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Optimal formation and dissolution of two-truck platoons on a highway stretch

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Abstract: This paper presents an optimal coordination strategy to form and dissolve two-truck platoons on a highway stretch. The main goal of this approach is to reduce fuel consumption and greenhouse gas emissions while increasing the traffic throughput. The proximity of the vehicles in this configuration provides a more efficient airflow around the trucks reducing the overall energy demand. An optimization problem is formulated considering the merging, platooning and splitting phases of the coordination and is solved using an interior-point algorithm. The savings potential is analyzed according to the three main coordination characteristics: initial separation distance, difference of both trucks desired velocity and minimum platooning distance. Increasing the initial separation distance and the desired velocity difference results in an increased energy cost. Imposing a longer platooning distance can increase the traffic throughput at the cost of a higher energy consumption needed to meet the constraints of the problem. Considering two trucks initially separated by 15 km in a 200 km highway stretch, the expected energy savings is 4.9%.

Keywords: Platoon, Coordination, Optimization, Energy Savings

INTRODUCTION

The demand for freight transportation is increasing (IPCC, 2014) and the expansion of the road infrastructure is very limited (Tsugawa et al., 2016). Besides, the transportation sector generates high levels of greenhouse gas emissions. For instance, in Brazil, almost 21% of the total CO_2 emissions come from the road transportation sector (Ministério da Ciência, Tecnologia e Inovação, 2016) and in the United States, trucks of all sizes represent almost half of the total emissions coming from the road transportation sector (U.S. Environmental Protection Agency, 2016). One possible solution to those issues is the formation of truck platoons, i.e., a set of trucks in the same lane traveling with small inter-vehicle distances. The first truck is driven manually by a human driver and the following trucks are driven autonomously by the control system. Truck platoons can increase traffic throughput due to a more compact arrangement of the traveling vehicles while increasing energy savings and reducing greenhouse gas emissions due to more efficient airflow (Hucho and Ahmed, 1998).

Trucks have to be capable of forming and dissolving platoons. This can be achieved adjusting the departure schedule to make trucks meet each other on a highway intersection. However, fleet owners are not willing to share their itinerary with competitors and would form platoons only within their own fleets (Bhoopalam et al., 2018). Alternatively, trucks in transit can be coordinated on the fly through the adjustment of their velocities in order to decrease the separation distance between them up to the formation of the platoon. Eventually, platoons have to be split depending on the route each truck has to follow. In general, trucks have different starting points, destinations and time restrictions. Despite the benefits of the platoon formation, the coordination strategy with the lowest fuel consumption is not evident. Thus, this paper presents an optimal coordination strategy to coordinate two trucks on a highway stretch considering the merging, platooning and splitting phases.

LITERATURE REVIEW

Several research groups contributed to truck platoon studies, for instance, the Chauffeur I and II (Bonnet and Fritz, 2000; Fritz et al., 2004), PATH (Shladover, 2007), KONVOI (Kunze et al., 2011), SARTRE (Chan, 2016), Energy ITS (Tsugawa, 2014) and COMPANION (Eilers et al., 2015). Each of those groups focused on different aspects of truck platooning presenting theoretical and experimental analyses related to fuel savings, emissions reduction, stability, control design, wireless communication and coordination strategies. The knowledge acquired provided valuable insights to the development of the current cooperative adaptive cruise control (CACC) necessary to form and maintain truck platoons. With the further improvements in communication technologies and reliability, truck platooning is likely to be the first vehicular automation to penetrate the market (Lammert et al., 2014).

Research about truck platoons can be separated in three different areas: fuel consumption in platoons, platoon maintenance and truck coordination (Mendes et al., 2017). Addressing the latter, Liang et al. (2016a) proposed an algorithm to coordinate scattered trucks on a highway. The algorithm is capable of merging adjacent vehicles pairwise in order to reduce the overall fuel consumption. An optimization problem is formulated to provide the speed profiles necessary to form platoons in an energy efficient manner. This problem is solved using the *fmincon* function of Matlab. In a given iteration of the algorithm, the potential of fuel savings is calculated for each pair of adjacent trucks based on the results of the optimization. Truck pairs with the greatest savings potential have their velocity changed in order to form the platoons. When the trucks are in the process of forming platoons they are not considered by the algorithm and, in the following iterations, the newly created platoons are then considered to form even bigger platoons. The proposed method is evaluated through simulations and provided up to 3.8% of fuel savings with two trucks forming platoon on a 280 km stretch after a 12.8 km initial separation distance.

Zhang et al. (2017) investigate the coordination of two trucks with the same origin and destination, but with different delivery time schedules. For this, the authors formulated the problem of departure time scheduling considering the fuel consumption, labor cost and schedule miss penalties. In this case, the time constraint is soft and the cost associated to lateness or earliness is considered in the cost function. Based on the delivery characteristics, it is possible to verify if the transportation should be realized with the platoon formation or independently. This is, verify if the platoon can compensate the schedule miss penalty. Scenarios with one intersection are also investigated.

The influence of traffic density can affect the collaboration opportunities and coordination efficiency (Liang et al., 2016b). The merging time can be delayed when traveling in higher traffic conditions and platoons cannot even be formed due to vehicles blocking the approximation. Saeednia and Menendez (2016) developed a discrete event system to assist the decision to form or dissolute platoons based on the traffic conditions. The authors emphasize that platoons are moving bottlenecks that negatively influences the flow of the highway. Then, Saeednia and Menendez (2017) presented an iterative consensus-based algorithm to form platoons without excessive velocity variations by each vehicle. In this case, the trucks are treated as agents that have to agree on some specific characteristics of the platoon and adjust their velocity appropriately. This algorithm allows the adaptation of the speed profile according to the traffic condition along the highway.

Generally, the contributions in the literature consider simplified scenarios with a few vehicles. In some cases, the simplified results are used as heuristics in extensive and complex highway networks with thousands of vehicles (Larson et al., 2015). However, the extensive set of roads show several stretches of low average flow velocities imposed by legislation, pavement quality, construction work and congestions. In this conditions, the benefits of platoon can be completely lost or even generate maneuvers with a higher energy consumption. With the velocity limitations, the aerodynamic effect is less relevant and the speed profiles cannot be realized. In practice, there are intermittent highway stretches that present favorable conditions to form platoons.

This paper presents a coordination strategy that considers two trucks on a highway stretch with high average velocity and low congestion rates. To avoid schedule miss penalties or unexpected high fuel consumption after the considered stretch, the platoon have to be split and the trucks have to exit the highway stretch as if no coordination occurred. The methods used here are a direct extension of the optimization problem proposed by Liang et al. (2016a). The main contributions of this paper lies in the consideration of the splitting phase in the optimization problem and the presentation of sensitivity analyses considering the initial separation distance, difference of both trucks desired velocity and minimum platooning distance.

PROBLEM FORMULATION

The coordination proposed in this paper considers the formation of two-truck platoons on a highway stretch. The truck traveling in front is called the first truck and the one behind is called the second truck. Both trucks have a nominal velocity, i.e., the average velocity they intend to keep along the highway stretch. Each new truck entering the considered stretch provides its nominal velocity and starts broadcasting its GPS data through a V2I communication system. A central processing station is responsible for receiving the information from the available trucks, run the coordination algorithm and provide the speed profile that both trucks should follow to save fuel.

Figure 1 illustrates the coordination problem. The first truck enters the highway stretch and travels with its nominal velocity, as no other truck is available to form a platoon. Once the second truck enters the stretch, the central station evaluates the velocity profiles of the maneuver starting at instant t_i. The dashed lines show the trajectory each truck would have if no coordination was performed. This is called the nominal case and we assume that the first and second trucks travel with constant nominal velocities v_{1n} and v_{2n}. d_f measures the distance between the position of the first truck up to the end of the considered highway stretch and d_{12i} is the initial separation distance between both trucks. For the coordination proposed in this paper, v_{1n}, v_{2n}, d_f and d_{12i} are known.

The trucks should change their velocities to form platoons if doing so would save more fuel compared to the nominal case. The coordination procedure is composed by three phases. The first one is the merging phase where the first truck slows down to travel with velocity v_{1m} and the second truck speeds up to travel with velocity v_{2m}, where $v_{1m} < v_{2m}$. Both trucks form a platoon at t_m. After the platoon is formed, the set of trucks travel a distance d_p at velocity v_p up to the beginning of the splitting phase at t_s. During this last phase, the first and second trucks travel with velocities v_{1s} and v_{2s}, respectively, where $v_{1s} > v_{2s}$. The trucks reach the end of the highway stretch at t_f and the final separation distance is d_{12f}. Note that, at the end, both trucks reach the same position they would have if the nominal case was performed.

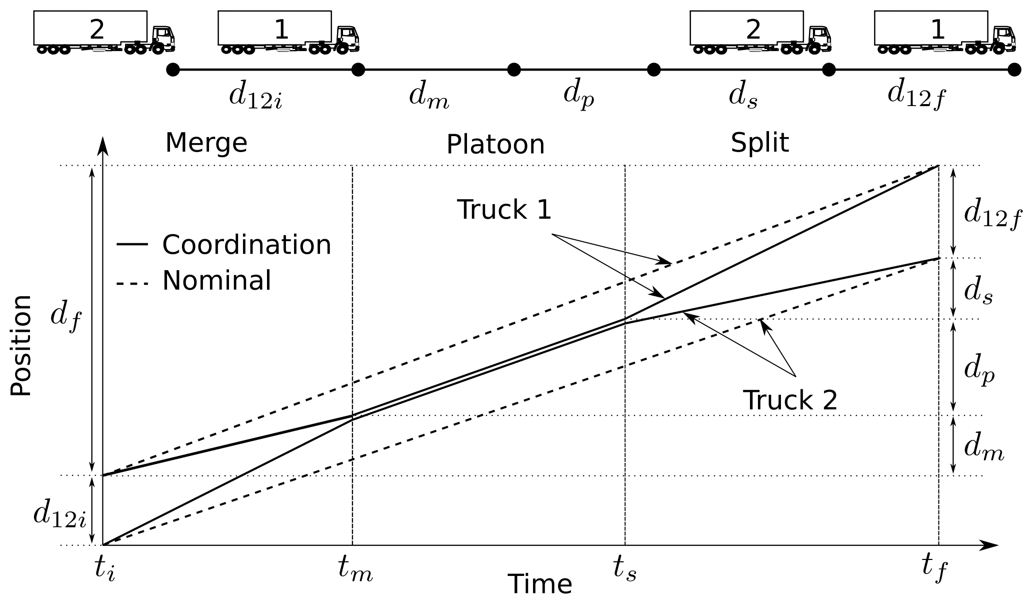

Figure 1 – Coordination of two trucks on a highway stretch and comparison between the nominal (dashed lines) and the coordinated (solid lines) trajectories of the two trucks considering the merging, platooning and splitting phases.

The longitudinal dynamics of a single truck can be modeled as

$$\begin{aligned} \frac{ds}{dt} &= v \\ m_e\frac{dv}{dt} &= F - R - G - D \\ &= F - mgc_r\cos\theta(s) - mg\sin\theta(s) - \frac{1}{2}\rho A c_d v^2\Phi(d), \end{aligned} \tag{1}$$

where the kinematics is given by the longitudinal position of the vehicle along the road s and its longitudinal velocity v. The inertial parameters are given by the total mass m and the effective mass m_e. F is the net applied longitudinal force, R is the rolling resistance, G is the longitudinal contribution of the gravity force and D is the aerodynamic drag force. θ denotes the road slope, g the gravitational constant, c_r the rolling resistance coefficient, ρ the air density and c_d the air drag coefficient. Finally, Φ is the air drag reduction factor that regulates the contribution of the aerodynamic drag as a function of the current distance to the preceding vehicle d. When platooning $1 > \Phi > 0$ and when in standalone $\Phi = 1$.

The energy consumption of a single truck can be written as

$$E = \int_{t_i}^{t_f} F\, v\, dt \tag{2}$$

and the main interest here is to achieve a maneuver more energy efficient than the nominal case. This is,

$$E_{coordination} + c_{th} < E_{nominal}, \tag{3}$$

where $E_{coordination}$ is the energy cost when the vehicles are coordinated to form a platoon and $E_{nominal}$ is the energy cost when no coordination occurs. c_{th} defines the threshold to be overcome by the coordination strategy.

Substituting Eq. (1) in Eq. (2), we have

$$E = \int_{t_i}^{t_f} \left(m_e\frac{dv}{dt} + mgc_r\cos\theta(s) + mg\sin\theta(s) + \frac{1}{2}\rho A c_d v^2\Phi(d) \right) v\, dt. \tag{4}$$

For the proposed optimization problem, Eq. (4) is then simplified. Assuming the same initial and final velocities, the contribution of the acceleration term is zero. Moreover, when evaluating Eq. (3) using Eq. (4), the roll resistance and gravity terms from the coordinated and nominal cases cancel each other out since they are only position dependent. Using the same rationality, the parameters of the aerodynamic terms in Eq. (3) can also be canceled out. Thus, since we are only interested in comparing the nominal and coordinated cases, the acceleration, roll resistance and gravity terms are neglected as well as the parameters associated with the aerodynamic drag. Then, the energy consumption for a single truck is written as

$$E = \int_{t_i}^{t_f} v^3 \, dt. \tag{5}$$

For further details on the simplification procedure, see Liang et al. (2016a).

The energy cost of two coordinated trucks on a highway stretch, as illustrated in Fig. 1, is given by

$$J = \underbrace{\int_{t_i}^{t_m} \left(v_{1m}^3 + v_{2m}^3\right) dt}_{\text{Merge}} + \underbrace{\int_{t_m}^{t_s} v_p^3 \, \Phi_{12} \, dt}_{\text{Platoon}} + \underbrace{\int_{t_s}^{t_f} \left(v_{1s}^3 + v_{2s}^3\right) dt}_{\text{Split}}, \tag{6}$$

where $\Phi_{12} = \Phi_1 + \Phi_2$ is the lumped air drag reduction factor that accounts for the contributions of the first and second trucks during the platoon phase.

Assuming constant velocities during each phase, the energy cost in Eq. (6) is written as

$$J = \underbrace{v_{1m}^3 (t_m - t_i) + v_{2m}^3 (t_m - t_i)}_{\text{Merge}} + \underbrace{v_p^3 (t_s - t_m) \, \Phi_{12}}_{\text{Platoon}} + \underbrace{v_{1s}^3 (t_f - t_s) + v_{2s}^3 (t_f - t_s)}_{\text{Split}}. \tag{7}$$

It can be shown that the duration of each phase can be written as

$$(t_m - t_i) = \frac{d_{12i}}{v_{2m} - v_{1m}} \tag{8}$$

$$(t_s - t_m) = \frac{d_f - \frac{d_{12i} v_{1m}}{v_{2m} - v_{1m}} - \frac{d_{12f} v_{2s}}{v_{1s} - v_{2s}} - d_{12f}}{v_p} \tag{9}$$

$$(t_f - t_s) = \frac{d_{12f}}{v_{1s} - v_{2s}} \tag{10}$$

and the traveled distance associated to each phase can be written as

$$d_m = \frac{d_{12i} \, v_{1m}}{v_{2m} - v_{1m}} \tag{11}$$

$$d_p = d_f - \frac{d_{12i} \, v_{1m}}{v_{2m} - v_{1m}} - \frac{d_{12f} \, v_{2s}}{v_{1s} - v_{2s}} - d_{12f} \tag{12}$$

$$d_s = \frac{d_{12f} \, v_{2s}}{v_{1s} - v_{2s}}, \tag{13}$$

where the final separation distance is

$$d_{12f} = \left(1 - \frac{v_{2n}}{v_{1n}}\right) d_f + d_{12i}. \tag{14}$$

The total time of the maneuver can be quantified based on the velocities of the first truck as

$$t_f = \frac{d_f}{v_{1n}} = \frac{d_m}{v_{1m}} + \frac{d_f - (d_m + d_s + d_{12f})}{v_p} + \frac{d_s + d_{12f}}{v_{1s}}. \tag{15}$$

Substituting Eqs. (8), (9), (10) and (14) in (7), the energy cost becomes

$$
\begin{aligned}
J &= \underbrace{\frac{d_{12i}v_{1m}^3}{v_{2m}-v_{1m}}+\frac{d_{12i}v_{2m}^3}{v_{2m}-v_{1m}}}_{\text{Merge}}+\\
&\underbrace{+v_p^2\left(d_f-\frac{d_{12i}\,v_{1m}}{v_{2m}-v_{1m}}-\frac{\left(1-\frac{v_{2n}}{v_{1n}}\right)d_f\,v_{2s}}{v_{1s}-v_{2s}}-\frac{d_{12i}\,v_{2s}}{v_{1s}-v_{2s}}-\left(1-\frac{v_{2n}}{v_{1n}}\right)d_f-d_{12i}\right)\Phi_{12}+}_{\text{Platoon}}\\
&\underbrace{+\frac{\left(1-\frac{v_{2n}}{v_{1n}}\right)d_f v_{1s}^3}{v_{1s}-v_{2s}}+\frac{d_{12i}v_{1s}^3}{v_{1s}-v_{2s}}+\frac{\left(1-\frac{v_{2n}}{v_{1n}}\right)d_f v_{2s}^3}{v_{1s}-v_{2s}}+\frac{d_{12i}v_{2s}^3}{v_{1s}-v_{2s}}}_{\text{Split}}. \qquad (16)
\end{aligned}
$$

Dividing Eq. (16) by d_f and using equation (15) to eliminate v_p, the optimization problem is formulated as

$$
\begin{aligned}
\min_{v_{1m},v_{2m},v_{1s},v_{2s}} \quad & \underbrace{r_d\frac{v_{1m}^3}{\Delta v_m}+r_d\frac{v_{2m}^3}{\Delta v_m}}_{\text{Merge}}+\\
& \underbrace{+\frac{\left(1-r_d\frac{v_{1m}}{\Delta v_m}-r_v\frac{v_{2s}}{\Delta v_s}-r_d\frac{v_{2s}}{\Delta v_s}-r_v-r_d\right)^3}{\left(\frac{1}{v_{1n}}-\frac{r_d}{\Delta v_m}-\left(r_v\frac{v_{2s}}{\Delta v_s}+r_d\frac{v_{2s}}{\Delta v_s}+r_v+r_d\right)/v_{1s}\right)^2}\Phi_{12}+}_{\text{Platoon}}\\
& \underbrace{+r_v\frac{v_{1s}^3}{\Delta v_s}+r_d\frac{v_{1s}^3}{\Delta v_s}+r_v\frac{v_{2s}^3}{\Delta v_s}+r_d\frac{v_{2s}^3}{\Delta v_s}}_{\text{Split}} \qquad (17)
\end{aligned}
$$

$$
\text{s.t.} \quad 0 \le 1-r_d\frac{v_{1m}}{\Delta v_m}-r_v\frac{v_{2s}}{\Delta v_s}-r_d\frac{v_{2s}}{\Delta v_s}-r_v-r_d-r_p \qquad (18)
$$

$$
0 \le v_{2m}-v_{1m} \qquad (19)
$$

$$
0 \le v_{1s}-v_{2s} \qquad (20)
$$

$$
0 \le v_{max}-\frac{1-r_d\frac{v_{1m}}{\Delta v_m}-r_v\frac{v_{2s}}{\Delta v_s}-r_d\frac{v_{2s}}{\Delta v_s}-r_v-r_d}{\frac{1}{v_{1n}}-\frac{r_d}{\Delta v_m}-\left(r_v\frac{v_{2s}}{\Delta v_s}+r_d\frac{v_{2s}}{\Delta v_s}+r_v+r_d\right)/v_{1s}} \qquad (21)
$$

$$
0 \le -v_{min}+\frac{1-r_d\frac{v_{1m}}{\Delta v_m}-r_v\frac{v_{2s}}{\Delta v_s}-r_d\frac{v_{2s}}{\Delta v_s}-r_v-r_d}{\frac{1}{v_{1n}}-\frac{r_d}{\Delta v_m}-\left(r_v\frac{v_{2s}}{\Delta v_s}+r_d\frac{v_{2s}}{\Delta v_s}+r_v+r_d\right)/v_{1s}} \qquad (22)
$$

$$
v_{1m},v_{2m},v_{1s},v_{2s} \in [v_{min},v_{max}], \qquad (23)
$$

where $r_d=\frac{d_{12i}}{d_f}$ is the separation distance ratio, $r_v=\left(1-\frac{v_{2n}}{v_{1n}}\right)$ is the nominal velocity ratio, $r_p=\frac{d_{min}}{d_f}$ is the minimum platoon distance ratio, $\Delta v_m = v_{2m}-v_{1m}$ and $\Delta v_s = v_{1s}-v_{2s}$. Equation (15) is used to calculate the value of v_p a posteriori. Equation (18) impose the minimum platoon distance d_{min} based on the inequality $d_{min} \le d_p$. Equations (19) and (20) ensure the existence of the merging and splitting phases making $0 < d_m$ e $0 < d_s$ (See Eqs. (11) and (13)). Finally, constraints (21)-(23) guarantee that the coordination velocities are kept within the specified bounds, v_{min} and v_{max}. The remainder of this paper uses the *fmincon* function of the software *Matlab* to solve the problem formulated in Eqs. (17)-(23).

It can be demonstrated that for equal nominal velocities and neglecting the separation phase the optimization problem presented in this paper results in the problem formulated by Liang et al. (2016a). This is, the problem formulated by them is a special case of the more general approach presented here.

PRACTICAL EXAMPLE

To illustrate the potential of the proposed coordination strategy, a practical example is presented. Assume a 200 km highway stretch and two trucks initially separated by 15 km. The nominal velocities are v_{1n}=80 km/h and v_{2n}=80 km/h. This is, the two trucks intend to travel in parallel trajectories (See Fig. 1). The velocity bounds are set as v_{min}=40 km/h and v_{max}=100 km/h. During the platoon phase, the value of $\Phi_{12}=\Phi_1+\Phi_2$ is 1.7 indicating, for instance, that the first truck contributes with Φ_1=1 and the second truck with Φ_2=0.7. This drag reduction of 30% is a typical value experienced by the second truck when the inter-vehicle distance is approximately 20 m (Turri et al., 2017).

Figure 2 illustrates the velocity and position profiles of both trucks during the coordination maneuver provided by the optimization problem.

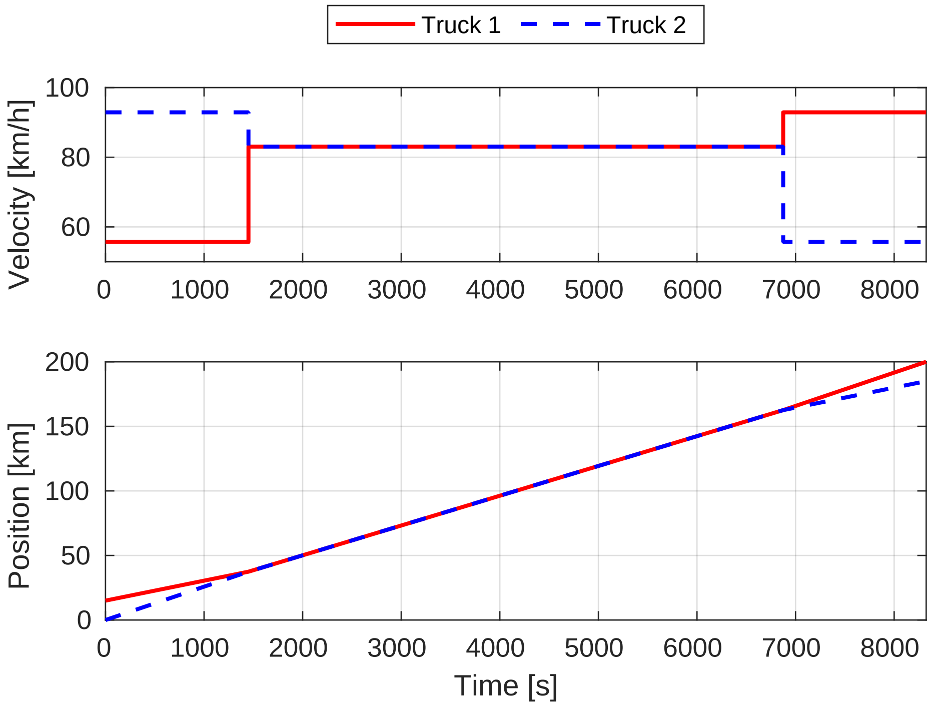

Figure 2 – Velocity (above) and position (below) profiles of a two-truck coordination maneuver on a 200 km highway stretch and 15 km initial separation distance.

During the merging phase, the first truck travels at v_{1m}=56 km/h and the second truck at v_{2m}=93 km/h. The platoon is formed at t_m=1450 s and the set of trucks travels with velocity v_p=83 km/h. The splitting phase starts at t_s=6875 s. During this last phase, the first truck travels at v_{1s}=93 km/h and the second truck at v_{2s}=56 km/h. Note that the velocity of the first truck during the merging phase is equal to the velocity of the second truck during the splitting phase and vice versa. The energy savings achieved in this particular example reached 4.9%.

SENSITIVITY ANALYSES

In order to improve the understanding of the coordination strategy proposed in this paper, the problem formulated in Eqs. (17)-(23) is solved for different values of the three main parameters that characterize the coordination scenario on a highway stretch: separation distance ratio r_d, nominal velocity ratio r_v and minimum platoon distance ratio r_p. As in the example above, the value of Φ_{12} is 1.7 for all the following analyses. The nominal velocities are v_{1n}=v_{2n}= 80 km/h and the velocity bounds are set large enough to avoid saturation.

Varying the separation distance ratio r_d

By varying the separation distance ratio, $r_d = \frac{d_{12i}}{d_f}$, of the coordination problem, the overall energy consumption and the optimal velocities can be verified in a normalized approach. In other words, the following analysis presents the effect of the ratio between the initial separation distance d_{12i} and the distance d_f on the normalized velocities and energy cost.

The nominal cost is calculated using the nominal velocities and is written as

$$J_{nom} = v_{1n}^2 d_f + v_{2n}^2 \left(d_{12i} + d_f - d_{12f}\right). \tag{24}$$

Substituting Eq. (14) in (24) and dividing the result by d_f, as done in the problem formulation, the considered nominal cost becomes

$$\frac{J_{nom}}{d_f} = v_{1n}^2 + v_{2n}^2 \frac{v_{2n}}{v_{1n}}. \tag{25}$$

Moreover, the minimum platoon ratio is $r_p = 0.01$ meaning that the trucks have to travel in a platoon through at least 1% of the distance d_f. In Fig. 3, the normalized velocities are presented. The velocities of the first and second trucks are normalized using v_{1n} and v_{2n}, respectively. The platoon velocity is normalized using the average velocity $v_{avg} = (v_{1n} + v_{2n})/2$. In this case, the optimization problem converge to velocities $v_{1m} = v_{2s}$ and $v_{2m} = v_{1s}$, in agreement with the practical example above.

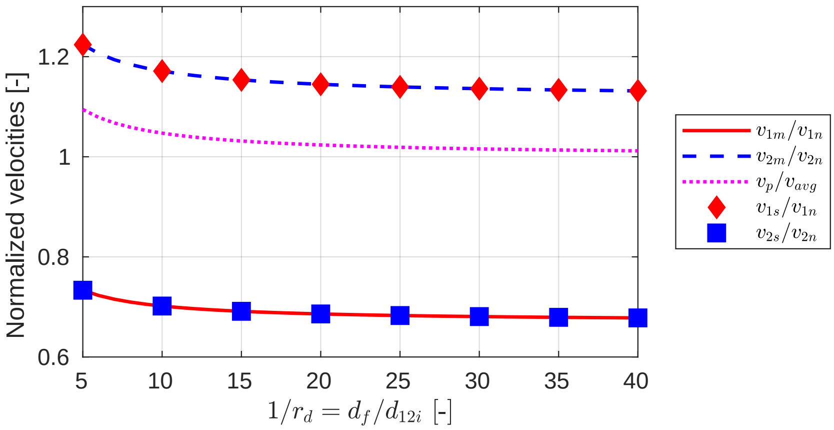

Figure 3 – Normalized velocities for different values of the separation distance ratio r_d. In this analysis, r_p=0.01 and $v_{1n} = v_{2n}$

It can be seen that the first truck has to increase speed and the second truck has to decrease speed during the merging phase since $v_{1m}/v_{1n} < 1$ and $v_{2m}/v_{2n} > 1$. Similarly, the dissolution of the platoon requires that the first truck speeds up and the second truck slows down. During the platoon phase both trucks travel faster than the nominal velocity for all values of the separation distance ratio. As $1/r_d$ decreases, the normalized velocities increase in order to meet the constraints of the optimization problem.

In Fig. 4, the normalized cost is shown. The calculated energy cost is normalized using Eq. (25). It can be seen that the platoon formation becomes beneficial when $d_f/d_{12f} > 8.5$. This is called the break-even ratio. Moreover, the energy savings exceed 10% for $d_f/d_{12f} > 25$.

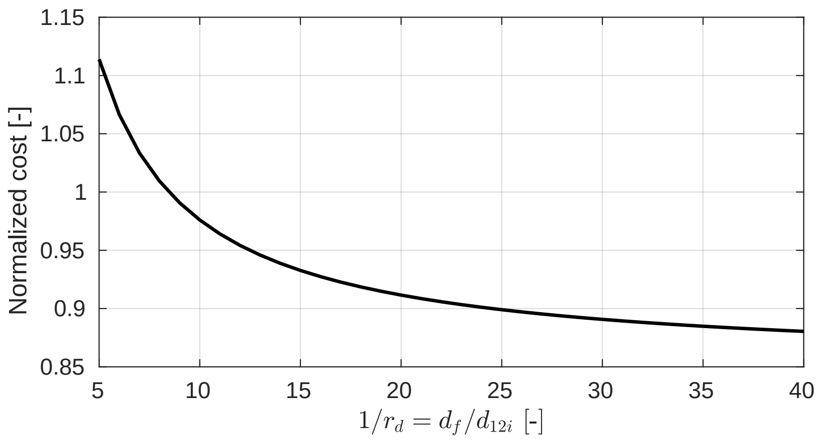

Figure 4 – Normalized cost for different values of the separation distance ratio r_d. In this analysis, r_p=0.01 and $v_{1n} = v_{2n}$

The curves obtained in this section differs from the ones obtained by Liang et al. (2016a) because of the different approach proposed in this paper. However, as expected, the general trend prevails. The nominal cost decreases monotonically as d_f increases for a given d_{12f} distance. This phenomenon occurs due to the possibility of the trucks to travel longer distances together to increase energy savings and overcome the cost associated to the formation and dissolution of the platoon.

Varying the nominal velocity ratio r_v

The effects of diverging nominal trajectories ($v_{1n} > v_{2n}$) on the normalized coordination velocities and cost are explored in this section.

In figure 5, the normalized velocities are shown for different values of $r_v = \left(1 - \frac{v_{2n}}{v_{1n}}\right)$. In this case, r_p=0.01 and d_f/d_{12i}=20. As the difference of the nominal velocities increases, the first truck moves slower during the merging and splitting phases. The opposite is expected for the second truck that has to move faster in both phases. Moreover, the platoon velocity also increases as the value of r_v increases.

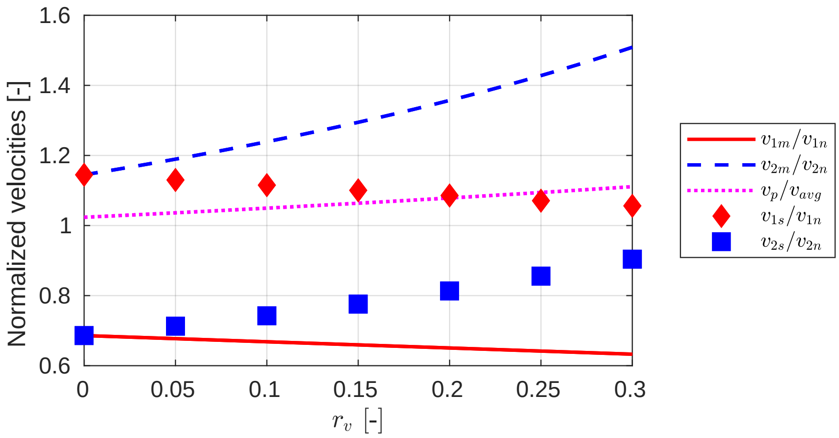

Figure 5 – Normalized velocities for different values of the nominal velocity ratio r_v. In this analysis, r_p=0.01 and $d_f/d_{12i} = 20$.

In figure 6, the normalized cost can be seen as a function of r_v for different values of d_f/d_{12i} indicating that platooning on a highway stretch can still be beneficial even when the trucks tend to move apart from one another. For a given value of d_f/d_{12i}, the normalized cost increases with the increase of the nominal velocity difference between the two trucks. In other words, for a more diverging maneuver, the cost to form the platoon increases. If the ratio d_f/d_{12i} is small, the break-even ratio is achieved for small values of r_v. As d_f/d_{12i} increases, the crossing of the break-even ratio occurs for higher values of r_v. Indeed, as the trucks have a longer distance to travel together, the cost of formation and dissolution can be better compensated during the platoon phase. Besides that, it can be seen that for $r_v = 0$ the normalized cost is equal to the values shown in Fig. 4, as expected.

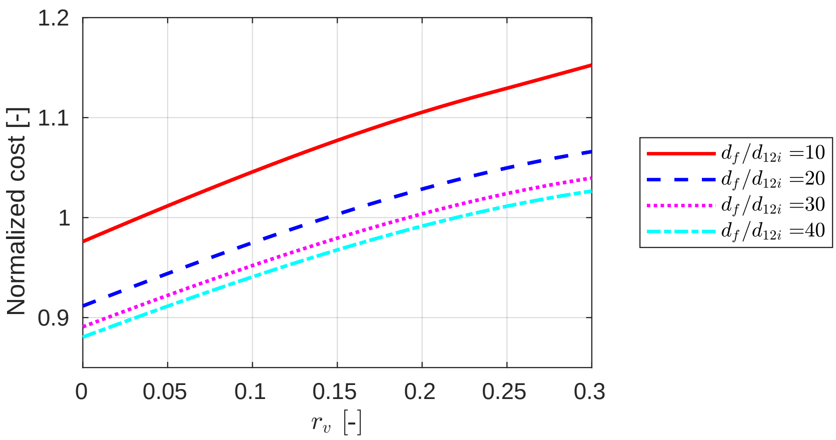

Figure 6 – Normalized cost for different values of the nominal velocity ratio r_v. In this analysis, r_p=0.01.

Varying the minimum platoon distance ratio r_p

Sometimes, it may be desired to impose a minimum platoon distance d_p. This way, the trucks travel longer distances in a more compact arrangement increasing the throughput of the highway. However, this strategy may increase the fuel consumption due to a higher effort necessary to meet the exit constraints from the highway stretch.

In Fig. 7, the normalized velocities are shown. It can be seen that the normalized velocities are constant up to a certain point where the trucks have to change their velocities more abruptly to achieve the desired maneuver. The range of r_p with constant normalized velocities generates optimal maneuvers with a longer platoon distance than that imposed by r_p. When $r_p > 0.6$ and for increasing values of r_p, the first truck during the merging phase and the second truck during the splitting phase have to decrease their velocity more sharply. For the same values of r_p, a small increase can be observed for the remaining normalized velocities.

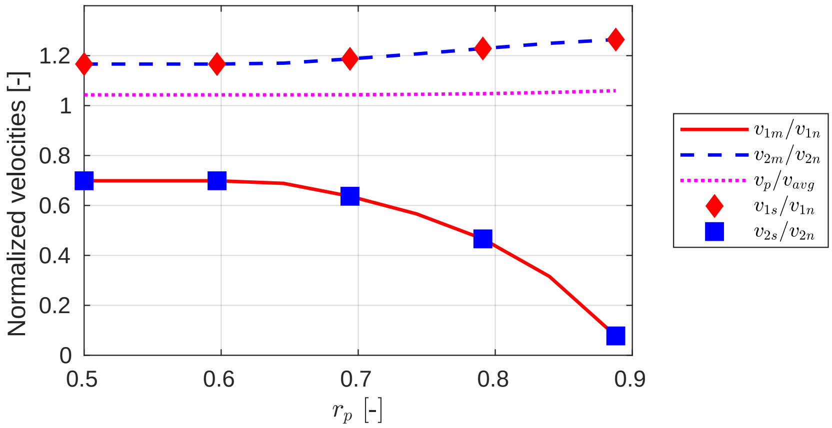

Figure 7 – Normalized velocities for different values of the minimum platoon distance ratio r_p. In this analysis, $v_{1n} = v_{2n}$ and $d_f/d_{12i} = 11$.

In figure 8, the normalized cost can be seen for different values of d_f/d_{12i}. For low values of r_p, the cost function is constant because the optimization problem converges to a longer platoon distance than that imposed by r_p. When the minimum platoon distance increases, the normalized cost also increases in order to meet the minimum platoon distance and the coordination constraints simultaneously. For values of d_f/d_{12i} equal to 9, 10 and 11, the break-even ratio is reached for r_p equal to 0.71, 0.81 and 0.87, respectively. For $d_f/d_{s1} \geq 12$, the break-even ratio is never reached because increasing r_p would make the problem infeasible.

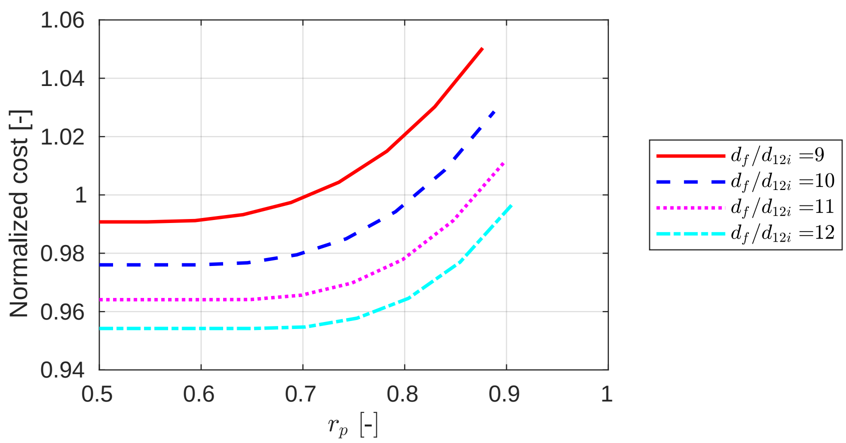

Figure 8 – Normalized cost for different values of the minimum platoon distance ratio r_p. In this analysis, $v_{1n} = v_{2n}$.

CONCLUSIONS

This paper presents an optimal coordination strategy to form and dissolve two-truck platoons on a highway stretch. The optimization problem is solved using an interior-point algorithm implemented through the *fmincon* function of the software *Matlab*. A practical example illustrates two trucks initially separated by 15 km on a 200 km highway stretch. In this case, the proposed coordination strategy generates a maneuver that requires 4.9% less energy than the non-coordinated maneuver. Moreover, sensitivity analyses are presented varying the three main coordination characteristics: initial separation distance, difference of both trucks desired velocity and minimum platooning distance. As the initial separation distance and desired velocity difference increases, a higher energy cost of the maneuver is expected. A longer platooning distance impose a trade-off between traffic density and fuel efficiency. This is, increased traffic throughput can be achieved at the cost of a higher energy consumption.

Future research should focus on the extension of the algorithm to coordinate 3 trucks simultaneously and on the evaluation of proposed methods through more realistic simulations considering, for instance, complex vehicle dynamics, longitudinal controllers and the road slope.

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