Vehicle Platooning Impact on Drag Coefficients and Energy/Fuel Saving Implications

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Abstract—In this paper, empirical data obtained from the literature were used to develop models that capture the impact of the vehicle position in a platoon of homogeneous vehicles and the distance gap to its lead (and following) vehicle on its drag coefficient. These models are developed for light duty vehicles (LDVs), buses, and heavy duty trucks (HDTs). The models that are fit using a constrained optimization formulation are then used to extrapolate the empirical measurements to a wide range of vehicle distance gaps. The results show a significant reduction in the vehicle fuel consumption when compared with those based on a constant drag coefficient assumption. Specifically, considering a minimum time gap between vehicles of 0.5 seconds running at a speed of 100 km/hr, the fuel reduction that is achieved is 5%, 17%, and 12% for LDV, bus, and HDT platoons, respectively. For longer time gaps (gap ≈ 2 seconds), the bus and HDT platoons still experience fuel reductions in the order of 8%, whereas LDVs incur negligible fuel savings.

Index Terms—Drag coefficient, vehicle platooning, connected automated vehicles, vehicle energy consumption.

I. INTRODUCTION

The objectives and contributions of this paper are two-fold. First, we develop general rational polynomial models that capture the impact of a vehicle position, in a platoon of homogeneous vehicles, and the distance gap to its lead (and following) vehicle on its drag coefficient. These models are developed for light duty vehicles (LDVs), buses, and heavy duty trucks (HDTs). Second, we demonstrate and use these models to estimate the potential fuel reductions associated with homogeneous platoons of LDVs, buses, and HDTs.

A. Literature Review and Background

Platooning is gaining momentum as an efficient strategy to increase roadway capacity and reduce vehicle fuel consumption, as several studies have suggested [1]–[9]. One of the key factors behind this reduction in fuel consumption is the relationship between the intra-platoon distance gap and the drag forces. The drag force generated on a vehicle consists of two main components, namely: (i) the skin friction drag, and (ii) the form drag. The skin friction drag depends mainly on the roughness and the total area of the vehicle subjected to the air flow. This type of drag is not affected by the distance gap between vehicles. The most important type of drag that is affected by driving in a platoon/convoy is the form drag. The form drag is a function of the vehicle shape and flow around it. This type of drag is dependent on how quickly and smoothly the air that separates from the vehicle rejoins downstream of the vehicle, i.e. the wake shape and turbulence level. In other words, the more the vehicle shape is streamlined, the less the form drag is. This type of drag can benefit the following vehicle by reducing its frontal dynamic pressure when following another vehicle at a closer spacing. This effect is observed in nature where birds fly in a streamline/wake of each other [10], [11] known as slip-streaming or drafting and was mimicked in fighter aircraft design [12]. Hence having two vehicles (one ahead and another behind) driving at a close distance gap affects the pressure forces on the vehicle, thus reducing the aerodynamic resistance force and producing fuel savings. However, the effect at a very close distance gap depends on some geometrical aspects and the type of vehicle platoons [1], [7], [13]–[16], i.e. LDVs, buses, and/or HDTs. The empirical data demonstrate a local peak in the drag force at short distance gaps. (See Section II).

Experimental work done by Zabat et al. [17] on LDV platoons was used in this study. The experiment was performed on scaled-down (1/8) 1991 General Motors Lumina APV vehicles in a wind-tunnel environment with drag measurements up to distance gaps of 3 and 2 vehicle lengths for the two and three-LDV platoons, respectively. The results showed a drag reduction of up to 15% for the lead vehicle and up to 30% for the trail vehicle in a two-LDV platoon at a distance gap of half a vehicle length. For distance gaps less than half a vehicle length, this effect was reversed and the lead vehicle produced a higher reduction in the drag coefficient compared to the trail vehicle. Hong et al. [18] verified this behavior at close distance gaps by performing a full-scale road test, and it was also observed in part of the wind tunnel test done by Marcu and Browand [19] in crosswind conditions.

For the bus platoons, an experimental study documented in [20], [21] was performed on 1 : 20 scaled-down cylindrical bus-shaped bodies (representing a Mercedes-Benz S 80 model) in a wind tunnel while conducting drag measurements for distance gaps of up to 5 bus lengths. The results show a drag reduction of up to 10% for the lead bus and up to 60% for the second bus in a two-bus platoon at a 10 m distance gap. For HDT platoons, most of the available data were fuel measurements for different intra-platoon distance gaps [4]–[6], [22]–[24] on a full-scale
truck in a road test environment with fuel measurements up to distance gaps of 2 truck lengths. To compute the equivalent drag coefficient, one may use the fuel model developed in [25] to relate the fuel consumption to the drag forces. In addition, [16] provide fuel measurements resulting from road tests of empty trucks at very close spacings of $5 \sim 20$ m, which is equivalent to time gaps of $0.23 \sim 0.9$ secs. At very close spacings, the fuel savings for the trucks encounter a different behavior (a local peak) as mentioned earlier. The same behavior has been reported in the wind tunnel drag measurements of [17], [26] and been pointed out in different sources [1], [7], [13]–[15]. However, we consider all the data [16], [27] to validate the model for the two-HDT platoon. In general, the dependence of the drag coefficient on the intra-platoon distance gap acts in favor of reduction of the resistance forces but may add complexity to the platoon car-following controller design [28], [29] through the non-linearity introduced by coupling the vehicle-platoon model, i.e. the drag coefficient is now dependant on the distance gap between vehicles in the platoon, $C_D = f(G = x_i - x_{i-1})$. The accurate modeling of the drag interaction between vehicles makes the controller design more efficient when it comes to finding the optimal control action using either robust or model predictive techniques [29]–[32] and reduces the uncertainty in the model predictions [33]. In other words, the modeling of the drag coefficient improves the efficiency and accuracy of the optimization problem and, in turn, improves the control action needed, as mentioned in [29]. In addition, for optimization problems that explicitly optimize fuel savings, modeling the fuel consumption accurately requires an analytical relationship between the drag coefficient and the platoon distance gap. Modeling the impact of platooning on the drag coefficient is critical to quantifying the fuel/energy consumption impacts of platooning strategies. Furthermore, in quantifying the fuel reductions associated with vehicle platooning strategies, the drag coefficient of all vehicles in a platoon for the full range of distance gaps is needed, which is not available from measurement/numerical data [34]. Hence, the need for an analytical function that describes the relation between the drag coefficient and the intra-platoon distance gap to extrapolate beyond the measurement/numerical spectrum is inevitable.

B. Paper Contribution and Layout

The two main contributions of this paper are: (1) we develop and present a unified model that characterizes the impact of the intra-vehicle distance gap and position in a platoon on the vehicle’s drag coefficient; and (2) we use this model to quantify the energy/fuel savings associated with homogeneous platoons of LDVs, buses, and HDTs. Specifically, this developed drag model is used to provide an analytic function that describes the relation between the drag coefficient and intra-platoon distance gap: (i) quantify the potential fuel consumption savings for different homogeneous platoons at a wider range of distance gaps beyond existing empirical measurements, (ii) quantify the potential fuel consumption savings for different homogeneous platoons for a new vehicle type without the need to perform experimental/numerical studies, (iii) to be used when the fuel consumption in the objective to be minimized [35] and for designing the controller associated with this objective [35] or other ones, i.e. maintaining time-headway for stability [36] or minimizing the error for vehicle following control [29].

In this paper, we examine the effect of the intra-vehicle platoon distance gap on the potential of fuel reduction for LDV, bus, and HDT platoons. The outline of the paper is as follows. In Section II, we present the empirical data available for each type of platoon. For LDV platoons [17], [26], the available data are the drag measurements on a 1 : 8 vehicle in wind tunnel testing. For bus platoons [21], the available data are drag measurements through wind tunnel tests on 1 : 20 scale cylindrical bus model [20]. For the HDT platoon modeling [22], [23], the data available for the two- and three-HDT platoons is fuel measurements through full-scale road testing. The fuel data for the truck platoon is used to compute the equivalent drag coefficient using the fuel model developed in [25]. In Section III, we present the optimization framework used to fit a model to the data and extrapolate beyond data range. In Section IV, we investigate the effect of the drag coefficient function on the potential fuel reduction for different vehicle types. In addition, we validate the two-HDT platoon model using other fuel data provided in the literature [27]. In Section V, we summarize the results and discuss the impact of the current work.

II. DRAG AND FUEL MEASUREMENTS FOR LDV, BUS, AND HDT PLATOONS

The data for the drag measurements versus the intra-platoon distance gap for each vehicle in two- and three-LDV platoons from Refs. [17], [26] are shown in Fig. 1. The distance gap, denoted by $G$ in all the figures and sections, is the distance measured from the rear bumper of the lead vehicle to the front bumper of the subject vehicle, i.e. for 2+ vehicle platoons, the distance gap is symmetrical for both the front and rear of a vehicle within the platoon. For the lead vehicle measurements, the difference in the drag coefficient, $C_D$, for both two- and three-vehicle platoons is negligible. The lead vehicles experience a 15% reduction in the drag coefficient at a distance gap of 2.5 m. For the second vehicle measurements, the drag coefficient for the second vehicle in the three-vehicle platoon, experiences more reduction compared to the second vehicle in the two-vehicle platoon for distance gaps less than 5 m. When the distance gap is larger than 5 m, the behavior of the drag coefficient of the second vehicle is reversed, i.e. the drag coefficient of the second vehicle in the three-vehicle platoon experiences less reduction compared to the second vehicle in the two-vehicle platoon. Comparing
the drag measurement at $G = 0$ from the experimental work done in [21]. The drag coefficient is normalized by the drag coefficient of a single bus, i.e. $C_{D\infty}$.

Fig. 2. Drag Coefficient ratio for empirical data, $C_D/C_{D\infty}$, for each bus in two- and three-bus platoons versus the distance gap, $G$, between buses from the experimental work done in [21]. The drag coefficient is normalized by the drag coefficient of a single bus, i.e. $C_{D\infty}$.

Fig. 3. Schematic showing how the geometry at short distance gaps differs from the LDV, HDT in [26] and Ref [37] influences and bus (cylindrical shape) from [21].

Fig. 4. Fuel ratio versus distance gap, $G$, for two-HDT platoons from references [22], [37]. (a) Fuel reduction ratio, $(F - F_{\infty})/F_{\infty}$, for two-HDT platoons from Ref. (37). The fuel consumption is normalized with respect to a single truck fuel consumption, i.e. $F_{\infty}$. (b) Fuel reduction ratio, $(F - F_{\infty})/F_{\infty}$, for two-HDT platoons from Ref. (22). The fuel consumption is normalized with respect to a single truck fuel consumption, i.e. $F_{\infty}$.

Fig. 5. Fuel ratio versus distance gap, $G$, for two- and three-HDT platoons from references [23], [37]. (a) Fuel reduction ratio, $(F - F_{\infty})/F_{\infty}$, for three-HDT platoons from Ref. (37). The fuel consumption is normalized with respect to a single truck fuel consumption, i.e. $F_{\infty}$. (b) Fuel reduction ratio, $(F - F_{\infty})/F_{\infty}$, for three-HDT platoons from Ref. (23). The fuel consumption is normalized with respect to a single truck fuel consumption, i.e. $F_{\infty}$.

the last vehicle in the three-vehicle platoon, the drag coefficient experiences more reduction over the full range of distance gaps compared to the second vehicle in the two-vehicle platoon. This is attributed to the effect of reducing the pressure on the last vehicle because of driving in the slipstream of more than one vehicle. Based on the results in [17], we assume that the drag reduction for the third vehicle in the platoon is almost the same as the remaining vehicles in the platoon, i.e. $C_D|_3 \approx C_D|_{3+}$. This result is also applied to bus and HDT platoons. On the other hand, at shorter distance gaps, the drag coefficient exhibits a local peak for the last vehicle in either the two- or three-vehicle platoons. Ultimately, the drag of the last vehicle in the platoon converges to a value higher than that of the lead vehicle at a zero gap. The data for the drag measurements for each bus in two- and three-bus platoons from [21] are shown in Fig. 2. Similar to the LDV platoons, the last bus in the three-bus platoon experiences more reduction in the drag coefficient compared to the last bus in the two-bus platoon. This is attributed to the same reason discussed earlier.

Unlike LDV platoons, the bus drag coefficient ratio for the last vehicle in the platoon does not exhibit a local peak. This is attributed to the dependence of the drag coefficient on the vehicle shape at short distance gaps, as shown in Fig. 3. In [21] the authors used a cylindrical prototype to model buses. Consequently, at zero gaps, unlike the LDV and HDT platoons, the platoon reverts to a single long cylinder. This explains why the wind tunnel results for the LDVs shows a local peak, which agrees with the HDT road test data, while the wind tunnel measurements on the cylindrical shapes do not exhibit this behavior. Consequently, the reduction of the drag coefficient to less than half the original value at a distance gap $G = 0$ raises some concerns about the credibility of the bus data at short distance gaps. Hence we removed the drag measurement at $G = 0$ from the bus data when performing the optimization described in the next section. The fuel data for the two-HDT platoons is shown in Fig. 4. The road test done in [22] examined a range of distance gaps ranging from $3 - 10$ m, which is considered a small range compared to the data in Fig. 4(a) from [37]. Since the data shown in Fig. 4(b) does not cover a wide range of distance gaps, which will impose some challenges when building the drag model, we used the data from [37].

Similarly for the three-HDT platoon in Fig. 5, we used the data [37] shown in Fig. 5(a) since it covers a wide range of distance gaps compared to the data [23] in Fig. 5(b). Furthermore, the change in the fuel behavior at short distance gaps is observed here for the data from [37] which is similar to the LDV. This behavior dictates a choice of a good function to capture the effects at both small and large vehicle spacings, which is not possible using a single power function [38]. For both HDT platoons, the equivalent drag coefficients for the data in Figs. 4(a), 5(a) are obtained through the fuel model developed in [25], which relates the fuel consumption to the various forces via the exerted power. The procedures used to convert from fuel consumption to the drag coefficient are shown in (9)–(11). The parameters of the vehicles used to obtain the data in the previous Figures are given in Table I. In the next section, we discuss the fitting procedure used to develop analytical models for LDV, bus, and HDT platoons.
III. FITTING DRAG MEASUREMENTS FOR LDV, BUS, AND HDT PLATOONS

In this section, we fit models to the empirical data for LDV, bus, and HDT platoons using a general rational polynomial function as given in (1).

\[
y(x) = \sum_{i=0}^{n} a_i x^i \tag{1}
\]

The advantage of using a rational polynomial rather than a power function is: (i) the rational polynomial function can capture different peaks based on the number of roots in both the numerator and denominator; and (ii) the rational polynomial function can capture the horizontal asymptotic function behavior, i.e. the function approaches zero as \( x \) approaches infinity.

The first property of the rational polynomial function is critical in capturing the behavior at small temporal gaps (local peak) and the second property captures an inherent property of the drag coefficient. For our case here, our objective is to have the drag function monotonically increase with the distance gap up to the drag coefficient of a single vehicle \( C_{D,0} \) while capturing the local peak at short gaps. The drag coefficient over a broad range of distance gaps can be defined as:

\[
\frac{C_D}{C_{D,0}} = \begin{cases} 
\frac{a_N G^N + a_{N-1} G^{N-1} + \ldots + a_1 G^1 + a_0}{b_N G^N + b_{N-1} G^{N-1} + \ldots + b_1 G^1 + b_0} & 0 < G \leq G_o \\
1 & G \geq G_o \tag{2}
\end{cases}
\]

where \( G_o \) is the critical distance gap above which the drag force on a vehicle is not affected by the presence of other vehicles either in front or behind it, i.e. \( C_D/C_{D,0}(G_o) = 1 \). \( C_{D,0} \) is the drag coefficient of a single vehicle in the absence of any other vehicles in its vicinity. The drag coefficient should be constrained to ensure that it does not exceed 1.0 by adding the following condition \( C_D/C_{D,0}(G) = \min(C_D/C_{D,0}(G), 1.0) \). The objective of the curve fitting is to find the parameters of the rational polynomial function that best represent the empirical data for each of the cases presented in Figs. 1, 2, 4, 5, i.e. the optimal parameters that minimize the sum of squared error between the fitted function and the field measurements [38]. Since we do not have measurements beyond certain distance gaps, the point \( G_o \) can be obtained through optimization. This limited coverage of data is caused by the nature of the underlying experiment or computational resources for each case. However, given that these models would capture vehicle interactions in the field general models are needed. For a set of initial conditions, a different local optimum solution can be obtained with different values of \( G_o \). Hence, to determine the value of the critical distance gap, \( G_o \), its value was assumed to be unknown and was estimated through the optimization procedure. The nonlinear least square data fitting is formulated as follows

\[
\min_{z} \sum_{j=1}^{N_p} \left( \frac{C_D}{C_{D,0}}(G_j) - \frac{C_D}{C_{D,0}}(G_{j,T}) \right)^2 \tag{3}
\]

subjected to the nonlinear constraint

\[
0.5 \leq \frac{C_D}{C_{D,0}}(G_j) \leq 0.8 \tag{4}
\]

where \( z = \{a, b, G_o\}^T \) is the vector of the design variables, \( N_p \) is the number of empirical observations available for each case, and the subscript \( M \) stands for measurements. We used the constrained nonlinear solver \texttt{fmincon} in Matlab with Sequential-Quadratic-Programming to identify the optimum parameters (i.e. calibrate the proposed functions). The nonlinear constraint in (4) is used only for the HDT data where there are no data recorded for the minimum gap defined in each experimental setup. The constraint was introduced to ensure that the function that approximates the drag behavior does not extrapolate to infeasible values in this small range, i.e. \( 0 \leq G \leq G_{j=1} \). In addition, a bounding constraint on the value \( G_o \) can be introduced if the data does not cover a wide range of distance gaps. The constraints on \( G_o \) guarantee feasible estimates of this variable. In all the cases, the nonlinear least square optimization was applied without introducing bounding constraints on \( G_o \).

Noteworthy is the fact that we used the general optimization technique for modeling the drag behavior since the function is non-linear in the model coefficients and given that typical curve fitting procedures can only find the equation parameters, \{a, b\}^T, given the vectors x and y. However in our case; (i) the last point of the vector x, \( G_o \) is one of the variables to be determined, \( z = \{a, b, G_o\}^T \), and cannot be estimated using standard curve fitting procedures [38], (ii) the nonlinear constraint in (4) needs to be invoked for the reasons mentioned earlier. These two conditions cannot be addressed using standard curve fitting procedures, as demonstrated in the codes that are provided in the supplementary documents. To get good initial conditions for the parameter \( G_o \), we applied the standard curve fitting procedures considering the power function as

\[
y = ax^b + c \tag{5}
\]

This provided us with an initial solution to run our optimizer. The coefficients of the power model are given in Table II. As shown
The drag coefficient ratio, \( \frac{C_D}{C_{D,\infty}} \), for two-LDV platoons using the power model in (5). The drag coefficient is normalized with respect to the single vehicle drag coefficient, i.e. \( C_{D,\infty} \). The data in the Figure is based on the experimental measurements in [26].

**TABLE III**

| Parameters | Two-LDV | Three-LDV |
|------------|---------|-----------|
| Lead       | Trial   | Lead      | Trial   |
| \( a_1 \)  | 0.1500  | 0.1700    | 0.1700  |
| \( a_2 \)  | 0.2000  | 0.2000    | 0.3000  |
| \( b_1 \)  | 0.3000  | 0.3000    | 0.3000  |
| \( b_2 \)  | 0.4000  | 0.4000    | 0.4000  |

The coefficient of determination (\( R^2 \)) for the rational polynomial model is tabulated in Table VI for each model. The optimum parameters for each vehicle type and platoon configuration are summarized in Tables [III–V] for rational polynomial of order \( N = 3 \). The order \( N = 3 \) was found to be optimal for modeling purposes given that it captures both the local peak at short distance gaps and the asymptotic behavior at large gaps without introducing infeasible peaks elsewhere in the gap range. In all cases, the drag coefficient ratio for the lead vehicle converges to unity very quickly when compared to the middle and the last vehicle, i.e. the critical distance gap at which the lead vehicle is no longer influenced by the rear ones.

In Figs. 7, 8, the data fitting results are shown for two- and three-LDV platoons. The experimental data are extracted from the work of Zabat et al. [17], [26]. As illustrated in Figs. 7, 8, the models for the lead vehicle in both the two- and three-LDV platoons are very similar. Noteworthy is the fact that the rational polynomial captures the local peak in the drag behavior as shown in Figs. 7(b), 8(b). Capturing such behavior would not be possible if a power function is used as in Reference [38], which is essential for extrapolating the fuel savings to shorter gaps. In addition, the distance gap \( G_o \) obtained from optimization are within a reasonable range, as shown in Figs. 7(a), 8(a). The inclusion of the parameter \( G_o \) in the optimization enhances the accuracy of the model extrapolation over a wider range of distance gaps. This point represents a predictor for the no-influence point between vehicles. However, it should be noted that the model error for extrapolating is typically larger than that for interpolating. The \( G_o \) parameter should thus be considered as an upper bound for the distance gap between vehicles where fuel savings are achievable [28], [29].

![Fig. 6](image_url)

**Fig. 6.** Drag Coefficient ratio, \( \frac{C_D}{C_{D,\infty}} \), for two-LDV platoons using the power model in (5). The drag coefficient is normalized with respect to the single vehicle drag coefficient, i.e. \( C_{D,\infty} \). The data in the Figure is based on the experimental measurements in [26].

**TABLE IV**

| Parameters | Two-HDT | Three-HDT |
|------------|---------|-----------|
| Lead       | Trial   | Lead      | Trial   |
| \( a_1 \)  | 0.1500  | 0.1700    | 0.1700  |
| \( a_2 \)  | 0.2000  | 0.2000    | 0.3000  |
| \( b_1 \)  | 0.3000  | 0.3000    | 0.3000  |
| \( b_2 \)  | 0.4000  | 0.4000    | 0.4000  |

![Fig. 7](image_url)

**Fig. 7.** Drag Coefficient ratio, \( \frac{C_D}{C_{D,\infty}} \), for two-LDV platoons. The drag coefficient is normalized with respect to the single vehicle drag coefficient, i.e. \( C_{D,\infty} \). The data in the Figure is based on the experimental measurements in [26].

(a) Drag coefficient ratio, \( \frac{C_D}{C_{D,\infty}} \), versus distance gap for two-LDV platoon.

(b) Zooming in to elaborate the behavior at short distance gaps for two-LDV platoon.

**TABLE V**

| Parameters | Bus-Platoon |
|------------|-------------|
| Lead       | Trial       |
| \( a_1 \)  | 0.1500      |
| \( a_2 \)  | 0.2000      |
| \( b_1 \)  | 0.3000      |
| \( b_2 \)  | 0.4000      |
| \( G_o \)  | -           |

![Fig. 8](image_url)

**Fig. 8.** Drag Coefficient ratio, \( \frac{C_D}{C_{D,\infty}} \), for three-LDV platoons. The drag coefficient is normalized with respect to the single vehicle drag coefficient, i.e. \( C_{D,\infty} \). The data in the Figure is based on the experimental measurements in [26].

(a) Drag coefficient ratio, \( \frac{C_D}{C_{D,\infty}} \), versus distance gap for three-LDV platoon.

(b) Zooming in to elaborate the behavior at short distance gaps for three-LDV platoon.
In Figs. 9, 10, the results for two- and three-HDT Platoons are shown. The drag coefficient for the two- and three-HDT Platoons in Figs. [9(a), 10(a)] are based on the measurements in Ref. [37]. The drag coefficients are calculated from the fuel measurements via the relations defined in (6)–(8). Similarly to the LDV Platoons, the local peak at short distance gaps is captured as shown in Figs. 9(b), 10(b). As mentioned earlier, capturing this behavior is essential when extrapolating the fuel savings to short distance gaps.

In Figs. 11, 12, the results for the two and three bus platoon are shown. The fitting is based on the experimental measurement in Fig. 2 collected from [21]. Based on the measurements for the lead car in Fig. 1, the curve for the lead bus in the presence of one or more buses behind it is assumed to be identical. Hence the data and the approximation curves in Figs. 11, 12 are identical. The data shown in Fig. 12 for the case of the second bus in a three-bus platoon is obtained by assuming that the drag coefficient for the second bus in a two-bus platoon is the average of the result of the last bus in a two- and three-bus platoon. This approximation is based on the observation of the car results in Fig. 1. As was the case with the LDV and HDT platoons, the behavior at short gaps (local peak) is obtained here by removing the drag value at a zero gap. As shown in Figs. [11(b), 12(b)], the behavior is recovered which agrees with what is observed in the LDV wind tunnel and HDT road data. The value of the drag coefficient at a zero gap is more reasonable than what is reported from the wind tunnel measurement.

IV. FUEL CURVES FOR LDV, BUS, AND HDT PLATOONS

In this Section, we examine the effect of using the drag model developed in Section III on the platoon fuel consumption. The fuel model is developed by Rakha et al. [25] to calculate the instantaneous fuel consumption. The instantaneous power in kW is calculated as

\[
P(t) = \frac{R(t) + 1.04 m a(t)}{3600 \eta_d} v(t) \tag{6}
\]

where \(m\) is the vehicle mass in kg, \(a(t)\) is vehicle acceleration in \(m/s^2\) at instant \(t\), \(v(t)\) is the vehicle speed in \(km/h\) at instant \(t\), \(\eta_d\) is the drive-line efficiency, and \(R(t)\) is the resistance force in \(N\) at instant \(t\). The resistance force \(R(t)\) is calculated as

\[
R(t) = \frac{\rho}{25.92} C_d C_r A_f v(t)^2 + gm \frac{C_r}{1000} (C_1 v(t) + C_2) + g m G(t) \tag{7}
\]

where \(\rho\) is the air density at sea level and 15 °C, \(C_d\) is the vehicle drag coefficient, \(C_h\) is the correction factor of elevation, \(A_f\) is the vehicle frontal area in \(m^2\), \(g\) is the gravitational acceleration, \(G(t)\) is the roadway grade, and \(C_r, C_1\), and \(C_2\) are the rolling resistance parameters. The fuel consumption is then calculated using power computed using (6) as

\[
F(t) = \begin{cases} 
\alpha_0 + \alpha_1 P(t) + \alpha_2 P(t)^2, & P(t) \geq 0 \\
\alpha_0, & P(t) < 0 
\end{cases} \tag{8}
\]
where the coefficients $\alpha_0$, $\alpha_1$, and $\alpha_2$ are calculated using the power and fuel consumed using the Environmental Protection Agency (EPA) fuel ratings [25]. To obtain the equivalent drag coefficient for trucks that is shown in Figs. 9(a), 10(a) from the fuel measurements in Figs. 4(b), 5(b), the fuel ratio is defined as

$$\frac{F_{\infty} - F}{F_{\infty}} = \Delta$$

$$\Rightarrow F = F_{\infty}(1 - \Delta)$$

$$= (\alpha_0 + \alpha_1 P(t) + \alpha_2 P(t)^2) n$$

where $F_{\infty}$ is the fuel consumption rate of the vehicle when no other vehicles are present either in-front or behind it, $n$ is the amount of fuel consumed for the same condition. The power is then calculated from (8) as

$$P = \frac{n a_0 + \sqrt{n^2 a_1^2 - 4 n a_2 (n a_0 - F)}}{2 n a_2}$$

(10)

Hence the drag coefficient from the force relation in (7) is computed as

$$C_D = \frac{P \times 3600}{\sqrt{\pi}} \frac{1}{2 \rho V_r^2 A_f C_h}$$

(11)

where $R_{\infty}$ is the resistance force of the vehicle when no other vehicles are present either in-front or behind it. To account for the effect of cross-wind, a modification to the axial resistance force is added, as shown in Fig. 13.

$$F_x = D \cos(\alpha) - L \sin(\alpha)$$

(12)

To calculate the axial force coefficient $C_x$, either knowledge of both the drag and lift coefficients ($C_D$ and $C_L$) has to be known or direct measurement/calculation of $C_x$ is sufficient as described in [19]. The grade resistance force is accounted for in the total resistance force $R(t)$, presented earlier in (7).

In Fig. 14, the fuel reduction ratio is shown for the case of two- and three-LDV platoons for two different vehicle types: A and B. The parameters for the two cars are given in Table VII. For the two-vehicle platoon in Fig. 14(a), the second vehicle experiences fuel reductions more than the lead vehicle; up to 6% for the second one with no savings for the lead one at a distance gap of 10 m. For shorter distance gaps, $G < 2 m$, the fuel savings to the lead vehicle becomes more than that for the trail vehicle due to the presence of the previously described local peak. This non-linear behavior results in outcomes that may not appear logical at first glance; however, this is consistent with empirical observations. Similarly for the three-car platoon in Fig. 14(b), the third, the second, and the lead vehicle experience up to an 8%, 5%, and 0% fuel reduction, respectively. The different car parameters have a negligible effect on the fuel reduction curves. It should be noted that these results agree with what is reported in [39] with regards to fuel savings derived from wind tunnel measurements. Specifically, they suggest that other parameters should be included in wind tunnel-based models (e.g. the turbulence level), when comparing to fuel estimates from on-road tests. In Fig. 15, the fuel reduction ratio is shown for the case of two- and three-truck platoons for two different truck types: X and Y. The fuel reduction curves are consistent with those for the LDV platoons. For the two-truck platoon in Fig. 15(a), the second truck experiences fuel reductions more than the lead truck by up to 6% at a distance gap of 50 m while the lead one...
experiences a \(-1.5\%\). Similarly for the three-truck platoon in Fig. 15(b), the third, the second, and the lead experience up to a \(7\%\), \(7\%\), and \(1\%\) reduction in fuel consumption, respectively at a distance gap of 50 m. As was the case with the LDV platoon, the trail and middle trucks in both the two- and three-HDT platoons experience a local peak at gaps of less than 20 m. In Fig. 16, the fuel reduction ratio is shown for the case of two- and three-bus platoons for two different bus types: M and N. This trend of fuel reduction is consistent with that for LDV and HDT platoons. For the two-bus platoon in Fig. 16(a), the second bus experiences fuel reductions more than the lead bus with up to \(20\%\) reductions for the second one with no savings for the lead one at a distance gap of 50 m. Similarly for the three-bus platoon in Fig. 16(b), the third, the second, and the lead bus experience up to a \(21\%\), \(7\%\), and \(0\%\) fuel reduction, respectively. As was the case with the LDV and HDT platoons, at shorter gaps, \(G < 10 m\), specifically for the three-bus platoon, the savings of the lead bus exceeds that of the trail bus due to the presence of a local peak. In Fig. 17, the variation in the fuel reduction ratio for the LDV, bus, and HDT platoons as a function of the time gap for different vehicle speeds is presented. Since it is more appropriate to specify a gap between vehicles in terms of time (headway) in designing a vehicle platoon controller [28], [29], [36], [40], we transformed the x-axis in the figures to time gaps. Accounting for the communication, controller and mechanical latency, a time gap \(\geq 0.5 \text{ secs}\) is typical (see Refs. [41], [42]) producing fuel reductions of \(5\%\), \(16\%\), and \(12\%\) for LDV, bus, and HDT platoons running at a speed of 100 km/hr, respectively. These results agree with what have been found in the numerical simulation by Alam et al. [3] for the HDT platoon. In addition to the fuel reductions, the lower time gap has the benefit of increasing the roadway capacity. For instance, based on the vehicle lengths in Table I and a travelling speed of 100 km/hr, the headway of the LDV, bus, and HDT vehicles is 0.678 secs, 0.932 secs, and 1.317 secs, respectively. These are equivalent to ideal saturation flow rates (ignoring lane changing effects and assuming ideal weather and roadway conditions) of 5,309, 3,862, and 2,733 veh/hr/ lane, respectively. These values provide sizeable improvements over typical ideal LDV saturation flow rates of 2,450 veh/hr/ lane (Highway Capacity Manual).

To further investigate the platoon fuel savings, the fuel reduction for the three different platoon types is shown in Fig. 19 as a function of the distance gap/time gap at a velocity of 100 km/hr. The distance gap and time gap are provided on the same x axis for clarity purposes. At time gaps of 0.5 secs, the savings for LDV, bus, and HDT are \(5\%\), \(16\%\) and \(12\%\) respectively. Alternatively, for a time gap of 2 secs, we can see that the bus and HDT platoons still produce a significant amount of fuel reduction, with savings up to \(7.5\%\), for both respectively while for the LDV Platoons the savings are almost \(0.6\%\). Depending on the state-of-technology platooning at shorter than 0.5 secs gaps may be achievable. The fuel savings of the bus and HDT platoons are very close over most of the time gap range, which suggests that both drag behavior for bus/HDT platoons could be used interchangeably. As such, given that the truck data were
behavior was recovered in the bus platoon data by eliminating the drag measurements at the zero gap.

Furthermore, the critical distance gap, the gap at which the drag coefficient is not affected by the vehicle ahead of it, was determined through optimization.

The model for the lead truck in the two-HDT platoons was validated against fuel savings from in-field experimental measurements obtained from the literature. Good agreement was observed with the empirical data. We were unable to validate the trail truck model given the noise observed in the empirical data.

The developed drag models were used to quantify the average fuel savings for different types of platoons. The results show a potential decrease in the fuel consumption directly proportional with the intra-platoon distance/time gap. The bus and heavy duty truck platoons show more potential for energy savings at longer time gaps when compared to the light duty vehicle platoons due to their larger cross section areas and less streamlined form.

In addition, the results show that fuel savings of the bus and HDT platoons are very close over most of the time gap range, suggesting the use of the HDT drag coefficients for buses given that they are deemed more reliable.

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