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EFFECTS OF VEHICLE ADD-ONS ON GREENHOUSE GAS EMISSION

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Abstract*-The primary objective of this study is to experimentally measure the aerodynamic properties of various commonly used vehicle add-ons (police siren, advertising sign, taxi sign and roof rack) and roof load (e.g., ladder and barrel) under a range of vehicle operating speeds and yaw angles using RMIT Industrial Wind Tunnel. The study was conducted using a reduced scale (25%) detailed model of a production car manufactured in Australia. The results show that the vehicle add-ons have notable impact on aerodynamic drag as they can generate 5 to 40% more aerodynamic drag depending on yaw angles. The taxi sign has minimum impact and the advertising sign has highest impact on aerodynamic drag. Also roof load such as ladder and barrel can significantly increase the drag. Furthermore, the aerodynamic drag was related to a range of commonly used fuels e.g., petrol, diesel, compressed natural gas (CNG), liquefying petroleum gas (LPG) consumption and their relative greenhouse gas emissions.*

Keywords: Vehicle aerodynamics, Drag coefficient, Vehicle add-ons, Greenhouse gas emission and Fuel

1. INTRODUCTION

Currently most cars, trucks, mini vans, pickups (utility vehicles), and buses are equipped with various add-ons including roof-rack, ladder, ski-rack, bicycle rack, advertising signboard, police and ambulance sirens, taxi sign, tool box, barrels, etc. for personal, recreational, commercial and/or professional uses. These add-ons can generate additional aerodynamic drag based on their external shapes, sizes and placements. Aerodynamic drag (D) depends on the size of a vehicle (projected frontal area, A), the drag coefficient (C_D) which is a measure of the flow quality around the vehicle, and the square of the vehicle speed (V) as expressed in equation 1.

$$D = \frac{1}{2} C_D \rho V^2 A \tag{1}$$

where, ρ is the air density. Aerodynamic drag with a medium-sized car typically accounts for about 75-80% of the total resistance to motion at 100 km/h [1]. Therefore, reducing aerodynamic drag contributes significantly to the fuel economy of a car as well as the reduction of green house gas emissions. For this reason, drag remains the focal point of vehicle aerodynamics. While for a long time, top speed was the motivation for reducing drag in many countries, today, it is the fuel economy and emissions. Fuel consumption is defined as the volume of fuel used to travel a given distance. It can be specified as litres per 100 kilometres (L/100 km). Attachments, such as outside mirrors and antennas, have high drag coefficients if their drag is related to their individual frontal areas. However, their frontal areas are small compared to the overall frontal area of a vehicle. Therefore, their share to the overall vehicle drag is small, even though not negligible. Although the individual drag of these add-ons is less, the cumulative effect of these small contributions makes a significant amount. Furthermore, these add-ons also contribute to wind noise and dirt deposition. These add-ons not only increase the fuel consumption and running cost but also significantly accelerate deterioration of air quality. Additionally, the increased fuel consumption creates extra pressure on national energy security. A study by Snyder [2] indicated that in the US, if it was possible to reduce fuel consumption by as little as 1% (which typically equates to merely 0.1 L/100 km for a standard car), US $30 million could be saved annually. Additionally, the economic benefit of fuel consumption reduction is also an equally important environmental upside. The world's oil resources are finite. As of 2009, the world burnt over 1.3 trillion litres of petrol and diesel each year for powering hundreds of millions cars and trucks. If this is coupled with unsustainable depletion and the high levels of pollution (namely CO_2) generated by burning fossil fuels, it becomes overwhelmingly apparent as to why reducing fuel consumption, if only by a small percentage, is so important to the world we live.

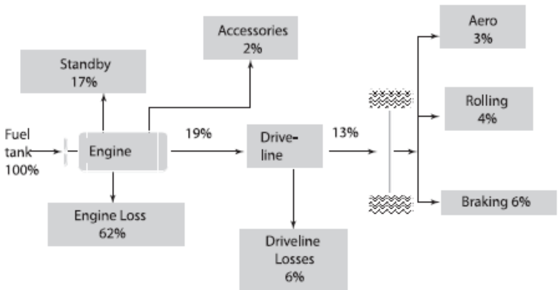
For every litre of petrol used in a motor vehicle, 2.3 kilograms of carbon dioxide (CO_2), a major greenhouse gas, is released from the exhaust. For example, the Australian transport sector accounts for around 76 million tons of Australia's total net greenhouse gas emissions, representing about 13.5% of Australia's total emissions [3]. Fuels differ in the amount of carbon and energy they contain as well as other characteristics, with implications for fuel economy and greenhouse emissions. The Table 1 lists the amount of CO_2 emitted from the exhaust for each litre of a particular fuel.

Energy density is a term used for the amount of energy stored in a given system or region of space per unit volume. For fuels, the energy per unit volume is sometimes a useful parameter. Comparing, for example, the effectiveness of hydrogen fuel to gasoline, hydrogen has a higher specific energy than gasoline does, but, even in liquid form, a much lower energy density. The higher the energy density of the fuel, the more energy may be stored or transported for the same amount of volume. The energy density of a fuel per unit mass is called the specific energy of that fuel. Table 1 also shows that diesel has higher specific energy whereas the specific energy of CNG is less than a quarter of diesel.

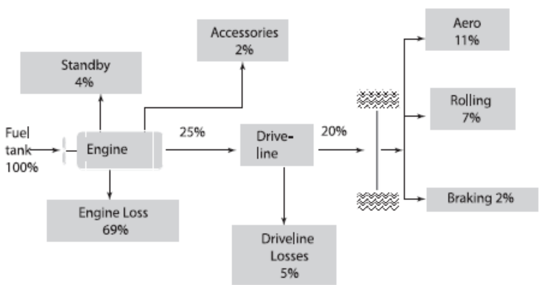
Table 1: Fuel properties

Fuel Type	Specific Energy (MJ/L)	CO_2 Emissions/Litre of Fuel Consumed (kg)
Petrol	34.8	2.3
Diesel	38.6	2.7
LPG	27.7	1.6
CNG	9	1.6

Road load energy, or the energy demanded at the wheels, can be calculated by evaluating the vehicle equation of motion over a specific driving cycle. US Department of Energy indicated driving cycle model for urban and highway driving conditions [4]. These models are shown in Figure 1.



(a) Urban driving



(b) Highway driving

Fig 1: Energy dissipation for a midsize passenger car

The aerodynamic effects on current designs of vehicle add-ons spoilers, roof racks, taxi signs and ladders were not well studied and documented. Although the primary focuses of vehicle manufacturers and researchers have been concentrated on fuel saving devices of the commercial vehicles till to date [5-8]. As the number of passenger cars have been increased significantly worldwide, it is utmost important to study the effects of various add-ons of passenger cars on fuel cost as well as environmental impact. Limited research has been undertaken in this regard.

The primary objective of this study is to investigate the aerodynamic effects of vehicles add-ons and their impact on fuel consumption. Therefore, the main focus will be on vehicle aerodynamic drag that is generated by various add-ons such as roof-rack, taxi sign, ladder and police and advertising sign.

2. METHODOLOGY

The RMIT Industrial Wind Tunnel was used to measure the aerodynamic properties of various add-ons. The tunnel is a closed return circuit wind tunnel with a turntable to simulate the cross wind effects. The maximum speed of the tunnel is approximately 145 km/h. The rectangular test section dimensions are 3 meters wide, 2 meters high and 9 meters long, and the tunnel's cross sectional area is 6 square meters. A plan view of the tunnel is shown in Figure 2. The tunnel was calibrated prior conducting the experiments and air speeds inside the wind tunnel were measured with a modified National Physical Laboratory (NPL) ellipsoidal head pitot-static tube (located at the entry of the test section) which was connected through flexible tubing with the Baratron® pressure sensor made by MKS Instruments, USA. The experimental car model was connected through a mounting sting (see Figures 3) with the JR3 multi-axis load cell, also commonly known as a 6 degree of freedom force-torque sensor made by JR3, Inc., Woodland, USA. The sensor was used to measure all three forces (drag, lift and side forces) and three moments (yaw, pitch and roll) at a time. Each set of data was recorded for 10 seconds time average with a frequency of 20 Hz ensuring electrical interference is minimised. Multiple data sets were collected at each speed tested and the results were averaged for minimising the further possible errors in the raw experimental data.

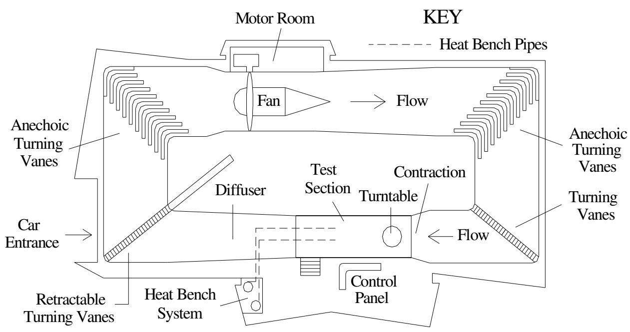


Fig.2: A plan view of RMIT Industrial Wind Tunnel

In order to keep the airflow around the test vehicle as practical as possible, a 25% scale model of a family size passenger production vehicle was used. The model is a true replica of a General Motors Holden VT Commodore family size passenger vehicle (see Figures 3 and 4). Various vehicle add-ons such as police siren, taxi sign, advertising sign, roof-racks including the roof load such as ladder and barrel were designed and manufactured for attaching with the base car model. These add-ons were 25% scale of their full size to match the scale model. Figure 5 shows different add-ons used in this study.

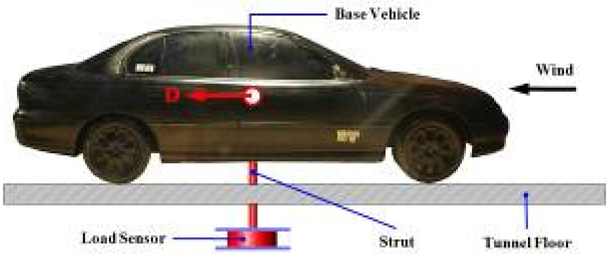


Fig.3: Schematic of the experimental setup

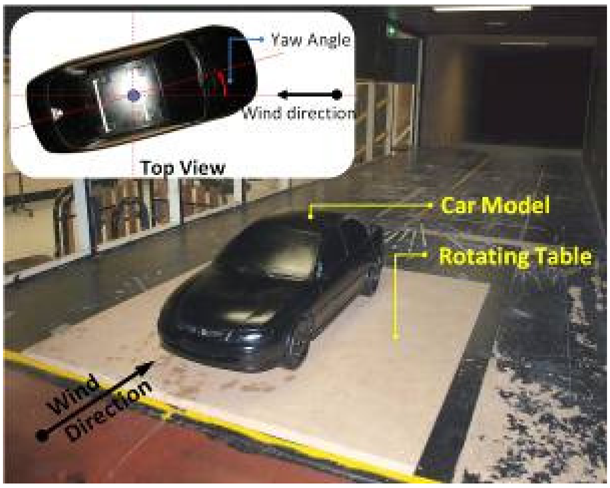


Fig.4: Experimental arrangement in the test section of RMIT Industrial Wind Tunnel

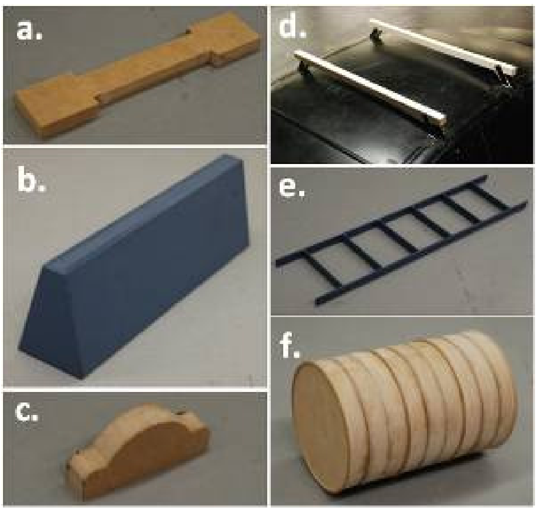


Fig.5: Different add-ons used in this study

The test vehicle was mounted on a six component force sensor type (type JR-3) in the test section of the wind tunnel as shown in Figures 3 and 4. All three forces (drag, lift and side force) and their corresponding moments were measured. The vehicle was tested alone first and then tested with each set of add-ons as shown in Figure 6.

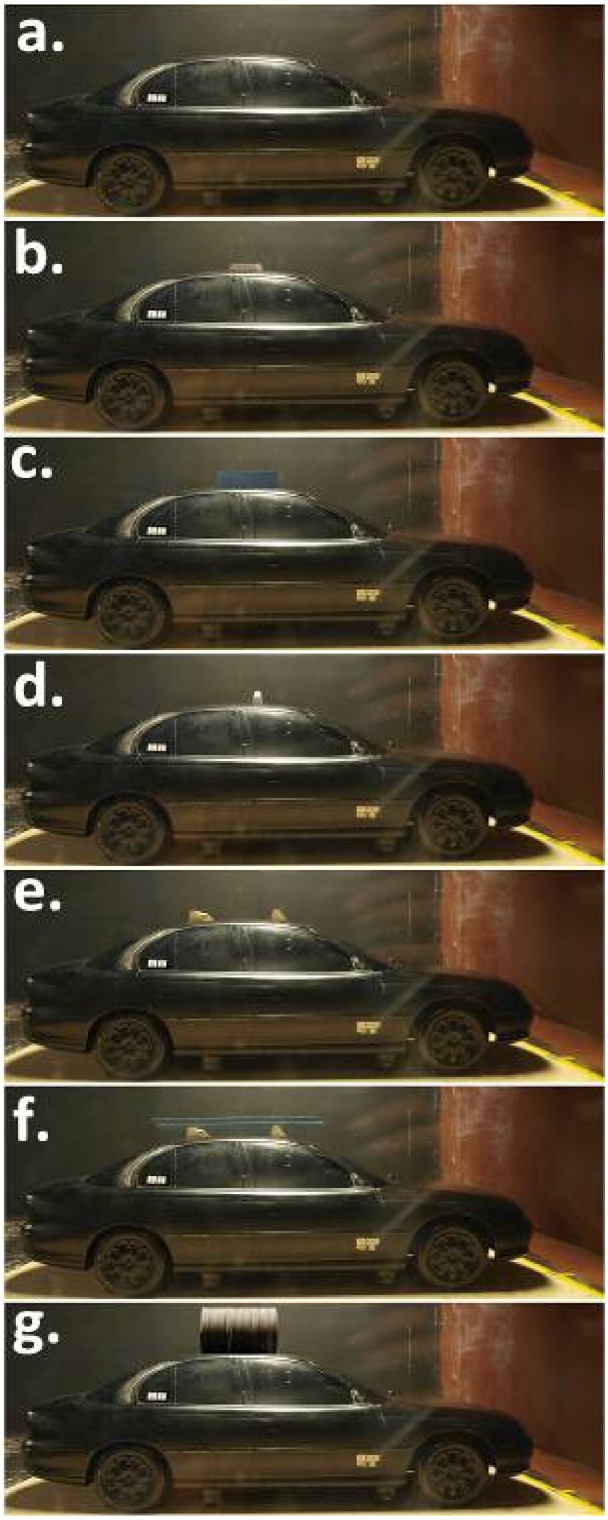


Fig.6: Wind tunnel test configurations for different vehicle add-ons

Tests were conducted at a range of wind speeds (40 km/h to 120 km/h with an increment of 10 km/h) under four yaw angles (0º, 10º, 20º and 30º) to simulate the crosswind effects. Yaw angle (ψ) can be defined as the angle between the vehicle centreline and the mean direction of airflow experienced by the vehicle as indicated in Figure 4.

3. RESULTS AND DISCUSSION

In this paper, only drag force (*D*) data and its dimensionless quantity drag coefficient (C_D) are presented. The C_D was calculated by using the following formula:

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 A} \quad (2)$$

The C_D as a function of speed for various configurations of vehicle add-ons at 0º yaw angle is presented in Figure 7. The figure shows that the base vehicle has almost constant C_D value about 0.4. Similar results were found by Alam at al. [9]. Generally, C_D values for midsize passenger car are ranges from 0.3 to 0.5 depending on the aerodynamic design of the car. The base vehicle without any add-on attached has the lowest C_D value among all other configurations tested. Test vehicle with any add-ons always shows an increase of C_D value. The base vehicle with a barrel has the maximum C_D value among all other add-on tested. The projected frontal area also increases with the add-on attached to the base vehicle. Table 2 represents the percentage increase of drag coefficient (C_D) and projected frontal area (*A*) over the base at 0º yaw angle.

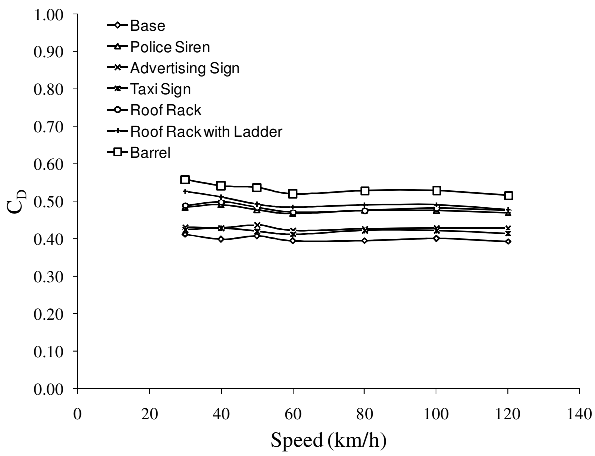


Fig.7: Drag coefficient as a function of speed for different test configurations at ψ = 0º

Table 2: Percentage increase of drag coefficient (C_D) and projected frontal area (*A*) over the base at ψ = 0º

Add-ons	C_D	*A*
Police Siren	19.3%	0.9%
Advertising Sign	7.2%	0.8%
Taxi Sign	5.1%	2.0%
Roof Rack	20.4%	1.2%
Roof Rack with Ladder	24.0%	2.5%
Barrel	33.1%	4.9%

The results show that the overall projected frontal area increased by using different add-ons. Police siren has an increase of about 1% projected frontal area over the base whereas the frontal area is increased about 5% with the barrel. As the projected frontal area increases the drag coefficient is also increased. However, increase of C_D also depends on the placement of the add-on on the base vehicle.

As mentioned earlier that the base vehicle model has also been tested alone with all the add-ons with different combinations at other yaw angles (ψ = 10º, 20º and 30º) to study the cross wind effect. The percentage of aerodynamic drag increases due to police siren, advertising sign, taxi sign, roof rack, roof rack with a ladder and a barrel over the base vehicle is shown in Figure 8 for four yaw angles (ψ = 0º, 10º, 20º and 30º).

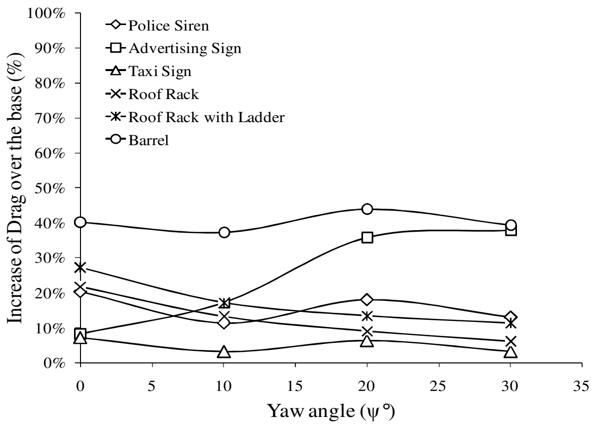


Fig.8: Drag increase over base vehicle in percentage as a function of yaw angle

The yaw angles have different effects on different add-ons depending on their position on the base vehicle. For example, aerodynamic drag increases with the increase of yaw angles for tapered advertisement sign. The advertising sign has increased the aerodynamic drag an average of 8%, 17%, 36% and 38% at 0º, 10º, 20º and 30º yaw angles respectively (see Figure 8). With an increase of yaw angles, the advertising sign generated more drag as its projected frontal area increased. Additionally, the airflow around the advertising sign became more complex and chaotic with yaw angle increase. On the other hand, for the roof rake and roof rake with a ladder, drag decreases with increase of yaw angles as at higher yaw angle these configurations become more streamlined than at 0º yaw angle. Police siren, taxi sign and barrel shows fluctuations of drag with yaw angles. Table 3 represents the percentage increase of average drag over the base on yaw angle variation from 0º to 30º.

Table 3: Percentage increase of drag (*D*) on yaw angle variation from 0º to 30º over the base

Add-ons	Average drag increase
Police Siren	15.6%
Advertising Sign	24.7%
Taxi Sign	5.0%
Roof Rack	12.5%
Roof Rack with Ladder	17.3%
Barrel	40.0%

The results show that the about 5% drag increased with the taxi sign and about 40% drag increased with the barrel. It is clear that the size of the add-on plays important role for the increase of drag. Alam at al. [9]

showed that antenna drag is negligible as size is very small compared to the overall area. But roof racks substantially increase the drag; it is worth removing them when they are not needed. Also roof load such as ladder and barrel can significantly increase the drag. These add-ons also impact the directional stability as the vehicle's centre of gravity changes and the overall lift is reduced due to the disturbance of the flow over the roof [1].

The increase of drag also impacts on the fuel consumption. Fuel consumption as a function of vehicle speed is shown in Figure 9. Fuel consumption is calculated for 4 different types of fossil fuel (petrol, diesel, LPG and CNG) using the urban driving model mentioned earlier. As the specific energy is different for different fuel, for same power output less amount of diesel is required. On the other hand, fuel consumption is about 4 times higher in CNG than diesel. Figure 9 also shows that fuel consumption increasing with the increase of speeds. As the fuel consumption increases, the CO_2 emission also increases. Figure 9 shows the CO_2 emission as a function of speeds for different types of fuel. It is clearly indicated in the figure that CNG has higher rate of CO_2 emission and LPG has lower rate of CO_2 emission among these fuels for same power output.

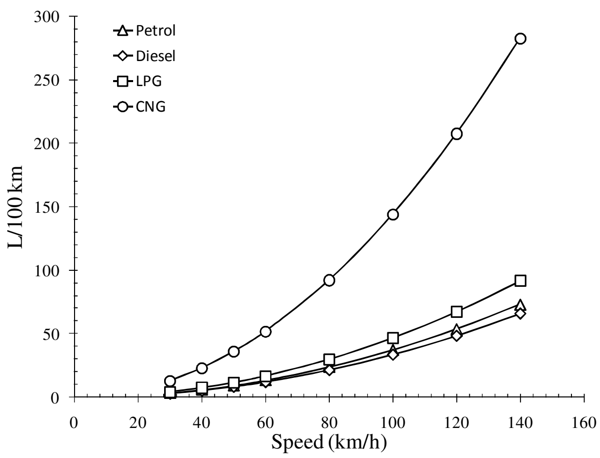


Fig.9: Fuel consumption as a function of speed

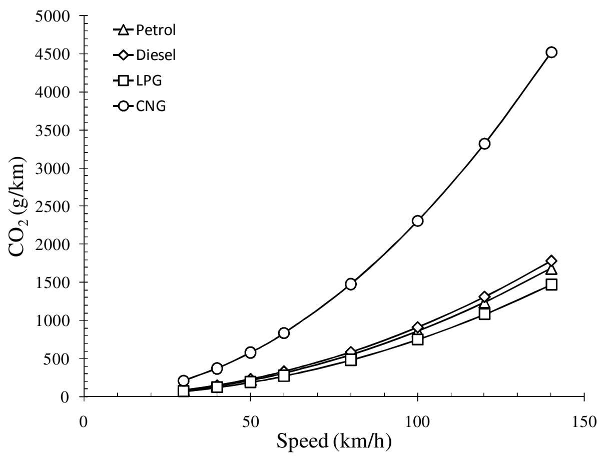


Fig.10: CO_2 emission as a function of speed

It is also important how much fuel is consumed to travel for a given distance. LPG has higher energy density than CNG. However, LPG and CNG have lower greenhouse emissions per litre of fuel consumed than petrol and diesel, but also have lower energy content. Therefore, equivalent vehicles tend to consume more of LPG than petrol to travel a given distance. In the case of diesel, its greenhouse emissions per litre are higher than petrol, but engines designed to operate on diesel tend to be far more fuel-efficient than petrol engines. To be sure that one vehicle has lower greenhouse emissions than another.

Using Figures 9 and 10, it is possible to calculate the annual fuel consumption as well as the CO_2 emission for four different types of fuels. For instance, a passenger car travelling 15,000 kilometres annually and running at an average speed of 60 km/h can produce 4626 , 4896, 4043 or 12444 kg of CO_2 if using petrol, diesel, LPG or CNG respectively.

4. CONCLUSIONS

The following conclusions have been made based on the experimental study undertaken here:

a) The vehicle add-ons have notable impact on aerodynamic drag as they can generate 5 to 40% more aerodynamic drag depending on yaw angles.

b) The taxi sign has minimum impact and the advertising sign has highest impact on aerodynamic drag. Also roof load such as ladder and barrel can significantly increase the drag.

c) The average fuel consumption considerably increases due to vehicle add-ons. Type of fuel has impact on fuel consumption. Diesel fuel is more fuel efficient than CNG, LPG and petrol. However, LPG is more effective for greenhouse gas emission than diesel.

d) Vehicle add-ons substantially increase aerodynamic drag; it is worth removing them when they are not needed. The removal of these add-ons will not only save fuel consumption but also reduce significant amount of greenhouse gas emission.

5. ACKOWLEDGEMENT

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7. NOMENCLATURE

Symbol	Meaning	Unit
D	Drag force	(N)
C_D	Drag coefficient	Dimensionless
V	Wind Speed	(m/s)
ρ	Air Density	(kg/m^3)
ψ	Yaw angle	(Degree)
A	Projected frontal Area	(m^2)