Cornering Stability Analysis of Double Decker Bus at KM15 of Cameroon Highlands – Simpang Pulai Road

by

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ABSTRACT

Double decker buses are widely used on Malaysian road today because of its ability to increase the profits for the coach operatorsthrough the reduction of fuel consumption and its operating maintenance cost as well as the ability to carry more passengers per trip compared to single deck buses. Because of the popularity of using double decker buses for a long distance travel is keep increasing, it has become a major concern in road safety since many fatal accidents happened involving this type of vehicle. On 20th December 2010, Malaysia was shocked by news of the horrific accident that resulted 27 passengers killed out of 37 passengers at KM15 Cameroon Highlands- SimpangPulai road. This is the worst historical road accident in the nation's history. The accident started after the vehicle hit a divider and overturned on its way down from Cameron Highlands. It landed on its roof in a ditch about 51m away from the divider. The bus was heading to Kuala Lumpur from Cameron Highlands. The Malaysian Institute of Road Safety (Miros) has found double decker buses to be not suitable for long distance travel especially on winding, mountainous regions with steep slopes roads like in Sabah, Sarawak and Cameroon Highlands as they have high centre of gravity. There are many possibilities of the factor to happen. To get the confirmation of the exact factor of the accident, an analysis is carry out at the place where the accident is happened. Method used in the analysis is by visiting the site, calculation of the slip and tip angle and speed of the vehicle, modelling and simulation of double decker bus using Adams Car software.

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ABBREVIATIONS

CG	=	Centre of Gravity
MIROS	=	Malaysian Institute of Road Safety Research
KM	=	Kilo metre
FYP	=	Final Year Project

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND OF STUDY

Double decker buses have been widely used since many years ago for many countries such as in London. The purpose of this bus is to carry more passengers in one time and to reduce the fuel consumptions and therefore less maintenance is required. Overseas countries such as in London has used this bus to carry tourists to show them the beauty of their country but the bus is only run on a flat road. Different situation happened in Malaysia where the double decker bus is used for a long distance travel and run on all the road conditions. There are some advantages and disadvantages of using this vehicle for a long distance travel. The advantages are it has the ability to cut down the cost for the vehicle maintenance and also fuel consumption by carrying more passengers at one time. Meanwhile, the disadvantages are it has higher centre of gravity compared to other vehicle. If the high-deck bus is designed with full headroom in both decks, there is a possibility for the bus to be top heavy and become unstable and unsafe, except with the use of a counterweight system. This can lead to serious high-deck bus accidents if the use of this type of commercial vehicle keeps on increasing, unless safety countermeasures are considered and implemented. Figure 1.1.1 below shows that for the five-year period (2000 – 2005), there was a 25.35% increments in accidents involving commercial vehicles especially buses and lorries with buses experiencing more than a 100% increment (from 1,040 in 2000 to 2,405 in 2005).Most of the bus crash victims are innocent victims such as the passengers and other third party road users.[1]

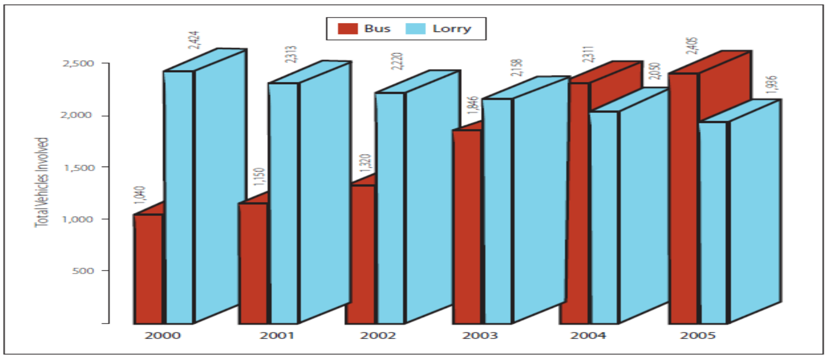


Figure 1: Bus and lorry accident statistics in Malaysia (2000-2005)

For this project, the analysis is carried out at KM15 Cameroon Highlands-SimpangPulai road. At this point where the most tragic accident happened in last three years involving double decker bus had cause 27 out of 37 passengers killed. The map below is taken from google map showing the route from Cameroon Highlands to SimpangPulai. It can be seen that there are many curvy and sharp bend road all the way to SimpangPulai. The point A is the point where the double decker bus started to move and the point B is the point where the accident happened.

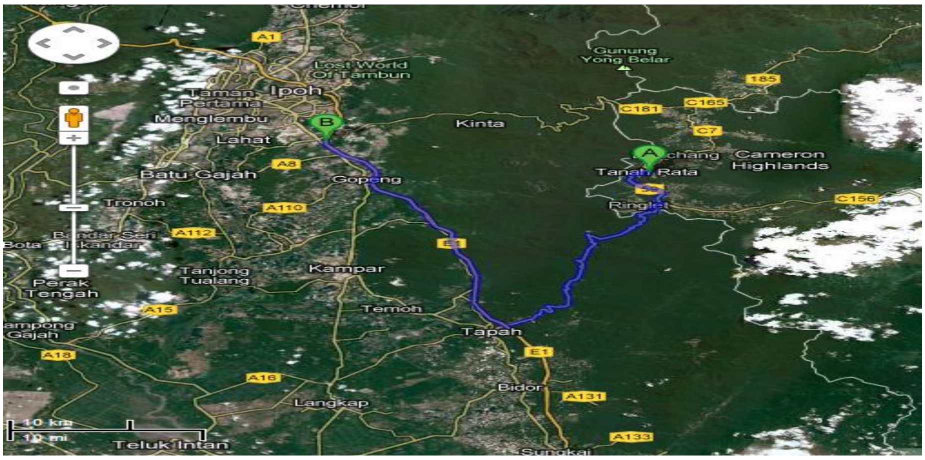


Figure 2: Map of Cameroon Highlands-SimpangPulai Road [2]

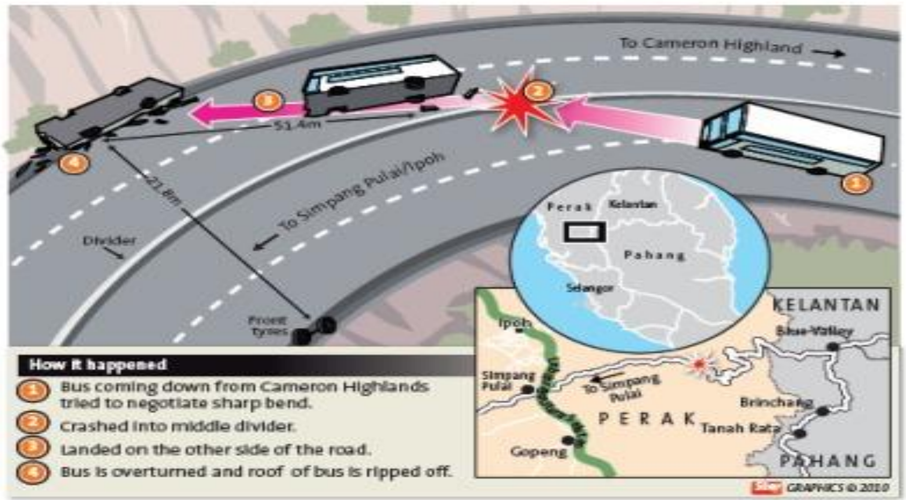


Figure 3: The layout of the accident[3]

Figure above shows the layout of the accident. The bus is coming down from Cameroon Highlands and it tried to negotiate sharp bend but the bus had lost the control and becomes unstable causes it to hit the divider and overturned into the ditch. The bus landed on its roof at the opposite road. Therefore, an analysis of cornering stability of double decker bus on that road is carry out to reveal the causes of the accident to happen.

1.2 PROBLEM STATEMENT

Due to many fatal accidents happened which has result to a large number of passengers killed, a few causes have been identified. The causes can be divided into two sections, the design of double decker bus and road design. For the design of double decker bus, one of the problems have been identified which is the centre of gravity of the bus is higher compared to single deck bus causes it to unstable when the driver driving in a fast motion. For the road design, the steep slope with the sharp corner at KM15 Cameroon Highlands- SimpangPulai road is not suitable for a heavy vehicle which has higher CG to pass through the road. It should be clear that every vehicles have its own driving limitations. This is affected by many things like the shape, weight, and height of the vehicle. Though there are many studies on the stability of buses but not many were done for double decker buses.

1.3 OBJECTIVE

The main objective of this study is to calculate the stability of the double decker bus at cornering road in KM15 Cameroon Highlands-SimpangPulai road by using calculation of slip and tip angle equations with regard to bus speed and simulation by using Adams Car software to validate the result.

1.4 SCOPE OF STUDY

For this cornering stability analysis for double decker bus, it will be done in two parts. The first one would be the preliminary research of the basics of the double decker bus dimensions and road design theories. During this period it is essential to gain as many knowledge as possible to smoothen the project progress. All of this will be done in final year project 1.

The second part of the project is where the experimentation is done. The model is used to run the cornering stability experiment. After the experiment is done the data is collected at the experiment site. The data will then interpret so that it could be turned into results. The result is than validated using the Adams Car and MATLABs software by MSC Software Company. The simulation is used to validate whether the calculation done on the data interpretation is correct or there is different value for the experiment. This will be done in final year project 2.

The parameters have been narrowed down into two categories:

Road Design

1. Radius of curvature of the road
2. Degree of the slope road

Double Decker Bus

3. Centre of gravity of double decker bus
4. Speed limit of double decker bus
5. Slip angle of double decker bus when it goes overspeed
6. Tip angle of double decker bus when it touch the divider

1.5 RELEVANCY AND FEASIBILITY

Since double decker buses are becoming more popular nowadays as they increase the passengers capacity and reduce the fuel consumptions, the coach operators must ensure that their buses are safe to be used for a long distance travelling by checking the maintenance regularly and meeting with the bus's driver oftenly to motivate them to work with high commitment where the safety comes first. These are very important in order to reduce the number of accident happen. By having cornering stability analysis for double decker buses, people all around the world get to know the limitations of the double decker buses when it go through the corner section. This analysis would help to raise the awareness and hopefully the accident number will reduce successfully.

This project analysis is divided into three parts which are data collection, computer software based and a few calculations. It could be finished in the given time and the longest part would be preparing the double decker bus model and simulation by using Adams Car Software. The objective will achieve if the project runs smoothly without any delay.

CHAPTER 2: LITERATURE REVIEW/THEORY

Slip Angle and Vehicle Rollover

2.1 Slip Angle

Slip angle is the difference between the direction a vehicle is travelling and the direction that the body of the vehicle is pointing.Slip angle is related to the lateral load or cornering force of the tire. As lateral loads increase due to higher cornering speeds, tires creep to the outside of the turn and therefore move in a direction that is different from their heading.

Generally, cornering force increases as the vertical load increases, but the increase is not proportional to the load. The tire's ability to develop cornering force, in relation to its vertical load, is known as its "cornering coefficient". Tire cornering coefficient declines as vertical load increases. However, the inertial forces of a vehicle in a turn increase in proportion to the increase in weight. Consequently, tires that are more lightly loaded can handle greater g-loads during turns, which is a feature that is especially relevant to the handling characteristics of low mass vehicles. The graph below provides the relationship between slip angle, vertical load, and lateral cornering force.[4]

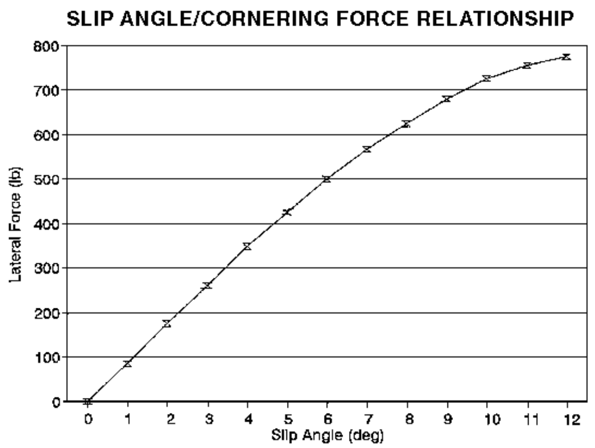


Chart 1: Tire Cornering Forces

2.2 Rollover on a Straight Road

The turning moment (M), as described in Figure 2.2.1, is a main factor contributing to the initiation of a rollover accident on a straight road.

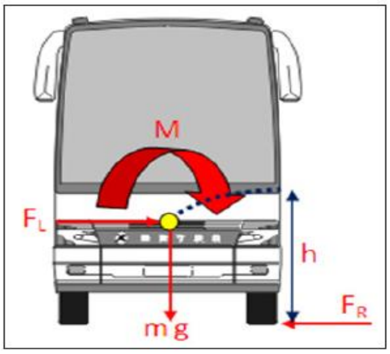


Figure 4: Free body diagram (FBD) of a bus turning moment

In order for a rollover to occur, the conditions explained hereafter must be satisfied. The first condition would be the rotation of the vehicle around the axis with the outside wheel as the pivot point. This situation is considered a worst-case scenario when a bus collides with a failed guardrail causing the bus to rollover. The bus tipped on its side given that the lateral sliding moment is larger than the turning moment:

$$M = mg\,\frac{w}{2}\,\mu > mg\,\frac{w}{2} - hF_L$$

And the kinetic energy of the bus is greater than the potential energy resulted from CG displacement in height that makes it unstable:

$$E_{kin} > mg\Delta h$$

In the figure and equations,

$m$is the total mass of the bus,

$\mu$is drag factor of the road,

$g$is the gravitational constant,

$w$is the extended track width, and

h is the height of CG from pivot point.

Based on the analysis, high-deck buses in Malaysia would most likely to rollover when they are travelling at 90 km/h with an impact angle of 15°. The speed of 90 and 120 km/h were considered in the analysis since 90 km/h is the speed limit for buses on expressways while the latter is the maximum speed at which a bus can realistically travel. Impact angles of 15° and 25° considered were based on the minimum and maximum impact angles recommended in the NCHRP 350 test. In addition, the range of CG height between 1.05 m to 1.40 m is used to represent Malaysian buses.

For another worst-case scenario in which a bus collides with a concrete barrier, similar conditions as described above still apply. However, this time, the pivot point is shifted from the outside wheel to top of the barrier (900 mm high STEP barrier) as illustrated in Figure 2.2.2.

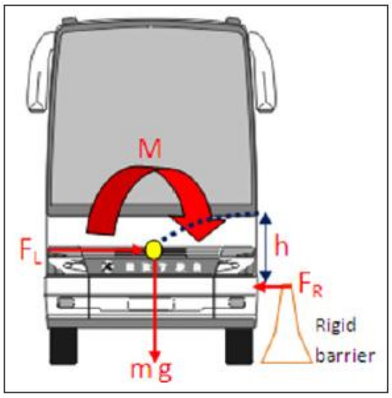


Figure 5: FBD of bus turning moment in a collision with a rigid barrier

The analysis shows that high-deck buses will most probably survive a collision with a rigid barrier without rolling over if the vehicle is travelling at 90 km/h at a maximum impact angle of 8°. Similarly, at 120 km/h the bus is most likely to not go into a rollover even at an impact angle of 6° during a collision. Additionally, the critical CG height that will not result in a rollover was found to be 1.56 m. From this analysis, it is proven that a rigid barrier works better than a semi-rigid barrier in preventing a high-deck bus rollover.

2.3 Rollover at a Curved Road

Table 2.3.1 was taken from A Guide on Geometric Design of Roads by the Malaysian PWD. It lists the standard minimum radius of a curve to be used for the designated speed and maximum super elevation rates in Malaysian urban roads. In this table, the minimum radius of a curve is calculated based on a predetermined designated speed at a road stretch.

Table 1: Minimum radius of a curve

Design speed (km/h)	Minimum radius (m)	
	e = 0.06	e = 0.10
120	710	570
100	465	375
80	280	230
60	150	125
50	100	85
40	60	50
30	35	30
20	15	15

Apart from that, the critical speed of a curve can also be determined based on how sharp the curve is, how much bank is in the roadway, and the coefficient of friction of the road surface. A vehicle cornering at a speed exceeding this critical speed will begin to spin around its centre of mass and leave the roadway.

Subsequently, the vehicle will lose control, which can further lead to a rollover. This can happen to any driver regardless of a person's driving skills or years of experience.A vehicle with higher CG such as a high-deck bus is more vulnerable to rollover, even at a speed well below the critical speed of a curve. As a high-deck bus is manoeuvring a curve, the weight of the vehicle together with its occupant will shift to the outside front tyre due to the centrifugal force. A rollover will occur if the bus is travelling at a high speed because the CG of the bus shifts as well.[5]

CHAPTER 3: METHODOLOGY

Methodology used for this cornering stability analysis is research methodology. General, it is done by using several methods:

1. Site visit

   The author go the KM15 Cameroon Highlands – SimpangPulai Road where the analysis is carried out to see the design of the road such as the slope degree, the curved radius , the divider and the road surface.

2. Data collection and calculation

   The data collected from the site visit to KM15 Cameroon Higlands-SimpangPulai road is used for mathematical equation such as slip angle equation and tip angle equation to get the result that the analysis need.

3. Modelling and simulation using adams car software

   After done with the data collection and calculation, results will be obtained based on the calculation. The data collected will be used to model the double decker bus and simulate it using adams car software to strengthen the analysis.

3.1 Research methodology flow in details

For overall methodology for final year project analysis are as below:

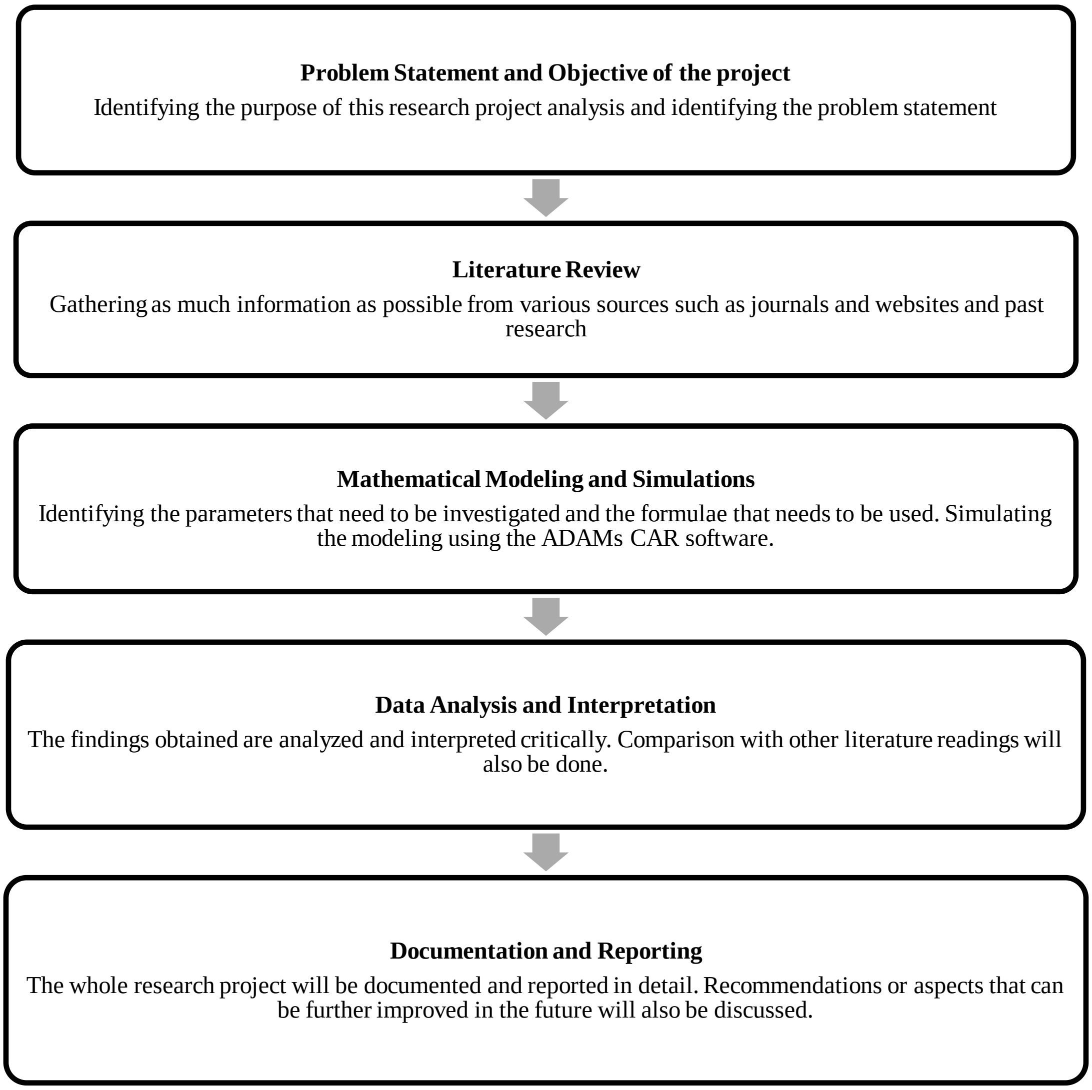
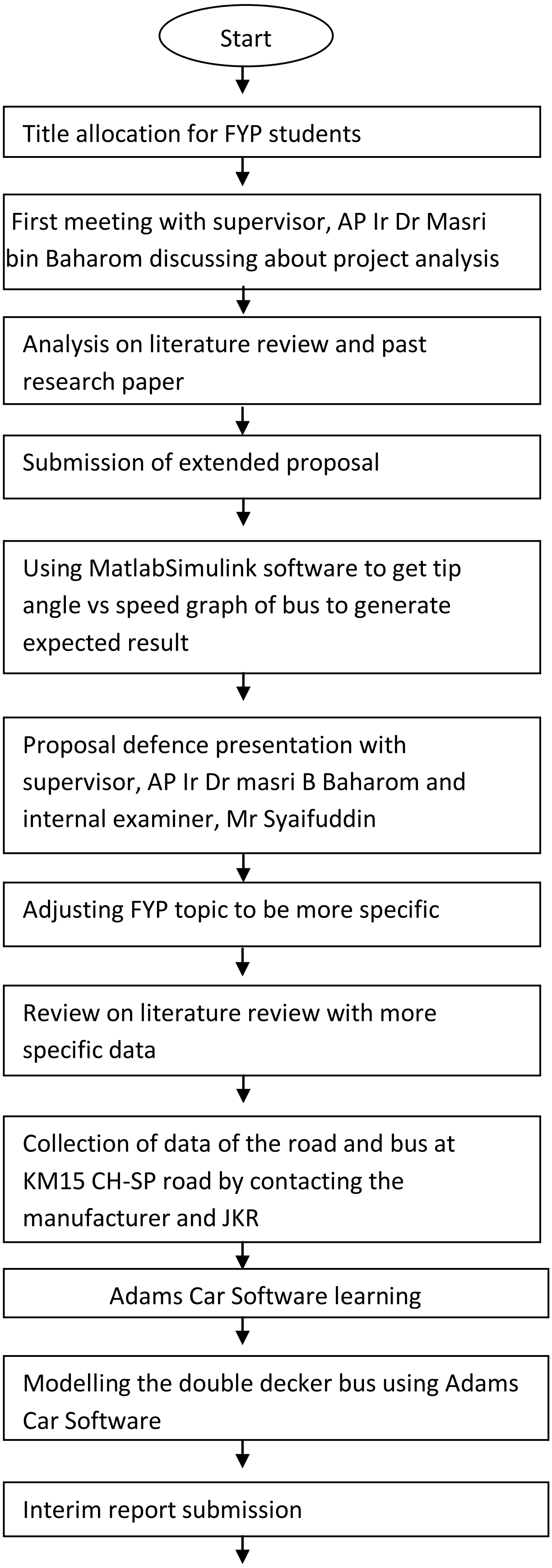
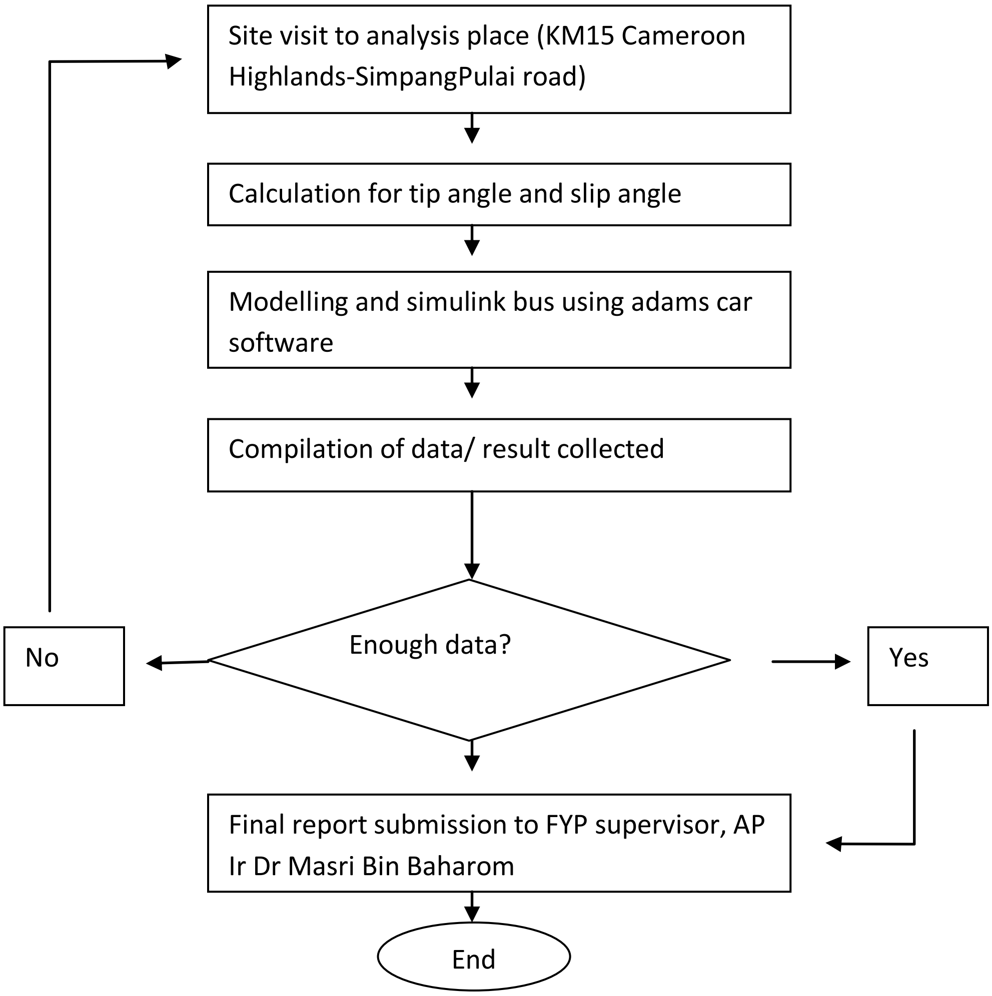


Chart 3.: Overall Methodology

3.2 PROJECT FLOW OF ACTIVITIES FOR FYP 1 & 2





3.3 TOOLS

1. Matlab software
2. Adams car software
3. Mathematical equations
   a) By using slip angle equation
   b) By using tip angle equation

3.4 GANTT CHART AND KEY MILESTONE

3.4.1 For FYP 1

No	Study Plan	Number of Week														
		1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Title															
2	Preliminary Research Work and Literature Review															
3	Submission of Extended Proposal															
4	Expected result by using simulink of Matlab Software															
5	Proposal Defence Presentation															
6	Adams Car Learning															
7	Submission of Interim Draft Report															
8	Submission of Interim Final Report															

3.4.2 For FYP 2

No	Study Plan	Number of Week													
		1	2	3	4	5	6	7		8	9	10	11	12	13
1	Project Work Continues														
2	Submission of Progress Report														
3	Project Work Continues														

4	Pre-SEDEX											☐			
5	Submission of Draft Report												☐		
6	Submission of Dissertation (soft bound)													☐	
7	Submission of Technical Paper													☐	
8	Oral Presentation														☐
9	Submission of Project Dissertation (Hard Bound)														☐

= process   ☐ = suggested milestone

Overall Key milestone

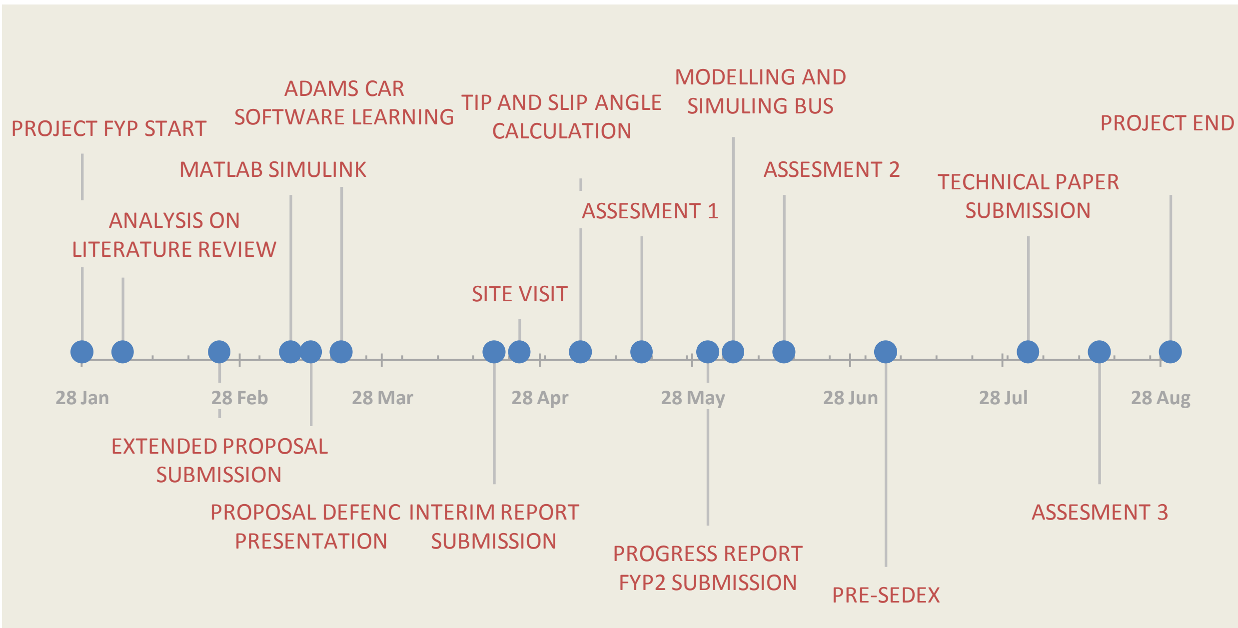


Figure 6: Key milestone for overall FYP analysis project

CHAPTER 4: FINDINGS ON ANALYSIS

The analysis is complete when the result of slip angle and tip angle is obtained by using calculation and computer software based by varying the speed of the double-decker bus. The value of radius of curvature and degree of slope at KM15 Cameroon Highlands-SimpangPulai Road are constant when calculated. By using the slip and tip angle equation, result can be generated and validated by using MATLAB and ADAMs CAR software by showing the graphs and also tabulated data.

Slope Angle Road Calculation by using SpeedView Application.

Experiment is done by using SpeedView application installed in android with the help from satellite to determine the exact height of road at a certain points. Data obtained as below:

Time (s)	Height (m)
5	51
10	51
15	50
20	50
25	50
30	50
35	49
40	48
45	46

The distance taken from point 1 to last point = 350m

Velocity of Vehicle during the experiment is kept constant = 30km/h @ 8.33m/s

The graph below shows the height of road from above the sea level in meter versus time in seconds.

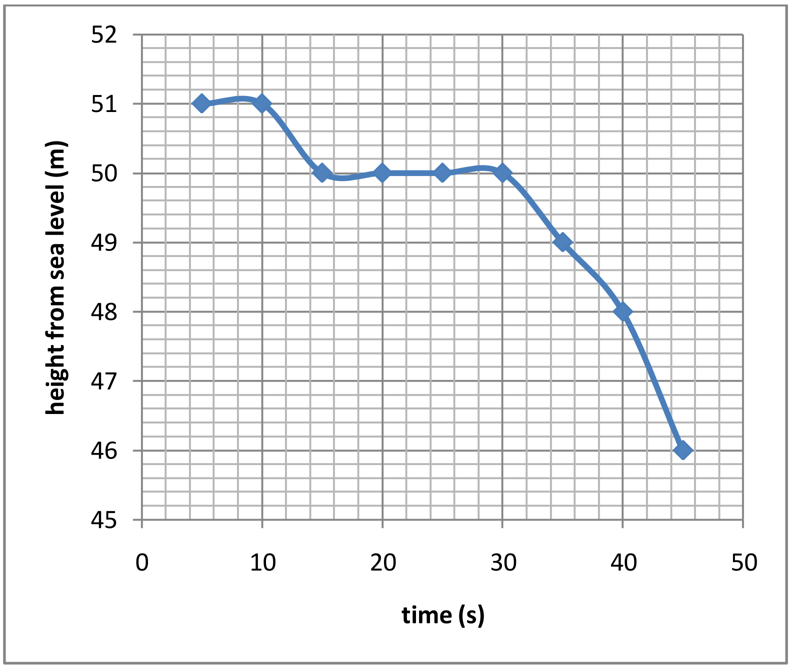
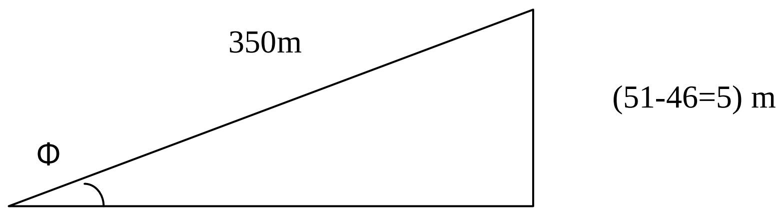


Figure 7 : Graph of height of road above the sea level versus time

From the calculation below, the slope angle of the road is obtained.



Φ = sin ^-1 (5/350)

=0.81 degree

<u>Radius of Curvature Calculation by using Accelerometer Application</u>

Data is recorded when the vehicle is turning at the cornering part of the road by using accelerometer application installed in android mobile. Lateral acceleration is obtained which later will be used in radius of curvature calculation. The data obtained is showed below:

Time (s)	Ay (m/s^2)
13.931	8.77
15.051	6.33
15.821	7.12
17.021	5.37
18.061	7.75
19.055	5.96
19.9	9.04
20.881	6.95
21.931	6.21
22.981	6.08
23.821	5.64
25.091	5.27
233.545	**80.49**
19.46208	**4.1357**

Total = red colour

Average = green colour

Graph of lateral acceleration versus time in seconds.

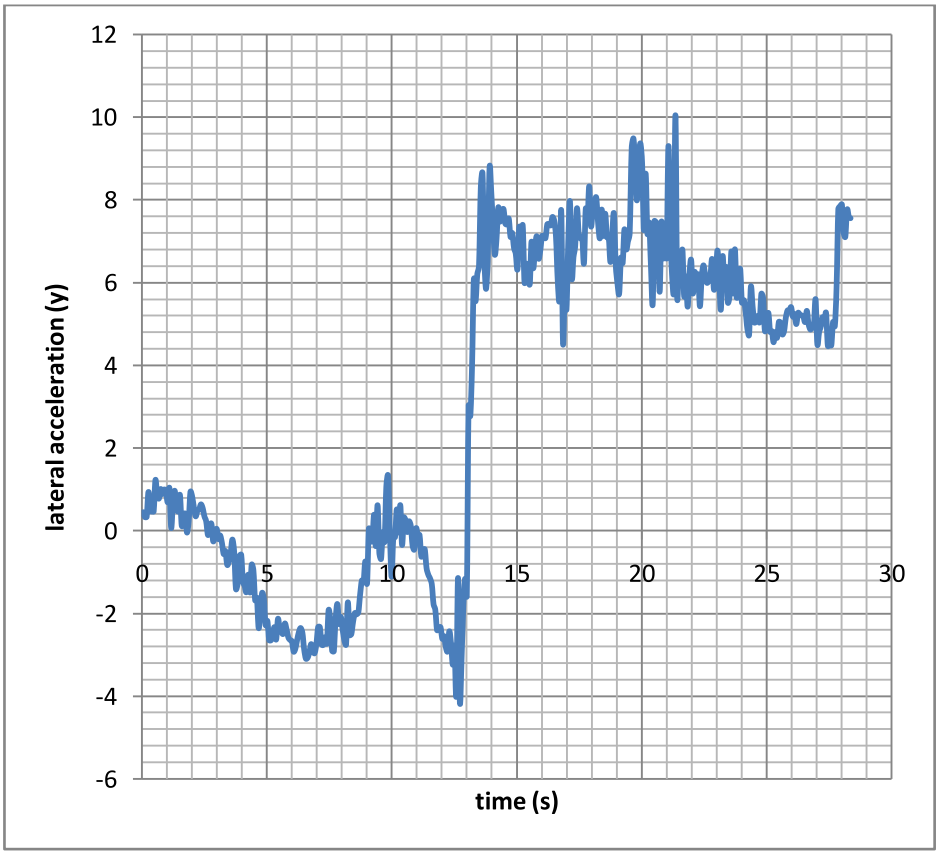


Figure 8: Graph of lateral acceleration versus time

By using simplified equation, radius of curvature is obtained as showed below;

R = V^2/ Ay

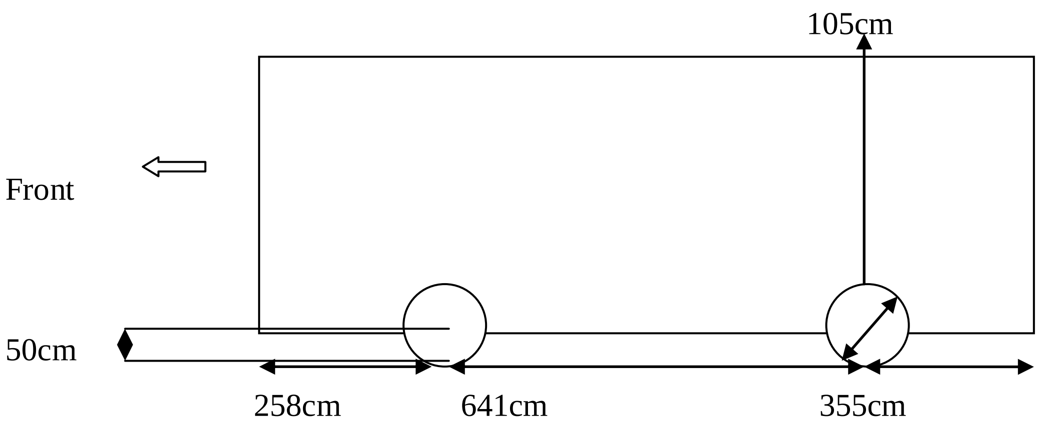
= (8.333^2)/ (4.1357)

= 16.78 m

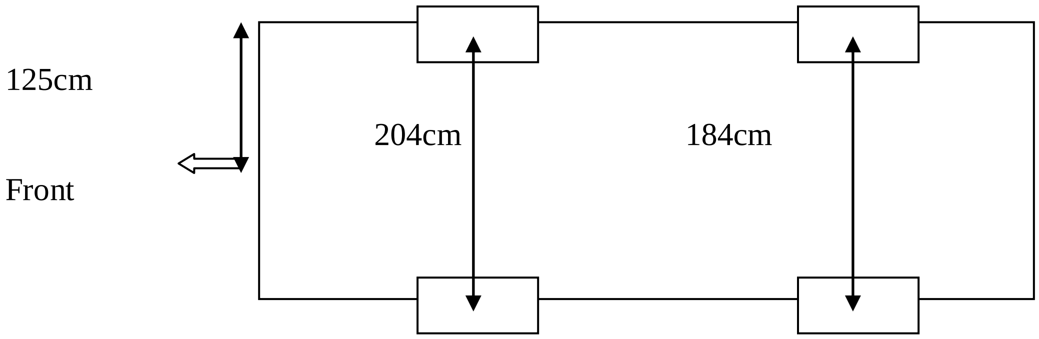
Figure 3 : The interested corner situated in the map

Physical Measurement of Double Decker Bus

Side View



Bottom View



<u>Other Information About the bus</u>

Due to the limited resources, some of the information about the bus was gathered from the manufacturer data. Firstly, the bus type, brand, was conforming, and then based on the information, the data was found in the manufacturer web sources.

Vehicle	
Model	CBC 1725/ 59 Manual Transmission
Description	CBC 1725/ 59 bus chassis with rear engine and full air suspension - Manual Transmission
Engine	
Model	Mercedes-Benz OM 906 LA. II
Type	6 cylinders, in-line, turbo-charged and intercooled
Maximum output	180 KW (245 HP) @ 2,300/ min
Chassis weight	
Gross vehicle weight (GVW)	18,500 kg
Suspensions	
Front	Air suspension with two air bellows and Four telescopic and double-acting
Rear	Air suspension with four air bellows, two longitudinal bars and two levelling valves and Four telescopic and double-acting with stabilizer

Figure 4 : The chassis of the bus

Matlab Simulink Work

Roll angle

By using equation,

$$\phi = \frac{W h_l V^2/(R g)}{K_{\phi f} + K_{\phi r} - W h_l}$$

Where;

W= weight of the vehicle (12550kg)

h= height from CG to ground (0.97m)

V= velocity (variable)

R= radius of curvature (16.78m)

g= gravitational force (9.81kg/m^3)

KΦf= front suspension roll stiffness (1960Nm/deg) } (VijayKumar, 2010)

KΦr= rear suspension roll stiffness (12970Nm/deg)

By using Matlabsimulink, the graph from the below work flow is obtained;

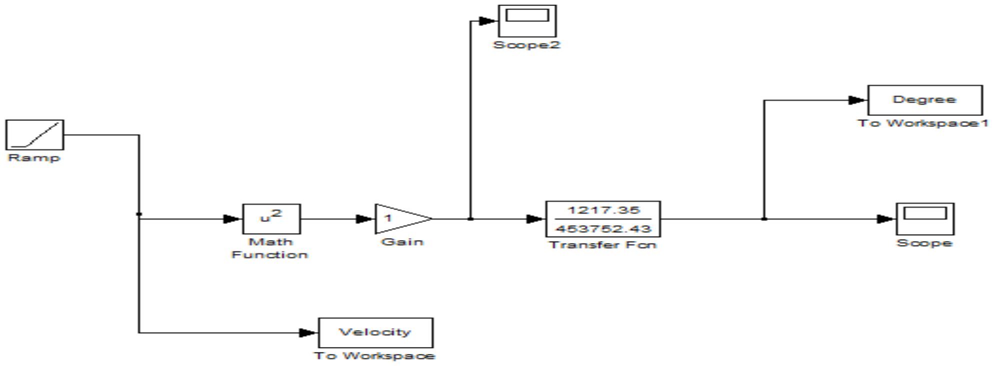


Figure 5 : Work Flow of Roll Angle calculation

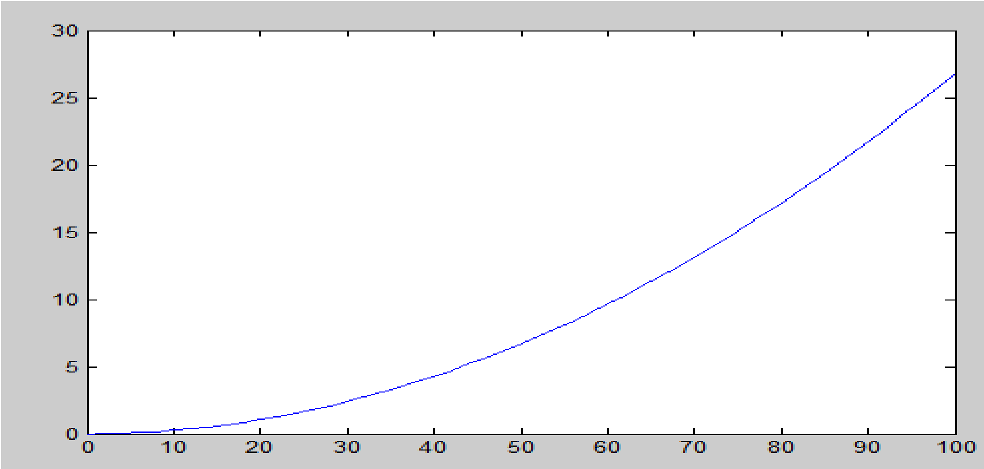


Figure 12 : Graph of roll angle versus velocity

Based on the data producedim figure 21, it shows that as the speed of the vehicle increase, the roll angle is increased thus will caused the bus to roll over.This is because the sharper the corner, the lower the value, therefore the higher the roll angle. The lateral acceleration depends on the slope angle, the vehicle center-of-gravity height and the vehicle track width. The larger the slope angle, the higher the rollover lateral acceleration, therefore the velocity is higher.

Sideslip angle at CG

By using equation,

$$\beta = 57.3\ c/R - \alpha_r$$
$$= 57.3\ c/R - W_r\ V^2/(C_{\alpha r}\ g\ R)$$

Where;

B= sideslip angle

c= length of wheelbase x (1/3) = (2.14m)

R= radius of curvature (16.78m)

Wr= load at rear tire (82077N)

V= velocity (variable)

Car= cornering stiffness (1380.5 kg/deg)

g= gravitational force (9.81kg/m^3)

By using Matlabsimulink, the graph from the below work flow is obtained;

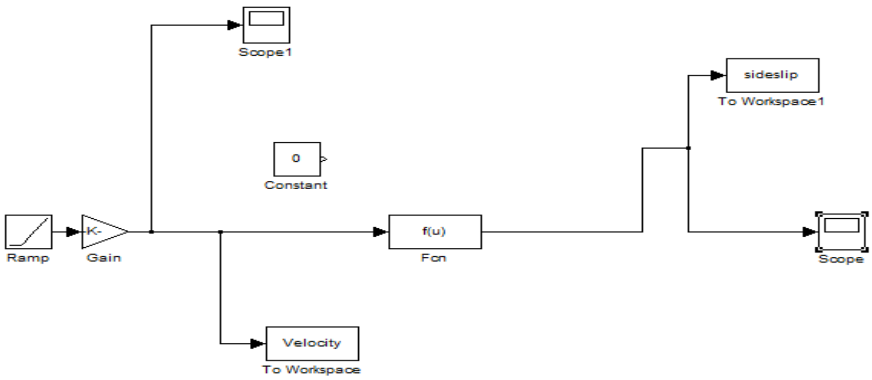


Figure13: Workflow of Sideslip angle

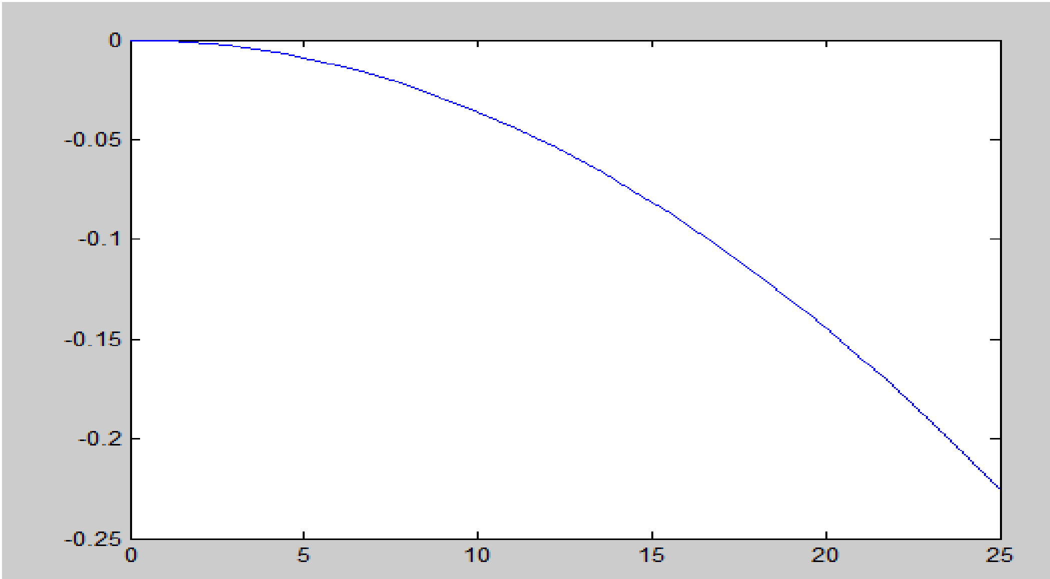


Figure 14: Graph of sideslip angle versus speed (m/s)

Based on graph 23, the result shows that as the speed increase, the sideslip will increase at the negative angle. This negative sign occur because of the direction of the move. Apart from that, there are many other causes that cause the bus to rollover such as inexperienced driver, the surface of the road, and tire condition.

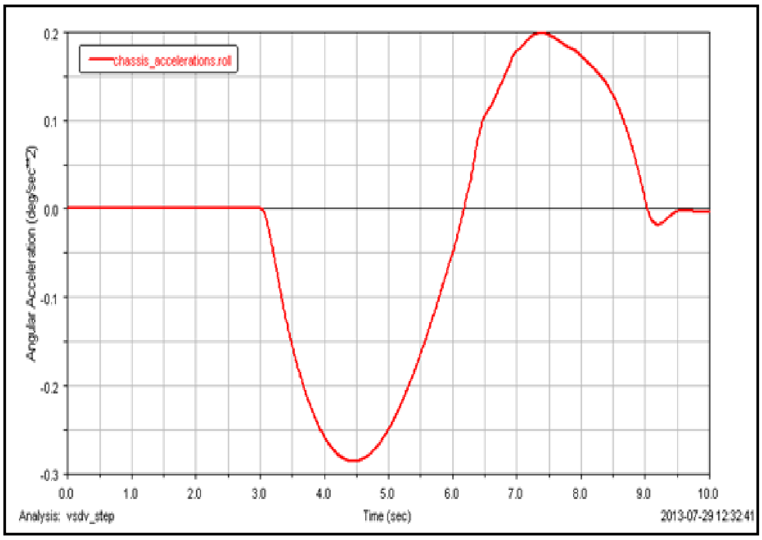
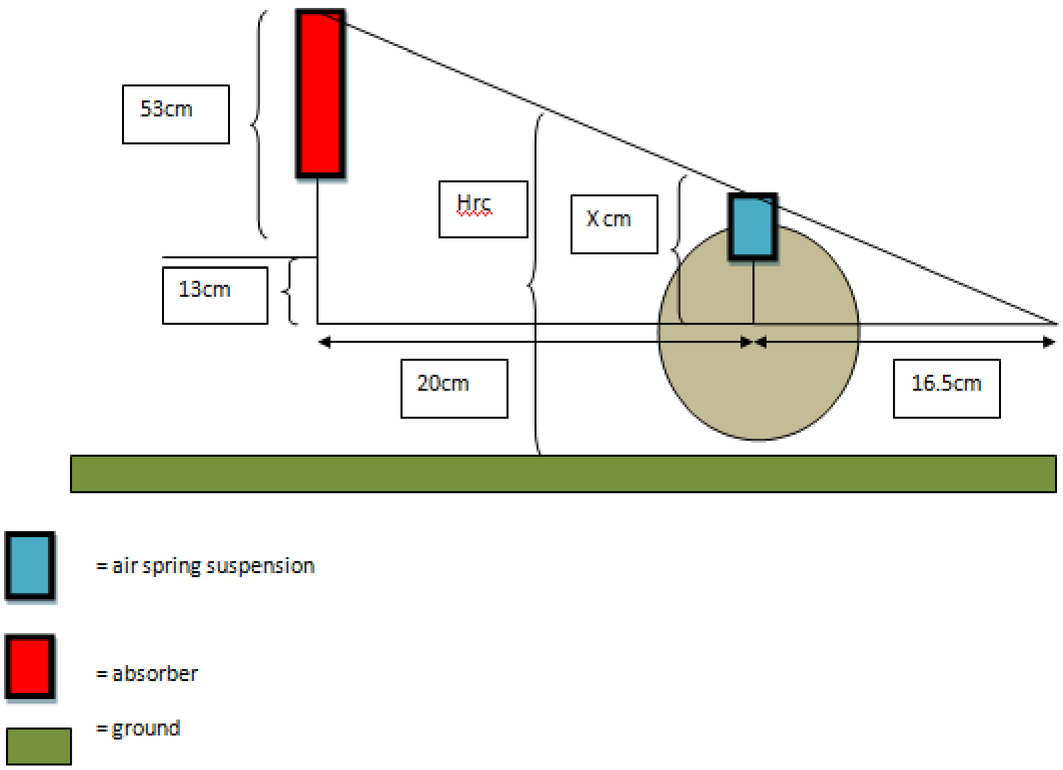


Figure 15 : Graph of the roll angle versus time

Angular acceleration start to increase as the cornering begins until it reaches to –0.29 at 4.5sec. Then the angular acceleration reaches 0.2 before back to zero due to the stabilization of the bus after the cornering done.

Height of roll centre Calculation at front suspension



Tan Φ = (53+13)/ (20+16.5)

Therefore, Φ = 61.06 °

Tan 61.06° = x / (16.5)

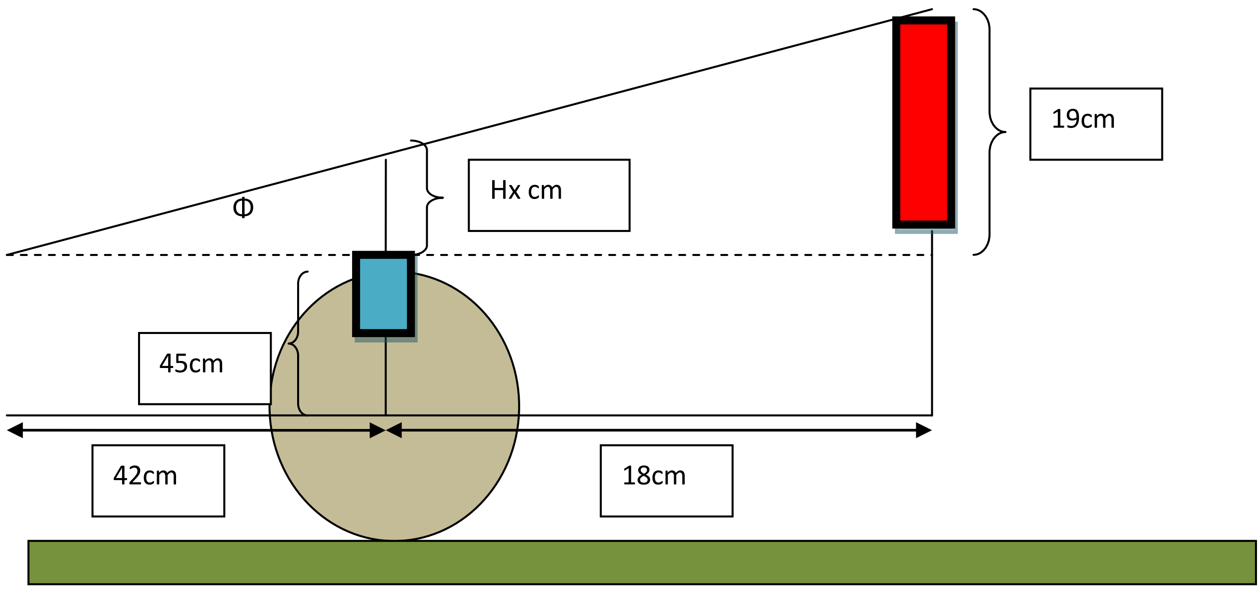
Therefore, X = 29.8 cm

Radius tire = 52cm

Hrollcentre (Hrc) = 52cm + 29.8 cm

= 81.8cm

Height of roll centre Calculation at rear suspension



= air spring suspension

= absorber

= ground

Hx = (19/60) x 42 = 13.3 cm

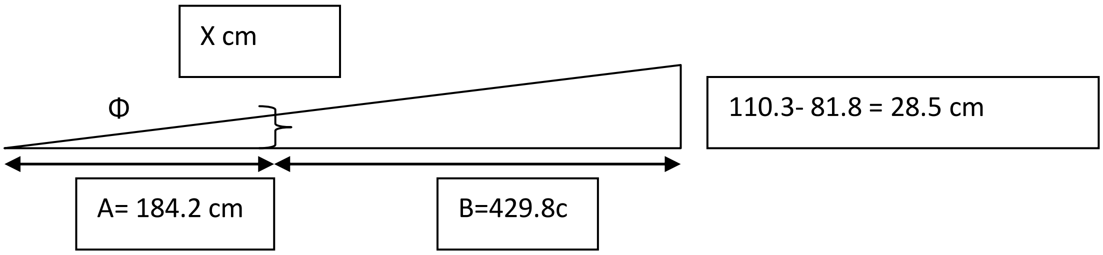
Radius tire = 52cm

Hrollcentre (Hrc) = 52cm + 13.3 + 45 cm

= 110.3 cm

Different in height of Roll Center and Centre of Gravity

*assume that the double decker weight distribution is 70:30 at front and rear load.



To find X ;

Tan Φ = 28.5/ 614 = 0.05

Therefore, Φ = 2.66

X = tan 2.66 x 184.2 cm = 8.6 cm

Delta Height roll centre and Cg = 97 cm – (81.8 + 8.6 cm)

= 6.6 cm = 0.066 m

Roll Moment at Different Height of Centre of Gravity

Roll moment has been identified by three different height of centre of gravity which are single-deck bus, double-decker bus with empty passenger and double decker bus with full passenger. In this case, the number of passengers are 40 person and the average mass for each person is 60kg. Below is the table for the bus data and roll moment calculated.

Type of Bus	Parameters	
Single Deck Bus	Mass (kg)	10400
	Radius of Curvature (m)	16.78
	Height of CG (m)	0.85
	Height of Roll Centre (m)	0.904
	Delta Height (m)	0.54
Double Deck Bus (empty passengers)	Mass (kg)	12550
	Radius of Curvature (m)	16.78

	Height of CG (m)	0.97
	Height of Roll Centre (m)	0.904
	Delta Height (m)	0.066
Double Deck Bus (full passengers)	Mass (kg)	14950
	Radius of Curvature (m)	16.78
	Height of CG (m)	0.94
	Height of Roll Centre (m)	0.904
	Delta Height (m)	0.036

The following equation is use to determine the roll moment at different height of CG.

Roll Moment = Mass x ((Velocity x Velocity)/ Radius of Curvature) x Delta Height

The graph below is generated by using the data and the above equation.

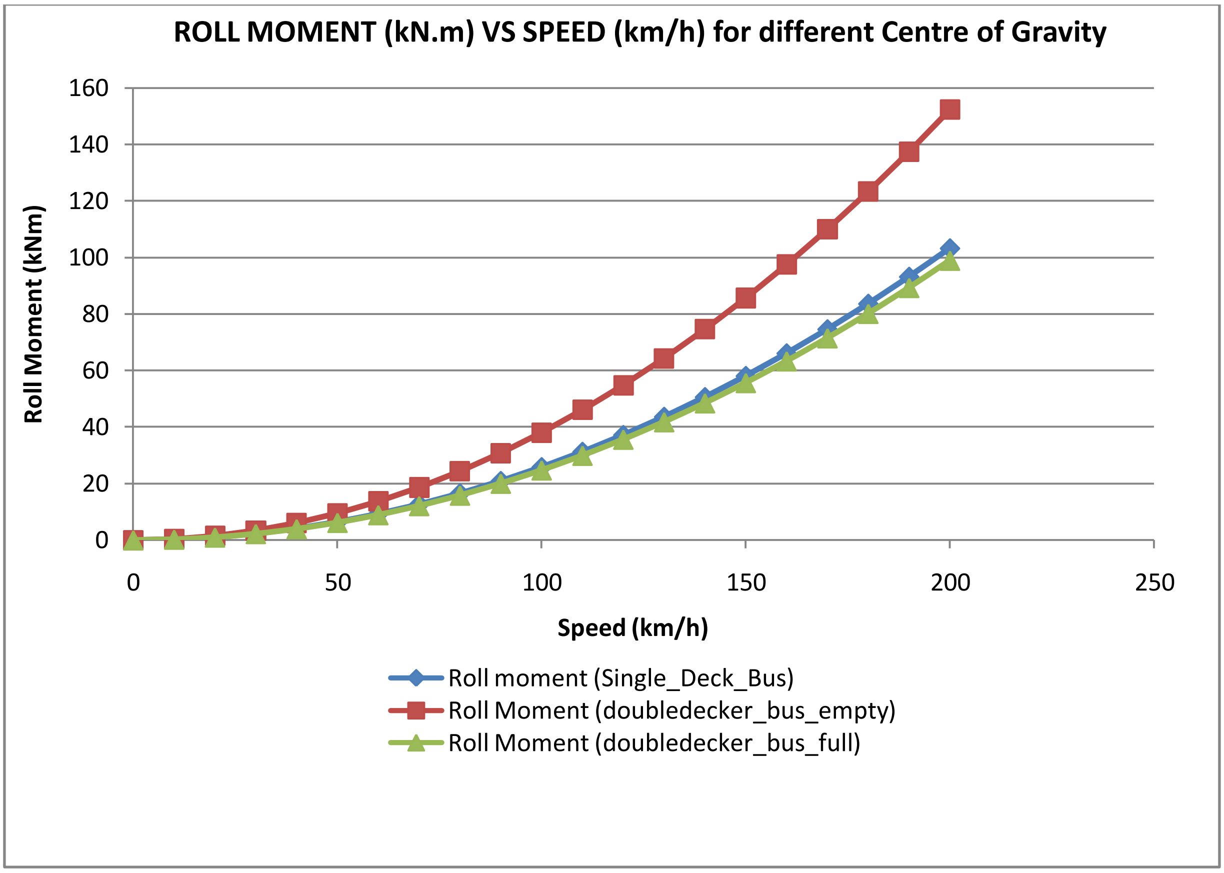


Figure 16 : Roll Moment at Different CG Vs Speed

From the graph it shows that, for the single deck bus graph, the roll moment value is almost the same with the double decker bus with full passengers' graph. This show that even with double decker bus with more load have the same effects as the single deck bus with passengers. The roll moment for double decker bus with no passengers is the highest compared to the two buses. It shows that the higher the CG, the higher the roll moment.

Roll Moment for Rollover to Happen

To make a make vehicle to begin to rollover, the vehicle must experienced Moment at lateral force is greater than moment at vertical force. To find both moment, the equation below is used,

Roll Moment at Lateral Force

1) M1=Mass x (Velocity*Velocity/ Radius of Curvature) x Hcg
2) M2=Mass x gravitational acceleration x (track width/ 2)

If M1 is greater than M2, the vehicle will start to rollover.

Therefore, from the data, M2 can be calculated manually and the result is shown as below:

M2= 12550kg x 9.81 x (2.04/2)/1000 = 125.58 kN.m

For M1, the result is generated in the form of table and graph as shown below;

V(km/h)	V(m/s)	M1 (kN.m)
0	0	0
10	2.777778	5.597814491
20	5.555556	22.39125796
30	8.333333	50.38033042
40	11.11111	89.56503186
41	11.38889	94.0992616
42	11.66667	98.74544762
43	11.94444	103.5035899
44	12.22222	108.3736885
45	12.5	113.3557434
46	12.77778	118.4497546
47	13.05556	123.6557221
48	13.33333	128.9736459
49	13.61111	134.4035259

50	13.88889	139.9453623
60	16.66667	201.5213217

The graph is shown as below;

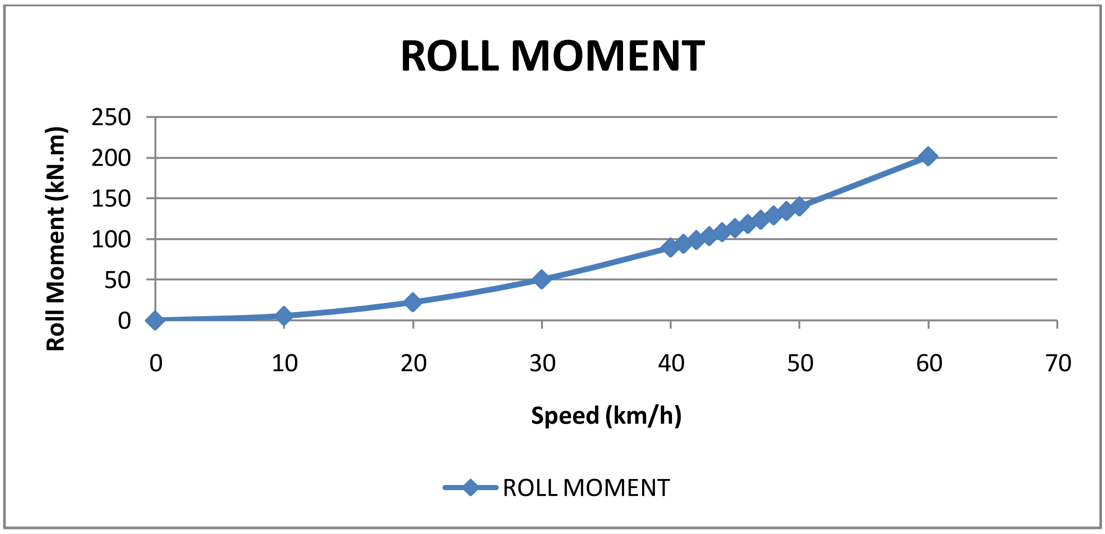


Figure17: Roll moment of Double Decker bus VS Speed

From the results generated, it can be seen that at 48 km/h the moment is 128.97 kN.m. This value is bigger than M2 where 128.97 kN.m is bigger than 125.58 kN.m. Therefore, at this speed the double decker bus, started to have rollover at the KM15 Cameroon Highlands-Simpang Pulai road.

CONCLUSION

This final year project is basically to analyse the cornering stability of double decker bus at KM15 Cameroon Highland- SimpangPulai road where at this point also known as “black spot” is believed to be the worst accident happened in last 3 years. This “black spot” begins on a relatively straight road but with a very steep gradient and continues into a very sharp bend. Therefore, a study about the road and its relation to double decker bus need to carry out in order to know the root cause of the accident and as an initiative to prevent from the accident to happen again. When it comes to over speed issues, the double decker bus has higher tendency to tilt as it has higher centre of gravity and it becomes worse if the bus hit the road divider because the height of the divider is not enough to prevent the bus from going to the opposite lane. At KM15 Cameroon Highlands-SimpangPulai road, the divider is about 1 metre height and when the bus hit the divider; it will help the bus to tip with higher angle causes the bus to land on its roof. Based on the previous studies, double decker bus is not suitable to run on curvy and steep slope road like the road at KM15 Cameroon Highland- SimpangPulai because many possibilities of the accident to happen. The government should take the issue seriously and the “black spot” need to be improved immediately by widening the sharp bend in order to prevent more lives being lost. The most suitable road to run double decker bus is on the flat and non-curvy road.

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