# EXPERIMENTAL ANALYSIS OF GYROSCOPIC EFFECT ON VEHICLE VIBRATION AND ACCIDENT POTENTIAL 

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# EXPERIMENTAL ANALYSIS OF GYROSCOPIC EFFECT ON VEHICLE VIBRATION AND ACCIDENT POTENTIAL 

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Dedicated to myself

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#### Abstract

This thesis concerns with the experimental analysis of gyroscopic effect on vehicle vibration and accident potential. The objective of this thesis is to investigate the vehicle vibration, roll and yaw limits in various driving maneuver. The thesis describes the method to collect the vehicle's centre of gravity performance in term of moment and movement. The centre of gravity is assumed as the vehicle rigid body. Uncontrolled roll and yaw moment will cause different impact as it reach the limit depends on the contributed factors and condition. Due to variation of design, different geometry and external influences, study on roll and yaw will be different for every type of car. Thus, it is important to study and to address the relationship of centre of gravity performance and moment limit to reduce accident tendency due to uncontrolled roll and yaw moment. Three different driving maneuver had been evaluate for this study purpose which are steady state cornering with constant radius, load and lane change maneuver. The test is perform in Universiti Malaysia Pahang (UMP) and the data used for the analysis is obtained test using UMP Test Car which has been installed with MTi (gyroscope), Global Positioning System and DEWESoft software for data acquisition purpose. The post-processing method was performed using Flexpro and Microsoft Office Excel. The post-processing method to determine the roll and yaw angle is being done in Flexpro using the FPScript function. Finally, the results of analysis were represented in graph. From the graphs represented, some discussions are made according to the experiment performed. Comparisons of all the tests are made in achieving the conclusion. It is observed that the roll and yaw have its own limits based on the CG performance of the vehicle. The results concluded that the limit is strongly dependent to the turning radius and load variation. For steady state cornering, R3 is the limit for roll while R4 is the limit for yaw. As for the load variation, 50 kg load give the most uncontrolled roll and yaw. At $30 \mathrm{~km} / \mathrm{h}$ for lane change test, the yaw is uncontrollable and roll is uncontrolled at $60 \mathrm{~km} / \mathrm{h}$. Improvements can be made by finding the exact location of CG that will give the exact limits of a vehicle. Finally, the methods and results for verification in this thesis are only applicable for passenger car.


#### Abstract

ABSTRAK

Tesis ini adalah berkaitan dengan analisis eksperimental pada kesan giroscopik terhadap getaran kenderaan dan potensi kemalangan. Tujuan tesis ini adalah untuk mengetahui getaran kenderaan, serta had roll dan yaw pada berbagai cara pemanduan. Tesis ini menjelaskan kaedah untuk mengumpul momen dan prestasi gerakan pada pusat graviti kenderaan. Pusat graviti adalah satu titik bagi mewakili seluruh badan kenderaan. Momen roll dan yaw yang tidak terkawal akan menimbulkan kesan yang berbeza pada had tertentu berdasarkan faktor keadaan sekitar. Oleh sebab variasi reka bentuk, geometri yang berbeza dan pengaruh luar, kajian yang dijalankan pada roll dan yaw adalah berbeza untuk setiap jenis kereta. Dengan demikian, adalah penting untuk mempelajari dan mengetahui hubungan prestasi pusat graviti dan had roll dan yaw untuk mengurangkan kecenderungan kemalangan akibat momen roll dan yaw yang tidak terkawal ini. Tiga cara memandu yang berbeza itu telah dijalankan bagi kajian ini iaitu steady state menikung dengan memalarkan radius dan beban serta penukaran lorong jalan. Kajian ini dijalankan di Universiti Malaysia Pahang (UMP) dan data yang digunakan untuk analisis diperolehi dengan menguunakan kereta ujian UMP yang telah dilengkapkan dengan MTi (giroskop), Sistem Posisi Global dan perisian DEWESoft untuk tujuan pengambilan data. Kaedah pemprosesan pasca dilakukan menggunakan Flexpro dan Microsoft Office Excel. Kaedah pemprosesan pasca adalah untuk menentukan sudut roll dan yaw dilakukan di dalam Flexpro menggunakan fungsi FPScript. Akhirnya, hasil daripada analisis diwakilkan di dalam graf. Dari graf diwakili, beberapa perbincangan yang dibuat sesuai dengan percubaan yang dilakukan. Perbandingan dari semua ujian dilakukan dalam mencapai kesimpulan ini. Didapati bahawa roll dan yaw memiliki had sendiri berdasarkan prestasi pusat graviti kenderaan. Kesimpulannya, had-had ini sangat bergantung dengan jari-jari berputar dan variasi beban. Untuk menikung steady state, R3 adalah had untuk roll, sementara itu R4 adalah had untuk yaw. Bagi ujian variasi beban, beban 50 kg memberikan roll dan yaw yang paling tidak terkawal. Pada kelajuan $30 \mathrm{~km} / \mathrm{j}$ untuk ujian penukaran lorong jalan, yaw tidak dapat dikawal dan roll adalah tidak terkawal pada kelajuan $60 \mathrm{~km} / \mathrm{j}$. Perbaikan dapat dilakukan dengan mencari lokasi pusat graviti kenderaan yang paling tepat kerana ini akan memberikan had-had yang tepat. Akhirnya, kaedah dan keputusan dalam laporan ini hanya boleh diaplikasikan untuk kenderaan penumpang sahaja.


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## LIST OF SYMBOLS

| $\mathrm{a}_{\mathrm{y}}$ | Lateral acceleration |
| :---: | :---: |
| $C_{f}$ | Front cornering coefficient |
| $C_{r}$ | Rear cornering coefficient |
| $\mathrm{F}_{\mathrm{y}}$ | Lateral force |
| $\mathrm{F}_{\mathrm{yf}}$ | Lateral force of rear axle |
| $\mathrm{F}_{\mathrm{yr}}$ | Lateral force of rear axle |
| g | Gravity |
| GyrX | Roll rate of Xsens MTi |
| GyrZ | Yaw rate of Xsens MTi |
| $h_{u l}$ | Height of unladen vehicle |
| $h_{V} 0$ | Centre of gravity height |
| $i_{u l}$ | Ratio of centre of gravity height to height of unladen vehicle |
| $K_{u S}$ | Understeer coeefficient |
| 1 | Wheelbase |
| $I_{f}$ | Centre of gravity distance to the front axle |
| $I_{r}$ | Centre of gravity distance to the rear axle |
| M | Mass |
| $m_{V f}$ | Front axle load |
| $m_{V r}$ | Rear axle load |
| $m_{V t}$ | Total weight |
| $M_{x}$ | Moment about x -axis |
| $M_{y}$ | Moment about y-axis |
| $M_{z}$ | Moment about z-axis |


| $p$ | roll rate |
| :--- | :--- |
| $q$ | yaw rate |
| $r$ | pitch rate |
| R | Radius of curvature |
| R1 | Radius 1 |
| R2 | Radius 2 |
| R3 | Radius 3 |
| R4 | Radius 4 |
| $t$ | Track |
| $t_{r}$ | Transversal position of CG |
| V | Velocity |
| $V_{\text {char }}$ | Characteristic velocity |
| $V_{\text {crit }}$ | Critical velocity |
| $\mathrm{W}_{\mathrm{f}}$ | Front weight |
| $\mathrm{W}_{\mathrm{r}}$ | Rear weight |
| X | P-axis |
| Y | roll angle |
| $\boldsymbol{Z}$ | yaw angle |
| $\varphi$ | Z-axis |

## LIST OF ABBREVIATIONS

| AHRS | Attitude and Heading Reference System |
| :--- | :--- |
| CAN | Controller Area Network |
| CG | Centre of Gravity |
| DAS | Data Acquisition System |
| GPS | Global Positioning System |
| MT | Manual Transmission |
| PUSPAKOM | Pusat Pemeriksaan Kenderaan Berkomputer |
| SUV | Sport Utility Vehicle |
| UMP | Universiti Malaysia Pahang |

## CHAPTER 1

## INTRODUCTION

### 1.1 INTRODUCTION

Vehicle dynamics is a field that concern with handling and stability of a vehicle. Many experiment had been done before by engineers in determining the various vehicle effect on dynamics, handling, stability and maneuverability due to its configuration. The stability of a vehicle is strongly dependent on the height of the centre of gravity (CG) but it is hardly to configure the exact CG location as it is varied dynamically.

Excessive cornering rollovers occur when cornering forces destabilize the vehicle. As a vehicle rounds a corner, three forces act on it. Cornering forces and force of inertia make the vehicle roll towards the outside of the curve. The force of the vehicle's weight acts downward through the CG in the opposite direction. When the tire and inertial forces are enough to overcome the force of gravity, the vehicle starts to turn over. Most passenger vehicles will slide or spin before this happens.

Stability is always studied in vehicles that have high CG location such as sport utility vehicle (SUV), and vehicle combination. Here, the experiment is performed to analyze the passenger car performance in term of roll and yaw for various driving maneuver. Thus, some references are made to find the appropriate method in performing this analysis.

### 1.2 PROBLEM STATEMENT

The car movement could subdivide in yaw, roll, pitch rotation, and $\mathrm{X}, \mathrm{Y}, \mathrm{Z}$ movement. In mathematical form, it is a good to analyze or assume the car as a point where the total mass is located at the centre of gravity. When related to road accident, uncontrolled roll and yaw moment will cause serious impact to the car itself as well as the driver and passengers.

Based on the significant of this effect, many research and development had been introduce since the first car start to move on the road. Due to variation of design, different geometry and external influences, study on roll and yaw will be different for every type of car.

In normal driving maneuver, many component in vehicle will cause minor moment and $\mathrm{X}, \mathrm{Y}$ and Z movement which also known as vibration. The value is low but it still affects the driver and passengers' comfort. Normally, the value is difficult to detect by end-user. Continuous exposed to this vibration will cause exhaustion. In certain drastic driving condition, such as acceleration, deceleration, slip and cornering, total moment and $\mathrm{X}, \mathrm{Y}, \mathrm{Z}$ movement will increase proportionally and as it achieve highest limit, accident would be the final consequences. Since the car have different design parameters that vary for other vehicle, it is important to study and to address the relationship of centre of gravity performance and moment limit to reduce the accident tendency due to uncontrolled roll and yaw moment. This study is specifically for Proton Persona car. However, the same method is applicable to other type of car.

### 1.3 PROJECT OBJECTIVES

The objectives of the project are:
i. To collect the vehicle's centre of gravity performance in term of moment and movement data.
ii. To evaluate the vehicle vibration, roll and yaw limits in various driving maneuver.

### 1.4 SCOPES OF PROJECT

In achieving those objectives, these scopes had been introduced:
i. Literature review
ii. Test car system installation and Data Acquisition System (DAS) setup
iii. Experiment procedures preparation
iv. On-road testing and data collection
v. Centre of gravity moment and movement analysis
vi. Final report preparation

### 1.5 FLOW CHART

Process flow chart provided to give an overview the project of this study. Figure 1.1 shows the methodology proposed for investigating this research. In allocate the time for this project a Gantt chart had been made as in Appendix A1 and A2.


Figure 1.1: Flow chart

## CHAPTER 2

## LITERATURE REVIEW

### 2.1 INTRODUCTION

This chapter is mainly explaining about the basics of this study. First of all, the readers are exposed to reference frame of the vehicle which defines the coordinate system used in this study. Later, the centre of gravity of vehicle as an important point in this study is discussed in vehicle as rigid body subchapter. The stability condition of vehicle and handling types of vehicle is introduced to readers as it is the main knowledge in perform this study. Going through the chapter, the roll moment is discussed as it is a measurement of rollover limits.

### 2.2 THE REFERENCE FRAME

The reference frame refers to the coordinate system used in vehicle dynamics. This reference frame can be chosen either as earth fixed coordinate, vehicle (or component) fixed or horizontally orientated and moved with the vehicle. Figure 2.1 show the DIN 70000 / ISO 8855 coordinate system.


FIGURE 2.1: DIN 70000 / ISO 8855 coordinate system

The X -axis is a longitudinal axis passing through CG and directed forward. The Y-axis goes laterally to the left from the driver's viewpoint. The Z-axis makes the coordinate system a right hand rule. When the car is parked on a flat horizontal road, the Z -axis is perpendicular to the ground, opposite to the gravitational acceleration, g. The relationship of the vehicle fixed coordinate system to the earth fixed coordinate system is defined by Euler angles.

This euler angles can be shown by the vehicle orientation of three angles which are roll angle $\varphi$ rotate about X -axis, pitch angle $\theta$ rotate about Y -axis and yaw angle $\psi$ rotate about Z -axis. Rate of the rotation angles are important in vehicle dynamics, thus, it is called as roll rate, $p$, pitch rate, $r$ and yaw rate, $q$ respectively.

### 2.3 VEHICLES AS RIGID BODY

A vehicle is made up of many components distributed within its exterior envelope. For its single mass represention, the vehicle is treated as mass concentrated at CG. The point mass at the CG, with appropriate rotational moments of inertia, is dynamically equivalent to the vehicle itself for all motions in which it is reasonable to assume the vehicle to be rigid.

Low CG is always desirable, as they are deals with driving dynamic problems and increased vehicle performance during cornering and braking. The position of a vehicle centre of gravity is highly dependent on the load; when people get into the vehicle or luggage is loaded in the boot or onto the roof (Reimpell et al., 2001).

The body lowers when it is loaded. Loads such as passengers and in particular the luggage carried on the roof, results in higher overall centre of gravity. It is much simpler to determine the position experimentally by weighing. For this, both the empty vehicle should be observed and when it is occupied by passengers. When the vehicle is weighed, it must be standing on a completely horizontal plane and with each axle on a weighbridge.

The weighed front axle load and the rear axle load give the total weight of the vehicle

$$
\begin{equation*}
m_{V t}=m_{V f}+m_{V r} \tag{2.1}
\end{equation*}
$$

The balance of moments around front and rear axle in conjunction with the wheelbase $l$ in the longitudinal direction, gives the centre of gravity distances $l_{f}$ to the front and $l_{r}$ to the rear axle

$$
\begin{equation*}
l_{f}=\frac{m_{V r}}{m_{V t}} \times l \tag{2.2}
\end{equation*}
$$

In determining the CG height, ratio for the empty condition, $i_{u l}$ is propose. The empty vehicle is compared with the empty height of the unladen vehicle

$$
\begin{equation*}
i_{u l}=\frac{h_{v 0}}{h_{u l}} \tag{2.3}
\end{equation*}
$$

For the passenger car, Reimpell et al. (2001) has proposed that the ratio would be 0.377 . If the CG of loaded vehicle is not known, it can be judged using

$$
\begin{equation*}
h_{v 0}=(0.377 \pm 0.02) h_{u l} \tag{2.4}
\end{equation*}
$$

According to Genta and Morello (2009) vehicles, like most machines, have a general bilateral symmetry. If the CG lies in the symmetry plane, it is impossible to compute the transversal position of the CG. Thus, a transversal position of CG can be estimated by

$$
\begin{equation*}
t_{r}=\frac{t}{2} \tag{2.5}
\end{equation*}
$$

### 2.4 STABILITY

Vehicles are obviously stable at very low speeds. Historically, there was no particular interest in issues of stability until the propulsion systems had developed enough to allow high speeds to be reached. Stability and handling problems were typically addressed more by experiment than by analysis. At above of the critical speed, $V_{\text {crit }}$, the stability criterion will not satisfied and the car will be unstable. This criterion for stability can be determined by

$$
\begin{equation*}
\frac{\left(l_{f}+l_{r}\right)^{2} C_{f} C_{r}}{V^{2}}+\mathrm{M}\left(l_{r} C_{r}-l_{f} C_{f}\right)>0 \tag{2.6}
\end{equation*}
$$

Several interesting facts can be observed from the stability criterion, in equation above. First, if the first term involving $1 / \mathrm{U}^{2}$ will be a large positive number than the criterion will be satisfied. This confirms the obvious idea that all vehicles are stable at very low speeds. Second, if the second term in above equation is positive, the car will surely be stable at any speed. The second term is positive when

$$
\begin{equation*}
l_{r} C_{r}>l_{f} C_{f} \tag{2.7}
\end{equation*}
$$

This condition is called as understeer while for oversteer properties the second term is become negative

$$
\begin{equation*}
l_{r} C_{r}<l_{f} C_{f} \tag{2.8}
\end{equation*}
$$

In order for the car to remain in a steady turn, the moments about the center of mass from the front and rear axles must sum to zero. Otherwise, constant angular momentum and angular velocity cannot be maintained (Karnopp, 2004). For vehicle to continue moving in intended direction, sum of forces in lateral direction from tires must be equal to mass times centripetal acceleration.

$$
\begin{equation*}
\Sigma \mathrm{F}_{\mathrm{y}}=\mathrm{F}_{\mathrm{yf}}+\mathrm{F}_{\mathrm{yr}}=\frac{\mathrm{MV}^{2}}{\mathrm{R}} \tag{2.9}
\end{equation*}
$$

For moment equilibrium by equating the front and rear moment the equation for front axle force

$$
\begin{equation*}
\mathrm{F}_{\mathrm{yf}}=\frac{\mathrm{W}_{\mathrm{f}}}{\mathrm{~g}}\left(\frac{\mathrm{~V}^{2}}{\mathrm{R}}\right) \tag{2.10}
\end{equation*}
$$

and rear axle force

$$
\begin{equation*}
\mathrm{F}_{\mathrm{yr}}=\frac{\mathrm{w}_{\mathrm{r}}}{\mathrm{~g}}\left(\frac{\mathrm{~V}^{2}}{\mathrm{R}}\right) \tag{2.11}
\end{equation*}
$$

where the $\left(\frac{\mathrm{V}^{2}}{\mathrm{R}}\right)$ is can be substitute with lateral acceleration.

### 2.5 HANDLING

The steady state handling characteristic can be classified to three categories which are neutral steer, understeer and oversteer. Neutral steer vehicle is defined as when it is accelerated with the steering wheel fixed, the turning radius remains the same.

For an understeer vehicle, when it is accelerated with the steering wheel fixed, the turning radius increases. As the vehicle is driven through a curve, the front wheels lose adhesion before the rear wheels, causing the front wheels to push toward the outside of the curve and make the turning radius increases. In this case, characteristic the lateral acceleration at the CG causes the front wheels to slip sideways to a greater then at the rear wheels (Karnopp, 2004). For an understeer vehicle, a characteristic speed $V_{\text {char }}$ is the speed at which the speed required at which the steer angle required to negotiate a turn is equal to $2 \mathrm{~L} / \mathrm{R}$ and identified as

$$
\begin{equation*}
V_{\text {char }}=\sqrt{\frac{g l}{K_{u s}}} \tag{2.12}
\end{equation*}
$$

Jazar (2007) states that the third handling characteristic is oversteer. For vehicle that is oversteer, when it is accelerated in a constant radius turn, the driver must decrease the steer angle. This cause the slip angle on the rear wheels to increase more by the lateral acceleration at the CG. As the vehicle is driven through the curve, the rear wheels lose adhesion before the front wheels, causing the rear of the vehicle to slide outward. CORSSYS- Datron (2001) mentioned as a result, the turning radius of the vehicle is smaller than it should be as compared to the rotation applied to the steering wheel. For an oversteer vehicle, a critical speed $V_{\text {crit }}$ is the speed at which the steer angle required to negotiate any turns is zero and identified as

$$
\begin{equation*}
V_{c r i t}=\sqrt{\frac{g l}{-K_{u s}}} \tag{2.13}
\end{equation*}
$$

### 2.6 ROLL MOMENT

Roll moment is important because load is transferred in the lateral direction in cornering due to the elevation of the vehicle CG above the ground plane. Roll moment also influenced the stability which the slip angle describes the direction difference between the wheel rim level and the moving direction of the wheel speed vector.

As the vehicle turns with greater lateral acceleration that will causes greater lateral force on the wheel, it will cause instability within the vehicle. The vehicle is considered as at the state of beginning of rollover while the wheel is started to lift-off. It is possible for a driver to quickly steering out the turn to reduce the lateral acceleration to a level that will return vehicle on the right position.

Theoretically, rollover becomes irrecoverable only when the roll angle becomes so large that the CG of the vehicle passes outboard of the line of contact outside wheels. This limit corresponds to the point in Figure 2.2. While, Table 2.1 shows the typical value of rollover threshold for various type of vehicle.


Figure 2.2: Rollover threshold for unstable vehicle

Source: Gillespie (2000)
Table 2.1: Typical value of rollover threshold for various type of vehicle

| Vehicle Type | CG Height <br> $(\mathbf{c m})$ | Tread <br> $(\mathbf{c m})$ | Rollover Threshold <br> $(\mathbf{g})$ |
| :---: | :---: | :---: | :---: |
| Sports Car | $45.7-50.8$ | $127.0-152.4$ | $1.1-1.5$ |
| Compact Car | $50.8-76.2$ | $127.0-152.4$ | $1.1-1.5$ |
| Luxury car | $50.8-61.0$ | $152.4-165.1$ | $1.2-1.6$ |
| Pickup truck | $76.2-88.9$ | $165.1-177.8$ | $0.9-1.1$ |
| Passenger van | $76.2-101.6$ | $165.1-177.8$ | $0.8-1.1$ |
| Medium truck | $114.3-139.7$ | $165.1-190.5$ | $0.6-0.8$ |
| Heavy truck | $152.4-215.9$ | $177.8-182.9$ | $0.4-0.6$ |

## CHAPTER 3

## METHODOLOGY

### 3.1 INTRODUCTION

This chapter is mainly explaining about the method used in performing experiments and also specified all the parameter in this study. First of all, is estimating the CG location that is a very important point that represents the whole vehicle body. Later, the readers are exposing to the experimental system which consists of the sensors used and also the most important device is data acquisition system. Going through the chapter, all the test method performed is simplified in this chapter. Finally, the chapter ended with method analyzing the data and how to present the results.

### 3.2 CENTRE OF GRAVITY ESTIMATION

First of all, the CG location has to be estimate in collecting the vehicle CG performance. The CG height and distance of CG location to front axle is going to estimate as the CG of the track width can be obtained directly from the track. The important values in estimating the CG is the front and rear weight of the vehicle. A dynamic scale for vehicle had been used as it is an appropriate scale to weigh vehicle. As shown in Figure 3.1, a vehicle is going to be weighing on a dynamic scale.


Figure 3.1: A dynamic scale for weigh vehicles at PUSPAKOM Kuantan Branch.

As mentioned in previous chapter, CG location is varied with different load because of weight distribution. Thus, four configurations of passenger in vehicle had been proposed as in appendix in varying the load distribution. The front and rear weight is measured and recorded for each configuration. The four configurations of passengers are displayed in Appendix B.

### 3.3 EXPERIMENTAL SYSTEM

### 3.3.1 Xsens MTi

The sensor used in this project is Xsens MTi that is embedded with processor capable of calculating roll, pitch and yaw in real time, as well as outputting calibrated 3D linear acceleration. As mentioned by Xsens (2009), the MTi is a gyro-enhanced Attitude and Heading Reference System (AHRS). The MTi is an excellent measurement unit for stabilization.

The coordinate system used is the right handed Cartesian co-ordinate system as defined in Figure 3.2. This co-ordinate system is body-fixed to the device and is aligned well to the external housing of the MTi.


Figure 3.2: MTi with coordinate fixed system

The output orientation can be presented in different parameterizations such as unit quaternions, roll, pitch, yaw and rotation Matrix. A positive is defined according to the right hand rule (corkscrew rule) means a positive rotation is defined as clockwise in the direction of the axis of rotation as shown in Figure 3.3. In collecting the vehicle CG performance, the Mti is mounted approximately at the CG of the car. This MTi then is connected to the DEWETRON for data acquisition by using RS-422 MTi cable, an USB-serial data and power cable that have converter.


Figure 3.3: Right hand rule means a positive rotation is defined as clockwise in the direction of the axis of rotation.

### 3.3.2 Test Car

The test vehicle used for this project is Proton Persona Elegance 1.6 (MT), a 4door sedan provided by Universiti Malaysia Pahang shown in Figure 3.4. Table 3.1 show the vehicle specification of the test vehicle.

Table 3.1: Vehicle specification for Proton Persona Elegance 1.6 (MT)

| Vehicle Properties | Details |
| :--- | :---: |
| Make | Proton |
| Model | Persona Elegance 1.6 (MT) |
| Bodystyle | 4-door sedan |
| WheelBase (mm) | 2600 |
| Overall Length (mm) | 4477 |
| Overall Width (mm) | 1725 |
| Overall Height (mm) | 1438 |
| Front Track (mm) | 1475 |
| Rear Track (mm) | 1470 |
| Min. Turning Radius (m) | 0 |
| Kerb Weight (kg) | 1195 |
| Ground Clearance (mm) | 0 |
| Steering | Rack \& Pinion, Hydraulic Power Assisted |
| Front Suspension | MacPherson strut |
| Rear Suspension | Multi-Link, Stabilizer Bar |
| Front Brakes | Vent Disc |
| Rear Brakes | Drum |
| Std. Tyre Size | 190/60 R15 |
| Std. Wheel Size | 15 |



Figure 3.4: UMP Test Car

### 3.3.3 Data Acquisition System (DAS)

DEWESoft 6 is the fast and easy to use data acquisition software develops by DEWETRON. Dewesoft is taking a major role in all kinds of data recording applications in automotive industry, especially in development laboratories and test facilities, where the ability to acquire data from all different sources creates major advantage. This software not only about standard interfaces like analog, digital, counters, CAN, GPS and video channels, but made to support special devices like gyro platform from Genesys or torque wheels from Kistler, everything of course perfectly synchronized with other sources.

Figure 3.5 show the user interface of DEWESoft 6 and this software offers 32bit data interface for acquisition, storage and processing. This software also has high performance data acquisition, online display, online mathematics and filter functions. DEWESoft is easy because it has plug-in technology for user extensions, fast and comfortable data export to other applications.


Figure 3.5: DEWESoft display screen

### 3.4 PRELIMINARY TEST

The preliminary test is performed in Universiti Malaysia Pahang (UMP) Pekan Campus. This test is performed to determine the maximum speed for each test and the location of the testing depends on the suitability of the testing. The safety precaution procedure such as clean the sand on the road, ensure the traffic condition safe and fasten the seat belt during testing is based on this preliminary test. The vehicle performance noted during the preliminary test and the optimum distance to achieve the speed were recognized. The maximum speed for each gear was determined as in the Table 3.2.

Table 3.2: Maximum speed for each gear to shift

| Gear to be shifted | $\mathbf{2}$ | $\mathbf{3}$ | $\mathbf{4}$ | $\mathbf{5}$ |
| :---: | :---: | :---: | :---: | :---: |
| Maximum Speed (km/hr) | 20 | 40 | 60 | 80 |

### 3.5 STEADY STATE CORNERING TEST

Cornering behavior is important mode of handling. Handling is responsiveness of a vehicle to driver input. Driver vehicle is a closed loop system, but for characterization open loop behavior is used. DEWETRON (2009) states that the steadystate circular test is an open-loop test maneuver to determine the driving behavior of passenger cars or light trucks. In particular, this test method aims to identify the vehicles road-holding ability, its self-steering properties and comfort.

There are three methods to measure the steady-state circular driving behavior which are constant radius, constant load and constant speed. To ensure good test results, the steady-state between the increments should last at least 3 seconds. Attention should also be paid to an even tire wear which is why the tests should be performed in alternating driving directions.

The first method of steady state cornering test is constant radius. In measuring the roll and yaw rate, the cornering radius were maintained constant while the vehicle speed is varied. This test had been varied with four different radiuses with four different speeds for each radius. For this experiment purpose the test was conducted at two different roundabouts in UMP. R1 is the inner lane of first roundabout while the outer lane was named as R2. R3 and R4 are named for the roundabout 2 with inner and outer lane respectively as shown in Figure 3.6. Based on preliminary results, the suitable speed for this test were $25 \mathrm{~km} / \mathrm{h}, 30 \mathrm{~km} / \mathrm{h}, 40 \mathrm{~km} / \mathrm{h}$ and $50 \mathrm{~km} / \mathrm{h}$ but for the R3 and R4 speed at $50 \mathrm{~km} / \mathrm{h}$ is not tested cause of safety condition of the vehicle. Each experiment was run five times for a full complete circle of a radius with constant speed.


Figure 3.6: Test location in UMP for roundabout 1 and roundabout 2

As for the constant load method, the test was performed at R1.The load is placed at the boot of the vehicle with total weight of the passengers are 132 kg while the driver weight is 80 kg . Both passengers and driver weights are remains constant for each different test. The load was varied with two different weights which were 25 kg and 50 kg . The test was run at speed as the same as R1 in constant radius method. The vehicle speed was maintained constant for each experiment and run for five times for a full complete circle of a radius as can be seen in GPS.

### 3.6 LANE CHANGE TEST

Lane change test is significance of overtaking maneuver. The Government of South of Australia (2005) states that lane change procedure consists of driving a vehicle through a set track, which simulates a lane change maneuver. The vehicle is driven from the initial lane to another parallel lane and back again to the original lane.

This test is conduct to study the effect of roll and yaw on vehicle body in rapid changes of steer angle. The only parameter that had been varied for this test is the speed. Speed of $30 \mathrm{~km} / \mathrm{h}, 40 \mathrm{~km} / \mathrm{h}$ and $60 \mathrm{~km} / \mathrm{h}$ had been chosen and the speed is maintained constant while in the track.

The track setup is based on Figure 3.7. The black dot is representing cone, the cone must be placed on the straight line and must be parallel to each others. The vehicle is driven with constant speed and once the vehicle enters the section ithe recording data was started. The vehicle is driven along the cone path. The recording data is being stopped, when the car is on the section $v$. The recording is considered failed when the vehicle is moving more than the velocity range. The test for each speed is repeated in five times.


Figure 3.7: Lane change track setup

### 3.7 ON ROAD TESTING AND DATA COLLECTION

Before the test was started all this conditions and steps had been taken as intial procedure. As the vehicle engine started fuel level is be checked to avoid the vehicle stopped when test is performed. The power supply is switch on so that the system is started to run. Ensure the functionality of the computer and the video camera and if one
of the devices is not properly function, check the connection and the wiring. Opened the DEWESoft software and ensure the camera is working well on the software. Rename the file before start the test and the time for each data recorded is noted separately to make the data collection is easier and to distinguish the failed run from the fine run.

After initial procedure had been done, the vehicle is driven to the test track as mentioned in each testing above. Data is collected by storing it in the DEWESoft as soon as the test starts. As mentioned in each test, the storing data is taken from the entrance and exit of the track. For the roundabout, the data is collected for a one complete circle as can be seen in the GPS shown in Figure 3.8.


Figure 3.8: Starting and stopping point for a full complete circle in GPS

### 3.8 POST - PROCESSING METHOD

Mainly, Flexpro Version 7.6 was used in post-processing method for data analysis and presentation. Flexpro incapable to handle a single data. Thus, helps from Microsoft Office Excel 2007 (Excel) is being used. Flexpro had more advantage compared to Excel. Flexpro can give a superior graphing and capabilities in handling
data. Table 3.3 shows the comparison between Flexpro and Excel. Excel workbooks can be opened directly in Flexpro which give extra advantage of Flexpro.

Table 3.3: Comparison between Microsoft Office Excel 2007 and Flexpro 7.6

Microsoft Office Excel 2007
Manage data in worksheet Incapable to handle large data Incapable to handle data with void value
Perform cell-by-cell data analysis. However, analysis can be slow if many cells used.

Flexpro 7.6
Manage data in dataset
Capable to handle data up to 2GB
Capable to handle data with void value
Data sets use to handle large amount of data easily.

Here, the data is imported from DEWEsoft as signals. Three data had been reduced and exported from DEWEsoft which are vehicle velocity (Velocity), roll rate (GyrX), and yaw rate (GyrZ). The average Velocity is taken from the GPS while the RMS value of GyrX and GyrZ are taken from the MTi. RMS value is used as the GyrX and GyrZ values were very small. These three signals are analyzed before representing it in graphs.

There are five runs in an experiment. Thus, the best run among the five was taken before furthered to the next analysis. In determined the roll and yaw angle, data is taken from GyrX and GyrZ. Mean value of each angle and velocity is taken by using analysis object in Flexpro. Then, the roll angle and yaw angle value is plotted versus with velocity in a graph.

## CHAPTER 4

## RESULTS AND DISCUSSION

### 4.1 INTRODUCTION

Chapter 4 is discussing the results obtain after analysis made. The result of CG variation is shown here as the important point to be determining in this study. This chapter is furthered the results by soma discussion made based on the graph shown. Beyond this chapter a conclusion is made to conclude the results achieved.

### 4.2 CENTRE OF GRAVITY

Objective of this study is to collect the vehicle's CG performance in term of moment and movement data. Thus, it is a must to find the CG location by substituting value in the Eq. (2.2) and Eq. (2.4). The configuration of passenger on method in weighing the car is attached in the Appendix B. Table 4.1 show the results obtain after calculation had been made.

Table 4.1: Location of centre of gravity height and centre of gravity distance from front axle with it respecting configuration

| Configuration | $\boldsymbol{l}_{\boldsymbol{f}}(\boldsymbol{m m})$ | $\boldsymbol{h}_{\boldsymbol{v}}(\boldsymbol{m m})$ |
| :---: | :---: | :---: |
| 1 | 1078.05 | 542.13 |
| 2 | 1071.75 | 523.19 |
| 3 | 1122.30 | 501.26 |
| 4 | 1163.64 | 479.33 |

While for transversal position of CG, the value is 736.25 mm . From analysis made on the distribution weight of the vehicle, it is found that the weight ratio distribution of front to rear is $60: 40$. The MTi was mounted at the forth configuration as the experiment is perform with the passenger configuration as shown in Appendix B. The weight of driver and total weight of passenger at the rear seat and was remain constant as during the test which are 212 kg .

### 4.3 STEADY STATE CORNERING

It is known that the car is understeer for all steady state cornering test where the gradient is $0.18 \%$. By substituting this value in Eq. (2.12) the $\mathrm{V}_{\text {Char }}$ of this vehicle is $42.85 \mathrm{~km} / \mathrm{h}$.

### 4.3.1 Constant radius

Firstly is to define the all the four radius, by taking the distance reading from GPS. Table 4.2 list all radius and average distance from GPS.

Table 4.2: GPS distance and radius of roundabout

| Radius | Average Distance <br> $(\mathbf{m})$ | Radius <br> $(\mathbf{m})$ |
| :---: | :---: | :---: |
| R1 | 325.50 | 51.80 |
| R2 | 340.00 | 54.11 |
| R3 | 164.20 | 26.13 |
| R4 | 182.40 | 29.03 |

Result of the analysis is shown in Figure 4.1 below. As shown in the Figure 4.1, it can be categorized into two groups which each of the group represent a roundabout. In roundabout 1 which the radius are greater than 50 m , the vehicle is not much to roll as the roll angles are smaller than the roundabout 2 .


Figure 4.1: Relationship between Roll $\left({ }^{\circ}\right)$ and Velocity $(\mathrm{km} / \mathrm{h})$ for steady state cornering test with constant radius

As can be seen, at $25 \mathrm{~km} / \mathrm{h}$, the roll angle is about the same range from 0.01 to $0.02^{\circ}$. The steering input for those radiuses is about the same that results the roll rate range from -0.012 to $0.012 \mathrm{rad} / \mathrm{s}$ with a point is out of the range. At $30 \mathrm{~km} / \mathrm{h}$, the body angle for R 1 is $0.03^{\circ}$ while body angle for R 2 is $-0.025^{\circ}$. The body angle was turn to other direction but yet the deflection is not huge. The roll rate average for R 1 is -0.05 $\mathrm{rad} / \mathrm{s}$ meanwhile R 2 roll rate is $-0.07 \mathrm{rad} / \mathrm{s}$. It is simplified that as the small difference of roll angle is not affected by the roll rate except the direction of vehicle body movement. The lateral acceleration made by R2 is lesser than R1.

When the vehicle speed was at $40 \mathrm{~km} / \mathrm{h}$, the difference between the body roll angle of R 1 and R 2 is $0.035^{\circ}$ which the vehicle body when corner at the R 2 roll more. It is verified that roll rate at the R 2 is greater than the roll rate at the R 1 . In the final vehicle velocity that had been tested which the car was driven at $50 \mathrm{~km} / \mathrm{h}$ at the constant speed, the roll angle for both radiuses are about the same. The value is very near to $0^{\circ}$ where this is the highest possibility of the car to be in stable a condition. Amazingly, the roll rate range for R1 and R2 at $50 \mathrm{~km} / \mathrm{h}$ and $25 \mathrm{~km} / \mathrm{h}$ is the same. The curve made by
roundabout 2 for R3 and R4 is quite similar and can be said that it is identical. There is not much difference for the roll angle when turn at R3 and R4 at $25 \mathrm{~km} / \mathrm{h}$. The body turn exactly at $-0.125^{\circ}$ for R 3 as for the R 4 , the roll angle made is exactly at $-0.10^{\circ}$. The difference between both angles is only $0.025^{\circ}$. It can be concluded that at $25 \mathrm{~km} / \mathrm{h}$, although the vehicle make a cornering at radius with the range of $\pm 3 \mathrm{~m}$, the yaw and roll angle give not much difference.

At $30 \mathrm{~km} / \mathrm{h}$, the roll angle of R4 and R1 is the same which the angle made by the vehicle to roll is $0.05^{\circ}$. At the same velocity, roll angle made by the vehicle body is $0.075^{\circ}$ where the difference made with R4 is the same as at $25 \mathrm{~km} / \mathrm{h}, 0.025^{\circ}$. The final testing of steady state cornering, the speed reach for roundabout 2 is $40 \mathrm{~km} / \mathrm{h}$. Based on the graph, it shows that the two value give greater difference. Roll angle at R4 is $0.075^{\circ}$ where as for R 3 the angle made is $0.175^{\circ}$

Same as the Figure 4.2, the graph shown in Figure 4.2 seems to be identical for two different roundabouts. At $25 \mathrm{~km} / \mathrm{h}$, the deviation of yaw angle made by R1 and R2 do not give much difference where as R3 and R4 are the same. This is because as stated before the radius for $\pm 3 \mathrm{~m}$ does not affect the vehicle performance much. Increasing the vehicle speed to $30 \mathrm{~km} / \mathrm{h}$, the vehicle is still can be controlled by driver because not much angle made by vehicle at R3 and R2. The value of yaw at both radius is approximately to $0^{\circ}$ where can be stated there that the car is in the most stable condition. R1 and R4 the characteristic of yaw at this speed is the same as roll because the angle made is approaching each other.


Figure 4.2: Relationship between Yaw $\left({ }^{\circ}\right)$ and Velocity (km/h) for steady state cornering test with constant radius

As the vehicle goes to $40 \mathrm{~km} / \mathrm{h}$, the response between steering and yaw angle of the body is the same. It goes the same direction but differ in the value. R4 has the greatest value of yaw angle which is $0.32^{\circ}$ meanwhile R 2 give smaller response to the vehicle body which is $0.01^{\circ}$. Other two value for is located between these two value which are almost $0^{\circ}$ and $0.15^{\circ}$ for R3 and R1 respectively. Test at roundabout 1 had been extended to $50 \mathrm{~km} / \mathrm{h}$. The value for both radiuses is reaching towards each other approaching to $0^{\circ}$. As going through the graph in the appendix the response between the steer angle and vehicle yaw angle is the same and identical except at $50 \mathrm{~km} / \mathrm{h}$. Eventhough the angle is $0^{\circ}$ but the yaw rate had some disturbance where the vehicle body does not give exact response to the steering. In analyzing the curve, at speed below $40 \mathrm{~km} / \mathrm{h}$, the points share the same quadratic curve while at $50 \mathrm{~km} / \mathrm{h}$ the points is on the other curve which results in different gradient and coefficient.

### 4.3.2 Constant load

Another experiment for steady state cornering is constant load. In Figure 4.3, as the load increase, the CG location also moved. This behavior is much closed related to the vehicle body where the CG represents the rigid body of vehicle at a point. Based on the graph, the roll angle is increasing from $25 \mathrm{~km} / \mathrm{h}$ until the velocity reach $30 \mathrm{~km} / \mathrm{h}$ means the car is deflected in a small angle compared the angle of $25 \mathrm{~km} / \mathrm{h}$. This is also due to the increasing of lateral force as the velocity increase. The vehicle is deflected to the right as represents as the positive value in the graph below for vehicle with no load and 25 kg while vice versa for 50 kg load. This also shows that vehicle with load less than 25 kg , the vertical force on the left side of the body is greater than right side of the vehicle and the load is distributed more on the left side while vice versa for load greater than 50 kg .


Figure 4.3: Relationship between $\operatorname{Roll}\left({ }^{\circ}\right)$ and Velocity (km/h) for steady state cornering test with constant load

As the velocity increase to $40 \mathrm{~km} / \mathrm{h}$, the roll angle of 25 kg additional load is increase while for vehicle with no additional load and 50 kg load the roll angle decrease rapidly. For vehicle with no load, the vehicle tries to overcome the instability by deflecting the vehicle roll angle to the other direction even the lateral force is greater. For vehicle loaded with 25 kg and 50 kg , the angle of the vehicle is deflected greater than before where for 25 kg the direction of roll angle increase with positive value and for 50 kg load the roll angle increase with negative value. At this speed, the vehicle does not react to overcome the instability because the signal received by the body is bad as it is approaching $\mathrm{V}_{\text {Char }}$. The lateral force acting on the body is greater than before as the velocity increased for the same mass. The load distribution also remains on the left side of the body is greater than right side of the vehicle for 25 kg load and the load is distributed more on the left side while the load is distributed more on the right side for 50 kg additional load of vehicle. For vehicle with no load, the load distribution is equal for both sides which make the vehicle turn in stable state then with loaded vehicle.

Then, the vehicle speed is increased till reach the maximum value of $50 \mathrm{~km} / \mathrm{h}$ taking R1 as the turning radius. Here, the roll angle curve for vehicle without additional load is deflected to $0^{\circ}$. For 25 kg and 50 kg load the roll angle is decrease rapidly far away from $0^{\circ}$. As mentioned in above paragraph the vehicle with no load tries to overcome the instability. Thus, the curve plotted is sinusoidal curve which we can predict the angle for velocity greater than $50 \mathrm{~km} / \mathrm{h}$. While the 25 kg and 50 kg load the performance of CG are bad as the roll angle does not react to overcome the instability. The vehicle had achieved limit as the vehicle reach $40 \mathrm{~km} / \mathrm{h}$.

For the yaw angle, results shown as in Figure 4.4. The yaw angle for vehicle with no load and 25 kg load is about the same at $25 \mathrm{~km} / \mathrm{h}$ while for 50 kg additional load, the yaw angle is near to $0^{\circ}$ and it is more stable at this velocity compare with other vehicle loading. As the vehicle speed up to $30 \mathrm{~km} / \mathrm{h}$, the yaw angle increase to $0.10^{0}$ for vehicle with no load. For 25 kg and 50 kg load the yaw angle decrease to $-0.05^{\circ}$ and $0.13^{\circ}$ respectively. This is due to the incremental value of lateral force that cause by the weight and velocity.


Figure 4.4: Relationship between $\operatorname{Yaw}\left({ }^{\circ}\right)$ and Velocity (km/h) for steady state cornering test with constant load

The yaw angle for loaded vehicle is increased to a maximum value of $0.17^{\circ}$ for 25 kg and increase to $-0.03^{\circ}$ for 50 kg load as the vehicle speeding up to $40 \mathrm{~km} / \mathrm{h}$. These are different to vehicle with no load which decreases to $0.035^{\circ}$ where it is approaching to $0^{\circ}$. The positive yaw angle made by the 25 kg load and negative yaw angle made by 50 kg load are to overcome the greater lateral force made by the vehicle.

As the velocity increase to $50 \mathrm{~km} / \mathrm{h}$, the yaw angle of the vehicle for all load are decrease rapidly. This is due to the instability of the vehicle because had over the $\mathrm{V}_{\text {Char }}$ which is approximately at $43 \mathrm{~km} / \mathrm{h}$. The lateral force is the highest at this moment because this is the maximum speed in this test. To prevent from accident, the yaw angle of vehicle body is deflected to negative direction.

### 4.4 LANE CHANGE TEST

Lane change test is another driving maneuver that been tested in this experiment. As the results established in Figure 4.5, the two curves of roll and yaw is identical but
have different constant value. Roll made by the body at $30 \mathrm{~km} / \mathrm{h}$ is $-0.25^{\circ}$ whereas the yaw is $-7.5^{\circ}$. The roll angle is smaller than yaw angle, same as the rate the roll rate is from -0.027 to $0.016 \mathrm{rad} / \mathrm{s}$ and the yaw rate is from -0.04 to $0.12 \mathrm{rad} / \mathrm{s}$.


Figure 4.5: Relationship between $\operatorname{Roll}\left({ }^{\circ}\right)$ and $\operatorname{Yaw}\left({ }^{\circ}\right)$ with Velocity $(\mathrm{km} / \mathrm{h})$ for lane change test

Roll and yaw is quite similar to each other where the value approximately at $0.10^{\circ}$. These show that roll and yaw having the same behavior and are close related as the value is the same. All the graph of steer angle, roll rate and yaw rate versus with time gives and identical graph referred as the input (steer) of vehicle gives the same output (roll rate and yaw rate) performance at the body while is overtaking a car at 40 $\mathrm{km} / \mathrm{h}$.

Even the value is different at $60 \mathrm{~km} / \mathrm{h},-0.28^{\circ}$ for the yaw angle and $0.20^{\circ}$ for the roll angle, the vehicle body is gone through the same path as steering input. As can be seen in appendix those two graphs are similar but slightly differ for the roll rate.

It can be concluded the limits of this vehicle performance is at about $40 \mathrm{~km} / \mathrm{h}$. Based on the all graph in this chapter, above $40 \mathrm{~km} / \mathrm{h}$ the curve is going downward. Where all the roll and yaw angle is deviated far away from the average value. This
limitation can be compared with the theoretical value by substituting the understeer gradient, $0.18 \%$ in Eq. (2.12) to the $\mathrm{V}_{\text {Char }}$ of this vehicle. On some calculation the $\mathrm{V}_{\text {Char }}$ is equal to $42.85 \mathrm{~km} / \mathrm{h}$. In supporting this conclusion, the preliminary test made had shown that beyond this limit the car is unstable as the vibration increases.

## CHAPTER 5

## CONCLUSION AND RECOMMENDATIONS

### 5.1 CONCLUSION

Overall, the first objective of this study had been achieved by done the on road testing which are steady state cornering with constant radius, load and lane change test. The second objective also had achieved as the finding shows the roll and yaw limit in these three tests. As can be seen from the results, the vehicle gives a good performance at speed below the $42.85 \mathrm{~km} / \mathrm{h}$. Beyond this speed, it is hard to find the characteristic and predict the movement of the car. In chapter 4 it had been analyzed that above the critical speed the performance of CG is not well distributed. This put the vehicle in an unstable condition which can cause the vehicle to accident.

From analysis made for steady state cornering of constant radius the roll limit is at the R3 which the roll angle made by the vehicle was $0.16^{\circ}$ while for the yaw angle is limited at R4 where the angle made by the vehicle is $0.32^{\circ}$. For the constant load the roll had limit when the vehicle make turn at R1 with 50 kg additional load. The roll angle made was $0.25^{\circ}$. As for lane change test, the roll angle limit which is $0.19^{\circ}$ is achieved at the maximum speed of $60 \mathrm{~km} / \mathrm{h}$. Contrast with the yaw, the limit is at minimum speed of $30 \mathrm{~km} / \mathrm{h}$ which the yaw angle made by the body is $-1.16^{\circ}$.

### 5.2 RECOMMENDATIONS

In acquiring more accurate results, this study had to be perform with more precise location of CG. This can be done by measure the rear axle weight when the front axle is lifted up. Ensure that the vehicle is not falling and stable when measuring.

The gyroscopic effect can be studied by comparing the load configuration. This study only considers the placement of load at the boot of the vehicle. In future, this load can be place at the rear passenger seat whether on the left or right sides. The unpaved road condition also can be perform. The roll and yaw effect can be compared with the paved road as in this study.

Besides that, the pitch effect also can be studied because this study only focuses on the effect of roll and yaw. It is also recommended to the future researcher to continue this study by experimenting with other driving maneuver such as slalom test, Fishhook test, single change maneuver, acceleration and deceleration test.

## REFERENCES

Cain, S.M. and Perkins, N.C. 2009. Steady State Handling Charecteristics of a Bicycle. Technical Report.University of Michigan.

Denton, T. 2006. Advanced Automotive Fault Diagnosis.USA: Burlington.

DEWETRON. 2010. Steady State Circular Driving Behaviour Measurements According to ISO 4138. DEWETRON Ges.m.b.H. 02/2010

Genta, G. and Morello, L. 2009. The Automotive Chassis Volume 2: System Design. Springer.

Gillespie, T.D. 2000. Fundamentals of Vehicle Dynamics. USA: SAE.

Government of South Australia. 2005. Lane Change Maneuver Test Procedures. FACT Sheet. (MR807 05/06)

Hirschberg, W. 2003. Basics of Vehicle Dynamics Measurement and Analysis. Slide. Styria: Graz University of Technology

Jazar, R.N. 2007. Vehicle Dynamics: Theory and Application. New York: Springer.

Karnopp, D. 2004. Vehicle Stability. California: Marcel Dekker.

Reimpell, J., Stoll, H. and Betzler, J.W. 2001. The Automotive Chassis: Engineeering Principles. New York: Butterworth- Heinemann

The New Persona Elegance. 2010. Brochure. Shah Alam: Proton Edar

Weimert, K. 2002. Understanding ESP. Slide. Wetzlar: CORRSYS-Datron

Xsens. 2009. MTi and MTx User Manual and Technical Documentation. Xsens Technology B.V.

## APPENDIX A1

## GANTT CHART FOR FINAL YEAR PROJECT 1

| NO | ITEM\WEEK | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | Literature Review |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 2 | Rollover Theory \& Related Formula |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 3 | Gyroscope Study |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 5 | Gyroscope Installation Procedure |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 6 | Data Acquisition System Installation Procedure |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 7 | Road Condition Evaluation |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 8 | Driving Mode Factor |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 9 | Velocity Range Selection |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 10 | Design of Experiment |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 11 | FYP 1 Presentation |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

## APPENDIX A2

## GANTT CHART FOR FINAL YEAR PROJECT 2

| NO | ITEM\WEEK | 1 | 2 | 3 | 4 |  | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | Literature Review |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 2 | Installation \& experiment setup |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 3 | Steady state cornering with constant radius test |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 4 | Steady state cornering with constant load |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 5 | Lane change test |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 6 | Centre of gravity moment and movement analysis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 7 | Final Report Preparation |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 8 | FYP 2 Presentation |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

## APPENDIX B

## PASSENGER CONFIGURATION IN WEIGHING VEHICLE

1) Vehicle without passenger and driver

2) Vehicle loaded with driver and a passenger

3) Vehicle loaded with driver
and passenger


## APPENDIX C1

EXPERIMENTAL RESULT FOR STEADY STATE CORNERING AT R1


## APPENDIX C2

EXPERIMENTAL RESULT FOR STEADY STATE CORNERING AT R2


## APPENDIX C3

EXPERIMENTAL RESULT FOR LANE CHANGE TEST

|  |  |  |
| :---: | :---: | :---: |
|  |  |  |
|  |  |  |
|  |  |  |

