7th IFAC Symposium on Advances in Automotive Control
The International Federation of Automatic Control
September 4-7, 2013. Tokyo, Japan

When is it Fuel Efficient for a Heavy Duty Vehicle to Catch Up With a Platoon?

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Abstract: Vehicle platooning has in recent years become an important research field for the vehicle industry. By establishing a platoon of heavy duty vehicles, the fuel consumption can be reduced for the follower vehicles due to the slipstream effect. However, as vehicles are scattered on the road driving by themselves, coordination amongst the vehicles is required. In this paper we study the problem of when it is beneficial for a heavy duty vehicle to drive faster in order to catch up and join a platoon. We derive a formula, based on flat road and with no vehicle accelerations, to calculate if it is more fuel-efficient for a vehicle to drive faster and platoon or keep driving alone. Depending on the distance between the vehicles and the distance to the destination, the fuel savings vary. For a trip of 350 km, with a distance of 10 km to the vehicle ahead, the fuel saving could be up to 7 % if the follower vehicle decides to increase the speed from 80 km/h to 90 km/h in order to catch up and form a platoon, assuming an air drag reduction of 32 % when platooning. Sensitivity analysis has shown that the speeds need to be relatively accurate in order to not give any false positive catch up decisions.

1. INTRODUCTION

In recent years many efforts have been focused on reducing the fuel consumption of heavy duty vehicles (HDVs). Studies include optimizing the engine and driveline as well as utilizing the road more efficiently by taking advantage of the gravitational force on downhills. The air drag acting upon the vehicle is an important aspect to consider. It constitutes 23 % of the total force that acts against a 40 t HDV when driving on a typical road (Sandberg, 2001). Jing et al. (2010) have studied how the air drag coefficient c_D can be reduced by 10 % by using a wind deflector and a dome on an HDV model in a wind tunnel. El-Alti et al. (2012) have made experimental and computational studies by attaching flaps with active flow control at the back of a trailer model to reduce the overall air drag coefficient c_D with 3.9 %.

Another approach to reduce the air drag is to form platoons, that is, to form a string of vehicles driving close behind each other. An early study of the platooning concept was studied by Levine and Athans (1966). Their work considered control design rather than air drag reductions for vehicle platoons. Air drag reduction in a platoon was studied by Zabat et al. (1995) who used vehicle models in a wind tunnel. Their work showed that the air drag reduction varies depending on the intermediate distance between the vehicles. Similar conclusions were made by Bonnet and Fritz (2000). Tsuei and Savas (2000) studied the transient behavior of the air drag force in a wind tunnel on a platoon during different passing maneuvers. Alam (2011) showed that it is possible to save up to 7.7 % fuel for the follower HDV when driving at 70 km/h on a highway with 1 s time gap between two identical vehicles. Similar results were shown by Zhang and Ioannou (2004). Robinson et al. (2010) indicate a possible fuel reduction of up to 20 % when platooning. Current literature assumes that the vehicles already are in a platoon. However this is not always the case in practice, hence it is important to study how and when to form platoons.

In this work, we focus on analyzing when it is feasible to coordinate HDVs that are not in a platoon to form a platoon to reduce the fuel consumption. Coordinating scattered HDVs on the road can be done in several ways, for example; rerouting the vehicles to align when the roads merge ahead or if the vehicles are on the same road then the lead vehicle can slow down or the follower vehicle can catch up. In this paper, we focus on the latter example; when we have vehicles on the same road and the follower vehicle drives faster to catch up a platoon. However, by driving faster the vehicle consumes more fuel before it can join a platoon for reduced air drag. It is not evident when a platoon should be joined. We consider a fuel model to achieve a break-even value of the ratio between the distance to the vehicle ahead and the distance to the destination. The break-even ratio can be explained as when driving faster to catch up and form a platoon would cost an equal of fuel compared to driving as originally planned. Therefore, if the distance ratio to the vehicle ahead is smaller than the break-even ratio, there are fuel saving potentials. The concept is illustrated as in Fig. 1. Our method can be implemented in different ways, such as vehicle-to-infrastructure communication with road side units, vehicle communication through cellular networks or through a fleet management system.

The main contribution of this paper is to investigate when it is favorable for scattered HDVs to form a platoon by driving faster to catch up on the same road. We assume that the road is flat and that the lead vehicle maintains its current speed throughout the whole route. By assuming that the route is sufficiently long, the acceleration and deceleration phase can be neglected. Depending on how much the air drag is reduced when platooning, we give some indication of possible fuel saving potentials.

* This work was supported by VINNOVA - the Swedish Governmental Agency for Innovation Systems within the FFI program under contract 2011-01144.

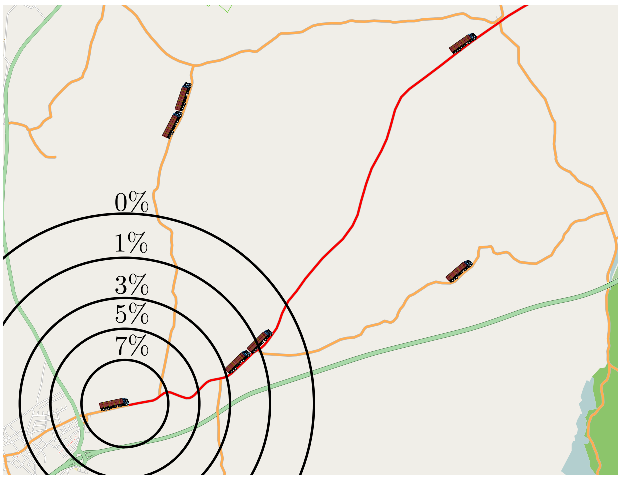

Fig. 1. Radii of fuel saving potentials if the HDV in the inner circle decides to catch up and merge to form or join a platoon. The largest radius shows the break-even ratio; beyond that radius, there are no fuel savings.

The outline of this paper is as follows. First we give the problem formulation in Section 2, where we also present the HDV and fuel model. In Section 3, we derive the break-even ratio from the fuel model. We introduce a platooning incentive factor in Section 4, which indicates when it is favorable to make a catch-up action. In Section 5, a sensitivity analysis is given for the break-even ratio model as well as for the average normalized air drag reduction. In Section 6, our approach is compared against a verified simulation model. Finally, we end the paper with conclusions and discussions in Section 7.

2. PROBLEM DESCRIPTION

In this section, we present the HDV and fuel models that will be used throughout this paper together with the main idea for driving faster to join a platoon.

We consider a longitudinal vehicle model based on Newton's second law of motion:

$$\begin{aligned} m_t\frac{\mathrm{d}v}{\mathrm{d}t} &= F_{eng} - F_b - F_{ad}(v,d) - F_r(\alpha) - F_g(\alpha) \\ &= F_{eng} - F_b - \frac{1}{2}\rho_a A_a c_D v^2 \phi(d) \\ &\quad - mgc_r\cos\alpha - mg\sin\alpha \end{aligned} \tag{1}$$

where the engine force is denoted F_{eng}, the braking force F_b, the air drag force F_{ad}, the roll resistance force F_r, and the gravitational force F_g. As the considered scenarios do not include braking, we set $F_b = 0$. Furthermore, m_t denotes the accelerated vehicle mass, v the vehicle speed, α the slope of the road, ρ_a the air density, A_a the frontal area of the vehicle, c_D the air drag coefficient, $\phi \in [0,1]$ the reduced air drag, d the intermediate distance between the vehicles, m the vehicle mass, g the gravitational coefficient, and c_r the roll resistance coefficient.

We consider a fuel consumption model (Oguchi et al., 1996; Bosch, 2000; Scania CV AB, 2012):

$$f_c = \frac{\delta}{\bar{\eta}_{eng}\rho_d} v F_{eng} \tag{2}$$

with

$$\delta = \begin{cases} 1 & \text{if } F_{eng} > 0 \\ 0 & \text{otherwise} \end{cases}$$

where f_c [ml/s] denotes the instantaneous fuel consumption, $\bar{\eta}_{eng}$ the mean combustion efficiency of the engine, ρ_d the energy density of diesel fuel and δ indicates whether fuel is injected into the engine or not.

The total fuel consumption over time T is:

$$\begin{aligned} f_{tot} = \int_0^T \frac{\delta(t)}{\bar{\eta}_{eng}\rho_d} v(t) \Big(m_t \frac{\mathrm{d}v(t)}{\mathrm{d}t} + \frac{1}{2}\rho_a A_a c_D v^2(t)\phi(d(t)) \\ + mgc_r\cos\alpha + mg\sin\alpha \Big)\,\mathrm{d}t \end{aligned} \tag{3}$$

where we used (1) and (2) and where α depends on the road profile.

The reduction in air drag depends on the relative distance between the vehicles when platooning (Alam, 2011; Bonnet and Fritz, 2000), where the follower vehicle reduces its air drag significantly compared to the preceeding vehicle. However, in this paper we only consider air drag reduction for the follower vehicle and we consider the case with air drag reduction of 32 %, which correspond the relative distace of 10 m (Alam, 2011). There is an incentive to try and form platoons to reduce the fuel consumption. However, it is not always possible to start transporting the cargo in platoons due to different starting times, positions, and haulage companies. The possibilities for fuel saving lie in the coordination of the HDVs. Catching up to other HDVs leads to a greater fuel consumption during the catch-up phase, which may not be regained by platooning if the route all together is too short. Therefore this paper studies when it is feasible to attempt catching up and form platoons.

3. BREAK-EVEN RATIO

To decide when it is beneficial for the follower HDV to catch up one or more HDVs ahead, we derive the break-even ratio. We first consider one vehicle catching up and then the general case with several vehicles catching up.

3.1 One HDV Catching Up

Consider a long flat road with $\alpha = 0$. Suppose the acceleration or deceleration phases are negligible, that is $\frac{\mathrm{d}v}{\mathrm{d}t} = 0$. The engine is always active during forward motion on a flat road, hence $\delta = 1$ at all times. With a given distance to travel and a constant speed, the total fuel consumption can be written as:

$$f_{tot} = \frac{1}{\bar{\eta}_{eng}\rho_d} v (\frac{1}{2}\rho_a A_a c_D v^2 \phi + mgc_r) T. \tag{4}$$

In order to be more feasible for a vehicle to catch up a platoon ahead than driving alone, the fuel cost must be lower, hence

$$f_{tot}(\text{maintain speed}) \geq f_{tot}(\text{catch up}) + f_{tot}(\text{platoon}) \tag{5}$$

where equality is the break-even ratio.

Assume that the lead vehicle, that we want to catch up to, has the same destination and maintains its speed throughout the whole route. By inserting (4) in (5) and assume that there is no air drag reduction ($\phi = 1$) when the follower vehicle is driving alone, we get:

$$\begin{aligned} &\frac{1}{\bar{\eta}_{eng}\rho_d} v_a (\frac{1}{2}\rho_a A_a c_D v_a^2 + mgc_r) T_a \\ &\quad \geq \frac{1}{\bar{\eta}_{eng}\rho_d} v_c (\frac{1}{2}\rho_a A_a c_D v_c^2 + mgc_r) T_c \\ &\quad + \frac{1}{\bar{\eta}_{eng}\rho_d} v_p (\frac{1}{2}\rho_a A_a c_D v_p^2 \phi + mgc_r) T_p \end{aligned} \tag{6}$$

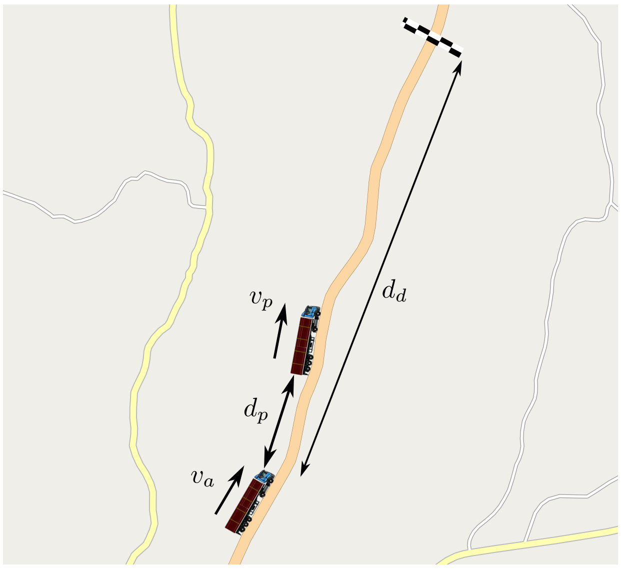

Fig. 2. The velocity of the follower HDV when driving alone is v_a. v_p denotes the velocity of the platoon ahead, d_p the current distance between the HDVs and platoon when deciding the feasibility, and d_d denotes the destination distance for the follower HDV (assuming that both the HDVs and platoon have the same destination).

where the subscript a, c, and p stands for *maintaining the speed alone*, *catching up to the platoon ahead*, and *platooning*, respectively. The following criteria must hold:

$$v_c > v_a, v_p \tag{7a}$$

$$T_a v_a = T_c v_c + T_p v_p. \tag{7b}$$

The first criteria (7a) says that the catch-up speed must be higher than the current speed of the follower and lead vehicles. The second criteria (7b) ensures that the travel distance is the same.

This gives us the following catch-up condition from (6) and (7b):

$$v_a^3 T_a \geq v_c^3 T_c + v_p^3 T_p \phi. \tag{8}$$

Introduce the distance to the destination for the follower vehicle, $d_d = T_a v_a$, and the distance between both platoons at the moment when the catching up is initiated, $d_p = T_c(v_c - v_p)$, see Fig. 2. We then obtain the following equation:

$$\frac{d_d}{d_p} \geq \frac{v_c}{v_c - v_p} \frac{v_c^2 - v_p^2 \phi}{v_a^2 - v_p^2 \phi}. \tag{9}$$

This gives us a catch-up condition where it is feasible to catch up to the vehicle ahead. Equality (the break-even ratio) gives equal fuel consumption.

By assuming that both the lead and follower vehicles drive at the same speed, $v_a = v_p$, then (9) can be written as:

$$\begin{aligned} \frac{d_d}{d_p} &\geq \frac{v_c}{v_c - v_p} \frac{v_c^2 - v_p^2 \phi}{v_p^2 - v_p^2 \phi} \\ &= \frac{r_v}{r_v - 1} \frac{r_v^2 - \phi}{1 - \phi} \end{aligned} \tag{10}$$

where $r_v = \frac{v_c}{v_p} > 1$. This theoretical break-even ratio can be plotted as the surface illustrated in Fig. 3. If the ratio d_d/d_p lies above the surface, then there is an incentive to catch up to the platoon ahead and form a bigger platoon.

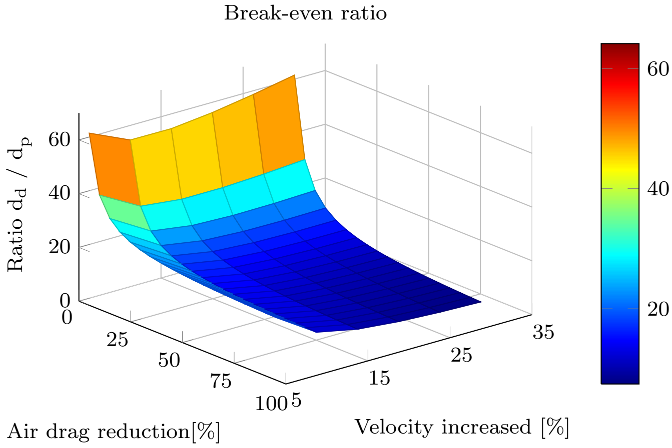

Fig. 3. Break-even ratio surface with respect to the air drag reduction and increased speed, r_v. If the ratio d_d/d_p lies above the surface, then there are fuel saving potential by catching up the platoon ahead.

3.2 Several HDVs in a Platoon Catching Up

In the previous subsection, only one HDV was considered. For n HDVs, the total fuel consumption is:

$$f_{tot,all} = \sum_{i=1}^{n} \frac{1}{\bar{\eta}_{eng} \rho_d} v(\frac{1}{2} \rho_a A_a c_D v^2 \phi_i + m_i g c_r) T \tag{11}$$

where m_i is the mass of vehicle i and ϕ_i its reduced air drag. Since (7) also holds for n vehicles, this gives us the following catch up condition for n HDVs in a platoon catching up:

$$v_a^3 T_a \geq v_c^3 T_c + v_p^3 T_p \frac{\sum_{i=1}^{n} \phi_i^*}{\sum_{i=1}^{n} \phi_i'} = v_c^3 T_c + v_p^3 T_p \hat{\phi} \tag{12}$$

where ϕ_i' is the air drag for i'th vehicle before catching up and ϕ_i^* is the new air drag for i'th vehicle after merging with the platoon ahead. Notice that for some vehicle i, $\phi_i' < 1$ since it is already in a platoon when catching up.

4. BENEFITS OF CATCHING UP

In this section, we introduce a platooning incentive factor, which indicates when a catch-up attempt is beneficial. Furthermore, the relative speed increase during the catch-up phase is discussed. At the end of the section, given the fuel model in (4), a typical driving scenario and its fuel saving possibilities are described.

4.1 Platooning Incentive Factor κ

Introduce the platooning incentive factor κ as:

$$\kappa = 1 - \overline{\psi}(d) \tag{13}$$

where,

$$\begin{aligned} \overline{\psi}(d) &= \frac{\int_0^d (1 - \delta_p(s)) F_{ad}(v_c) + \delta_p(s) F_{ad}(v_p) \phi \; \mathrm{d}s}{F_{ad}(v_a) d} \\ &= \frac{\int_0^d (1 - \delta_p(s)) v_c^2 + \delta_p(s) v_p^2 \phi \; \mathrm{d}s}{v_a^2 d} \end{aligned}$$

$$\delta_p(s) = \begin{cases} 0 & s < \dfrac{v_c}{v_c - v_p} d_p \quad \textit{(not platooning)} \\ 1 & \text{otherwise} \quad \textit{(platooning)} \end{cases}$$

where $\overline{\psi}(d)$ is the average air drag normalized with $F_{ad}(v_a)$ that the HDV is exposed to during the traveled distance,

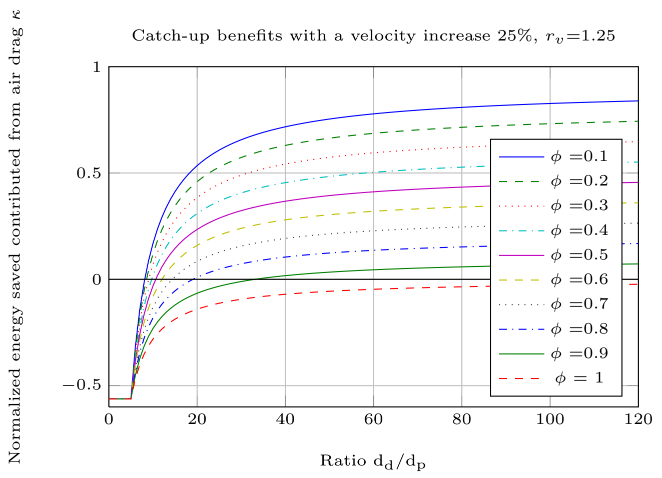

Fig. 4. κ with regard to different ϕ and a fixed velocity increase. Depending on how far the follower HDV will travel (normalized with the current distance between the HDVs), if $\kappa > 0$ then it will be feasible to perform a catch-up action and merge into a platoon.

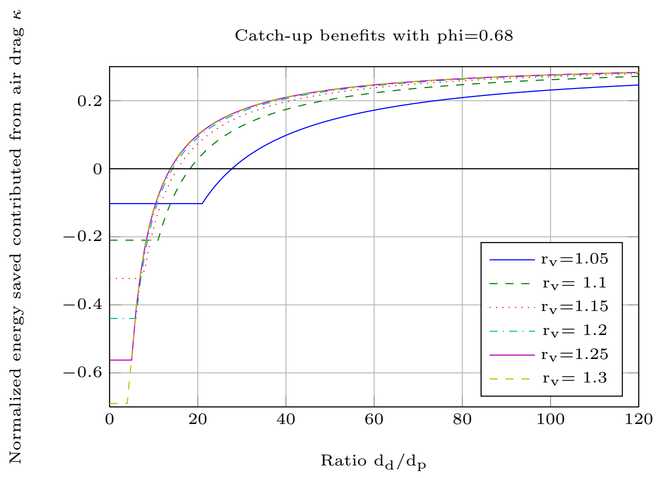

Fig. 5. κ with regard different velocity increases and a fixed ϕ. Depending on how far the follower HDV will travel (normalized with the current distance between the HDVs), if $\kappa > 0$ then it will be feasible to perform a catch-up action and merge into a platoon.

$\delta_p(s)$ is active when the catching-up vehicle is platooning, and s is the distance domain. The longer the vehicle can drive in a platoon, the smaller $\overline{\psi}(d)$ becomes. Note that $\overline{\psi}(d)$ converges to ϕ when d goes to infinity for a fixed finite d_p.

Given that the vehicle can catch up to the platoon ahead before it reaches its destination $d_d > \frac{v_c}{v_c - v_p} d_p$ and that both the following and lead HDVs have the same velocity $v_a = v_p$, then we obtain:

$$\overline{\psi}(d) = \frac{\int_0^d \delta_p v_c^2 + (1-\delta_p) v_p^2 \phi \, \mathrm{d}s}{\int_0^d v_a^2 \, \mathrm{d}s} = \frac{d_p}{d} \frac{r_v}{r_v - 1}(r_v^2 - \phi) + \phi. \tag{14}$$

Hence the platooning incentive factor becomes:

$$\kappa = 1 - \frac{d_p}{d} \frac{r_v}{r_v - 1}(r_v^2 - \phi) - \phi. \tag{15}$$

κ can be interpreted as how much energy is saved due the reduction in air drag. Often the destination is fixed making the travel distance $d = d_d$, while ϕ and r_v are parameters that can for example be set by the driver or the system. In such case, ϕ will correspond to the intermediate distance when platooning after catching up and r_v corresponds how much faster the driver or the system is willing to drive. If $\kappa > 0$ then there will be a fuel saving potential when catching up the platoon ahead. How κ varies with regard to the traveled distance and with varying ϕ and r_v are depicted in Fig. 4 and Fig. 5, respectively.

In Fig. 4, we have plotted how κ varies for different values of ϕ and a fixed relative velocity increase r_v when a catch-up action is made. Initially κ is low due to that the catch-up phase is a loss. When $d_d/d_p = 5$, the follower vehicle has joined the platoon and κ starts to increase thereafter. The increase varies depending on the value of ϕ. The lower ϕ, the higher air drag reduction, which means the quicker the follower vehicle will start to save fuel and the more it will save throughout the traveled distance. κ converges to the air drag reduction when d_d goes to infinity. The break-even ratio can be obtained at $\kappa = 0$. A similar plot is shown in Fig. 5, but now ϕ is fixed and r_v varies. The different initial values of κ is due to the increased relative velocity (squared) from $F_{ad}(v)$. The higher the catch-up velocity is, the quicker the vehicle will catch up the platoon and the sooner it starts to save fuel. The conclusion that can be drawn from Fig. 4 and Fig. 5 is that the lower ϕ is and the higher r_v is, the faster κ converges, which means more fuel saving potentials.

From Fig. 5, it looks like the higher r_v is the faster κ goes above 0. However, this is not true. By looking at (10), (14) and (15), all these three equations contain $\frac{r_v}{r_v - 1}(r_v^2 - \phi)$. This equation has one optimum for $r_v > 1$, which is depicted in Fig. 6, which depends on ϕ. This optimum gives us the minimum break-even ratio value, the minimum normalized air drag, and the maximum κ.

4.2 Fuel Saving Potentials

If we consider a 40 t HDV driving on a flat road at 80 km/h with the fuel model in (4), then 42 % of the fuel energy is used to overcome the air drag and the rest on roll resistance. For a lighter vehicle, the air drag plays a bigger role. Typical values of the parameters can be found in Sahlholm (2011). However, if the HDV was driving in a platoon already and has an air drag reduction of 32 % ($\phi = 0.68$), then the HDV would reduce its fuel consumption with 13.4 % compared to driving alone. If the HDVs were however scattered, then the fuel saving can be anywhere between 0 % and 13.4 % depending on how far their are separated initially and how far the HDVs will travel together.

Generally an HDV driver is allowed to drive 4.5 h in Europe without break. Now assume that two HDVs of 40 t each started driving at the same time at 80 km/h with a position difference of 10 km and they have the destination 340 km and 350 km away, respectively. Assume that the driver of the follower HDV allows a catch-up speed of 90 km/h ($r_v = 1.125$) and that the air drag reduction is 32 % for the follower HDV once they have formed a platoon. This will give us the break-even ratio 16.5, that is the destination should be 16.5 times longer than the distance between the HDVs, furthermore we have $\frac{d_d}{d_p} = 35 > 16.5$, $\overline{\psi}(d_d) = 0.83$, and $\kappa = 0.17$. Since the left side of the equation in (9) is larger than the right side, then the lead HDV is within the largest circle of

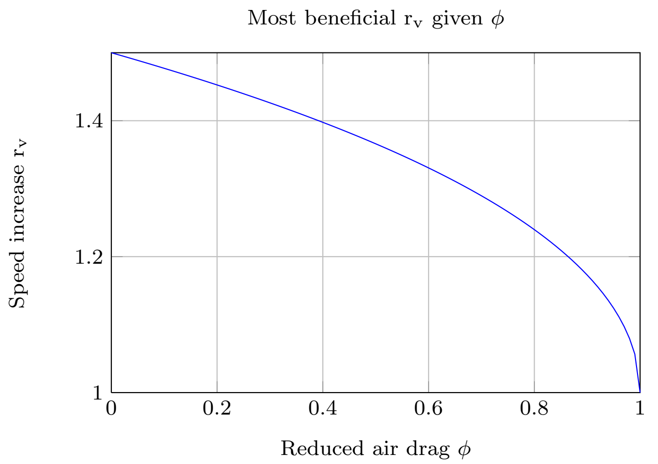

Fig. 6. This plot shows the most beneficial r_v^* to catch up with respect to ϕ.

Table 1. Perturbations allowed for one parameter at a time to have a ± 2, 5 and 10 % deviation of the ratio d_d/d_p, with the nominal values: $v_a = 80\,km/h$, $v_c = 90\,km/h$, $v_p = 80\,km/h$ and $\phi = 0.68$.

d_d/d_p	-10 %	-5 %	-2 %	+2 %	+5 %	+10 %
v_a	1.8 %	0.8 %	0.3 %	-0.3 %	-0.8 %	-1.5 %
v_c	4 %	1.6 %	0.6 %	-0.5 %	-1.2 %	-2.1 %
v_p	-1.1 %	-0.5 %	-0.2 %	0.2 %	0.5 %	0.9 %
ϕ	-13.2 %	-4.4 %	-1.5 %	2.9 %	5.9 %	8.8 %

the follower HDV in Fig. 1. Furthermore $\kappa > 0$, which means that there are benefits of catching up, therefore if the follower HDV drives at 90 km/h, it will take 1 h to catch up and would have traveled 90 km before catching up and merging. The remaining 260 km will be driven in a platoon at 80 km/h. The average normalized air drag is 83 % compared to driving alone at 80 km/h. Hence, by driving 90 km/h to catch up an HDV ahead and platoon at 80 km/h will give us a fuel saving of 7.1 % compared to driving 80 km/h alone the whole route of 350 km.

5. SENSITIVITY ANALYSIS

To study how robust these obtained results are, a sensitivity analysis is made for the break-even ratio as well as for the average normalized air drag reduction. In both cases, all parameters were fixed to obtain the nominal value. We perturbed one parameter at the time to see how much deviations were needed in order for the nominal value to deviate $\pm 2, 5$ and 10 %.

5.1 Break-Even Ratio

For analyzing the robustness of the break-even ratio, we use (9). Four parameters can be varied: v_a, v_c, v_p and ϕ. One parameter at a time varies until the nominal value deviates with $\pm 2, 5$ and 10 %. The nominal parameter values that is used are $v_a = 80\,km/h$, $v_c = 90\,km/h$, $v_p = 80\,km/h$ and $\phi = 0.68$, which gives us a nominal value of 16.5. The results are shown in Table 1.

Table 1 shows that the break-even ratio is sensitive to velocity perturbations, hence the velocities must be accurate. The most sensitive part is v_p, which is almost linear and this tells that it is better to overestimate the current speed of the HDV ahead than underestimating it in order to not give a false positive catch-up decision. The same thing applies for ϕ; it is better to overestimate the ϕ value than underestimating it, which means that the air drag reduction is more than what you estimated. It is good that the break-even ratio is least sensitive to the air drag reduction, since in reality the air drag reduction might be difficult to estimate. However, for our own HDV speed v_c (catch up speed) and v_a (current speed alone), it would be better to underestimate them rather than overestimating them. Notice that $v_c/v_a = 1.125$ which is only a 12.5 % velocity increase. This means that a small velocity perturbation affect the break-even ratio greatly due to the small span. The distance to the destination d_d and the distance between the vehicles d_p can also be perturbed. This would mean a proportional deviation on the break-even ratio for d_d and inverse proportional to d_p. Hence, it is better to underestimate d_d and overestimate d_p in order to avoid false positive catch-up decisions.

Table 2. Perturbations allowed for one parameter at a time to have a ± 2, 5 and 10 % deviation of $\overline{\psi}$, with the nominal values: $r_v = 90/80$, $\phi = 0.68$ and $d_p/d_d = 40$.

$\overline{\psi}$	-10 %	-5 %	-2 %	+2 %	+5 %	+10 %
r_v	3.9 %	1.6 %	0.5 %	-0.6 %	-1.2 %	-2.2 %
d_p/d_d	-10 %	-5 %	-2 %	2.1 %	5.1 %	10.1 %
ϕ	8.6 %	4.3 %	1.7 %	-1.8 %	-4.4 %	-8.7 %

5.2 Average Normalized Air Drag Reduction

For the average normalized air drag reduction $\overline{\psi}$, we use (14). Three parameters were varied. One at a time until the nominal value deviated with $\pm 2, 5$ and 10 %. The nominal parameter values were $r_v = 90/80$, $\phi = 0.68$ and $d_p/d_d = 40$, which gave a nominal value of 204. The results are shown in Table 2.

Table 2 shows that the average normalized air drag reduction is least sensitive to d_p/d_d and most sensitive to r_v. This again tells us that the velocities v_c and $v_a = v_p$ must be accurate. The sensitivity is linear in d_p/d_d and ϕ. It is better to overestimate d_p/d_d while it is better to underestimate r_v and ϕ in order to not give false positive catch up decisions. For a 40 t HDV, the air drag constitutes 42 % of the total force on a flat road from (4), which means that a deviation of 10 % from the nominal $\overline{\psi}$ would mean a fuel reduction deviation of 4.2 % from the nominal value. This indicates that the fuel reduction is not as sensitive. For a heavier vehicle, the air drag consists of even less compared to a lighter vehicle, which means that the fuel reduction is less. This also means that the heavier vehicle is even less sensitive for perturbations on the fuel reduction potentials.

6. SIMULATION EVALUATION

To verify our approach, we compare our results with an advanced and verified model that is used in Scania; the same simulation tool was used in Alam (2011). The setup for the model was an HDV with a vehicle configuration of 6×2, 440 hp engine with a 12 speed gear box.

To farily compare our approach with the advanced model, we only considered constant speed from the simulation tool (like in our approach). A simulation of the fuel consumption for constant speed of 80 km/h and 90 km/h was conducted, along with a separate simulation of the fuel consumption for 80 km/h with lowered air drag. These velocities most likely occur due to the maximum allowed velocity of 90 km/h in Sweden. The results are shown in

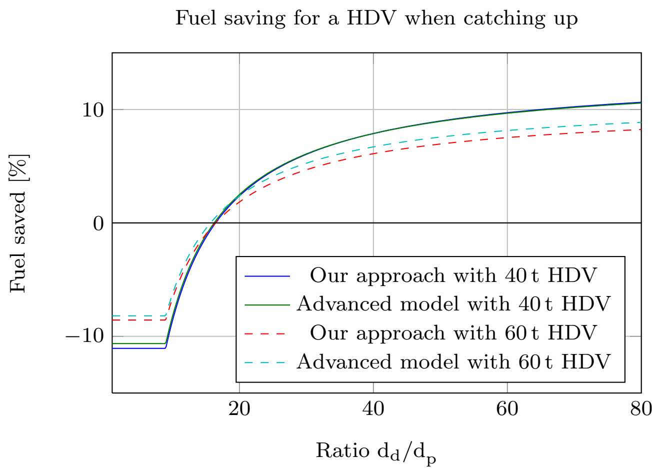

Fig. 7. The fuel savings when a 40 t and a 60 t HDV respectively catches up another HDV ahead compared to if the follower HDV had not done the action. The parameters are for $v_a = 80\,km/h, v_c = 90\,km/h, v_p = 80\,km/h$, and $\phi = 0.68$.

Fig. 7 with a 40 t and a 60 t HDV, respectively. The figures show the fuel savings when driving faster to join a platoon compared to having driven alone and not performed the catch-up action with respect to the ratio d_d/d_p.

From Fig. 7, we can conclude that our approach and the advanced model lie on top of each other for 40 t HDV. As mentioned earlier, for a 40 t HDV, the air drag constitutes 42 % of the total resistive force on a flat road. This means that the fuel saving converges to 13 % for $\phi = 0.68$ when d_d/d_p goes to infinity. The fuel loss at the beginning is due to the catch-up phase where the HDV has to drive faster. For a 60 t HDV, we notice a slight differences between the models. Our approach underestimate the fuel saving compared to the advanced model. Also the fuel savings are less due to the fact that the total force consists less of air drag for a 60 t HDV than compared to a 40 t HDV. This paper studies long distances that suit long haulage HDVs better and these are mostly heavily loaded. Hence, our approach gives a lower fuel saving estimate, which is preferred than a false positive catch-up decision.

One of the reasons for the difference in the models is the roll resistance coefficient $c_r(v)$, which is strictly increasing with the velocity while in our approach it is constant. Another reason is that we use a mean combustion efficiency in our approach while the advanced model uses a varying combustion efficiency depending on the engine speed, injected fuel, etc.

7. CONCLUSION

Since all HDVs do not start at the same time or positions, it is difficult to form platoons without coordination. In this paper, we have proposed a method for coordination by letting the follower vehicle drive faster and catch up with the lead vehicle. This however will consume more fuel during the catch-up, but will be compensated with the lowered air drag when platooning. If the vehicles can platoon long enough, there will be fuel saved compared to not having done the catch-up action. How large the fuel savings are depends on the initial distance between the HDVs and the distance to the destination. An example was given where we showed that a fuel saving potential of 7 % can be obtained by a coordinated catch-up strategy.

Furthermore, we introduced a new parameter called the platooning incentive factor κ, which indicates whenever there will be any benefits of catching up, which is when $\kappa > 0$. However, in reality due to uncertainties, one might add a threshold on κ in order to not give false positive catch-up decision and ensure fuel savings. Also given the sensitivity analysis, the break-even ratio and fuel saving are sensitive to speed uncertainties, which means that accurate speeds are necessary.

However, this approach only considered flat roads, which is not realistic, but it gives some indications on how far ahead an HDV has to look in order to form platoons with others to save fuel. Furthermore, accelerations and decelerations were not considered since they are negligible for long distances. Also, no traffic was considered, which would be interesting to study further to understand how it will affect the coordination decisions. Investigation on these are left as future work.

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