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

Kuo-Yun Liang* Jonas Mårtensson**
Karl Henrik Johansson**

* Scania CV AB, 151 87 Södertälje, Sweden (e-mail: kuo-yun.liang@scania.com).
** ACCESS Linnaeus Centre, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden (e-mail: jonas1@kth.se, kallej@kth.se)

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 downhill. 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 Zabet 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). Tsueg 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.
where \( f_c \) [ml/s] denotes the instantaneous fuel consumption, \( \eta_{eng} \) the mean combustion efficiency of the engine, \( \rho_d \) the energy density of diesel fuel and \( \delta \) indicates whether fuel is injected into the engine or not.

The total fuel consumption over time \( T \) is:

\[
 f_{tot} = \int_0^T \frac{\delta(t)}{\eta_{eng} \rho_d} v(t) \left( m_t \frac{dv(t)}{dt} + \frac{1}{2} \rho_a A_c D_v v^2(t) \phi(d(t)) \right) dt
\]

+ \( mgc_r \cos \alpha + mg \sin \alpha \) \( dt \)

(3)

where we used (1) and (2) and where \( \alpha \) 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 distance 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 \( \frac{dv}{dt} = 0 \). 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:

\[
 f_{tot} = \frac{1}{\eta_{eng} \rho_d} v \left( \frac{1}{2} \rho_a A_c D_v v^2 \phi + mgc_r \right) T.
\]

(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

\[
f_{tot}(\text{maintain speed}) \geq f_{tot}(\text{catch up}) + f_{tot}(\text{platoon})
\]

(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:

\[
 \frac{1}{\eta_{eng} \rho_d} v_f \left( \frac{1}{2} \rho_a A_c D_v v_f^2 + mgc_r \right) T_f
\]

\[
 \geq \frac{1}{\eta_{eng} \rho_d} v_a \left( \frac{1}{2} \rho_a A_c D_v v_a^2 + mgc_r \right) T_a
\]

\[
 + \frac{1}{\eta_{eng} \rho_d} v_p \left( \frac{1}{2} \rho_a A_c D_v v_p^2 \phi + mgc_r \right) T_p
\]

(6)
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:

$$v_c > v_a, v_p$$ \hspace{1cm} (7a)

$$T_a v_a = T_c v_c + T_p v_p.$$ \hspace{1cm} (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):

$$v_a^2 T_a \geq v_c^2 T_c + v_p^2 T_p \phi.$$ \hspace{1cm} (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:

$$\frac{d_d}{d_p} \geq \frac{v_c}{v_p} \frac{v_c^2 - v_p^2 \phi}{v_c - v_p}$$ \hspace{1cm} (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:

$$\frac{d_d}{d_p} \geq \frac{v_c}{v_c - v_p} \frac{v_c^2 - v_p^2 \phi}{v_c - v_p}$$ \hspace{1cm} (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:

$$f_{tot,all} = \sum_{i=1}^{n} \frac{1}{\rho_a g} \int_{v_s}^{v_c} \frac{1}{2} \rho_a A_a c_D v^2 \phi + m_i g c_r T_s$$ \hspace{1cm} (11)

where $m_i$ is the mass of vehicle $i$ and $\phi$, 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:

$$v_a^2 T_a \geq v_c^2 T_c + v_p^2 T_p \sum_{i=1}^{n} \phi_i = v_c^2 T_c + v_p^2 T_p \phi′.$$ \hspace{1cm} (12)

where $\phi′_i$ is the air drag for $i$’th vehicle before catching up and $\phi_i'$ 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 $\kappa$

Introduce the platooning incentive factor $\kappa$ as:

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

where,

$$\overline{\psi}(d) = \frac{\int_0^d (1 - \delta_p(s)) F_{ad}(v_a) + \delta_p(s) F_{ad}(v_p) \phi \, ds}{F_{ad}(v_a) d}$$

$$= \frac{\int_0^d (1 - \delta_p(s)) v_c^2 + \delta_p(s) v_p^2 \phi \, ds}{v_c^2 d}$$

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

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.
Catch-up benefits with a velocity increase 25%, $v_c=1.25$

\[ \psi(d) = \frac{\int_0^d \delta_p s^2 + (1 - \delta_p) v_c^2 \phi \, ds}{\int_0^d v_c^2 \, ds} = \frac{d_p}{v_c} \frac{r_v}{r_v - (r_v^2 - \phi)} + \phi. \] (14)

Hence the platooning incentive factor becomes:

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

$\kappa$ can be interpreted as how much time is saved due to the reduced drag in air. Often the destination is fixed making the travel distance $d = d_d$, while $\phi$ and $r_v$ are parameters that can for example be set by the driver or the system. In such case, $\phi$ 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 $\kappa$ varies with regard to the traveled distance and with varying $\phi$ and $r_v$ are depicted in Fig. 4 and Fig. 5, respectively.

In Fig. 4, we have plotted how $\kappa$ varies for different values of $\phi$ and a fixed relative velocity increase $r_v$ when a catch-up action is made. Initially $\kappa$ 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 $\kappa$ starts to increase thereafter.

From Fig. 5, it looks like the higher $r_v$ is the faster $\kappa$ goes above 0. However, this is not true. By looking at (10), (14) and (15), all these three equations contain $\psi(d) = \kappa > 0$. A similar plot is shown in Fig. 5, which depends on $\phi$. This optimum gives us the minimum break-even ratio value, the minimum normalized air drag, and the maximum $\kappa$.

### 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 phase 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 $\kappa = 0.17$. 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

\[ \psi(d) = \frac{\int_0^d \delta_p s^2 + (1 - \delta_p) v_c^2 \phi \, ds}{\int_0^d v_c^2 \, ds} = \frac{d_p}{v_c} \frac{r_v}{r_v - (r_v^2 - \phi)} + \phi. \]
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 a time to see how much deviations were needed in order for the nominal value to deviate ±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 $\phi$. One parameter at a time varies until the nominal value deviates with ±2.5 and 10%. The nominal parameter values that is used are $v_a = 80 \text{ km/h}$, $v_c = 90 \text{ km/h}$, $v_p = 80 \text{ km/h}$ and $\phi = 0.68$, which gives us a nominal value of 16.5. The results are shown in Table 1.

Table 1. Perturbations allowed for one parameter at a time to have a ±2.5 and 10% deviation of $\psi$, with the nominal values: $v_a = 80 \text{ km/h}$, $v_c = 90 \text{ km/h}$, $v_p = 80 \text{ km/h}$ and $\phi = 0.68$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>-10%</th>
<th>-5%</th>
<th>-2%</th>
<th>+2%</th>
<th>+5%</th>
<th>+10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_a$</td>
<td>1.8%</td>
<td>6.8%</td>
<td>6.3%</td>
<td>-0.3%</td>
<td>-0.8%</td>
<td>-1.5%</td>
</tr>
<tr>
<td>$v_c$</td>
<td>4%</td>
<td>1.6%</td>
<td>0.6%</td>
<td>-0.5%</td>
<td>-1.2%</td>
<td>-2.1%</td>
</tr>
<tr>
<td>$v_p$</td>
<td>-1.1%</td>
<td>-0.5%</td>
<td>-0.2%</td>
<td>0.2%</td>
<td>0.5%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$\phi$</td>
<td>-13.2%</td>
<td>-4.4%</td>
<td>-1.5%</td>
<td>2.9%</td>
<td>5.9%</td>
<td>8.8%</td>
</tr>
</tbody>
</table>

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.

5.2 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 ±2.5 and 10%. The nominal parameter values were $r_v = 90/80$, $\phi = 0.68$ and $d_p/d_a = 40$, which gave a nominal value of 204. The results are shown in Table 2.

Table 2. Perturbations allowed for one parameter at a time to have a ±2.5 and 10% deviation of $\psi$, with the nominal values: $r_v = 90/80$, $\phi = 0.68$ and $d_p/d_a = 40$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>-10%</th>
<th>-5%</th>
<th>-2%</th>
<th>+2%</th>
<th>+5%</th>
<th>+10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_v$</td>
<td>3.9%</td>
<td>1.6%</td>
<td>0.5%</td>
<td>-0.6%</td>
<td>-1.2%</td>
<td>-2.2%</td>
</tr>
<tr>
<td>$d_p/d_a$</td>
<td>-10%</td>
<td>-5%</td>
<td>-2%</td>
<td>2.1%</td>
<td>5.1%</td>
<td>10.1%</td>
</tr>
<tr>
<td>$\phi$</td>
<td>8.6%</td>
<td>4.3%</td>
<td>1.7%</td>
<td>-1.8%</td>
<td>-4.4%</td>
<td>-8.7%</td>
</tr>
</tbody>
</table>

same thing applies for $\phi$; it is better to overestimate the $\phi$ 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 $v_a$ (catch up speed) and $v_c$ (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 $d_a$ and the distance between the vehicles $d_p$ can also be perturbed. This would mean a proportional deviation on the break-even ratio for $d_a$ and inverse proportional to $d_p$. Hence, it is better to underestimate $d_a$ and overestimate $d_p$ in order to avoid false positive catch-up decisions.

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 $6 \times 2$, 440 hp engine with a 12 speed gear box.

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

Furthermore, we introduced a new parameter called the platooning incentive factor $\kappa$, 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 $\kappa$ 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, HDVs better and these are mostly heavily loaded. Hence, it will affect the coordination decisions. Investigation on these are left as future work.

REFERENCES


