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Vehicle area impact on fuel efficiency in platoon management

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ABSTRACT

Due to the continuous increase in highway transport, the expectation on the automotive manufacturer is increasing for more fuel-efficient solutions. Vehicle platooning attracts considerable attention from the manufacturers and customer business model because of reduced fuel consumption which gives more profits during transportation. Vehicle Platooning is a technique where highway traffic is organized into a group of close-following vehicles called platoon or convoy. In vehicle platoon management, the lead vehicle is led by one or more following vehicles in the longitudinal direction. This research work focuses on the impact of the vehicle area on fuel efficiency and also demonstrates the importance of vehicle area to achieve better fuel efficiency during platoon management. This paper has been divided into four sections, it starts with an introduction to the vehicle platoon and state of art. The second part of the work describes basic mathematical modeling to analyze vehicle area impact in platoon management. The third part describes the analysis of vehicle area impact in the platoon management and finally concluding the research work.

Keywords: *Vehicle Platoon, Vehicle Area, Platoon Management, Fuel Efficiency.*

I. INTRODUCTION

Improving vehicle fuel economy is one of the most important aspects in modern days to achieve customer needs and also to achieve greenhouse gas emission targets. Development is underway to improve the fuel economy and reduce pollution of the group of vehicles by reducing aerodynamic drag through vehicle platooning based on the Intelligent Transport System (ITS) technologies. A lot of research work has happened in vehicle platoon management and confirmed the benefits like improving fuel efficiency up to 15% [1] to [3], reduce CO2 emission [4] &[5], reduced damage because of the accident [5] &[6], more return of investment for fleet owners [5] &[6], improve travel time efficiency [5] &[6], road capacity optimization [5] &[6].

The benefits of the vehicle platoon management have been summarized in “Fig 1”. Vehicle platooning also called a road train vehicle can be defined as a group of vehicles that move coordinated in a specific order. In platooning concept, the lead vehicle will set action and the following vehicle shall follow the action as shown in “Fig 2”. It can be observed from “Fig 2”, that two different road train vehicles are going in two different lanes.

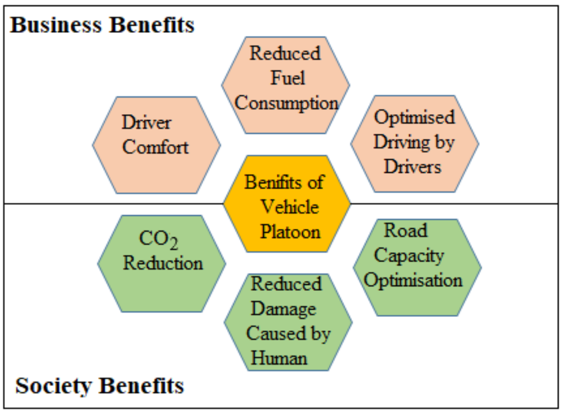

Fig. 1. Business and Society benefit because of Vehicle Platoon Management.

For example in lane-1 there are 3 vehicles in a platoon environment, where a truck with the notation ‘Leading V1’ is the leading vehicle and ‘Follower V2’ is a truck that is following “Leading V1’ vehicle and ‘Follower V3’ is a car following ‘Follower V2’ vehicle. Here, ‘Leading V1’ is the leader in the Lane-1 road which shall communicate other following vehicles for fuel efficiency and safe platoon management.

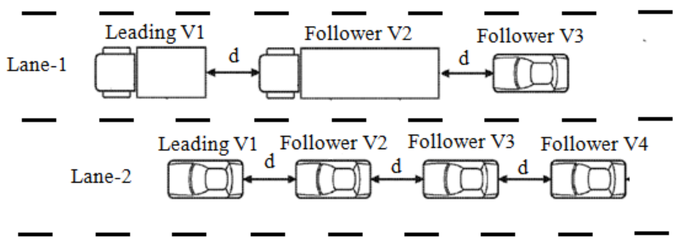

Fig. 2.Vehicle platooning example in 2 different lanes (Bird’s eye view)

As per SAE standard J3016 [8], vehicle platooning shall be categorized as partial driving automation (Level-2) to conditional driving automation (Level-3). If platoon management has to implement 100% on-road then it will be classified as conditional driving automation that is Level-3 automation. Considering potential benefits, many countries like US, Sweden, France, Germany, Japan, etc have given authority to automotive companies to perform a pilot study on the vehicle platoon. In this paper, we have put an effort to understand current research work in vehicle platoon management and focused mainly on vehicle area impacting in achieving fuel efficiency. And also, to understand the dynamics of the vehicle area and fuel consumption.

2. MATHEMATICAL MODELING

Before implementing platoon management, one should understand the basic physics of the vehicle platoon. A longitudinal vehicle model has been derived to understand the impact and benefits of the platoon. Past studies in the U.S. related to fuel economy improvements through platooning include the PATH program [9],[10], which studied platooning two to four vehicles using the linear mathematical model. In Europe, Safe Road Trains for Environment (SARTRE) [11], investigated the benefits of platooning and derived a linear mathematical model to demonstrate fuel efficiency, string stability analysis for stable platooning. Fuel efficiency achievement in platooning due to aerodynamic drag reduction is been demonstrated in reference [12].

It is quite evident that fuel efficiency in vehicle platooning is achieved because of reduced aerodynamic drag. Most of the aerodynamic drag (>90%) is the result of the pressure difference between the front portion of the vehicle to the rear portion of the vehicle. Current research has attempted to study the vehicle area impacting the aerodynamic drag in platoon management.

The mathematical model has been derived using SAE J2263 [13] road load measurement using Newton's law as stated in "(1)", where Vehicle Engine force (FEng) has to generate energy to overcome mechanical frictional resistance(FMech) Aerodynamic resistance (FAero), Tyre rolling resistance (FRoll) and Road gradient resistance (FGrad). Forces generated on the vehicle have been shown in "Fig 3".

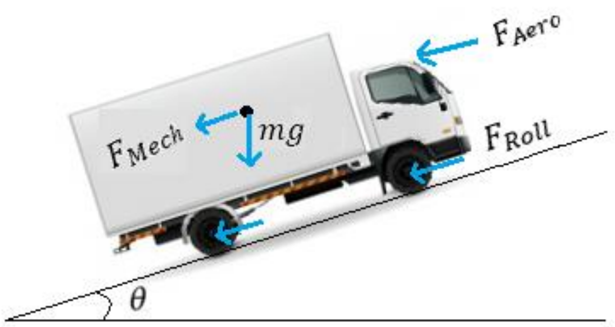

Fig. 3. The schematic diagram for vehicle longitudinal motion

$$F_{Eng} - F_{Mech} - F_{Aero} - F_{Roll} - F_{Grav} = m\frac{dV}{dt} \quad (1)$$

If we assume road is straight so θ=0, mechanical resistance is minimal so Eq-1 can be simplified as mentioned in '(2)'

$$F_{Eng} - F_{Aero} - F_{Roll} = m\frac{dV}{dt} \quad (2)$$

F_{Aero} can be furthered derived as in '(3)', where σ mass density of air, C_D is the aerodynamic drag coefficient, 'A' is the vehicle projected area in the direction of travel, 'v' is longitudinal vehicle velocity. In the current research work vehicle area in vehicle platoon management is the focus of study.

$$F_{Aero} = \frac{1}{2}\sigma A C_D v^2 \quad (3)$$

F_{Roll} can be further derived as in Eq-4, where m is vehicle mass and g is the acceleration due to gravity and C_r is the tyre rolling resistance coefficient, assuming on straight road α is zero.

$$F_{Roll} = mgC_r\cos(\alpha) = mgC_r \quad (4)$$

Reference [14] has derived and validated the fuel consumption model as shown in Eq-5 and the same model has been used in the current research work. Where in Eq-5, fc denotes the instantaneous fuel consumption, ηEng is the mean combustion efficiency of the engine, σd is the energy density of diesel fuel and δ indicates whether fuel is injected into the engine or not.

$$f_c = \frac{\delta}{\eta_{Eng}\sigma_d} vF_{Eng}$$

$$f_c = \frac{\delta}{\eta_{Eng}\sigma_d} vF_{Eng} \quad (5)$$

$$\delta = \begin{cases} 1 & F_{Eng} > 0 \\ 0 & Otherwise \end{cases}$$

Using Eq 3,4 & 5, the total fuel consumption from Eq3 can be represented as below Eq 6.

$$f_c = \frac{\delta}{\eta_{Eng}\sigma_d} v(m\frac{dv}{dt} + \frac{1}{2}\sigma A C_D v^2 + mgC_r) \quad (6)$$

Total fuel consumption over a time T for the solo vehicle can be represented as shown in Eq 7 when the engine is running, so δ is considered as 1 as mentioned in Eq 5.

$$f_{Solo} = \int_0^T \frac{\delta(t)}{\eta_{Eng}\sigma_d} v(t)\left(m\frac{dv(t)}{dt} + \sigma A C_D v^2(t) + mgC_r\right)dt$$

$$f_{Solo} = \frac{1}{\eta_{Eng}\sigma_d} v(\frac{1}{2}\sigma A C_D v^2 + mgC_r)T \quad (7)$$

Equation 7 defines the fuel consumption considering the vehicle in solo on a straight road ($\alpha = 0^0$). To derive total fuel consumption for platoon vehicles, one needs to understand important parameters.

In vehicle platooning, fuel efficiency benefits can be achieved by reduced air drag coefficient. The author in [15] has derived and validated the prediction formula of aerodynamic drag reduction in multiple vehicle platooning.

The generalized prediction formula for vehicles in the platoon is as mentioned in equation 8 and the author has predicted the equation based on the experiment results.

$$C_{DN} = 1 - [(1-\xi_1)(1-\xi_2)......(1-\xi_{N-1})]^2 \quad (8)$$

Where

$$\xi_1 = aC_{D1}^b(d_{12}/A_1^{1/2})^{-2/3}, \xi_2 = aC_{D2}^b(d_{23}/A_2^{1/2})^{-2/3},$$
$$\xi_{N-1} = aC_{DN-1}^b(d_{N-1}/A_{N-1}^{1/2})^{-2/3}....$$

Where 'a' is coefficient (a=1.05), C_{D1}, C_{D2}, C_{D3}, C_{DN-1} are coefficients of drag for first, second and N-1 vehicle respectively, b is coefficient b=0.2, d_{12} is the distance between the first and second vehicle, d_{23} is the distance between the second and third vehicle, d_{N-1} is the distance between the N-1 and N vehicle; A_1 is projected area of the first vehicle, A_2 is projected area of the second vehicle and A_{N-1} is projected area of the first vehicle.

3. MODEL IMPLEMENTATION

In the current work, three vehicles in the platoon management have been considered as shown in "Fig 4"., where lead and follower-1 vehicles are trucks and the follower-3 vehicle is a car.

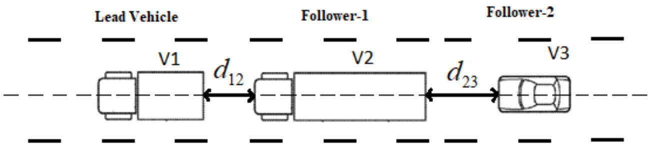

Fig. 4.Vehicle platoon consideration (bird's eye view)

The vehicle parameter used to study platoon management is as shown in table-I.

Table- I: Vehicle Parameters

Parameter	Symbol & Units	Lead Vehicle	Follower -1	Follower -2
Vehicle velocity	V (m/s)	11 to 27.8	11 to 27.8	11 to 27.8
Mass density of air	σ (kg/ m^3)	1.18	1.18	1.18
Vehicle front area	A (m^2)	8.74	11.2	2.58
Aerodynamic drag coefficient	C_D	0.52	0.61	0.278
Vehicle Mass	M (kg)	6200	8100	1800
Acceleration due to gravity	g (m/s^2)	9.8	9.8	9.8
Tyre rolling resistance	Cr	0.02	0.018	0.015
Fuel consumption	η_{Eng} (1/Js)	7000	9200	3110
Energy density of diesel	σ_d (MJ/Kg)	45	45	45
Inter vehicle distance	d_{12} & d_{23}(m)	NA	10 m	10 m

From above "(7)" & "(8)", fuel consumption model for Lead, Follower-1, and follower-2 can be derived as mentioned in "(9)", "(10)", "(11)". It is very clearly evident that fuel consumption is directly related to the area of the vehicle and aerodynamic drag. In next section will simulate the model by considering values in the table and study the fuel consumption behavior with and without vehicle platoon management.

$$f_{Lead} = \frac{1}{\eta_{Eng}\sigma_d} v(\frac{1}{2}\sigma AC_{D1}v^2 + m_1 gC_{r1})T \qquad (9)$$

$$f_{Follower-1} = \frac{1}{\eta_{Eng}\sigma_d} v(\frac{1}{2}\sigma AC_{D2}v^2 + m_2 gC_{r2})T \qquad (10)$$

$$f_{Follower-2} = \frac{1}{\eta_{Eng}\sigma_d} v(\frac{1}{2}\sigma AC_{D3}v^2 + m_3 gC_{r3})T \qquad (11)$$

4. RESULT AND DISCUSSION

Matlab tool has been used to simulate the fuel consumption pattern for Solo and Platoon management. To get fuel consumption for Solo vehicles, "(7)" has been used where has to get fuel consumption for vehicles in platoon management then "(9)", "(10)", and "(11)" has been used. From "Fig 5" and "Fig 6" it is very clearly evident that there is a very good amount of aerodynamic drag force reduction is happening during platooning environment for follower-1 and follower-2 vehicles when inter-vehicle distance is constant 10 meters.

As vehicle speed increases aerodynamic drag force also increases for constant inter-vehicle space distance. It can be observed that from "Fig 6 ", a fair amount of aerodynamic drag force reduction in the follower-1 vehicle compared to follower-2 vehicle and it is because of a very big distinction in area impact for both the vehicles. From "Fig 7", it can be observed that inter-vehicle distance is also very important in reducing aerodynamic drag force and after 70 meters of the gap of the inter-vehicle distance then platooning impact on reducing aerodynamic force will reduce.

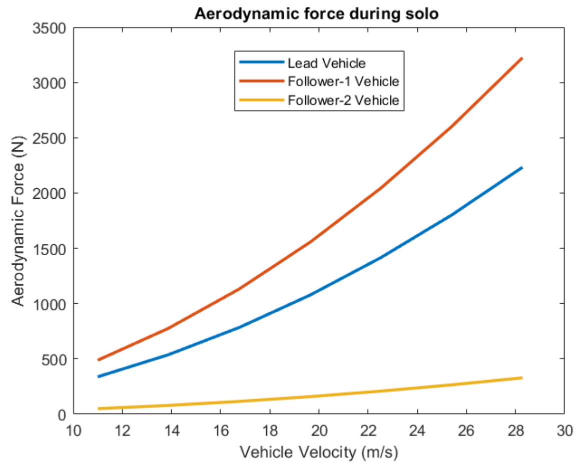

Fig. 5.The aerodynamic force with respect to change in Vehicle velocity in solo condition.

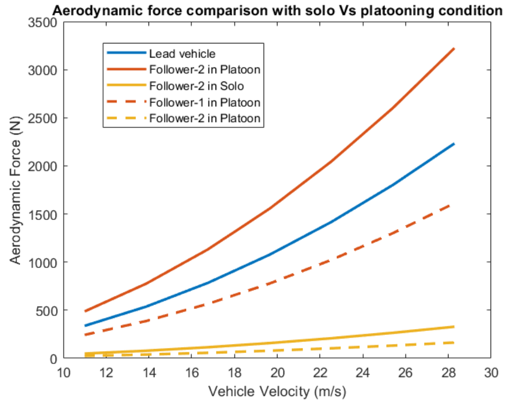

Fig. 6.Aerodynamic force comparison with solo Vs platooning condition.

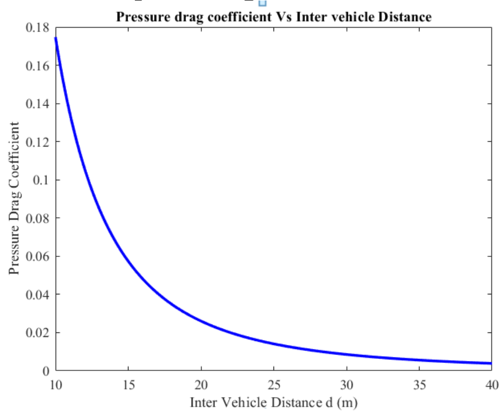

Fig. 7.Pressure drag coefficient with Inter vehicle distance

To understand vehicle area on the fuel efficiency two scenarios have been considered as shown in “Fig 8”. Both the scenarios have been analyzed using (8),(9),(10), and (11) and vehicle parameters have been considered as shown in Table-I. Analysis has been done for two different scenarios as shown in “Fig 8”, scenario-1 where lead vehicle rear area is 8.74 m^2 and follower-1 rear side of vehicle area is 11.2 m^2 and follower-2 rear side of vehicle area is 2.58 m^2. In scenario-2, the lead vehicle has been made as follower-1 and the follower-1 vehicle has been made as to the lead vehicle, follower-2 remains as same.

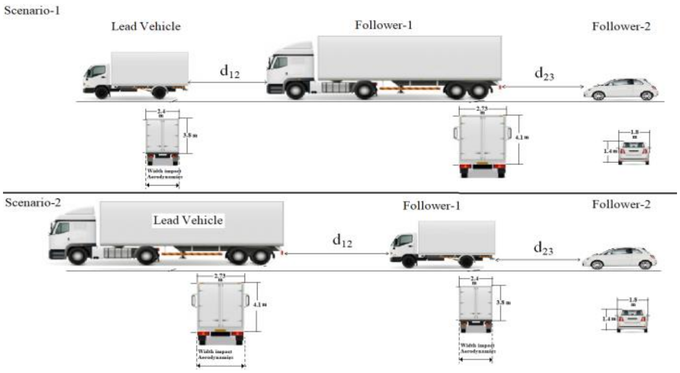

Fig. 8.Two scenarios of Lead and Followers vehicles

Research carried out in [15],[16] has demonstrated that when inter distance d_{12} & d_{23} is varied from 5m to 70m then the difference in fuel efficiency. In the current research work, 10m inter-vehicle distance d_{12} & d_{23} has been selected to study the performance of the vehicle area. For vehicles whose inter-vehicle distance is more than 60 m apart are considered vehicles with are not in longitudinal platoon management.

In scenario-1 total fuel efficiency can be achieved at vehicle constant speed 5 m/s (18 km/hr) is 0 but at the speed of 25 m/s (90 km/hr), total fuel efficiency achieved is nearly 6% compared to the non-platoon scenario. Similarly, for scenario-2, the total fuel efficiency achieved is nearly 10% at 25m/s vehicle speed. This clearly illustrates, scenario-2 is more fuel-efficient compared to scenario-1 and at 25 m/s 4% of more fuel efficiency can be achieved compared to scenario-1.

In scenario-1, the lead vehicle has an area of 2.58 m^2 so it has a 100% impact of aerodynamic force and the follower vehicle-1 area is 11.2 m^2 also experiences aerodynamic drag because the area different from the lead vehicle, follower vehicle-2 aerodynamic drag is negligible because of follower-1 vehicle. The main reason for achieving 4% more fuel efficiency in scenario-2 is because the total aerodynamic drag is reduced considering all three vehicles in longitudinal platoon management and here only the lead vehicle is impacted with aerodynamic drag and follower vehicle-1 and follower vehicle-2 shall enjoy the negligible aerodynamic drag because of bigger vehicle area ahead of the respective vehicle.

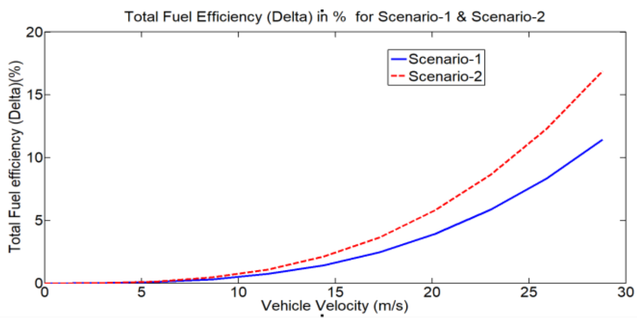

Fig. 9.Total fuel efficiency(Delta) in % for scenario-1 and scenario-2 for d_{12} & d_{23} is 10m

5. CONCLUSION

Platoon management is the current research domain in the automotive domain to achieve social and customer benefits. Customers with follower vehicles shall enjoy very good fuel efficiency in the platoon management. However, to achieve very good fuel efficiency quite a lot of factors have to be considered like vehicle to vehicle distance, vehicle speed during convey, vehicle area, etc.

This research work is more focused on the analysis of vehicle area impact during platoon management. It is evident that the vehicle area plays a significant role in achieving good fuel efficiency during platoon management. During new vehicle addition in platoon management then depending on the new vehicle area, platoon management shall identify the best vehicle position to achieve the best total fuel efficiency. The future part of our research work is on how to measure vehicle area using the deep-learning algorithm.

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