Study of Aerodynamics of Double Decker Bus for Driving Stability

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I. ABSTRACT

The title of this project is "Aerodynamic Study of Double Decker Bus for Driving Stability". As portrayed by the title the objective of this project is to evaluate the influence of aerodynamic forces on a double decker bus. The project is also done to ascertain the limits of the forces for driving stability. These objectives are meant to solve the problems faced by the increasing number of cases of overturned buses on the road. Besides that every vehicle has their own limitations on different terrains. This is affected by many things like the shape, weight, and height. Though there are many studies on the ability of the passenger car, not many researches are done on the commercial vehicle.

This study covers the experimentation and also simulation. The experiments are done in the windtunnel laboratory and the simulation is done using the Adams Software. The experiment is done for data collection and interpretation for the project and the simulation is done to validate the findings of the experiment. Through these activities the final result would be the achievement of the objective of the project.

II. INTRODUCTION

The study of road vehicle aerodynamics is quite different from aircraft aerodynamics. While most of the studies are mainly about reducing drag, reducing wind noise and noise emissions, some also study on preventing lift forces and unwanted forces that may disrupt the stability of a vehicle mainly at high speed and while cornering. This instability will cause over steer or under steer of the vehicle. Over steer is a condition when the angle of turn is more than required to clear a curve and conversely under steer is when the angle of turn is less than required to clear the curve on steady state.

To create more stability during cornering, the key component is the downforce. This concept is basically similar to the lift of that is required for the flight of an airplane but inversely. In short it could also be called a negative lift. Downforce would create a lateral force against the surface of the road giving more grip and enhancing performance during cornering and also speeding. This force is known as 'aerodynamic grip' that could be a function of car mass, tires, and suspension. The main attribute that affects the downforce is the shape including the surface area, aspect ratio, and cross section of the vehicle. The other aspect is angle of attack or vehicle orientation.

There is another theory that could be exploited to increase the downforce of a vehicle which is the Bernoulli's Principle. According to Bernoulli, for an inviscid flow, increasing speed of the flow would simultaneously decrease the pressure or the fluid potential energy. Implementing this to vehicle aerodynamics if the air flow beneath the vehicle is maximized it would create a very low pressure. The difference in pressure would result in a downwards lateral force or downforce.

For a double decker bus, the value of downforce is could be seen as small or very little comparing to the passenger vehicle. This is due to mainly the frontal area shape and the height of the vehicle. With that fact plus the weight of the vehicle during cornering, it makes the vehicle very unstable and has certain limits for the driving safety of the vehicle.

The purpose of the project would be:

- To evaluate the influence of aerodynamic forces on a double decker bus.
- To ascertain the limits of the aerodynamic forces for driving stability.

III. LITERATURE REVIEW

Generation of lift by road vehicle

Lift is an important factor in road vehicle aerodynamics, having a strong influence on stability, roadholding, and performance. For an object flying through the air, two factors that affects force lift generated the most are angle of attack and the camber (curvature of the body). Increasing both values would directly increase the lift generated.

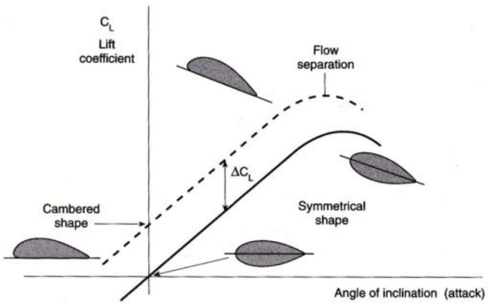


FIGURE 1: Effect of angle of attack, camber, and lift coefficient on an airplane.

The figure above shows that for a free-flying object, lift is produced by inclining a shape to the flow and giving it a cambered (curved) form. The cambered shape gives more lift at any given angle of attack. Therefore to create high lift in the other direction the cambered shape should be kept but the angle of attack should be changed to negative.

From the paper by J. B. Barlow [1] to minimize drag for rough configurations regardless of the aspect ratio, the clearance is to be made small, increasing the aspect ratio of drag. There is also a force reversal at some clearance for each configuration. In the range of clearences from his experiment, the rough configuration exhibit very large positive lift as the clearance decreases, and at intermediate clearance the lift is negative.

Lift is basically produced when the pressure on top of the vehicle is lower than the pressure underneath it. It is a misconception if said that a lower vehicle would have a higher downforce or smaller lift. Height does not affect the lift produced by a vehicle but it is rather the pressure difference is the main cause if generated lift.

L, Lift coefficient is could be calculated by [3]:

$$C_\mathrm{L} = \frac{L}{\frac{1}{2}\rho v^2 A} = \frac{2L}{\rho v^2 A} = \frac{L}{qA}$$

Where:
C_L is lift coefficient
ρ is fluid density
v is air speed
q is dynamic pressure
A is frontal area

Note that for convenience the frontal are is still the projected frontal area even though the lift is more directly related to the plane area.

Cornering forces

When a vehicle is cornering, the directions of the wheels are different than the motion. The difference between the orientation of the wheels and the direction of motion is called the slip angle. It may seem like the tyre is sliding slightly relative to the road, but due to the elasticity of the tyre this is not the case. The sideways motion is canceled by the tyre elastically distorting elastically to the region of the contact path. In this condition the tyre could contribute to the cornering force needed to allow centrifugal acceleration. The tyre cornering force increase linearly to slip angle up to a certain point where a maximum is reached.

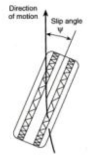


FIGURE 2: Slip angle.

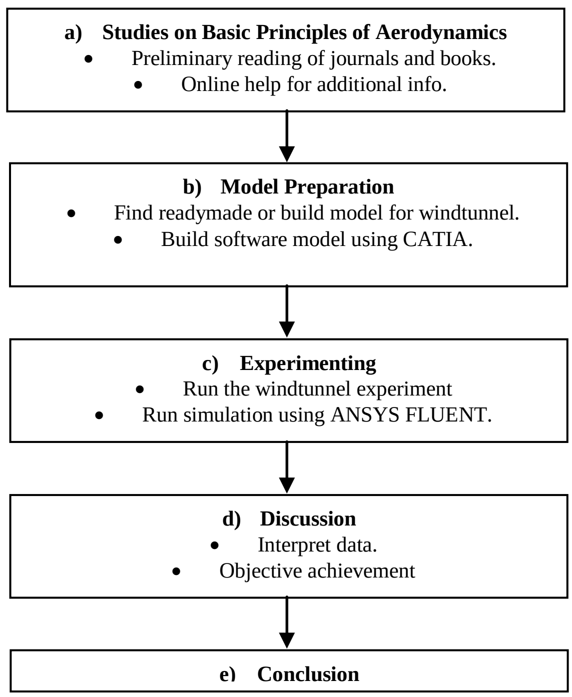
The figure above shows that under cornering, the tyre does not point towards the exact direction of the motion. The angle is called slip angle but this does not mean that the tires has to slide. The cornering motion is caused by the sum of the centripetal and centrifugal force. These forces are perpendicular to each other and have different value resulting in the cornering motion.

Effects of drafting

From the paper by S. Watkins and G. Vino [2], they concluded that despite drafting being generally being recognized as a method to reduce drag, their studies shows that a very close spacing could result in drag penalties. Thus the combined drag of a number of isolated vehicles has the potential to become lower than the same number of close-coupled convoy.

They also found very significant changes in lift for close spacing and these changes has been revealed to be the effect of rear vortices.

IV. METHODOLOGY



V. RESULTS

Table 1: Experiment results

Fan Speed (RPM)	Air Velocity (m/s)	Drag (N)	Downforce (N)
2000	19.96	1.66	0.89
2200	21.63	2.57	1.35
2400	23.15	2.79	1.56
2600	26.03	3.09	2.14
2800	28.61	3.64	2.24
3000	30.53	3.70	2.36
3200	32.61	3.92	2.66
3400	34.28	4.06	2.76
3600	36.16	6.43	3.07
3800	37.52	6.81	3.02
4000	38.67	6.70	3.12

From the table we could determine the velocity of the real vehicle which was modeled by the scale of 1:30 by assuming similarity of dynamic properties between the model and the real vehicle.

$$RE_m = RE_R$$

$$\frac{V_{\infty m} l_m}{\upsilon} = \frac{V_{\infty r} l_r}{\upsilon}$$

$$V_{\infty r} = \frac{V_{\infty m} l_m}{l_r}$$

It is known that l_m / l_r is equal to 1/30 therefore the equation would become

$$V_{\infty r} = \frac{V_{\infty m}}{30}$$

Table 2: Relative real velocity

Model (m/s)	Real (m/s)	Drag (N)	Downforce (N)	C_d	C_l
19.96	0.665	1.66	0.89	0.658	0.353
21.63	0.721	2.57	1.35	0.867	0.455
23.15	0.772	2.79	1.56	0.821	0.459
26.03	0.868	3.09	2.14	0.719	0.498
28.61	0.954	3.64	2.24	0.701	0.431
30.53	1.018	3.70	2.36	0.626	0.399
32.61	1.087	3.92	2.66	0.582	0.394
34.28	1.143	4.06	2.76	0.545	0.370
36.16	1.205	6.43	3.07	0.776	0.370
37.52	1.251	6.81	3.02	0.763	0.338
38.67	1.289	6.70	3.12	0.707	0.329

Averaging the value of Cd and Cl so we get
C_d=0.706339
C_l=0.400184
With the average value of C_l we could calculate the theoretical value of the aerodynamic drag and aerodynamic downforce at any given speed.

Table3 : Experimental Negative Lift Force (0 km/h < V < 110 km/h)

Relative speed (km/h)	Relative Speed (m/s)	Negative Lift (N)
0	0.0000	0.0000
10	2.7778	17.6054
20	5.5556	70.4216
30	8.3333	158.4486
40	11.1111	281.6864
50	13.8889	440.1350
60	16.6667	633.7945
70	19.4444	862.6647
80	22.2222	1126.7457
90	25.0000	1426.0375
100	27.7778	1760.5402
110	30.5556	2130.2536

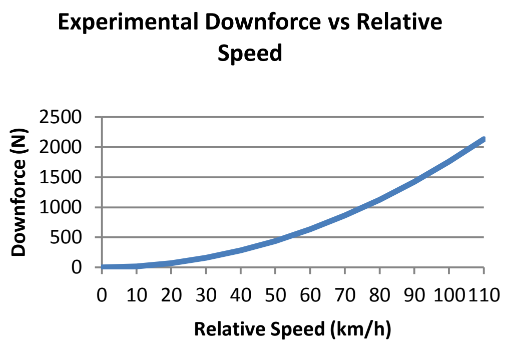


Table 4: Simulation Results

Direction	Pressure Force (N)	Viscous Force (N)	Total Force (N)
y	-757.37292	-5.7559	-763.12882
x	6891.9292	288.5462	7180.4754
z	-188.86937	0.674568	-188.1948

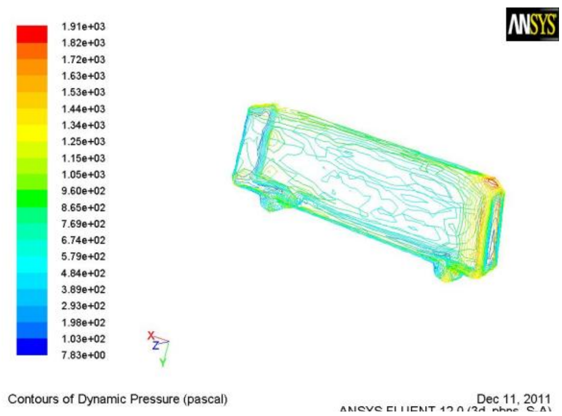


Figure 3: Contours of Dynamic Pressure

From the results obtained through the simulation done, the value of Cd and Cl could be obtained

$$F_l = C_l \times A_f \times P_{dyn}$$
$$F_d = C_d \times A_f \times P_{dyn}$$

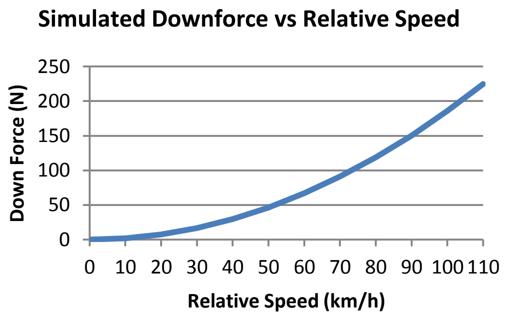
Where P_{dyn} is the dynamic pressure and A_f is the frontal area. These equations are rearranged to find the drag coefficient Cd and lift coefficient C_l. The dynamic pressure could be obtained from Figure 3 which is 1.91×10^3 Pascal. Forces value are obtained in Table 4 and it is known that the drag force acts on the X-direction and lift force acts on the Y-direction. The simulation is done using the real scale of the vehicle therefore the frontal area would be 9.5 meters. Solve the equation for C_l and get:

C_l=(-0.0421)

Here the value of lift force is negative because it is acting downwards rather than upwards.

Table 5: Simulated Negative Lift Force (0 km/h < V < 110 km/h)

Relative Speed (km/h)	Relative Speed (m/s)	Negative Lift (N)
0	0.0000	0.0000
10	2.7778	1.8574
20	5.5556	7.4298
30	8.3333	16.7170
40	11.1111	29.7192
50	13.8889	46.4362
60	16.6667	66.8681
70	19.4444	91.0149
80	22.2222	118.8766
90	25.0000	150.4532
100	27.7778	185.7447
110	30.5556	224.7511



The sliding condition could be calculated by using the condition for circular motion. In this project, the vehicle is counted as a rigid body, neglecting the effect of the suspension of the double decker bus. Another variable in the equation is the radius of the corner. For this project various radius of cornering is assumed which are 5 meters, 10 meters, 15 meters, and finally 20 meters. Calculations are done on both the experimental and simulated result. The purpose is that these two results has very different readings, therefore the data could be used to see if the aerodynamic downforce has any significance on the equation.

Table 6: Static Friction (Experimental)

		R = 5m	R = 10m	R = 15m	R = 20m
Relative Speed (km/h)	Negative Lift (N)	Slide Force (kN)	Slide Force (kN)	Slide Force (kN)	Slide Force (kN)
0	0.00	133.4	133.4	133.4	133.4
10	17.61	105.5	119.5	124.1	126.5
20	70.42	21.5	77.5	96.2	105.5
30	158.45	-118.3	7.6	49.6	70.61
40	281.69	-314.2	-90.2	-15.6	21.70
50	440.14	-566.1	-216.1	-99.5	-41.1

Table 7: Static Friction (Simulated)

		R = 5m	R = 10m	R = 15m	R = 20m
Relative Speed (km/h)	Negative Lift (N)	Slide Force (kN)	Slide Force (kN)	Slide Force (kN)	Slide Force (kN)
0	0.00	133.4	133.4	133.4	133.4
10	1.86	105.4	119.4	124.1	126.4
20	7.43	21.4	77.4	96.1	105.4
30	16.72	-118.4	7.50	49.50	70.5
40	29.72	-314.4	-90.4	-15.8	21.5
50	46.44	-566.4	-216.4	-99.8	-41.4

From the tables above, it is seen that the limits are different for different radius of cornering. To get the exact value of the relative speed, take the range of where the slide force value turns from positive to negative. The calculated speed at which the vehicle would be stable just before sliding is:

Table 8: Max Speed According to Cornering Radius

Radius (m)	Max Speed (km/h)
5	21
10	30
15	37
20	43

VI. DISCUSSION

The experiment part had many problems to start. First was to create a model small enough to fit in the windtunnel but not so small so that when the calculation for the relative velocity of the real vehicle, it would not be too small.

While running the experiment, vibrations could be seen on the model. This is probably due to the material used to make the model not heavy enough and the connection is not rigid enough. To get confirmation of this situation a computer simulation must be done so that the results could be verified. After the simulation is done further calculation could be done on both results and compared to see the similarities or difference between the two results.

When the results of the experiment and simulation are compared, a huge difference could be detected, indicating the error of the experiment which has high error. This verifies that there are many factors that affect the experiment that is done making the results less reliable. In this project the difference in the Cl obtained is about 10 times lower in the simulation compared to the experimental results.

Even though the data acquired from the experiment and simulation are different, the end result could be seen as the same. When the max speed during cornering before sliding of the double decker buss is calculated, the same value comes out. This shows that the downforce is too small compared to the mass of the double decker bus, hence making it negligible. It would be a different case for a light vehicle as the contribution of this force might be more significant.

From the interpretation of the data, it is seen that the max speed would vary with the changing radius of cornering. Therefore the cornering radius is made into a variable and the resulting speed obtained for a radius from 5 meters to 20 meters is from 21 km/h to 43 km/h.

VII. RECOMMENDATION

This project is also done by assuming that the double decker bus has a rigid body, neglecting the presence of suspensions. By considering the suspension system, the max speed of the cornering motion would increase as the suspension will act as a support and reduce the mass while cornering in the equation mv^2/r allowing higher V; which is velocity.

For a better result the experiment should be done on a 1:1 scale model but because of the constraints of the project it could not be done.

VIII. CONCLUSION

From the experimental and simulation work the forces acting on the model could be seen. We could see a trend where the forces are more dominant on high speed tallying the equation of:

$$F_l = C_l \rho \frac{A_f}{2} v_\infty^2$$

It could also be seen that there are many things that influences the stability of a double decker bus while moving in a circular motion like the suspension, center of gravity, and the tyre lateral force. For a more accurate result all these variables has to be taken into account.

This project also shows that the aerodynamic frocess on a double decker bus is less significant due to the high value in mass. It would be very hard to improve the performance of this type of vehicle by manipulating the aerodynamic forces that acts on it. Therefore it would be more efficient to improve other things like the position of center of gravity or the suspensions of the vehicle.

IX. REFERENCE

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[3] Barnard R. H., *Road Vehicle Aerodynamic Design*, Longman, England, 1996.