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A Fast Macroscopic Speed Planner for Electric Vehicle Platooning

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Abstract: Electric vehicles (EVs) have demonstrated significant advantages of high fuel economy and low maintenance cost over gasoline-powered vehicles and hybrid electric vehicles in moving people and goods. However, range anxiety remains as one of the main barriers in market penetration for EVs. Platooning has proven to be an effective approach to reduce aerodynamic drag resistance and thus extend EV ranges. However, taking full advantage of platooning to reduce energy consumption during a trip while satisfying the time constraint is a challenge. This paper is focused on the design and validation of the high-level speed planner of a two-level real-time platooning framework for EVs. The speed optimization problem in the high-level speed planner for the entire trip is reformulated into two speed profile optimization problems in two processes: 1) catch-up and then platooning, and 2) platooning and then break-away. Analytical solutions are derived for the optimal speed profiles in both processes. The analytical solutions capture the impacts of critical parameters such as initial and final inter-vehicle distances, and the leading vehicle speed.

Keywords: Electric Vehicle, Platooning, Speed Planner, Optimization

1. INTRODUCTION

Electric vehicles (EVs) have been considered as a promising solution for reducing emissions and mitigating climate change. However, one of the biggest concerns with EVs is range anxiety due to limited battery capacity and limited EV charging stations. Improving vehicle efficiency via platooning is an effective approach to extend EV driving range during highway operation where high aerodynamic resistance is encountered. This slipstream effect of following another vehicle in short distances in a platoon can potentially reduce fuel consumption by up to 20%, Robinson et al (2010). Vehicle platooning has become more viable and implementable than before, as new vehicle models are commonly equipped with advanced driver-assistance systems (ADAS) such as adaptive cruise control (ACC). With additional vehicle-to-vehicle (V2V) communication devices, vehicles on highways can be implemented with cooperative adaptive cruise control (CACC) and platooning for both safety enhancement and energy saving. Although platooning opportunity is abundant on highways, planning platoons and realizing the full fuel saving benefits are challenging since many factors need to be considered such as the leading vehicle speed, relative position to the leading vehicle, platoonable miles, and others. Extensive research studies have been conducted to achieve this goal. Yu et al (2016) utilize a model predictive control (MPC) to optimize platoon speed and inter-vehicle distance in platoons for minimizing fuel consumption. Other papers (e.g., Ozatay et al (2014) and Luu et al (2010)) are focused on optimization of speed profiles using dynamic programming (DP). However, most of the existing literatures in this category (e.g., Caltagirone et al (2015) and Torabi (2017)) are focused on optimizing the speed profile for the lead vehicle as an efficient driving strategy. A large body of studies have been conducted to optimize the speed of a target vehicle in the presence of multiple platoonable vehicles on the same route at a microscopic level. Boysen et al (2018), Kalbitz (2017), and Sturm et al (2020) provide a comprehensive assessment of current platooning control methods and optimization factors.

Although the optimization-based methods (e.g., MPC, DP) have demonstrated significant energy saving potentials in platooning applications, a priori knowledge of other vehicles on the road network during the prediction horizon or the entire trip are required. In practice, the priori knowledge of dynamic traffic information may be infeasible. Besides, these optimization-methods require high computational cost. Vehicle-to-cloud (V2C) communication can potentially be applied to implement the computational-expensive optimization methods. Applications of cloud computed DP framework in the optimization of hybrid electric vehicle and electric transit bus can be found in Wollaeger et al (2012) and Shi et al (2020), respectively. However, studies on fast algorithms for planning platoon speeds, which are suitable for real-time implementation, are rather limited. Deng and Ma (2014) proposed a fast Pontryagin Minimum Principle (PMP)-based algorithm for planning optimal speed profiles for the leading vehicle of a platoon on highway.

The contribution of this paper is to develop a two-level real-time implementable platooning framework for the following vehicle, which is an EV, to achieve the minimum energy consumption for given trips with platooning opportunities. The proposed EV platooning framework consists of a high-level speed planner and low-level speed or spacing control. This paper is focused on the design and validation of the high-level optimal speed planner based on analytical solutions derived using calculus of variation (COV).

The paper is organized as follows. The two-level EV platooning framework is presented in Section 2. The problem statement is described in Section 3. A model for platooned and non-platooned EVs is presented in Section 4. The analytical solution is presented in Section 5. The method and optimization results from simulation studies are discussed in Section 6. The conclusion is presented in Section 7.

2. OPTIMAL SPEED PLANNER FRAMEWORK

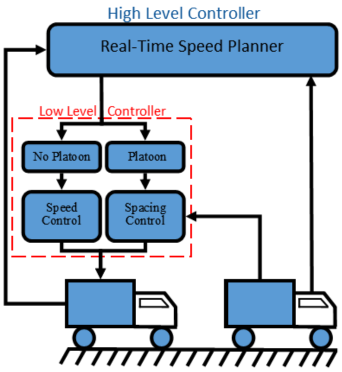

Figure 1. Framework for Real-Time Speed Planner.

As shown in Figure 1, the speed optimization framework consists of two layers: a high-level speed planner and a low-level speed/spacing control. In the high-level speed planner, the analytical solution is applied to optimize the vehicle speed at the macroscopic level for the entire trip based on current position and speed limits of the target EV and the schedules (e.g., entrance and exit of highway and average vehicle speed) of other vehicles on the same route. The optimization results from the high-level speed planner are periodically updated to reflect the updates on traffic condition (e.g., change of schedules of other vehicles). Once the optimal speed profile is planned from the high-level speed planner, a low-level speed control will be applied when the vehicle is not platooned with other vehicles. If the target vehicle is platooned with the other vehicle, then an inter-vehicle space control (e.g., Yang et al (2021)) will be applied instead. This paper will be focused on the high-level speed planner.

3. PROBLEM STATEMENT

The optimization problem for the high-level speed planner is stated in this section. In this study, we are investigating a scenario where a target EV (ego vehicle) is traveling a predefined route with a lead vehicle, which may provide platooning potential, traveling on the same route at different initial starting points. The objective of this study is to optimize the vehicle speed profile during the entire trip, including: the catch-up phase, platooning phase, and breakaway phase to minimize the energy consumption of the ego vehicle during the trip while satisfying the predefined trip time constraint. The following assumptions are adopted in the study: 1) All vehicles on the route are equipped with necessary sensors, V2V devices to support vehicle platooning. A fixed inter-vehicle distance is considered in all platooning scenarios. 2) Priori knowledge of the entrance and exiting of the potential leading vehicle and its average speed and relative position are available. 3) The impacts of platooning formation and split at the microscopic level on the total energy consumption of the trip are negligible. 4) All lead vehicles are controlled via cruise control, with small speed fluctuations such that the adverse impact of speed variation on energy consumption is negligible when compared to the benefit of platooning. Thus, platooning is the preferred driving strategy when a leading vehicle is nearby.

4. EV MODEL

The vehicle longitudinal dynamic model is based upon the road-load equation as shown in (1).

$$ma = F_d - mgC_{rr}\cos(\theta) - mg\sin(\theta) - \frac{C_d\rho A v^2}{2} \quad (1)$$

where m is vehicle mass, a is vehicle acceleration, F_d is the driving force of the vehicle, C_{rr} is the rolling resistance coefficient, θ is the road grade, C_d is the aerodynamic drag coefficient, ρ is the air density, A is the surface area of the vehicle, and v is the vehicle's velocity. Note that when there is no platooning $C_d = C_{d,NP} = 0.5$. When the ego vehicle is platooning with a lead vehicle, $C_d = C_{d,P} = 0.3$ in this study, Alam et al (2010).

The power required to overcome resistances acting against the EV can be seen in (2).

$$P = \frac{ma + mgC_{rr}\cos(\theta) + mg\sin(\theta) + 0.5C_d\rho A v^2}{\eta} v \quad (2)$$

where η is the powertrain efficiency of the EV. η was assumed to be constant throughout the trip, Burt et al (2008).

The overall energy consumption of the EV over the distance can be calculated as below, Han et al (2019).

$$E_d = \int_0^{t_f} F_d(t)v(t)dt = \int_0^{x_f} F_d(x)dx \quad (3)$$

$$E_d = \int_0^{x_f}\left(mv\frac{dv}{ds} + mg(C_{rr}\cos(\theta(x)) + \sin(\theta(x))) + \frac{C_d\rho A v^2}{2}\right)dx \quad (4)$$

$$E_d = \frac{1}{2}m(v_f^2 - v_0^2) + mg\Delta h + mgC_{rr}\Delta$$
$$+\frac{\rho A}{2}\int_0^{x_f} C_d(x)v^2(x)dx \quad (5)$$

where E_d is the energy required to cover a distance of x_f in time t_f, Δh is the elevation change during the trip, and Δx is the horizontal distance covered. The drag coefficient is a function of distance in platooning. As can be seen in (5), the overall energy consumption required to overcome the road grade and rolling resistance is independent of the speed profile.

The impact of vehicle speed fluctuations on the energy consumption due to aerodynamic resistance is described in (6), Han et al (2019):

$$\frac{\rho A}{2}\int_0^{x_f} C_d(x)v^2(x)dx = \frac{C_d\rho A(\bar{v}^2 + \Delta v^2)x_f}{2} \quad (6)$$

where $\bar{v} = (\int_0^{x_f} v(s)dx)/x_f$ is the average velocity over position; $\Delta v^2 = (\int_0^{x_f}(v(x) - \bar{v})^2 dx)/x_f$ is variance of speed.

According to (6), minimizing vehicle speed variance when C_d is constant, can result in the minimum energy consumption due to aerodynamic resistance. Thus, when operating in a non-platooning portion of the trip, the ego vehicle will travel at a constant speed. However, in the platooning portions of the trip, the ego vehicle may be subject to small fluctuations in the leading vehicle's speed with the assumption 4) in Section 3.

Since the energy consumption due to the rolling resistance, road grade, and powertrain efficiency do not depend on the speed profile, the high-level speed planner will be focused on minimization of the energy consumption due to the aerodynamic resistance. The part of driving force to overcome the aerodynamic resistance can be described in (7).

$$F_{d,a} = \frac{C_d \rho A v^2}{2} \tag{7}$$

5. OPTIMIZATION OF FOLLOWING EV SPEED

Figure 2 shows the position vs. time graph of the lead vehicle and the following vehicle. The points C and F denotes the starting point and ending point of the leading vehicle, respectively. The line C-F indicates that the leading vehicle is travelling at a constant speed. The points O and D' denotes the starting point and ending point of the following vehicle, respectively. The line O-D' presents the baseline operation where the following vehicle travels from O to D' at a constant speed and is platooned with a lead vehicle traveling at the same speed. The line O-A and B-D' represent the catch-up phase and break-away phase of the following vehicle, respectively, while the line A-B represents the platooning phase of the following vehicle. Point D represents the point where the following vehicle catches up and passes the lead vehicle while traveling at a constant speed from O to D'. The point D divides the line A-B into two platooning segments which are noted as A-D and D-B, respectively. The speed profile optimization problem for the entire trip is divided into two sub-problems: 1) speed profile optimization problem for the trip from O-D (catch-up and then platooning); and 2) speed profile optimization problem for the trip from D-D' (platooning and then break-away).

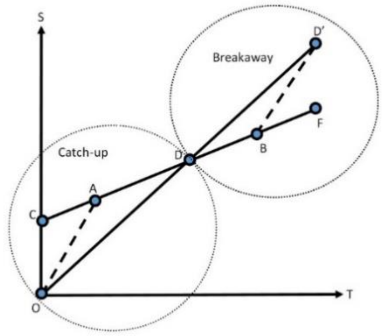

Figure 2: Time vs. position graph with key points.

5.1 Optimization of Vehicle Speed in the Catch-up Phase

Define v_1 as the velocity of the following vehicle while platooning from A to D. Thus, v_1 is the same as the leading vehicle speed denoted as v_l. v_2 represents the catch-up velocity of the following vehicle from O to A, and v_3 represents the velocity of the vehicle when traveling the entirety of the trip at a constant speed without platooning from O to D. x_1, x_2, and x_3 represent the distances of the platooned portion (A-D), non-platooned portion (O-A), and total distance of the trip from O to D, respectively. v_1,v_2, and v_3 generally satisfy the following inequality. The platooning velocity is assumed to be less than the optimal velocity traveled while not platooning, which is less than the catch-up velocity as shown in (8).

$$v_1 < v_3 < v_2 \tag{8}$$

The total distance of the trip from O to D is equal to the combined distance of the platooned portion (A-D) and non-platooned portion (O-A) of the trip as shown in (9).

$$x_1 + x_2 = x_3 \tag{9}$$

Next, define term Δ as the difference between v_2 and v_3 in (10). Note that $\Delta > 0$ at all times.

$$v_2 = \Delta + v_3 \tag{10}$$

Proposition 1: For a given total travel time from O to D (denoted as t_3) and travel distance (x_3), the optimal speed profile to achieve the minimal energy consumption for a vehicle travelling from O to D is a constant velocity at v_3 (w.r.t line O-D in Figure 2) where $v_3 = x_3/t_3$, with the following assumptions: 1) all the candidate speed profiles have the same aerodynamic drag coefficients, C_D and $\bar{C}_D$, for non-platooning and platooning, respectively; 2) the energy consumptions due to rolling resistance in these two speed profiles are identical; 3) the energy consumptions due to road grade is fixed for a given route, while acceleration/deceleration are negligible.

Proof: With the assumptions, the Proposition 1 can be proved by showing that the energy consumption due to aerodynamic resistance with speed profile O-D is the smallest, when compared to any other candidate such as O-A-D. First of all, a function f is defined as the difference of energy consumption due to overcoming aerodynamic resistance between the platooning speed profile, O-A-D, and the optimal non-platooning speed profile, O-D, in (11).

$$f = k(v_1^2 x_1 + v_2^2 x_2 - v_3^2 x_3) \tag{11}$$

where $k = 0.5\bar{C}_D \rho A$ which is a constant; $\bar{C}_D$ is the aerodynamic coefficient of drag for a vehicle with no platooning.

The travel time for segment O-A and segment A-D can be described in (12) and (13), respectively.

$$t_2 = \frac{x_2}{v_2} = \frac{x_2}{v_3 + \Delta} \tag{12}$$

$$t_1 = t_3 - t_2 = \frac{x_3}{v_3} - \frac{x_2}{v_3 + \Delta} \tag{13}$$

With (9), (12) and (13), v_1 can be calculated based on (14).

$$v_1 = \frac{x_1}{t_1} = \frac{x_3 - x_2}{t_3 - t_2} = \frac{x_3 - x_2}{\frac{x_3}{v_3} - \frac{x_2}{v_3 + \Delta}} \tag{14}$$

Then, by replacing v_1 in (11) with (14) and x_1 with $x_3 - x_2$ according to (14), f in (11) can be rewritten as in (15).

$$f = k\frac{[3v_3^2 x_1 + 2v_3 x_3 \Delta + 2v_3 x_1 \Delta + x_3 \Delta^2]\Delta^2 x_3 (x_3 - x_1)}{(v_3 x_1 + x_3 \Delta)^2} \tag{15}$$

According to the physical meanings of the variables in (15), it is easy to show $f > 0$. Thus, the Proposition 1 is proved. ■

To further simplify f, three new variables: r_0, r, and ϕ are defined. $r_0 = x_{OC}/x_3$ represents the ratio of the initial inter-vehicle distance between the ego and lead vehicle, x_{OC}, to the total distance of the trip. $r = x_1/x_3$ represents the ratio of the platooned distance to the total distance. $\phi = \Delta/v_3$ represents the change of vehicle speed due to the catch-up process normalized with respect to v_3.

After being normalized by $v_3^2 x_3$, performing some algebraic manipulation, and substituting r, and ϕ, $v_1^2 x_1 + v_2^2 x_2 - v_3^2 x_3$ becomes (16).

$$\alpha = \frac{v_1^2 x_1 + v_2^2 x_2 - v_3^2 x_3}{v_3^2 x_3} = \frac{[3r + 2\phi + 2r\phi + \phi^2](1 - r)\phi^2}{(r + \phi)^2} \tag{16}$$

Since the lead vehicle and the following vehicle meet at point A, the following relation can be established as $x_{OC} + v_1 t_2 = v_2 t_2$ which yields

$$t_2 = \frac{x_{OC}}{v_2 - v_1} \quad (17)$$

Combining (9), (10), and (14), t_2 can be rewritten as in (18)

$$t_2 = x_{OC} \Bigg/ \left[(v_3 + \Delta) - \frac{x_1}{\left(\frac{x_3}{v_3} - \frac{x_3 - x_1}{v_3 + \Delta}\right)} \right] \quad (18)$$

Then, x_1 can be expressed in (19)

$$x_1 = x_3 - (v_3 + \Delta) t_2 = x_3 - \frac{x_{OC}(v_3 + \Delta)}{\left[(v_3 + \Delta) - \frac{x_1}{\left(\frac{x_3}{v_3} - \frac{x_3 - x_1}{v_3 + \Delta}\right)} \right]} \quad (19)$$

Divide both sides of the equation by x_3 and simplify the equation using the definitions of r_0, r, and ϕ. Then, the following relation in (20) between r_0, r, and ϕ, can be resulted.

$$r = 1 - \frac{r_0(\phi + r)}{\phi} \quad (20)$$

From (20), r is expressed as a function of r_0 and ϕ in (21).

$$r(r_0, \phi) = \frac{(1 - r_0)\phi}{\phi + r_0} \quad (21)$$

According to (16) and (21), it is easy to see that α is a function of r_0 and ϕ as shown in (22).

$$\alpha(r_0, \phi) = \frac{[3r(r_0,\phi) + 2\phi + 2r(r_0,\phi)\phi + \phi^2](1 - r(r_0,\phi))\phi^2}{(r(r_0,\phi) + \phi)^2} \quad (22)$$

Based on road-load equation, the energy consumption of a vehicle with platooning all the way at the optimal constant speed, v_3, can be described in (23).

$$\bar{E}_{OD} = \bar{E}_{a,OD} + E_{r,OD} + E_g + E_{acc} \quad (23)$$

where $\bar{E}_{a,OD}$ represents the energy consumption due to aerodynamic drag resistance with platooning, $E_{r,OD}$ is the energy loss due to rolling resistance; E_g is the energy loss due to road grade; and E_{acc} is the energy consumed from acceleration. All terms are measured from the initial position, "O", to the final position, "D".

Assuming acceleration is negligible over the course of the trip and the rolling resistance will be the same for any speed profile, the equality $\bar{E}_{OD} = \bar{E}_{a,OD}$ can be obtained.

Following the same method for traveling directly from "O" to "D" with the same assumption, one can derive the energy from traveling from "O" to "A" to "D" in (24). Note that the vehicle is platooned in the segment A-D but not O-A.

$$E_{OAD} = E_{a,OA} + \bar{E}_{a,AD} = (\bar{E}_{a,OA} + \bar{E}_{a,AD}) + \tilde{E}_{a,OA} \quad (24)$$

where $\bar{E}_{a,OA}$ and $E_{a,OA}$ represent the energy consumption due to aerodynamic resistance with and without platooning, respectively. $\tilde{E}_{a,OA}$ represents the difference between $\bar{E}_{a,OA}$ and $E_{a,OA}$ due to the change of aerodynamic drag coefficient.

Define η in (25) which normalizes the energy consumed in (24) to the energy consumed from $\bar{E}_{OD} = \bar{E}_{a,OD}$.

$$\eta = \frac{E_{a,OAD} - \bar{E}_{a,OD}}{\bar{E}_{a,OD}} = \frac{(\bar{E}_{a,AD} + \bar{E}_{a,OA}) - \bar{E}_{a,OD}}{\bar{E}_{a,OD}} + \frac{\tilde{E}_{a,OA}}{\bar{E}_{a,OD}} \quad (25)$$

Since all the terms in (25) share the same reduced aerodynamic drag coefficient, (26) is resulted.

$$\frac{(\bar{E}_{a,AD} + \bar{E}_{a,OA}) - \bar{E}_{a,OD}}{\bar{E}_{a,OD}} = \frac{v_1^2 x_1 + v_2^2 x_2 - v_3^2 x_3}{v_3^2 x_3} = \alpha \quad (26)$$

In addition, $\tilde{E}_{a,OA}/\bar{E}_{a,OD}$ can be detailed as in (27).

$$\frac{\tilde{E}_{a,OA}}{\bar{E}_{a,OD}} = \frac{\tilde{C}_D (v_3 + \Delta)^2 (x_3 - x_1)}{\bar{C}_D v_3^2 x_3} \quad (27)$$

where $\tilde{C}_D = C_D - \bar{C}_D$.

Define $\beta = \tilde{C}_D/\bar{C}_D$ as the ratio of $\tilde{C}_D$ to $\bar{C}_D$. In this study, β is assumed to be constant at 0.667. Then, with the definitions of β, r, and ϕ, $\tilde{E}_{a,OA}/\bar{E}_{a,OD}$ can be simplified as $\tilde{E}_{a,OA}/\bar{E}_{a,OD} = \beta(1 + \phi)^2(1 - r)$. Based on that, η can be expressed as a function of r, and ϕ as shown in (35).

$$\eta(r_0, \phi) = \alpha(r, \phi) + \beta(1 + \phi)^2(1 - r) \quad (28)$$

Recall that r is a function of r_0, ϕ, and β is constant. Thus, η is a function of r_0 and ϕ. In practice, r_0 is generally considered as a known disturbance. ϕ is considered as the control input in this optimization problem to find the optimal ϕ w.r.t. the minimal η. The optimal ϕ can be solved using calculus of variation, with the first and second derivatives of η w.r.t. ϕ which are shown in (29) and (30), respectively. In addition, considering the constraint of speed, we have $\phi \in [\phi_{min}, \phi_{max}]$ where $\phi_{min} = 0$ and $\phi_{max} = v_{max}/v_3$.

$$\frac{d\eta}{d\phi} = \frac{r_0(2(\beta+1)\phi^3 + 3(\beta+1)(r_0 - 1)\phi^2 + 6(\beta+1)r_0\phi - r_0^3 + 3r_0^2 + 3\beta r_0 - \beta)}{(r_0 + \phi)^2} \quad (29)$$

$$\frac{d^2\eta}{d\phi^2} = \frac{2r_0((\beta+1)\phi^3 + 3(\beta+1)r_0\phi^2 + 3(\beta+1)\phi r_0^2 + r_0^3 + 3\beta r_0^2 - 3\beta r_0 + \beta)}{(r_0 + \phi)^3} \quad (30)$$

Once the optimal ϕ is solved, the optimal catch-up speed can be calculated using (31).

$$v_2 = v_3(1 + \phi) \quad (31)$$

5.2 Optimization of Vehicle Speed in the Break-away Phase

Proposition 2: Assume that the following vehicle has formed a platoon with the lead vehicle at the speed of v_l. Then, finding the optimal speed profile for break-away process which corresponds to the segment D-B-D' in Figure 2, is a direct extension of finding the optimal speed in the catch-up process which corresponds to the segment O-A-D in Figure 2.

Proof: It was assumed that there is another lead vehicle traveling at v_3 with initial inter-vehicle distance denoted by D-F' which is parallel with D'-F in Figure 3. Then, the original break-away process denoted by D-B-D' is translated into a break-in process D-B'-D' where D-B' is parallel with B-D'. It is easy to show that the speed profile in D-B-D' and the speed profile in D-B'-D' will result in the same energy consumption, if the energy consumption during the acceleration and deceleration process is negligible in both speed profiles. This is due to the fact that, in both cases, the following vehicle travel at the same speed profiles with platoon and without platoon.

As shown in (28), to minimize the η in the break-away case, r_0 information is needed. To differentiate from the catch-up case in notation, r_1, is defined for the break-away process as $r_1 = x_{FD'}/x_{DD'}$. The optimal ϕ in the break-away process can then be calculated in the same manner as the catch-up speed, using COV based on (28)-(30) with $\phi \in [\phi_{min}, \phi_{max}]$.

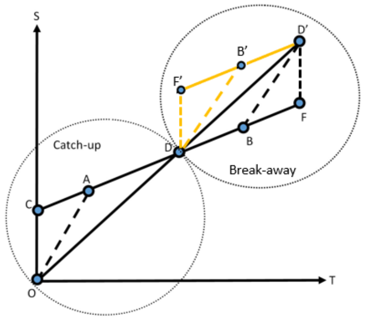

Figure 3. Illustration of Connection between Catch-up Problem and Break-away Problem.

6. SIMULATION STUDY AND ANALYSIS

6.1 Impact of Catch-up Speed and r_0 on Energy Consumption

Figure 4 illustrates the impact of ϕ on η at different r_0 (from 0.01 to 0.30) in the catch-up process (or r_1 in the break-away process). Figure 5 shows the variation of η over a wide range of ϕ with r_0 = 0.13. It is shown from Figure 4, when r_0 is small, η decreases with increasing ϕ until it reaches the minimal value. The optimal ϕ w.r.t. the minimum η gradually decreases as r_0 increases (e.g., ϕ = 0.3 at r_0 = 0.02 vs ϕ = 0.155 at r_0= 0.13). As r_0 increases up to 0.3, the optimal ϕ converges to zero. Thus, it can be concluded: 1) High catch-up speed is suggested to minimize the energy consumption during the trip from O-D, when r_0 is small. 2) The optimal catch-up speed is slower as r_0 increases in the range from 0.01 to 0.24, to achieve a balance between the energy consumption in the catch-up process (O-A) and platooning process (A-D). 3) When r_0 reaches 0.24 or higher, the optimal ϕ to achieve the minimum energy consumption during the trip is zero. In this case, the gain of energy consumption in the catch-up process offsets the benefits of platooning. 4) $r_0 = 0.24$ is the break-even point where deviating from the optimal speed profile with no platooning becomes less cost effective. The same conclusions can be drawn for the optimal values of ϕ when r_0 is replaced with r_1 in the break-away process.

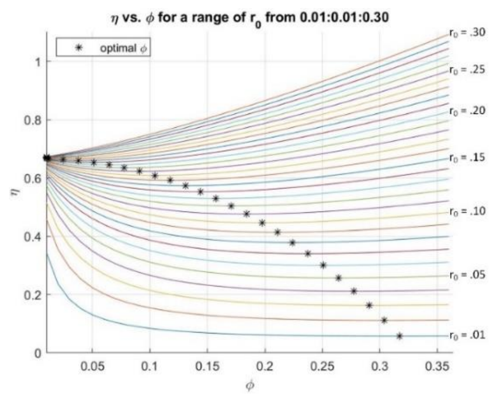

Figure 4: η vs ϕ for a given value of r_0 and r_1.

6.2 Case Studies

Six cases were studied to analyze the impact of initial and final inter-vehicle distance, x_{OC} and $x_{FD'}$ on the optimal catch-up speed (denoted as $v_{c,opt}$) and the optimal break-away speed (denoted as $v_{b,opt}$), respectively. In these case studies, v_l, the total distance, and the optimal speed with no platooning are held constant at 26 m/s, 100 km, and 33.33 m/s, respectively. Cases 1-3, represent three different scenarios with different combinations of x_{OC} and $x_{FD'}$, as shown in Figure 6 and Table 1. As shown in Figure 6, Case 1 has a smaller x_{OC} and a larger $x_{FD'}$, as represented by the O-C1 and F1-D', respectively. Case 2 has comparable x_{OC} and $x_{FD'}$, as represented by the O-C2 and F2-D', respectively. In Case 3, x_{OC} is much larger than $x_{FD'}$, as shown by O-C3 and F3-D', respectively.

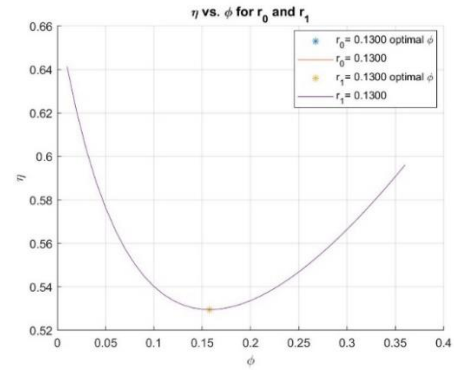

Figure 5: Impact of ϕ on η with r_0 (or r_1) = 0.13.

Table 1. Effect of initial and final inter-vehicle distance on the optimal catch-up and break-away speed.

Variable: x_{OC}						
Case	r_0	r_1	$x_{OC}[km]$	$x_{FD'}[km]$	$v_{c,opt}[\frac{m}{s}]$	$v_{b,opt}[\frac{m}{s}]$
1	.220	.220	1	21	34.23	34.23
2	.220	.220	5	17	34.23	34.23
3	.220	.220	10	12	34.23	34.23

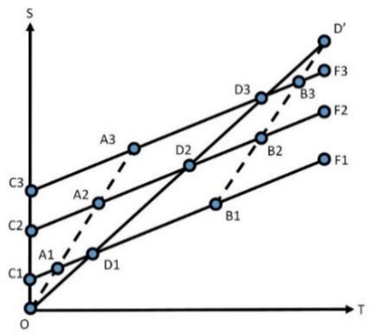

Figure 6: Vehicle position vs. time with different combinations of x_{OC} and $x_{FD'}$ in Cases 1-3

As shown in Figure 6, since v_l is the same in the three cases, C3-F3, C2-F2, and C1-F1 are parallel to each other and the sum of x_{OC} and $x_{FD'}$ are the same. Then, the relation in (32) is satisfied. Thus, there is a tradeoff between x_{OC} and $x_{FD'}$.

$$x_{OC} + x_{FD'} = x_{OD} - t_{OD} v_l \qquad (32)$$

where t_{OD} denotes the total travel time from O to D'.

In addition, it is straightforward to show that r_0 equals r_1.

According to (20), $v_{c,opt}$ and $v_{b,opt}$ in Cases 1-3 are the same, as summarized in Table 1. The total energy consumption due to aerodynamic resistance (assuming the surface area of the vehicle is 2.5 m^2 and air density is 1.225 kg/m^3) and the break-down in different segments (including catch-up portion, platooning portion, and break-away portion) are summarized in Table 1. As shown in Table 1, the energy consumption for the total trip and platooning portion are the same for all three cases. While there is a trade-off between the energy consumption in the catch-up portion and break-away portion, the sum of the two portions without platooning are the same since sum of x_{OC} and $x_{FD'}$ are the same as shown in (32). Thus, for a given v_l, the platooning distances are the same in all cases. x_{OC} has no effect on the optimal energy consumption.

Table 2. Energy consumption due to aerodynamic resistance for Cases 1 through 3.

Energy Consumption due to aerodynamic resistance.				
Case	Catch-up Energy [J]	Platooning Energy [J]	Breakaway Energy [J]	Total Energy [J]
1	$3.69 * 10^6$	$3.55 * 10^6$	$7.75 * 10^7$	$8.47 * 10^7$
2	$1.84 * 10^7$	$3.55 * 10^6$	$6.27 * 10^7$	$8.47 * 10^7$
3	$3.69 * 10^7$	$3.55 * 10^6$	$4.43 * 10^7$	$8.47 * 10^7$

Next, the impacts of v_l on $v_{c,opt}$ and $v_{b,opt}$ were investigated in Cases 4-6. For these cases, the initial distance between the two vehicles, x_{OC}, and the total distance are held constant at 10 km and 100 km, respectively. v_l was selected as 27 m/s, 28 m/s, 29 m/s, respectively, as shown in Table 3. Due to different v_l, r_0, which equals r_1, was calculated as 0.19, 0.16, and 0.13, in Cases 4-6, respectively. $v_{c,opt}$ and $v_{b,opt}$ for all three cases are summarized in Table 3. It was found, a higher v_l will result in higher $v_{c,opt}$ and $v_{b,opt}$. This is because a faster lead vehicle will result in a lower r_0 and r_1 value. As shown in Figure 4, a lower r_0 will directly lead to a higher value of ϕ and thus leading to faster $v_{c,opt}$ and $v_{b,opt}$.

Table 3. Effect of v_L on $v_{c,opt}$ and $v_{b,opt}$.

Variable: v_l						
Case	r_0	r_1	$x_{FD}{}'[km]$	$v_L[\frac{m}{s}]$	$v_{c,opt}[\frac{m}{s}]$	$v_{b,opt}[\frac{m}{s}]$
4	.190	.190	9	27	35.92	35.92
5	.160	.160	6	28	37.26	37.26
6	.130	.130	3	29	38.59	38.59

7. CONCLUSION

In this paper, a two-level real-time implementable EV platooning framework was proposed. A model-based analytical solution was derived using COV for optimizing the catch-up speed and breakaway speed for an ego vehicle with platoon potential due to the presence of a lead vehicle. The main conclusions include: 1) $v_{c,opt}$ and $v_{b,opt}$ depend on r_0 and r_1, respectively. 2) When v_l is constant, r_0 and r_1 will be the same. Thus, $v_{c,opt}$ and $v_{b,opt}$ are identical. 3) $r_0 = 0.24$ is the break-even point. 4) If v_l remains constant between cases, the catch-up speed remains the same regardless of the initial distance between the ego and lead vehicle. 5) Higher v_l will lead to lower r_0 and r_1 and thus higher $v_{c,opt}$ and $v_{b,opt}$.

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