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Road inclinations and emissions in platoon control via multi-criteria optimization

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***Abstract*— A well-organized platoon control may have advantages in terms of increasing highway capacity and decreasing fuel consumption and emissions. The paper proposes the design of the velocity of platoon. In the velocity design several factors must be taken into consideration such as fuel consumption, road inclinations, emissions and traveling time. Since the vehicles in a heterogenous platoon have different dynamic abilities, emission parameters, and fuel characteristics, the design task leads to a multi-criteria optimization problem. The design of the platoon control is based on the robust $\mathcal{H}_\infty$ control method. The method is illustrated through simulation examples.**

I. INTRODUCTION AND MOTIVATION

Several projects on platoon research have been supported by the European Union, see [1], [2], [3]. According to the principle of the platoon, the first vehicle is driven by a professional driver, while the following vehicles are under automated longitudinal and lateral control and these drivers are able to undertake other tasks. A well-organized platoon control may have advantages in terms of increasing highway capacity and decreasing fuel consumption and emissions. Since the safe and economical motion of the platoon is determined by the leader vehicle, it is crucial for the leader vehicle to use this piece of information during the journey.

The control design is based on external factors such as traffic situations (traffic jam), terrain characteristics (straight, road slopes), road types (highway, secondary road), speed limits. It is also based on different internal factors such as the dynamic abilities of vehicles in the platoon, their emission properties, fuel characteristics or reliability.

In a Hungarian project an automated vehicle platoon of heavy vehicles was developed. The goal of the project was to analyze the control algorithms and synthesize the experimental results, see [4].

The paper focuses on the design of the velocity of a platoon based on fuel consumption, road slopes, emissions and traveling time. The aim of the design is to achieve a balance between them by using a multi-criteria optimization method. Based on these factors each vehicle in the platoon is able to calculate its velocity independently of the other vehicles. Since traveling in a platoon requires the same velocity, the optimal velocity must be modified according to the other vehicles. In the platoon, the velocity of the leader vehicle determines the velocity of the following ones. The goal is to determine the velocity at which the members of the platoon travel as close to their own optimal velocity as possible.

The structure of the paper is the following. Section II presents the relationship between the velocity and road inclinations. Two design factors, i.e., the longitudinal control force and the traveling time, are also introduced. Section III presents emission models of commercial vehicles and the relationships between emission and road inclinations. Section IV discusses the multi-criteria optimization method. Section V presents the robust control of the platoon velocity. Section VI shows the operation of the platoon through simulation examples. Finally, Section VII contains some concluding remarks.

II. MODELING OF LONGITUDINAL FORCE AS A FUNCTION OF ROAD INCLINATIONS

A. Relation between the velocity and road inclinations

Several methods in which fuel consumption, travelling time and emissions are taken into consideration have already been proposed, see [5], [6]. The look-ahead control methods assume that information about the future disturbances to the controlled system is available. Finding a compromise solution between various performances leads to an optimization problem, see e.g. [7], [8], [9].

The relationship between the optimal velocity and the road inclinations was a topic of an earlier paper. Thus, the thoughts are only briefly summarized. The results in a detailed form are found in [10].

The route of the vehicle can be divided into n sections using $n+1$ number of points as Figure 1 shows. An important enhancement of this paper on [10] is that the division of the route is not necessarily of equal length. The rates of the inclinations of the road and those of the speed limits are assumed to be known at the endpoints of each section. The acceleration of the vehicle is considered to be constant between section points.

The velocity of the vehicle at the final point of a section $\dot{\xi}_j$ is expressed by using the velocity at the starting point $\dot{\xi}_i$, the acceleration and the driven distance s_j:

$$\dot{\xi}_j^2 = \dot{\xi}_i^2 + 2\ddot{\xi} s_j = \dot{\xi}_i^2 + \frac{2 s_j}{m}(F_{lj} - F_{dj}), \qquad (1)$$

where F_{lj} is the longitudinal force as the control signal and F_{dj} is the disturbance. The velocity at section point j should reach a predefined reference velocity $v_{ref,j}^2$ $j \in [1, n]$, which

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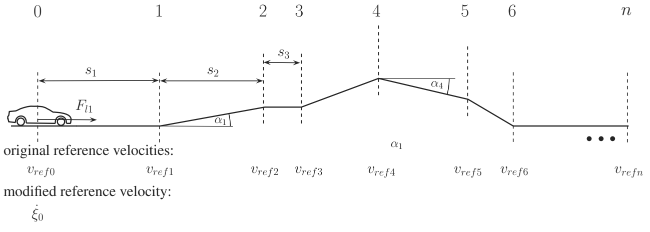


Fig. 1. Division of predicted road

is usually the maximum velocity of the vehicle (speed limit). Velocities of vehicle are described at each section point of the road. It is important to emphasize that the longitudinal force F_{lj} affects only the first section, and it does not affect the following sections. During the calculation of the control force it is assumed that additional longitudinal forces will not act on the vehicle. It is also an important goal to track the momentary value of the velocity, which is formalized in the following form: $\dot{\xi}_0^2 \rightarrow v_{ref,0}^2$.

The F_{di} disturbance force can be divided in two parts: the first part is the force resistance from road slope $F_{di,r}$, while the second part $F_{di,o}$ contains all the other resistances such as rolling resistance, aerodynamic forces etc. We assume that $F_{di,r} = mg\sin\alpha_i$ is known while $F_{di,o}$ is unknown.

In the next step a weight Q is applied to the momentary (initial) velocity and weights $\gamma_1, \gamma_2, ..., \gamma_n$ are applied to the reference velocities. The weights should sum up to one, i.e., $\gamma_1 + \gamma_2 + ... + \gamma_n + Q = 1$. While the weights γ_i represent the rate of the road conditions, weight Q determines the tracking requirement of the momentary reference velocity $v_{ref,0}$. Applying the expression of $\dot{\xi}_i$ for each section, and summarizing by i yields the following formula:

$$\dot{\xi}_0^2 + \frac{2s_1}{m}(1-Q)F_{l1} - \frac{2s_1}{m}(1-Q)F_{d1,o} = \vartheta \tag{2}$$

where the value ϑ depends on the predicted road slopes, the reference velocities and the prediction weights:

$$\vartheta = Qv_{ref,0}^2 + \sum_{i=1}^{n}\gamma_i v_{ref,i}^2 + \frac{2}{m}(1-Q)\sum_{i=1}^{n} s_i F_{di,r} \sum_{j=i}^{n}\gamma_j. \tag{3}$$

In order to take road inclinations into consideration in the control design, (2) is applied as a performance of the controlled system. By making an appropriate selection of the weights Q and γ_i the importance of predicted road condition is considered.

In the final step, a control-oriented vehicle model in which reference velocities and prediction weights are taken into consideration is constructed. The dynamical equation of the vehicle in the first section is the following:

$$F_{l1} = m\ddot{\xi}_0 + F_{d1,r} + F_{d1,o}. \tag{4}$$

Then equation (2) is rearranged in order to determine the modified velocity:

$$\dot{\xi}_0 = \lambda \tag{5}$$

where the parameter λ is calculated in the following way:

$$\lambda = \sqrt{\vartheta - 2s_1(1-Q)(\ddot{\xi}_0 + gsin\alpha)}. \tag{6}$$

Consequently, the predicted road conditions can be considered by velocity tracking. Calculation of λ requires the measurement of the longitudinal acceleration $\ddot{\xi}_0$.

B. Minimization of control forces

The aim of the control design is to minimize the longitudinal force in order to reduce the energy required by travelling.

The longitudinal force (F_{l1}) can be expressed as the linear function of weights Q and γ_i based on equation (5):

$$F_{l1} = \beta_0(Q) + \beta_1(Q)\gamma_1 + \beta_2(Q)\gamma_2 + \ldots + \beta_n(Q)\gamma_n \tag{7}$$

where β_i are the coefficients of γ_i, and they depend on prediction weight Q. In practice, a quadratic form is used in the minimization problem

$$z_1 = F_{l1}^2 \tag{8}$$

because of the simpler numerical computation. This task is a nonlinear optimization problem because of the prediction weights. With fixed prediction weight it becomes a quadratic optimization problem. Its solution is found in [11].

An important economic factor is that the journey time must be minimized. In this sense only the speed limits pose a serious limiting factor. Since the minimization of the longitudinal force may lead to longer time requirement, the minimization of the journey time is a contradictory factor. The difference between momentary velocity and reference velocity must be minimized, i.e.,

$$z_2 = |v_{ref,0} - \dot{\xi}_0| \tag{9}$$

It means that this optimization criterion can be fulfilled if the road inclinations are ignored. Consequently, the optimal solution of performance (5) is: $\breve{Q} \equiv 1$ and $\breve{\gamma}_i \equiv 0, i \in [1, n]$

III. MODELING OF EMISSIONS OF HEAVY-DUTY VEHICLES

A. Modeling of emissions

The rate of pollution released by road vehicles has become a serious environmental issue in the past decades. Modeling the amount and composition of exhaust gases is essential for an effective control aimed at minimizing emissions and fuel consumption. Various models have been developed in order to estimate vehicle fuel consumption and emission rates. These models can be classified by different criteria. Based on the scale of input variables, emission models fall into three categories: microscopic, macroscopic or mesoscopic models. Microscopic models use instantaneous speed and acceleration data to estimate vehicle fuel consumption and emission rates. Fuel consumption and emission estimates of the microscopic models are instantaneous rates as well. Macroscopic models (HBEFA, EMFAC)[12] use aggregated traffic variables obtained from loop detectors to estimate network-wide fuel consumption and emissions rates. Mesoscopic models use scales that lie in-between the macroscopic scale and microscopic scale, such as link-based estimates [13].

In case of analyzing individual vehicles (microscopic approach), emission models can be classified into further two categories based on the number of input variables: traffic situation models and average speed models. Input variables of the former models include information of the current traffic situation (VERSIT, VeTESS) [14], [15] or more specifically, instantaneous acceleration (VT-Micro) [16] in addition to the speed variable. Average speed models are used if no information is available of the current driving pattern apart from average speed and thus the output of the model is the emission assigned to validated measurement cycles of the average speed value (i.e. COPERT, PHEM) [17], [18].

In this paper one of the control objectives is the optimization of the emissions of a platoon during its journey. In the derivation of the cost functions, average speeds of subsequent road sections are used; average acceleration values are only available for initial sections of the journey, and no high acceleration values are expected as the controlled vehicles travel on motorway. Based on these considerations, an average speed model (COPERT IV) is utilized, which has been extensively used for road traffic emission modeling [19], [20], [21].

Emission can be characterised by its temporal rate (emission rate function) or - throughout a journey - by its spatial rate (emission factor function). The relationship between emission rate e_j^p and emission factor functions ef_j^p of vehicle j for pollutant p is as follows:

$$e_j^p(t) = ef_j^p(t) v_j(t) \tag{10}$$

where $v_j(t)$ denotes the instantaneous speed of vehicle j. The formula can be generalized for average emission factors and average emission rates for time intervals if instantaneous speed is substituted by trip-based average speed.

In the model COPERT IV, emission factors of the pollutants are modeled by convex rational functions of average vehicle speed. Emission factor functions are specific for different vehicle classes, fuel types, Euro norms and engine capacities. (Further on, the appellation 'vehicle type' involves the information of all the above vehicle data.) For vehicle type c and pollutant p:

$$ef^{p,c} = \frac{\beta_m^{p,c}\dot{\xi}(t) + \beta_{m-1}^{p,c}\dot{\xi}(t) + \ldots + \beta_0^{p,c}\dot{\xi}(t)}{\delta_n^{p,c}\dot{\xi}(t) + \delta_{n-1}^{p,c}\dot{\xi}(t) + \ldots + \delta_0^{p,c}\dot{\xi}(t)} \tag{11}$$

The following pollutants were modeled in the control design: CO, CO_2, NO_X and hydrocarbons (HC). These are considered the most significant exhaust gases causing both global (greenhouse effect) and local harms (health problems, acid rain). Elaborating the reaction stochiometrics of internal combustion engines a linear connection between fuel consumption and CO_2 emission of a vehicle can be stated, see [22].

$$ef^{CO_2,c} = K \cdot fc^c \tag{12}$$

where $[fc^c] = l/100km$ is the fuel consumption of vehicle type c. K is a constant factor, in case of Diesel fuel $K = 26.29$. Unfortunately, further analytic relationships cannot be drawn among emission functions of the pollutants as secondary reactions of internal combustion engines depend on several factors (i.e. engine and fuel type, engine load, technology of engine etc). Emission factors with the fuel consumption are illustrated in Figure 2.

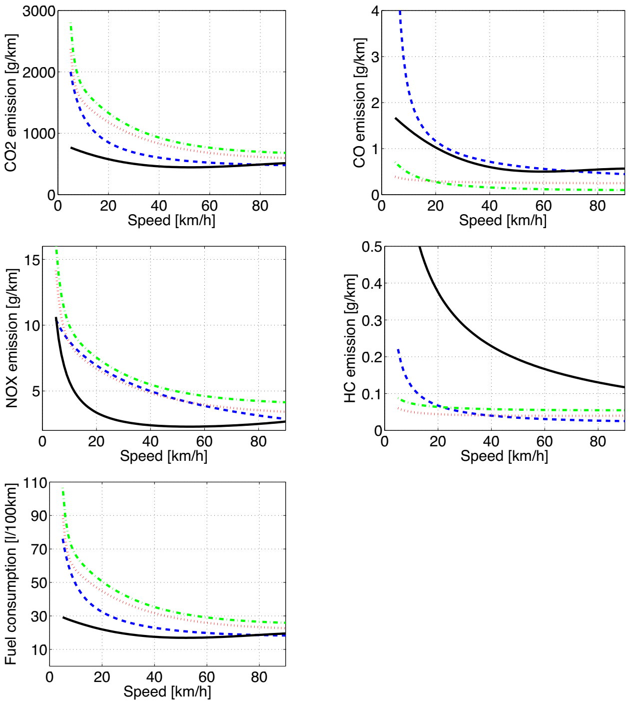


Fig. 2. Emission factors with the fuel consumption

The emission factor function (11) is an m-order polynomial function of speed, and as m-order polynomial functions constitute a linear space, the ith coefficient $\alpha_i^{p,platoon}$ for pollutant p of the average emission factor function is obtained as the linear combination of the coefficients of the vehicle classes: $\alpha_i^{p,platoon} = \sum_{c=1}^{N_c} \gamma_c \alpha_i^{p,c}$. The average emission factor function of the platoon: $ef^{p,platoon}(t) = \sum_{c=1}^{N_c} \gamma_c ef^{p,c}(t)$, where γ_c denotes the proportion of vehicle class c, N_c denotes the number of vehicles classes.

For reasons of simplicity assumed speed values are narrowed down to the speed range of motorways ($[60; 90] km/h$) and emission factors (solid) are approximated between these bounds by second order polynomial functions (dashed).

B. Relation between emission and road inclinations

In the previous section the modeling of emission was introduced. This method formalizes emission as a function of vehicle velocity and the effect of road inclinations are ignored in the model. In this section the applied average velocity model is augmented with the effects of road inclinations.

The dynamic effect of the road inclination on the i^{th} road section is formalized as: $F_{di,r} = mg \sin \alpha_i$, where m is the mass of the vehicle, α is the road inclination. In the case of road inclination this force modifies the longitudinal dynamics of the vehicle. The aim is to compute the increase in emission from this information. However, (11) shows that the emission can only be modified via velocity values. It means that it is necessary to compute an additive velocity value for the calculation of emission increase representing the modification of longitudinal dynamics by the road inclination.

In longitudinal dynamics the effect of the road inclination is replaced with an aerodynamic force, which is formalized as $F_{aer,i} = A_2 \dot{\xi}^2$, see Section II. In case of the formal equivalence of $F_{di,r}$ and $F_{aer,i}$, an additive velocity value $\dot{\xi}_{ef^{p,c},i}$ is computed:

$$\dot{\xi}_{ef^{p,c},i} = \sqrt{\frac{mg \sin \alpha_i}{A_2}} \tag{13}$$

The emission increase of the vehicle caused by the road inclination $ef_0^{p,c}$ in the i^{th} road section is computed using (11)

$$ef_{0,i}^{p,c} = \frac{\beta_m^{p,c} \dot{\xi}_{ef^{p,c},i}(t) + \ldots + \beta_0^{p,c} \dot{\xi}_{ef^{p,c},i}(t)}{\delta_n^{p,c} \dot{\xi}_{ef^{p,c},i}(t) + \ldots + \delta_0^{p,c} \dot{\xi}_{ef^{p,c},i}(t)} \tag{14}$$

C. Minimization of emission

The emission model of the heavy-duty vehicle is approximated by using a second-order polynomial function: $ef^{p,c} = \alpha_0 + \alpha_1 \dot{\xi}_0 + \alpha_2 \dot{\xi}_0^2$, where $\alpha_0, \alpha_1, \alpha_2$ are parameters. The unmeasured longitudinal disturbances are described with a similar form: $F_{d1,o} = A_0 + A_1 \dot{\xi}_0 + A_2 \dot{\xi}_0^2$. Therefore it is possible to formalize emission as the function of prediction weights Q and γ_i:

$$ef^{p,c} = ef^{p,c}(Q, \gamma_1, \gamma_2, \ldots \gamma_n) \tag{15}$$

The performance of the velocity is $|ef^{p,c}| \to Min!$, which leads to a practical minimization problem:

$$z_3 = (ef^{p,c})^2 \tag{16}$$

The minimization leads to a quadratic optimization problem with $(ef^{p,c})^2 \, (\hat{Q}, \hat{\gamma}_i)$.

IV. MULTI-CRITERIA OPTIMIZATION OF THE PLATOON CONTROL

The aim of this section is to find an optimal velocity $\dot{\xi}_0$ that guarantees the minimization of emission, the control force (fuel consumption) and traveling time. The fulfillment of these performances individually results in different Q, γ_i weights according to equation (5).

In the proposed method three further performance weights R_1, R_2 and R_3 are introduced.

- Performance weight R_1 ($0 \leq R_1 \leq 1$) is related to the importance of the minimization of the longitudinal control force F_{l1}.
- Performance weight R_2 ($0 \leq R_2 \leq 1$) is related to the minimization of $|v_{ref,0} - \dot{\xi}_0|$.
- Performance weight R_3 ($0 \leq R_3 \leq 1$) is related to the emission.

There is a constraint according to the performance weights $R_1 + R_2 + R_3 = 1$.

Thus the performance weights, which guarantee a balance between the optimizations tasks, are calculated in the following expressions:

$$Q = R_1 \bar{Q} + R_2 \breve{Q} + R_3 \hat{Q} = R_1 \bar{Q} + R_2 + \hat{Q} R_3 \tag{17a}$$

$$\gamma_i = R_1 \bar{\gamma}_i + R_2 \breve{\gamma}_i + R_3 \hat{\gamma}_i = R_1 \bar{\gamma}_i + R_3 \hat{\gamma}_i, \tag{17b}$$

where $i \in [1, n]$.

Based on the performance weights the modified reference velocity is determined by using (5). Using the optimization method the reference velocity λ of an independent vehicle can be calculated such a way that the road inclinations are also taken into consideration. In case of a platoon, each member of the platoon is able to compute its own reference velocity: λ_i. However, these reference velocities are not realized, because it is necessary to perform string stability in the platoon [23]. Moreover, velocities of the vehicles are not independent from each other, because velocity of the leader λ_1 influences velocity of the member of platoon $\dot{\xi}_{0,j}$.

The aim to find a reference velocity of the leader vehicle $\bar{\lambda}_1$, which results the generated velocities of all the vehicles $\dot{\xi}_{0,j}$ as close to their modified reference velocity λ_j as possible:

$$\sum_{j=1}^{n} |\lambda_j - \dot{\xi}_{0,j}| \to 0. \tag{18}$$

If a preceding vehicle changes its velocity, the follower vehicles will modify their velocities and track the motion of the preceding vehicle within a short time. Thus, there is a dynamic interaction between the velocities of the vehicles, which must be modeled. The velocities of the sequential vehicles can be modeled in the following way:

$$\dot{\xi}_{0,j}(t) = \dot{\xi}_{0,j}(t_0) + (\dot{\xi}_{0,j-1}(t) - \dot{\xi}_{0,j}(t_0))(1 - e^{-(t-t_0)/T}), \tag{19}$$

where T is the time delay and $\dot{\xi}_{0,j}(t)$ is the momentary velocity of the follower vehicle. In practical computations the transfer function G_j, which represents the transfer function between the velocity of preceding vehicle and the velocity of the follower, is introduced.

The optimization task leads to the following optimal solution, i.e. the transfer function of the required velocity $\bar{\lambda}_1$:

$$\bar{\Lambda}_1 = \frac{\sum_{j=1}^{n} \Lambda_j \prod_{k}^{j-1} G_k)}{\sum_{j=1}^{n} (\prod_{k=1}^{j-1} G_k)^2} \tag{20}$$

It means that the leader vehicle must track the required reference velocity $\bar{\lambda}_1$ (its Laplace transformation is denoted by $\bar{\Lambda}_1$).

V. ROBUST CONTROL DESIGN

In practice, the velocity of the headwind and the rolling resistance may change within a short section. The consequence of this assumption is that the model does not contain all the information about the predicted road disturbances, therefore it is necessary to design a robust speed control.

In the previous section the required velocity of the leader vehicle is determined. The velocity of the leader vehicle must track the required velocity. At the same time the other vehicles in the platoon must meet the string-stable requirement in order to guarantee the safe operation of the platoon. Consequently, two types of controllers must be designed: a velocity tracking controller for the leader vehicle and string stable controllers for the following vehicles. The design of controllers is based on robust $\mathcal{H}_\infty$ methods.

The model of longitudinal dynamics of each vehicle in the platoon contains actuator dynamics of both the driving and braking systems. It contains a delay in its operations, which can be approximated by a first-order system with an appropriately selected time constant: $\dot{F_{l1}} = (\tilde{F_{l1}} - F_{l1})/\tau$ where F_{l1} is the realized force, $\tilde{F_{l1}}$ is the desired force and τ is the delay of the system.

The state space representation of the longitudinal dynamics is the following:

$$\dot{x} = \begin{bmatrix}0 & 1/m\\ 0 & -1/\tau\end{bmatrix} x + \begin{bmatrix}0\\ 1/\tau\end{bmatrix} \tilde{F_{l1}} + \begin{bmatrix}-1/m\\ 0\end{bmatrix} F_{d1} \qquad (21)$$

with $x = \begin{bmatrix}\dot{\xi}_0 & F_{l1}\end{bmatrix}^T$. In this description the operations of driving and braking are handled simultaneously.

The performance specification of the leader vehicle differs from the performances of the followers in the platoon. The control design of the leader vehicle is a tracking problem formalized in (5). The aim of tracking is to ensure that the system output follows a reference value of velocity with an acceptable error, which is the performance of the system: $z_1 = \bar{\lambda}_1 - \dot{\xi}_{0,1}$, where the parameter $\bar{\lambda}_1$ is the required reference velocity. The other vehicle in the platoon must guarantee string stability. There are several strategies that ensure the string stability of the system, see [23], [24]. In the paper string stability is ensured by tracking the position, velocity and acceleration of the preceding vehicle, and tracking the position and velocity of the leader vehicle. The performance vector of the j^{th} vehicle is:

$$z_j = [\ddot{\varepsilon}_j;\ \dot{\varepsilon}_j;\ \varepsilon_j;\ \dot{\xi}_{0,j} - \dot{\xi}_{0,1};\ \xi_{0,j} - \xi_{0,1} + \sum L_i]^T, \quad (22)$$

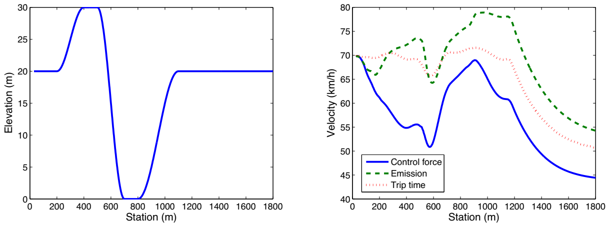
where L_i is the distance between two vehicles and $\varepsilon_i = \xi_{0,j} - \xi_{0,j-1}$ is the error of tracking.

The scheme of the control design differs for the leader vehicle and the other vehicles in the platoon. The reference signal R is the required reference velocity $\bar{\lambda}_1$ for the leader vehicle, while for the follower vehicles vector R contains the velocity and position of the leader and the preceding vehicles and the acceleration of the preceding one. The performance signal z also differs in the two cases. In case of the leader $z = z_1$ and in the other vehicles $z = z_j$. For the leader vehicle the measured signals are the velocity and acceleration of the vehicle, while the follower vehicles also require the velocity, position and acceleration information about the preceding and leader vehicles.

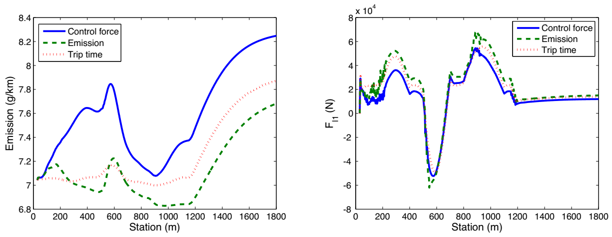
It is noted that the stability of the entire platoon control should also be analyzed. The designed velocity, which must be achieved by the robust control, can be considered as a reference signal of the controlled platoon. Consequently, the calculation of the reference signal influences the stability of the controlled system.

VI. SIMULATION RESULTS

The efficiency of the multi-criteria optimization method is illustrated using heterogenous heavy-duty vehicles. The platoon in the simulation example incorporates four heavy-duty vehicles, the weights of which are $14 - 20t$, and the leader and the second one have Euro5 EGR Diesel engines, while the third and fourth have HD Euro III Diesel engines. The reference velocity of the vehicles is $v_{ref,i} = 70km/h$ in the first $1200m$, while after that $v_{ref,i} = 50km/h$ $,i \in [1, 10]$, and the terrain characteristics of the route of the platoon are shown in Figure 3(a). During simulation the calculation of the emission takes the road inclinations into consideration. Figure 3 shows the simulation results of the leader vehicle of the platoon.



(a) Terrain characteristics (b) Velocity



(c) HC, CO, NO_X emission (d) Longitudinal force F_{l1}

Fig. 3. Comparison of performances

In terms of emission the sum of the emissions of the leader and the third vehicle is presented. Three different strategies are illustrated: the minimization of F_{li}, the minimization of emission (HC, CO, NO_X), the minimization of trip time. In these simulations the corresponding performance weights(R_1, R_2, R_3) are tuned.

Figure 3(b) shows the velocities of the vehicles in the three cases. It shows that the minimum emission values can be obtained by higher vehicle velocities. In Section III the emission functions of the two engines are shown, and their minimum emissions are at different velocities. It means that the minimization is a more complex problem in this sense, however, the proposed method is able to reach the minimum emission in the aspect of the whole platoon. Figure 3(c) shows the emission. When velocity is reduced the longitudinal control force is also reduced as Figure 3(d) shows. However, at the same time emission increases significantly. Consequently, there is a conflict between the minimization of control force and the minimization of emission.

In the case of the minimization of traveling time the velocity of the leader vehicle is around $v_{ref,i}$, which results in almost the same velocity as that achieved by a conventional cruise control system. The simulation results illustrate that it is possible to achieve different performances by an appropriately selected strategy. The simulation example shows that the method guarantees a balance between saving energy, the minimization of traveling time and emission.

VII. CONCLUSION

The paper has proposed the design of a platoon velocity based on a multi-criteria optimization method. The optimization method is able to handle three performances, such as the minimization of the control force, traveling time and the emission of the platoon. Besides the optimization procedure a robust control design is also applied in order to handle the uncertainties of the system. The $\mathcal{H}_\infty$ robust control design is proposed for the leader and the members of the platoon.

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