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Look-ahead speed planning for heavy-duty vehicle platoons using traffic information

Ingrid Johansson [a,*], Junchen Jin [a], Xiaoliang Ma [a], Henrik Pettersson [b]

[a]System Simulation & Control, Department of Transport Science, Teknikringen 10, SE-100 44 Stockholm, Sweden
[b]Scania CV AB, 151 87 Södertälje, Sweden

Abstract

Freight transport is a fast increasing transportation mode due to the economic growth in the world. Heavy-duty vehicles (HDV) have considerably greater fuel consumption, thus making them a suitable target when new policies in road transport emphasize increased energy efficiency and mitigated emission impacts. Intelligent transportation systems, based on emerging V2X communication technology, open new possibilities for developing fuel-efficient driving support functions considering real traffic information. This indicates a large potential of fuel saving and emission reduction for freight transport. This paper studies a dynamic programming-based optimal speed planning considering a maximum acceleration model for HDVs. The optimal speed control is applied for the deceleration case of HDV platoons due to received information on traffic speed reduction ahead. The control can optimize fuel consumption as well as travel time, and theoretical results for the two cases are presented. For maximal fuel saving, a microscopic traffic simulation study is performed for single HDVs and HDV platoons running in real traffic conditions. The results show a decrease in fuel consumption of more than 80% compared to simulations without applying optimal control, while the fuel consumption of other vehicles in the simulation is not significantly affected.

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1. Introduction

The demand for freight transport is continuing to grow, while at the same time fuel consumption and emissions need to decrease in order to counteract climate change and reduce the environmental impact. One way to tackle this challenge is to make use of emerging intelligent transportation systems (ITS) such as infrastructure-to-vehicle (I2V), vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication. V2V communication can be used to

* Corresponding author. Tel.: +46-8-790-84-99 ; fax: +46-8-790-84-61.
E-mail address: ingrid.johansson@abe.kth.se

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manage heavy-duty vehicle (HDV) platoons on highways. HDV platooning means to group HDVs together with small inter-vehicle distances in order to reduce air-drag resistance and, thereby, reduce the fuel consumption, stated e.g. by Turri (2015).

How to manage cruising HDV platoons is currently a hot research topic. However, highway traffic also suffers from occasional congestions where the speed is lowered, thus forcing the platoons to decelerate from their preferred cruising speed. Assuming an I2V communication system on highways, information about the traffic state ahead can be disseminated, as shown by Grumert et al. (2015). In that way, HDV platoons can be informed that in a given distance the speed has to be decelerated to a given value. Additionally, it is well-known that the driving style has a significant influence on the energy efficiency for HDVs. Studies on optimal speed control with an objective of minimizing fuel consumption have been proposed since the 1980s, e.g. by Hooker et al. (1983). It is still a hot research topic due to the development of in-vehicle systems as well as ITS techniques. However, there is still a lack of studies on the effects on the other vehicles when HDVs or HDV platoons apply the optimal speed control strategies. This study applies an optimal control to decide the optimal deceleration trajectory with respect to fuel consumption as well as travel time. The effects are compared to the case with no applied optimal speed control and the effect on other vehicles is studied.

Traffic simulation is a widely applied tool for evaluation purposes in traffic management and operation practice. Among different classes of traffic simulation models, microscopic simulation models describe the traffic system at the vehicle level capable of modeling vehicle-vehicle and vehicle-road interactions within a traffic stream. Therefore, microscopic traffic simulation is an appropriate evaluation tool for research topics on V2V and V2I applications.

The remainder of the paper is structured as follows. Section 2 introduces the HDV models, optimal speed control strategies and HDV platoon modelling as well as the simulation framework applied for evaluation. Section 3 presents the simulation-based case study and discusses the results in the aspects of both HDVs and passenger cars. Section 4 closes the paper with conclusions and suggestions for future work.

2. Methodology

2.1. Maximum acceleration for an HDV

The acceleration capacity for an HDV is limited by its maximum acceleration and maximum deceleration. This study uses a constant value for the maximum deceleration, while the maximum acceleration is heavily dependent on the speed. Therefore, we model it by basic physical properties of HDVs.

Let M_i denote HDV mass, $m_{e,i}$ engine inertial mass, $m_{w,i}$ wheel inertial mass and $a_i(t)$ the acceleration for HDV i, where t denotes time. The forces acting on HDV i are the tractive force $F_{t,i}(t)$ produced by the engine, the braking force $F_{b,i}(t)$, the aerodynamic force function $F_{a,i}(t)$ depending on the HDV speed $v_i(t)$ and relative distance $d_i(t)$, the rolling resistance force $F_{r,i}(t)$ and finally the gravitational force $F_{g,i}(t)$. Newton's second law for HDV i is then

$$(M_i + m_{e,i} + m_{w,i})a_i(t) = F_{t,i}(t) - F_{b,i}(t) - F_{a,i}(t) - F_{r,i}(t) - F_{g,i}(t). \tag{1}$$

The air drag force, adapted from Alam (2014), is modelled by

$$F_{a,i}(t) = \frac{1}{2}\rho_a C_a A_i (1 - \psi(d_i(t)))v_i^2(t) \tag{2}$$

with

$$d_i(t) = \begin{cases} s_i(t) & \text{if } i > 0 \\ s_1(t) & \text{if } i = 0, \end{cases} \tag{3}$$

where ρ_a is air density and C_a denotes the air drag coefficient. Furthermore, A_i is the HDV frontal area, $v_i(t)$ is HDV speed and $\psi(d_i(t))$ is the air-drag reduction rate with respect to the relative distance $d_i(t)$, all for HDV i. Relative distance here means the inter-vehicle distance $s_i(t)$ in front of HDV i, except for the platoon leader, where it means the distance $s_1(t)$ to the HDV behind it. Some function values used for $\psi(d_i(t))$ were obtained from Hucho and Sovran (1993) with the missing values estimated by linear interpolation. The respective models of maximum tractive force, rolling resistance force and gravitational force used in this study are referred to Rakha et al. (2001), with

$$F_{t,i}^{max}(t) = \min(\eta_i \frac{P_i}{v_i(t)},\ M_{t,i} g \mu_i), \tag{4}$$

$$F_{r,i}(t) = C_{r,i} M_i g \cos\theta_i(t) \quad \text{and} \tag{5}$$

$$F_{g,i}(t) = M_i g \sin\theta_i(t), \tag{6}$$

where η_i and P_i are the transmission efficiency and the engine power and $M_{t,i}$ and μ_i are vehicle mass on tractive axle and the coefficient of friction between tires and pavement, respectively. $C_{r,i}$ denotes the rolling resistance coefficient, g is the standard acceleration rate due to gravity and θ_i is road grade, all for HDV i. With the braking force in Eq. 1 being zero, the maximum acceleration $a_i^{max}(t)$ of HDV i can be calculated as a function of current speed by

$$a_i^{max}(t) = \frac{F_{t,i}^{max}(t) - F_{a,i}(t) - F_{r,i}(t) - F_{g,i}(t)}{M_i + m_{e,i} + m_{w,i}}. \tag{7}$$

Note that the large mass of an HDV constrains $a_i^{max}(t)$ to small values, especially at high speeds.

2.2. Optimal speed control

The problem of determining a speed trajectory that is optimal in some aspect can be formulated mathematically as an optimal control problem and solved by discrete dynamic programming. This study has implemented an adapted version of the optimal control presented by Ma (2013).

2.2.1. General problem formulation

Consider a general formulation of a continuous time optimal control problem

$$\min_{\mathbf{u}(t)\in U} \phi(\mathbf{x}(T)) + \int_0^T f_0(t,\mathbf{x}(t),\mathbf{u}(t))\, dt \tag{8}$$

subject to the constraints

$$\begin{cases} \dot{\mathbf{x}}(t) = \mathbf{f}(t,\mathbf{x}(t),\mathbf{u}(t)) \\ \mathbf{x}(0) = \mathbf{x}_0 \\ \mathbf{x}(T) = \mathbf{x}_T \\ \mathbf{u}(t) \in U(t,\mathbf{x}(t)), \quad t \in [0,T], \end{cases} \tag{9}$$

where $\mathbf{x}(t)$ is the state of the controlled system, $\mathbf{u}(t)$ is the control input belonging to the control set $U(t,\mathbf{x}(t))$, $\phi(\mathbf{x}(T))$ denotes the final cost at final time T and $f_0(t,\mathbf{x}(t),\mathbf{u}(t))$ is the additive cost. $\mathbf{f}(t,\mathbf{x}(t),\mathbf{u}(t)$ is the system dynamics and the initial and final states of the system are given as $\mathbf{x}_0$ and $\mathbf{x}_T$, respectively. The total time T of the control is here free. Let $\mathbf{u}(\cdot)$ denote an admissible control and define the optimal cost-to-go function

$$J(t_k,\mathbf{x}_k,\mathbf{u}(\cdot)) = \phi(\mathbf{x}(T)) + \int_{t_k}^T f_0(t,\mathbf{x}(t),\mathbf{u}(t))\, dt \tag{10}$$

denoting the cost from some starting point $t_k \in [0,T]$. Basically, we want to find an optimal control $\mathbf{u}^*(\cdot)$ minimizing the cost-to-go function. Thus, the optimal cost can be defined as

$$J^*(t_k,\mathbf{x}_k) = \min_{\mathbf{u}(\cdot)\in U} J(t_k,\mathbf{x}_k,\mathbf{u}(\cdot)) = J(t_k,\mathbf{x}_k,\mathbf{u}^*(\cdot)), \tag{11}$$

and the total optimal cost from time 0 is analogously $J^*(0,\mathbf{x}_0)$.

2.2.2. Optimal speed trajectory control

For the application of HDV trajectory control, the state can be represented as the vector

$$\mathbf{x}_i(t) = [l_i(t) \;\; v_i(t)]' \tag{12}$$

with the control

$$u_i(t) = a_i(t), \tag{13}$$

where $l_i(t)$, $v_i(t)$ and $a_i(t)$ denote the travelled distance, the speed and the acceleration at time t, respectively, and $'$ denotes transpose. The objective is to minimize the total fuel consumption between the given states $\mathbf{x}_0$ and $\mathbf{x}_T$. The total travel time T is also optimized, since it is a free variable, and we define the additive cost function as

$$f_0(t,\mathbf{x}_i(t),u_i(t)) = \sigma c(\mathbf{x}_i(t),a_i(t)) + \lambda, \tag{14}$$

where $c(\mathbf{x}_i(t),a_i(t))$ denotes the instantaneous fuel consumption and σ and λ are positive weights for fuel consumption and travel time, respectively. Moreover, we note that no final cost is added at time T and that the control $a_i(t)$ will be constrained by the acceleration capacity of the vehicle. Equivalents to Eq. (8) and (9) can now be formulated as

$$\min_{a_i(t)\in U} \int_0^T (\sigma c(\mathbf{x}_i(t),a_i(t)) + \lambda)\, dt \tag{15}$$

subject to the constraints

$$\begin{cases} \dot{\mathbf{x}}_i(t) = [v_i(t) \;\; a_i(t)]' \\ \mathbf{x}_i(0) = \mathbf{x}_{i,0} = [0 \;\; v_i^{start}]' \\ \mathbf{x}_i(T) = \mathbf{x}_{i,T} = [D \;\; v_i^{final}]' \\ a_i(t) \in [a_i^{min},\, a_i^{max}(t)], \quad t \in [0,T], \end{cases} \tag{16}$$

where the given start and final distances are 0 and D and start and final speeds for HDV i are v_i^{start} and v_i^{final}, respectively. The acceleration is bounded between the maximum deceleration a_i^{min} and the maximum acceleration $a_i^{max}(t)$, which depends on the time.

2.2.3. Solution method

The problem presented in Section 2.2.2 was discretized and solved by backwards dynamic programming recursion. Since the total distance of the control was known, while the time was unknown, a space discretization of N steps with step size Δs was used. This simplified the state to $x_n = v_n$ and, consequently,

$$x_{i,n+1} = x_{i,n} + u_{i,n}, \tag{17}$$

$$u_{i,n} = \Delta v_{i,n}, \tag{18}$$

$$a_{i,n} = \frac{(v_{i,n}+\Delta v_{i,n})^2 - v_{i,n}^2}{2\Delta s_i} \quad \text{and} \tag{19}$$

$$\Delta t_{i,n} = \frac{\Delta v_{i,n}}{a_{i,n}}. \tag{20}$$

Here, $\Delta v_{i,n}$ and $\Delta t_{i,n}$, respectively, denote the variable speed difference and time difference for a given Δs_i and the other notation is equivalent to the continuous case. Accordingly, the backward dynamic programming recursion was

$$J(n,x_{i,n}) = \min_{a_{i,n}\in U} \{(\sigma c(x_{i,n},a_{i,n}) + \lambda)\Delta t_{i,n} + J(n+1,x_{i,n+1})\}, \tag{21}$$

where

$$J(n,x_{i,n}) = \sum_{n=0}^{N-1} (\sigma c(x_{i,n},a_{i,n}) + \lambda)\Delta t_{i,n}, \quad n = N-1,\ldots,0. \tag{22}$$

2.3. Fuel consumption model

A thermal engine based fuel consumption model, originally proposed by Oguchi and Katakura (2000) is applied for fuel analysis for HDVs and it is integrated with vehicle mechanical properties in this study. The fuel model computes fuel usage based on thermal efficiency, mechanical efficiency on friction resistance as well as vehicle kinetics. The instantaneous fuel consumption model in Eq. 21 can be summarized as

$$c(x_{i,n},a_{i,n}) = \begin{cases} c_i^{idle} + \frac{x_{i,n}}{\eta_i \varepsilon_i H} F_{t,i}(t_{i,n}) & \text{if } F_{t,i}(t_{i,n}) > 0, \\ c_i^{idle} & \text{otherwise,} \end{cases} \tag{23}$$

with the tractive force

$$F_{t,i}(t_{i,n}) = a_{i,n}(M_i + m_{e,i} + m_{w,i}) + F_{a,i}(x_{i,n}, t_{i,n}) + F_{r,i}(t_{i,n}) + F_{g,i}(t_{i,n}) \tag{24}$$

and the current time $t_{i,n}$ as

$$t_{i,n} = \sum_{k=0}^{n} \Delta t_{i,n}. \tag{25}$$

Furthermore, c_i^{idle} denotes the base energy consumption when HDV i is idling, ε_i denotes the thermal efficiency of the engine, H is the heat equivalence of the diesel fuel and η_i denotes the power transmission efficiency.

2.4. HDV platoon modelling

The HDV platoon was modelled with two different operational modes: a following mode and a hard-braking mode. The decision on which mode to use depends on the emergency distance gap between the vehicles in the platoon, defined as

$$s_e(t) = s_i(t) - v_i(t)\tau_i + \frac{v_i^2(t)}{2a_i^{min}} - \frac{v_{i-1}^2(t)}{2a_{i-1}^{min}} - s_i^{min}, \tag{26}$$

where $s_i(t)$, $v_i(t)$, a_i^{min} and τ_i denote, respectively, the inter-vehicle distance from the front bumper to the preceding vehicle's rear bumper, the speed, the maximum deceleration and the communication delay, all for HDV i. s_i^{min} denotes a pre-defined minimum gap when vehicle i stands still and $v_{i-1}(t)$ and a_{i-1}^{min} are the speed and the maximum deceleration of the preceding HDV $i-1$, respectively. If s_e is negative, the hard-braking mode with maximum deceleration is applied until a safe gap is achieved. If s_e is positive, the following mode is applied, operated by a modified version of the cooperative adaptive cruise control (CACC) by Arem et al. (2006). In this modified CACC version, the acceleration output is based on the speed difference $v_{i-1}(t) - v_i(t)$ between HDV $i-1$ and its following HDV i, the difference $s_i(t) - s_{d,i}(t)$ between actual distance gap s_i behind HDV i and the desired distance gap $s_{d,i}$ and the instantaneous acceleration $a_{i-1}(t)$ of the preceding HDV as

$$a_i^{CACC}(t) = k_a a_{i-1}(t) + k_v(v_{i-1}(t) - v_i(t)) + k_s(s_i(t) - s_{d,i}(t)), \tag{27}$$

where a_i^{CACC} denotes the acceleration for HDV i given by the CACC and k_a, k_v and k_s are constant feedback gains for the instantaneous acceleration, the speed difference and the distance gap difference, respectively, with values retrieved from Arem et al. (2006).

The function of desired distance gap is called a spacing policy, and can be decided in different ways. In this study, the widely applied spacing policy of constant time gap is used, expressing the desired distance gap as

$$s_{d,i}(t) = v_i(t)t_{d,i} + s_i^{min}, \tag{28}$$

with $s_{d,i}(t)$, $v_i(t)$ and s_i^{min} as previously defined and $t_{d,i}$ denoting the desired constant time gap for HDV i, defined as the time between the front bumper of HDV i and the rear bumper of the preceding HDV $i-1$ pass a fixed reference point using the current speed of HDV i. With a constant time gap, the distance gap is proportional to the speed.

2.5. Simulation framework

For the simulation evaluation of the proposed method, a software platform simulating HDV platooning has been developed and connected to version 0.19.0 of the open-source microscopic traffic simulator SUMO, proposed by Krajzewicz et al. (2012), where SUMO is used to create the simulation environment and other traffic. A car following model defines the speed of the following vehicle in relation to the vehicle ahead. The model proposed by Krauss et al. (1997), mainly based on safe speed, is applied to determine the instantaneous speed in the SUMO simulation. The speed $v_m(t+\Delta t)$ of the individual vehicle m for a time step Δt, is given by

$$v_m(t+\Delta t) = \max(0,\ v_m^{des}(t) - a_m(t)\Delta t), \tag{29}$$

with $v_m^{des}(t)$ denoting desired speed and $a_m(t)$ is a driver imperfection, modeled as a stochastic deceleration

$$a_m(t) = r \cdot a_m^{max} \cdot \zeta, \tag{30}$$

where r is a random number generated from a uniform distribution between 0 and 1, $\zeta \in [0,1]$ is an input parameter depending on the degree of imperfection and a_m^{max} is the maximum acceleration for vehicle m. The safe speed $v_m^{safe}(t)$ is defined as

$$v_m^{safe}(t) = v_m^l(t) + \frac{s_m(t) - v_m^l(t)\tau_m}{\frac{v_m(t)+v_m^l(t)}{2a_m^{min}} + \tau_m}, \tag{31}$$

where $v_m^l(t)$ is the speed of the leading vehicle ahead of vehicle m, $s_m(t)$ is the gap between vehicle m and its leader, τ_m is the reaction time of the driver in vehicle m, and a_m^{min} is the maximum deceleration of vehicle m. The desired speed $v_m^{des}(t)$ for vehicle m at each time t is calculated as the smallest value among the maximum speed, the speed using the vehicle's maximum acceleration ability, and the safe speed, i.e.

$$v_m^{des}(t) = \min(v_m^{max},\ v_m(t) + a_m^{max} \cdot \Delta t,\ v_m^{safe}(t)), \tag{32}$$

where v_m^{max} refers to the maximum speed of vehicle m, a_m^{max} is the maximum acceleration of vehicle m and Δt is the time step for each speed update. The parameters of the built-in driving behaviour model in SUMO are calibrated with empirical data from Swedish highways.

During simulations, the platooning platform exchanges data with SUMO by calling the Traffic Control Interface (TraCI). At each simulation step, vehicles are generated and inserted into the simulation network. Thereafter, the platooning platform calls TraCI to perform a one-step simulation in SUMO and send HDV data, such as instantaneous speed and position, back to the platooning platform. There, the CACC, or, when applied, the optimal control, updates the instantaneous HDV acceleration with the data and, accordingly, the HDV states in SUMO are overwritten by TraCI for the next simulation step. Meanwhile, all vehicle trajectories are recorded for evaluation purposes. The communication process is repeated until the pre-defined simulation period is finished.

3. Case study

3.1. Simulation test case

The simulation evaluation was performed on a 2 km long flat stretch of a two-lane highway without any curves, on-ramps or off-ramps. The simulation ran for 35 minutes, where the first 5 minutes were a loading period excluded from the results. The platoons were constituted by two HDVs with a constant time gap of 1 s and they were created before insertion into the simulation. The V2V communication delay within the platoons were considered to be zero. The speed limit at the start of the simulation was set to 90 km/h for HDVs and 120 km/h for passenger vehicles. At 1500 m, the speed limit changed to 60 km/h for all vehicles to illustrate the maximum speed of a congestion, which remained for the rest of the simulation. When the platoon leaders entered the communication range of 1000 m ahead of the congestion, they were informed about it and their current position in the simulation was extracted as starting point for the optimal control to determine the best trajectory. The simulation was performed with a traffic flow, measured in passenger car equivalents (PCE), of 1000 PCE/lane/h. One HDV is 3.5 PCE, and 10% of the simulated vehicles were HDVs, all driving in the right-most lane. An illustration of the simulation road segment is shown in Figure 1. The parameters used for HDV modelling are shown in Table 1 and they are based on a DC1307 480 hp EU5 diesel engine. For comparison, simulations without applying optimal control were performed, in which case SUMO controls the adjustment to the congestion speed limit. For both cases, fuel consumption for the passenger cars was also calculated by using the Comprehensive Modal Emissions Model (CMEM) by Barth et al. (2000).

3.2. Optimal speed control results

Using the test data described in Section 3.1, the optimal speed control was first evaluated theoretically for single HDVs with some different values of λ and σ. The results are presented in Table 2 and it is noteworthy that an

Table 1. Vehicle parameters.

Parameter	Description	Value	Unit
M	Vehicle mass	40,000	kg
g	Standard acceleration due to gravity	9.80665	m/s^2
ρ_a	Air density	1.29	kg/m^3
A	Frontal area	10.26	m^2
C_a	Air drag coefficient	0.56	–
C_r	Rolling resistance coefficient	1.50×10^{-3}	–
θ	Road grade	0	rad
η	Power transmission efficiency	0.94	–
P	Engine power	$358,000$	W
M_t	Mass on tractive axle	$11,000$	kg
μ	Coefficient of friction between tires and pavement	0.6	–
c^{idle}	Base fuel consumption	0.59×10^{-3}	kg/s
ε	Thermal efficiency of engine	0.44	–
H	Heat equivalence of diesel	44.8×10^6	J/kg
m_e	Engine inertial mass	0	kg
m_w	Wheel inertial mass	0	kg
a^{min}	Maximum deceleration for HDVs	-5	m/s^2

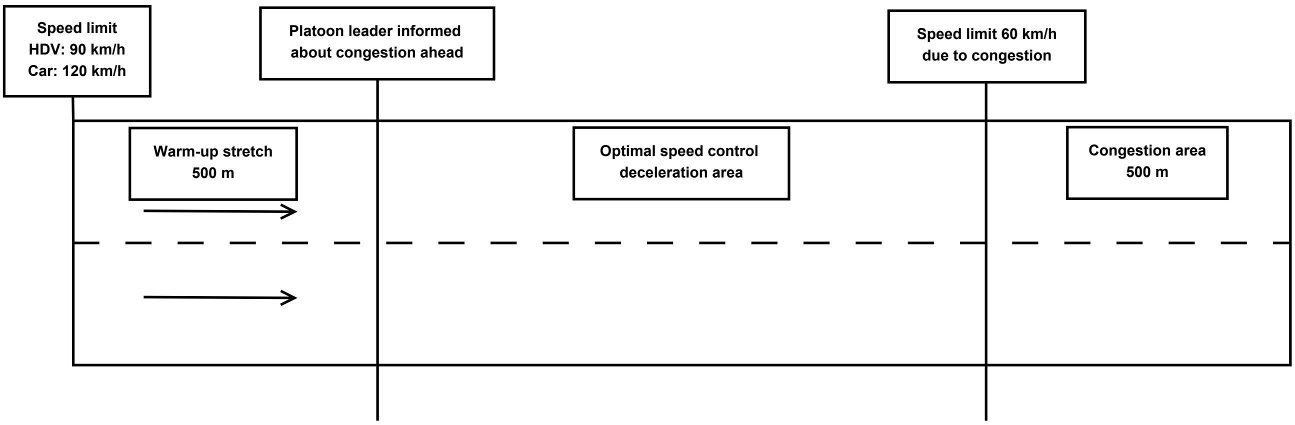

Figure 1. Illustration of the traffic simulation road segment.

optimization of fuel consumption gave a value more than 6 times lower compared to optimizing travel time, while the travel time increased only around 11%. For the cases optimizing a total monetary cost, the driver's wage and the cost for arriving late are from Zhang et al. (2016), converted from GBP to SEK. Both the exchange rate and the diesel price in SEK used for σ are from April 2016. The total fuel consumption and travel time in those cases did not differ from the fuel optimization case. The case of using a constant deceleration was also tested for comparison and rendered the longest travel time and a fuel consumption slightly higher than the fuel-optimized case. Figure 2 presents the theoretical speed trajectories for an HDV which is minimizing fuel consumption, travel time or using constant deceleration from 90 km/h to 60 km/h in 1000 m.

In conclusion, optimization solely with respect to fuel consumption was judged as the overall most efficient and, therefore, chosen to be evaluated by traffic simulation.

3.3. Simulation results

The simulation results are compiled from 10 runs of the test case described in Section 3.1 with the optimal control applied, and 10 runs without it. The average fuel consumption results for both cases are shown in Table 3. The fuel consumption for a single platoon-leading HDV is 0.2 kg/km, which is higher than the theoretical result of 0.17 kg/km for travel time optimization. When optimal control is applied, the fuel consumption drops to 0.031 kg/km, not far

Table 2. Theoretical results for applying optimal speed control.

Test case	σ	λ	Total fuel consumption [kg/km]	Total travel time [s]
Optimize total travel time	0	1	0.1743	40.2832
Optimize total fuel consumption	1	0	0.0264	44.7099
Optimize cost by the cost for arriving late and diesel price	13.988	0.17	0.0264	44.7099
Optimize cost by driver's wage and diesel price	13.988	0.03	0.0264	44.7099
Constant deceleration	-	-	0.0283	47.9962

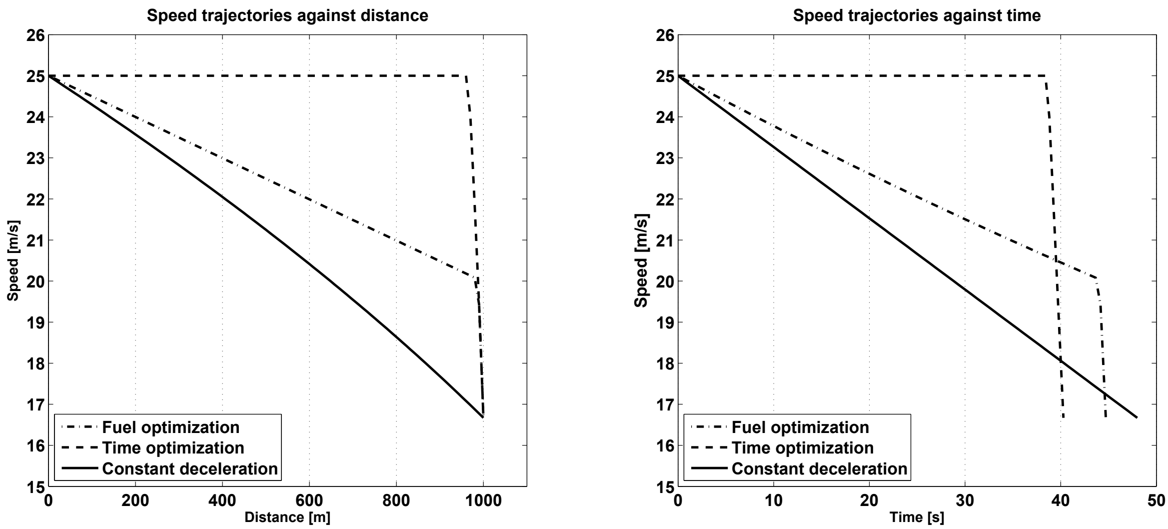

Figure 2. Theoretical speed trajectories for an HDV minimizing fuel consumption, travel time or using constant deceleration from 90 km/h to 60 km/h in 1000 m.

from the theoretical value of 0.026 kg/km, implying a decrease of 84% compared to the case of no optimal control. Similarly, the fuel consumption for whole platoons drop from 0.3477 kg/km to 0.0668 kg/km when optimal control is applied, a decrease of 81%. For both leading HDVs and whole platoons, the average standard deviation decreases when optimal control is applied. This is natural due to the increased conformity of the HDV driving behaviour. When calculating the average fuel consumption for a platoon, the platoon is considered as one object and, therefore, the average driven distance of the leader and the follower is used. This means that the fuel consumption for the platoon follower cannot be retrieved directly from the data in Table 3.

The fuel consumption for passenger cars does not change significantly, indicating that applying optimal speed control for HDV platoons does not affect surrounding passenger cars in a way that increases their fuel consumption in the scenarios.

Table 3. Average fuel consumption with and without optimal control applied.

Vehicles	Optimal control applied?	Mean total fuel consumption [kg/km]	Mean standard deviation
Leading HDVs	No	0.2007	0.0543
Leading HDVs	Yes	0.0313	0.0274
HDV platoons	No	0.3477	0.1086
HDV platoons	Yes	0.0668	0.0836
Passenger cars	No	0.0555	0.0178
Passenger cars	Yes	0.0541	0.0164

4. Conclusions and future work

In this paper, we have proposed an optimal speed control to determine the optimal speed trajectory for HDVs during deceleration, assuming the existence of an ITS using I2V communication to inform the platoon leader about future speed limitations. The control has been evaluated by microscopic traffic simulation with respect to optimization of fuel consumption and showed a decrease of 84% for platoon-leading HDVs and 81% for platoons, compared to simulations without optimal control. Simultaneously, the fuel consumption of surrounding traffic, in the simulation represented by passenger cars, was not affected by the application of optimal speed control for the HDV platoons.

These results are promising regarding fuel savings for HDV platoons as well as single HDVs. While the study investigates the potential effects of applying look-ahead traffic information, more work remains before the results can be used in practical applications. Technically, the dynamic programming recursion used to calculate the optimal trajectories is computationally costly. More efforts are required for improving the control method before real-time performance is achieved. In addition, the HDV platoon model in our study uses a simple cruise control and parameters from literature. A natural extension of the study is to incorporate a more detailed platoon control model. For example, CACC controllers with platoon stability investigated have already been proposed.

The current simulation scenarios only consider a deceleration case. To verify the practical usefulness of the control, more simulation studies are needed for real motorway cases where look-ahead traffic information is available. This also provides us with an opportunity to evaluate the effects of HDV platoons on other traffic in a comprehensive way.

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