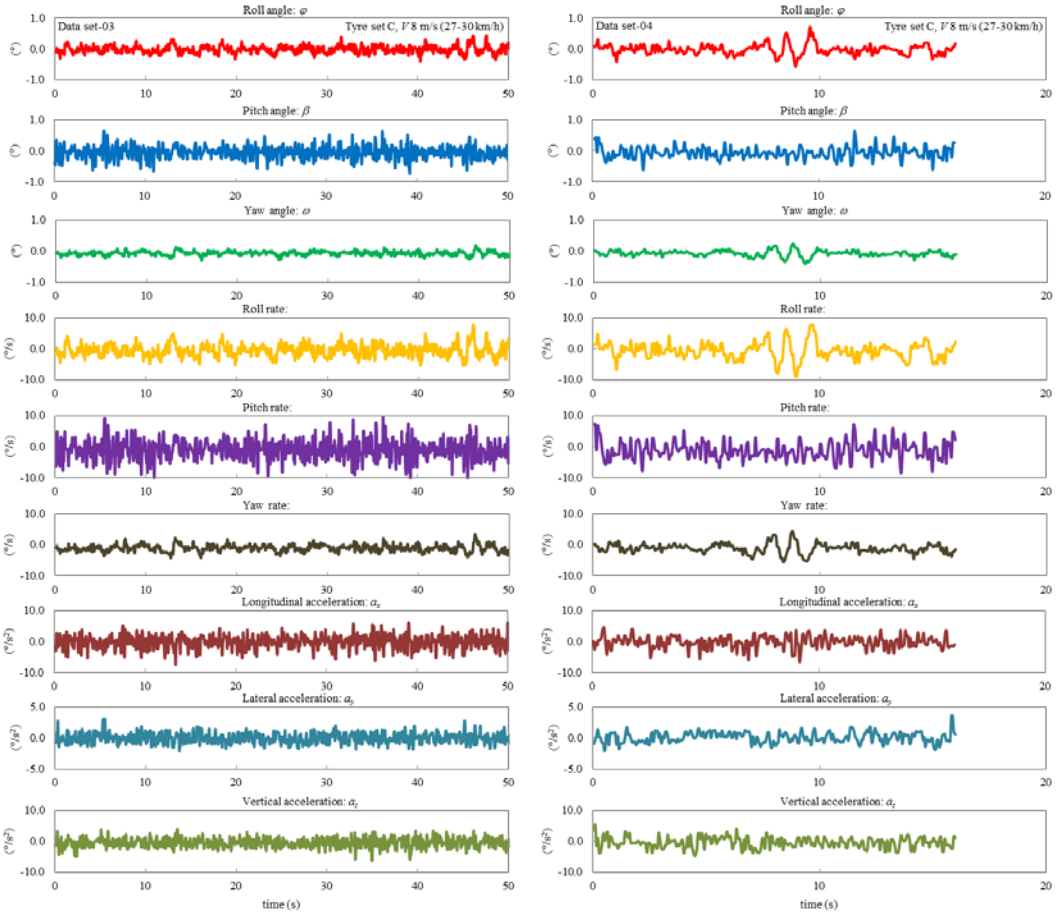


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Figure B-58 Dynamics Response Signals from Straight Run Test of Tyre Set C, (a) Data Set 03 and (b) Data Set 04

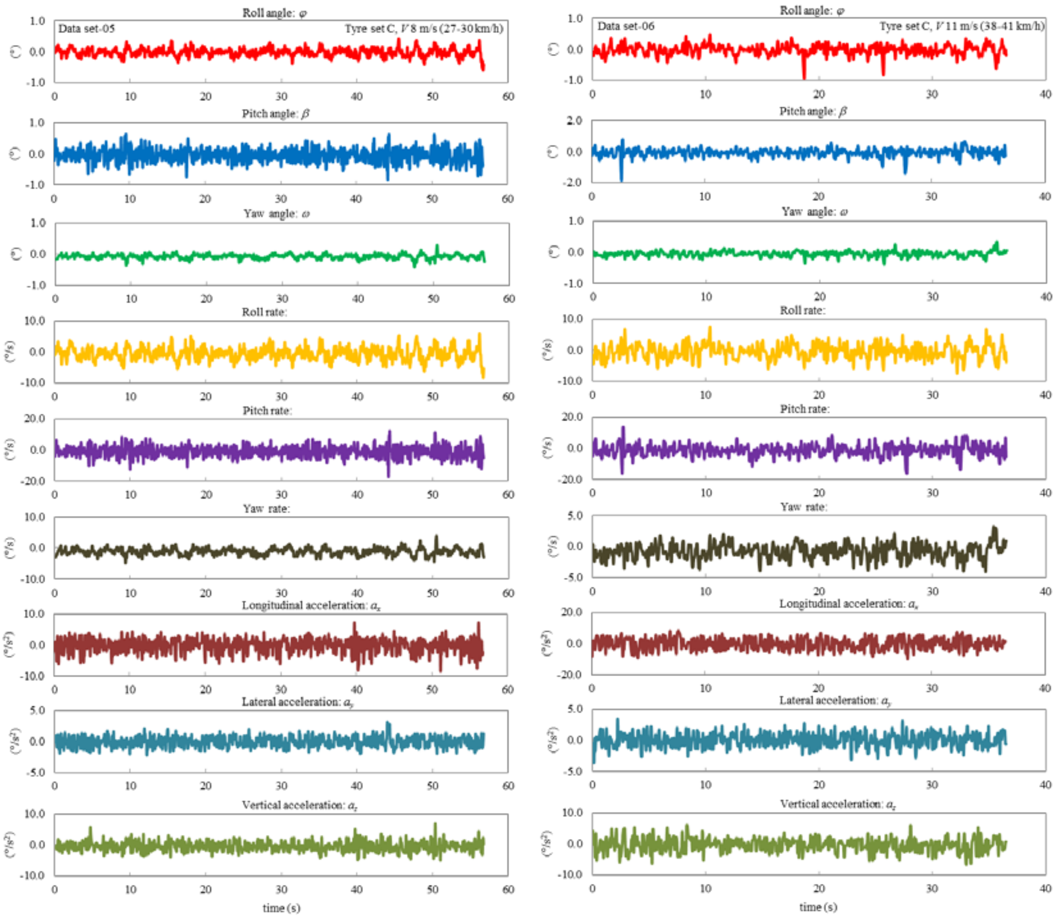

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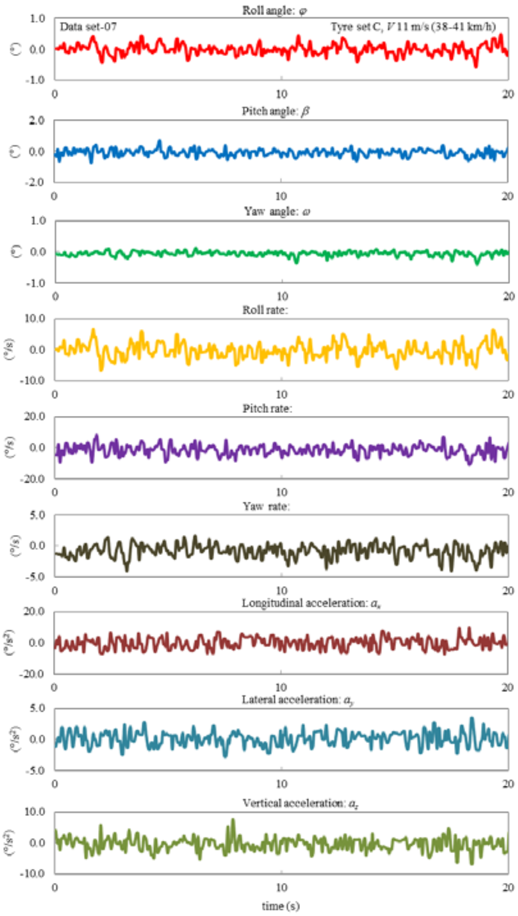
Figure B-59 Dynamics Response Signals from Straight Run Test of Tyre Set C, (a) Data Set 05 and (b) Data Set 06



(a)

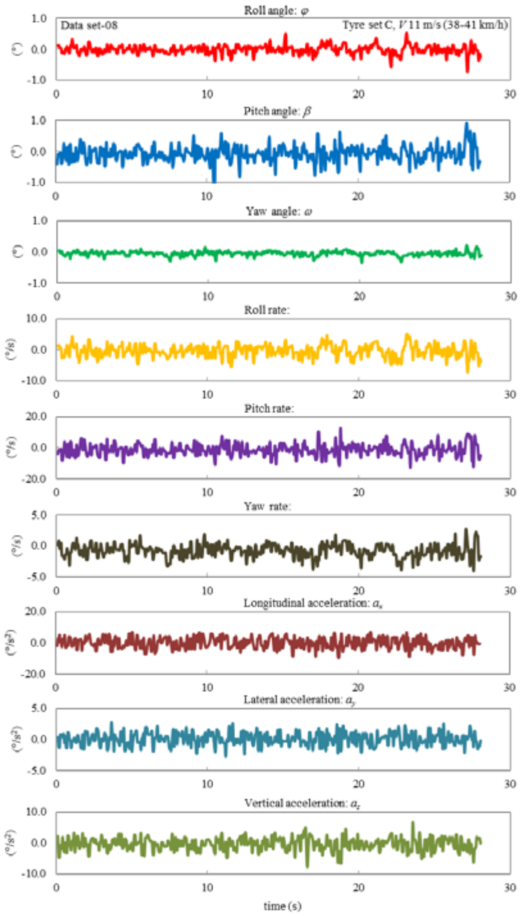


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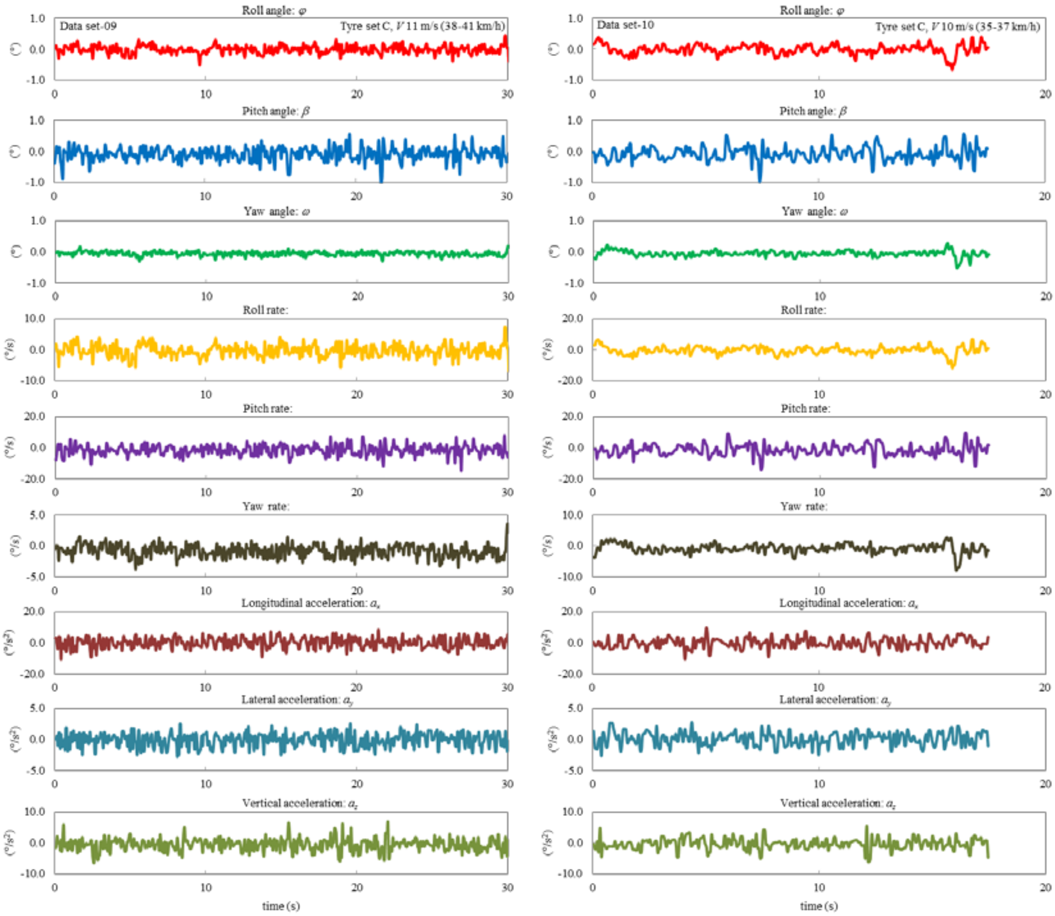
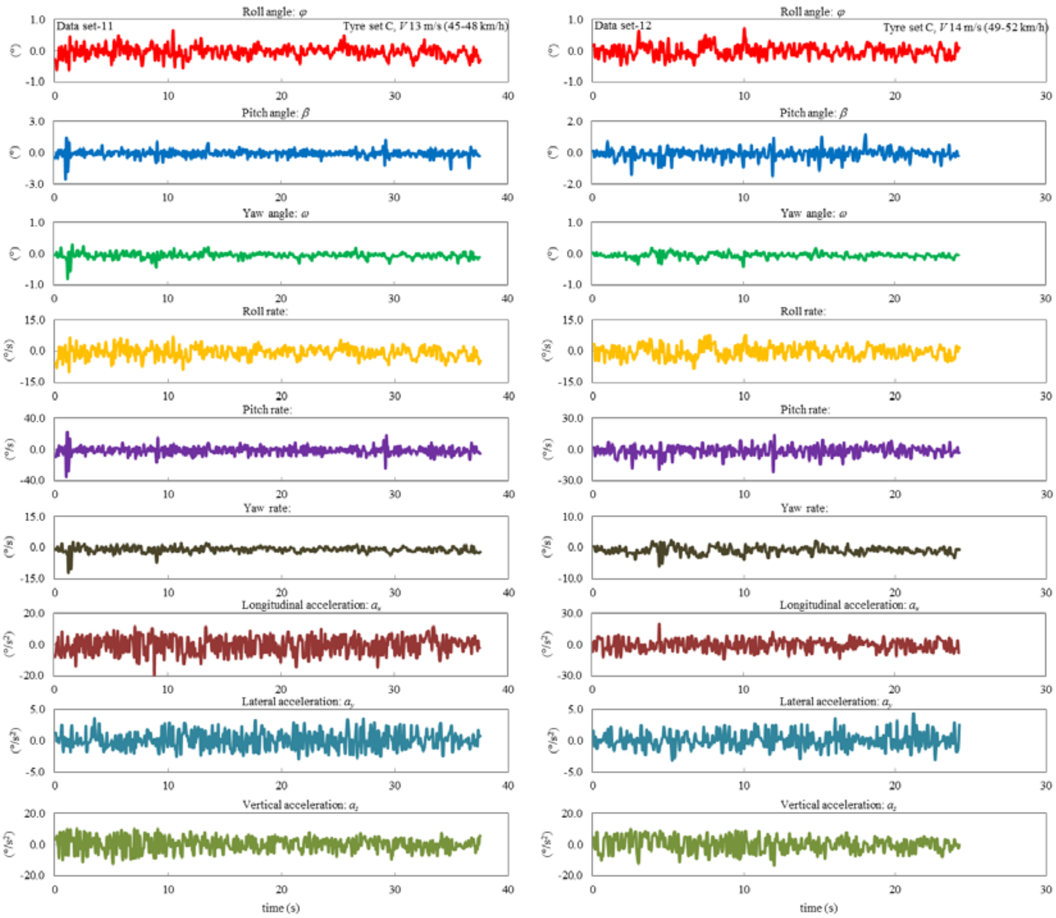
Figure B-60 Dynamics Response Signals from Straight Run Test of Tyre Set C, (a) Data Set 07 and (b) Data Set 08



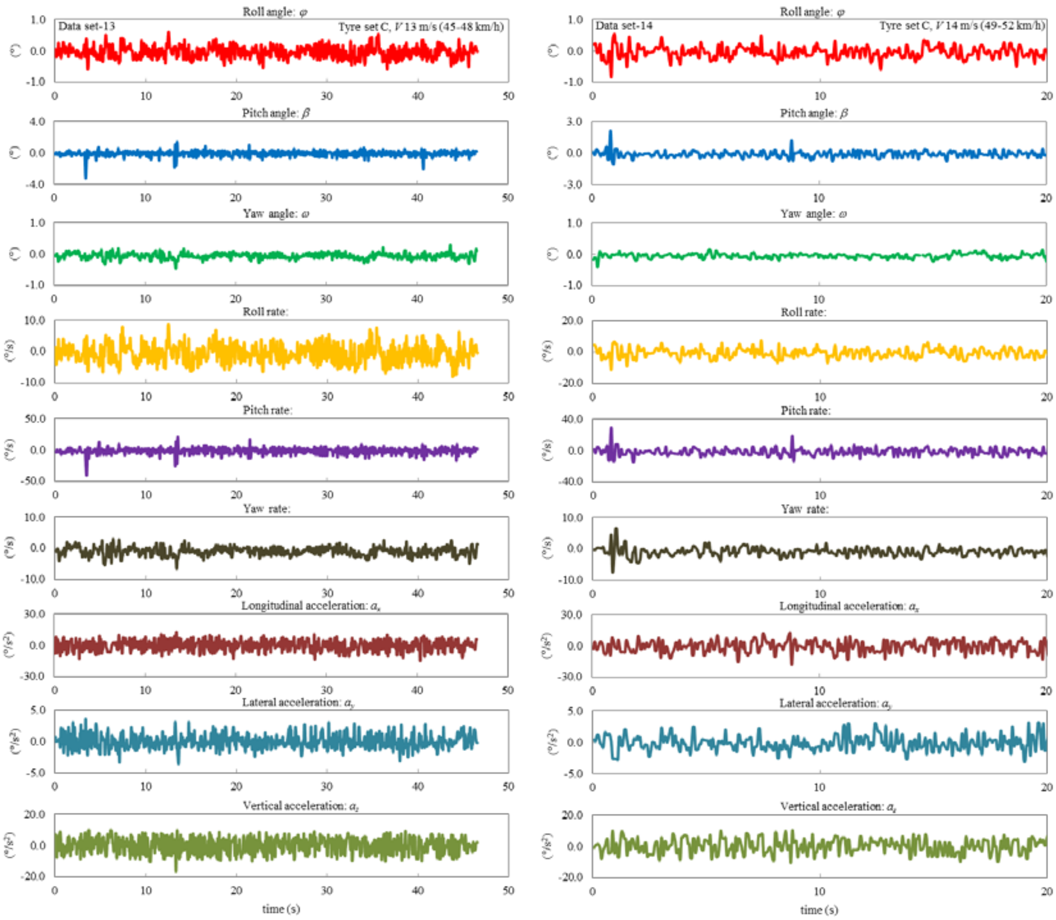
(a) (b)

Figure B-61 Dynamics Response Signals from Straight Run Test of Tyre Set C, (a) Data Set 09 and (b) Data Set 10



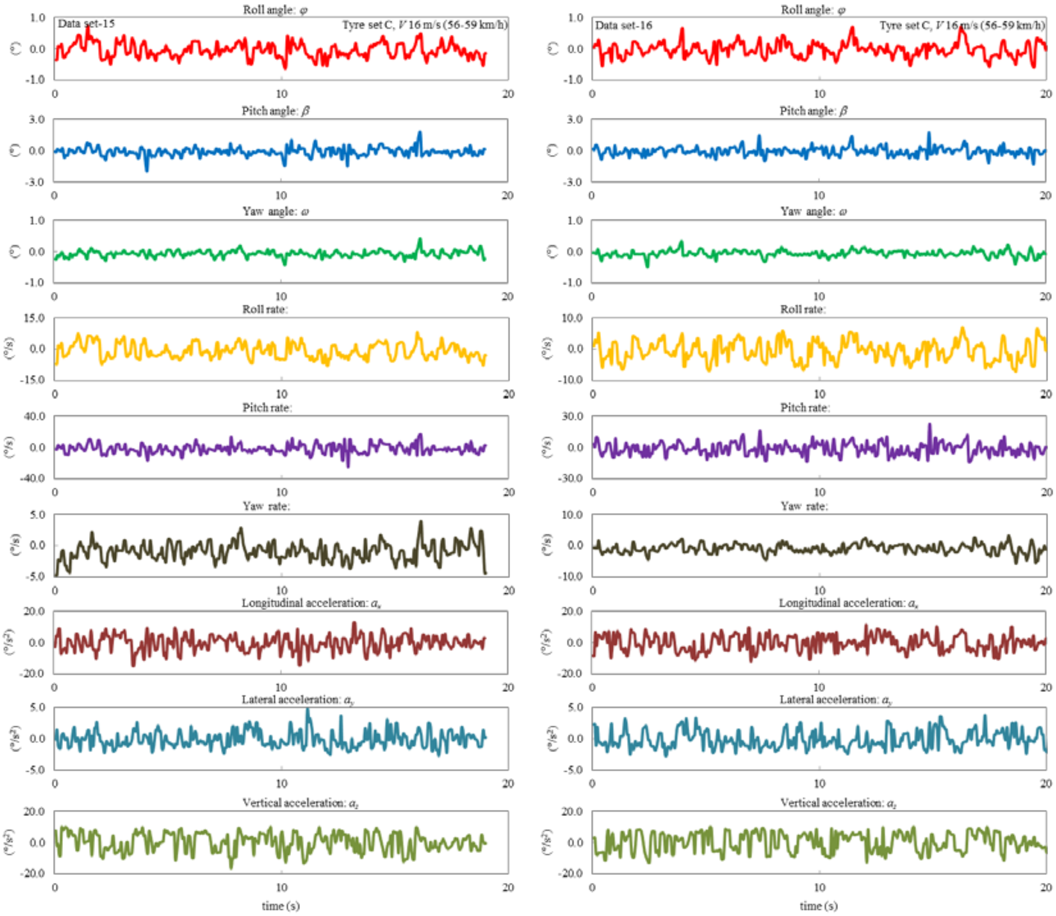
(a) (b)

Figure B-62 Dynamics Response Signals from Straight Run Test of Tyre Set C, (a) Data Set 11 and (b) Data Set 12



(a) (b)

Figure B-63 Dynamics Response Signals from Straight Run Test of Tyre Set C, (a) Data Set 13 and (b) Data Set 14



(a) (b)

Figure B-64 Dynamics Response Signals from Straight Run Test of Tyre Set C, (a) Data Set 15 and (b) Data Set 16

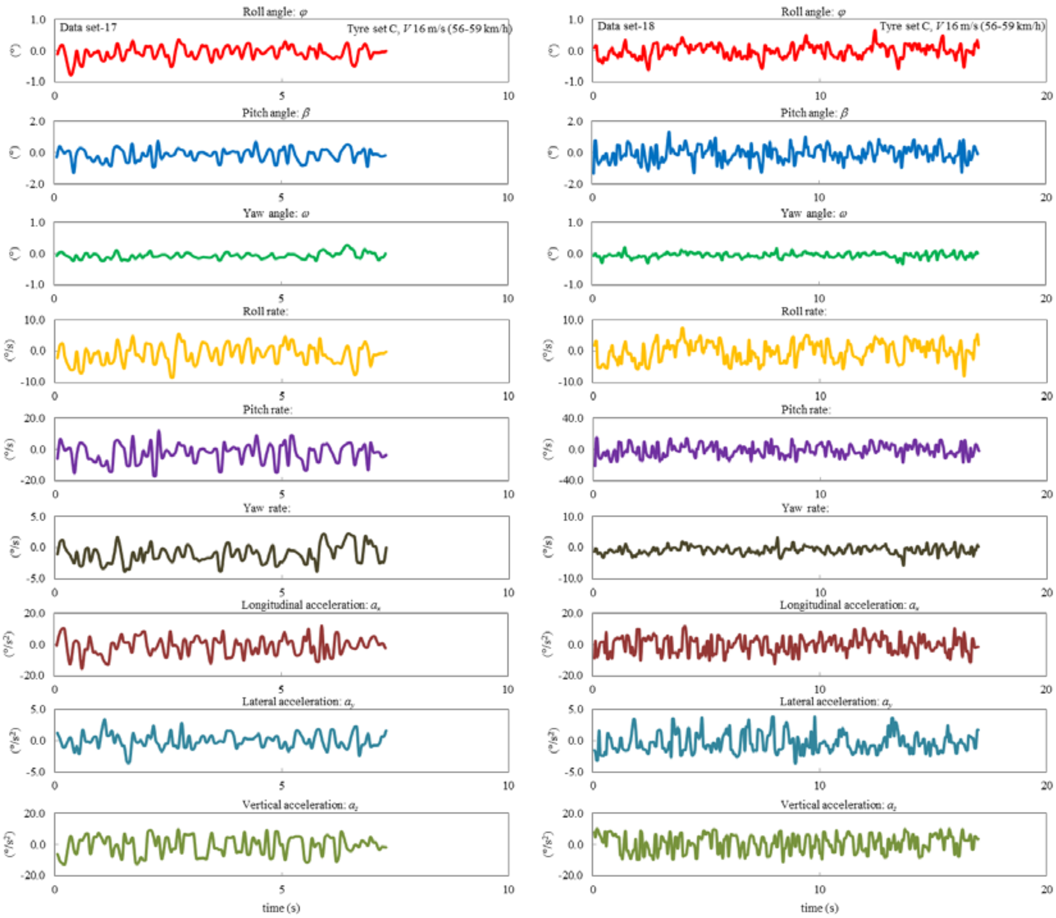


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Figure B-65 Dynamics Response Signals from Straight Run Test of Tyre Set C, (a) Data Set 17 and (b) Data Set 18

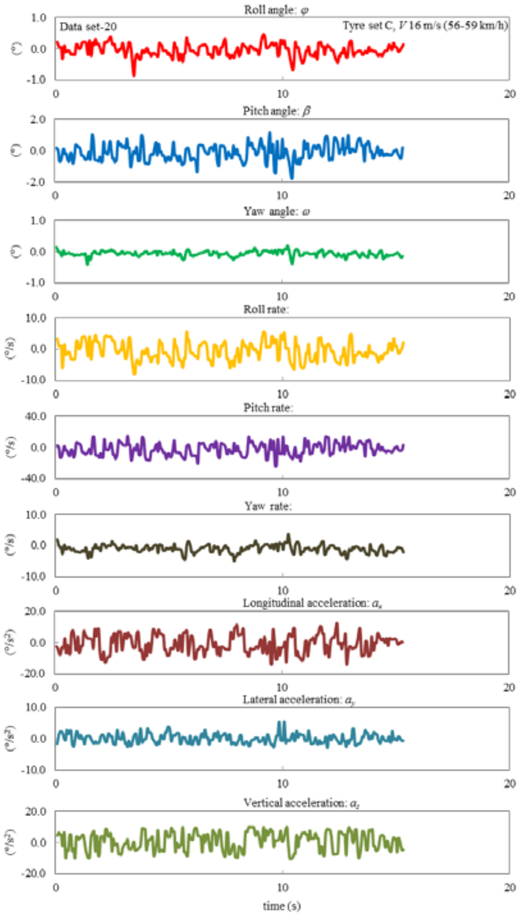

Figure B-66 Dynamics Response Signals from Straight Run Test of Tyre Set C, Data Set 20

APPENDIX C

Slalom Results

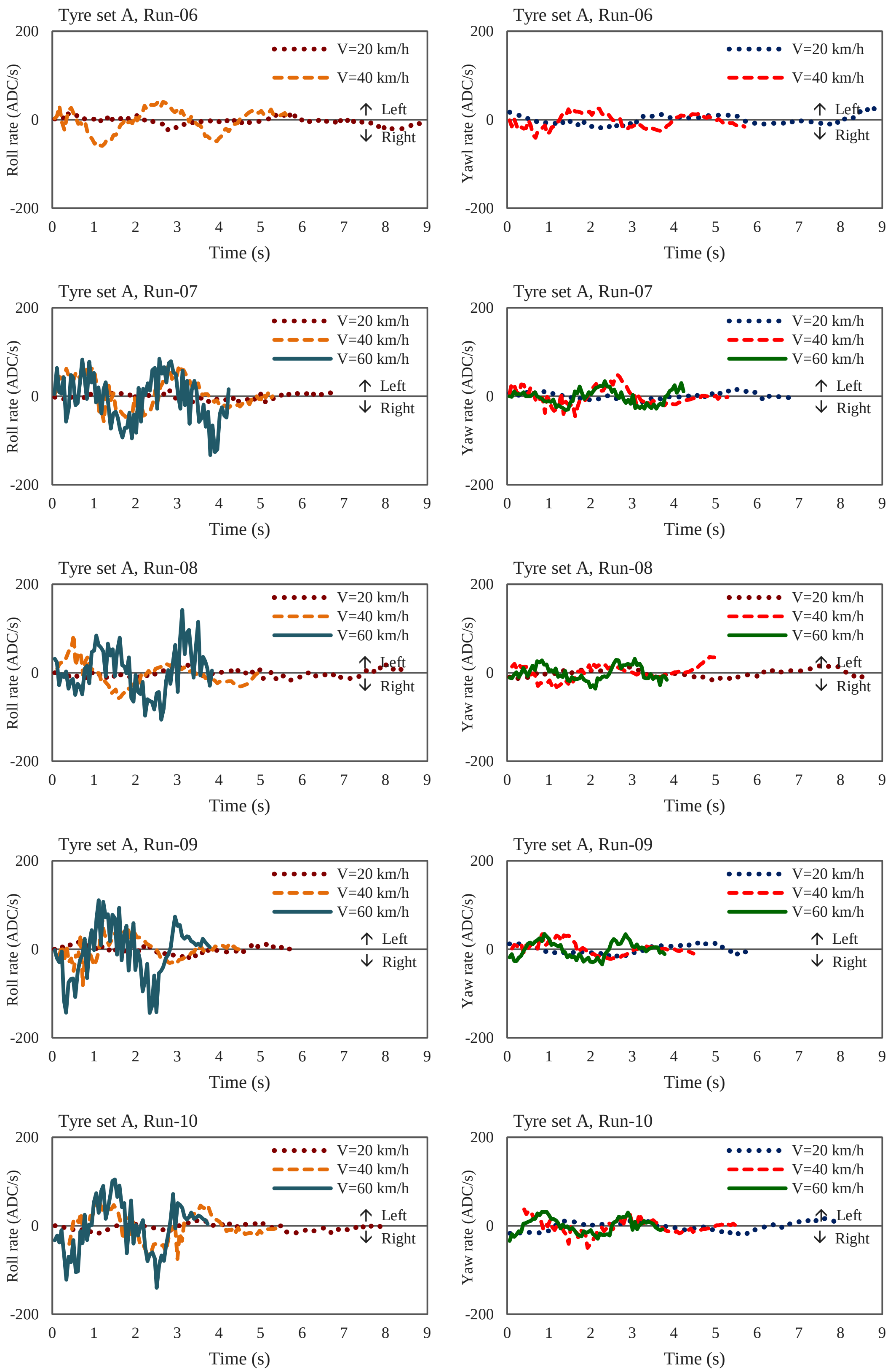

Figure C-1 Comparison of Roll Rate and Yaw Rate from Slalom Test of Tyre Set A Run no.6-10

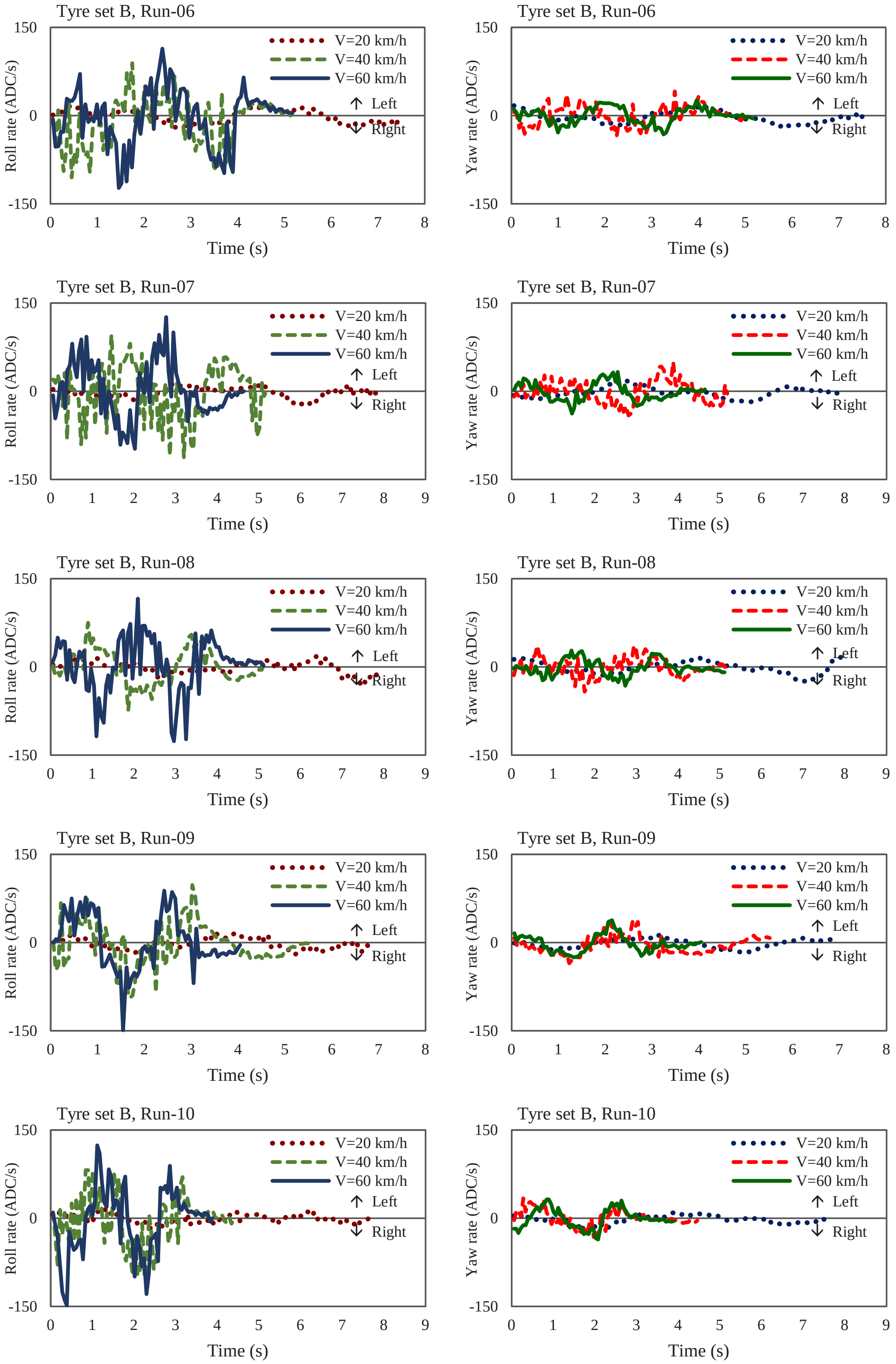

Figure C-2 Comparison of Roll Rate and Yaw Rate from Slalom Test of Tyre Set B Run no.6-10

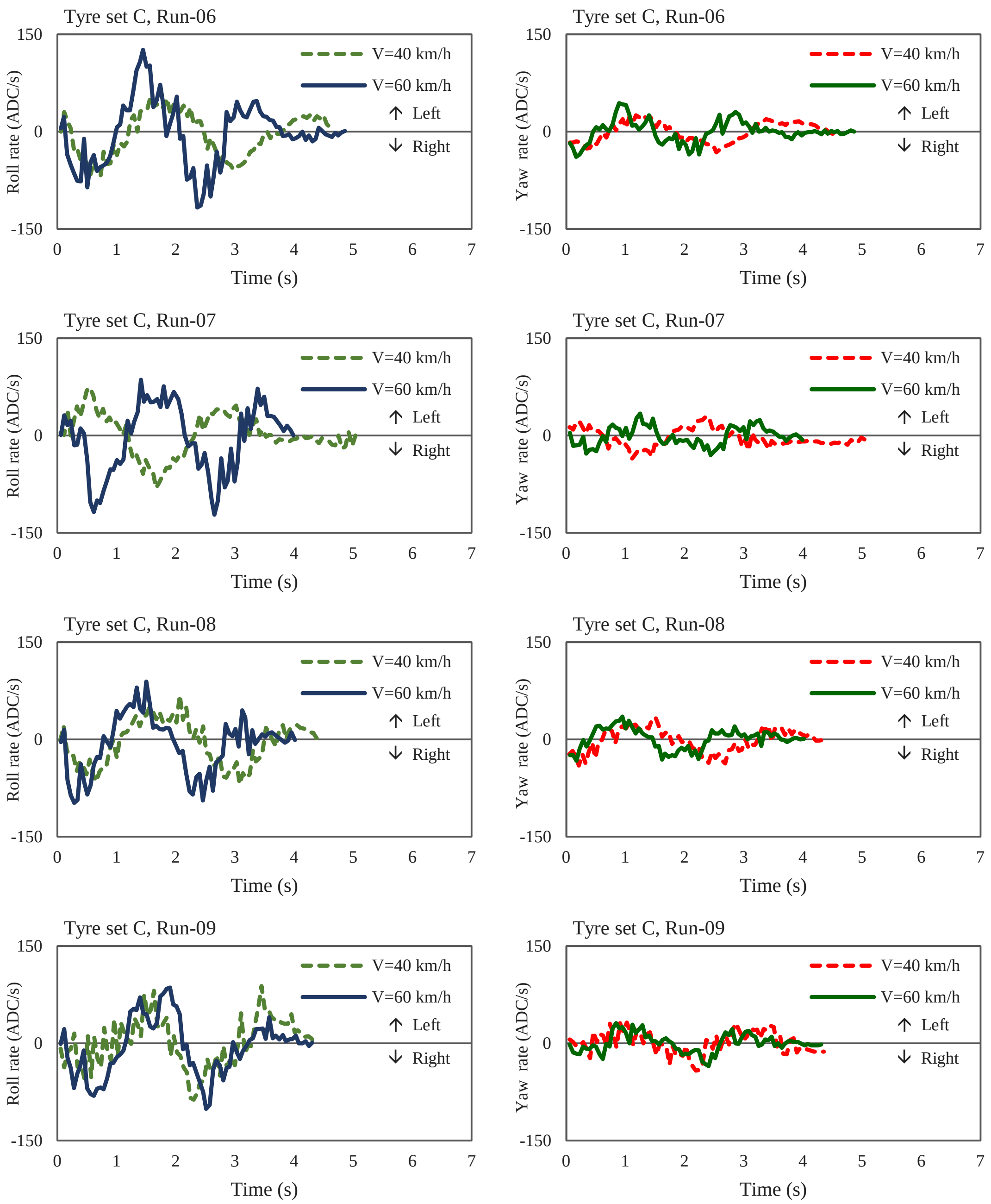

Figure C-3 Comparison of Roll Rate and Yaw Rate from Slalom Test of Tyre Set C Run no.6-9

APPENDIX D

List of Papers and Proceedings

Proceeding of the 9th APTE Conference

ENGINEERING JOURNAL

VITAE

Name Miss Chuthamat Laksanakit
Student ID 5410130032
Educational Attainment

Degree	Name of Institution	Year of Graduation
Bachelor of Engineering (Civil Engineer)	Mahanakorn University of Technology	1997
Master of Engineering (Civil Engineer)	Chiang Mai University	2003

Scholarship Awards during Enrolment

Student was financially supported by a scholarship of Rajamangala University of Technology Srivijaya, Songkhla and a Graduate Studies Grant of Prince of Songkla University.

Work–Position and Address

The student has been working as lecture at Division of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Srivijaya, Songkhla since 2004.

List of Publication and Proceeding

1) Institute: The 9th Asia Pacific Conference Transportation and the Environment (APTE 9th)
Article Title: Motorcycle Defects on Motorcycle Safety in Thailand
Year 2014

2) Institute: Engineering Journal
Article Title: A Simple Investigation into the Stability of Lightweight Motorcycle
Year 2016 (Volume 20 Issue 2, ISSN 0125-8281 (http://www.engj.org/), pp.199-210)