Adaptive Emission Control of Freeway Traffic via Compensation of Modeling Inconsistences

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***Abstract*—Nowadays when traffic jams and air pullution are very common, controlling the emission rate of the exhaust fumes is a significant task. Many difficulties make this problem more sophisticated, for example the present emission models sometimes need too many information so it is quite complex to work with them. On the other hand, the underlaying physics behind the hydrodynamic traffic models does not suggest unique mathematical formulation so we need adaptive controllers that iteratively improve the forecasts obtained by a rough initial model without tuning the parameters of a particular mathematical structure. In this paper a simple method is shown for determining the stationary solutions obtained from a hydrodynamic model for a realistic parameter range. The method is based on Robust Fixed Point Transformations (RFPT)-based adaptive control that needs only the main factors in the emission: the traffic density and velocity. For controlling it applies electric road signs for the prescribed velocities and allowed ingress rate from the ramp in the preceding sector. This is a new area for the RFPT, but as the simulations show it is successfully applyable to the problem.**

I. INTRODUCTION

The relationship between freeway traffic and health has been investigated for a long time, e.g. [1]. An important point of view is the emission rate of exhaust fumes, because under various meteorological conditions different emission rates can dissolve in the environment. The chemical composition of the exhaust depends on the actual traffic conditions (road slope, tyre friction, deceleration/acceleration and velocity), the particular properties of the various vehicles (engine types, their gearing system [2], etc.). For modeling these effects quite complex models were developed (e.g. [3], [4], [5], [6]) but their practical use is limited because normally the traffic control systems do not have enough information they need.

Development of proper models for the road traffic is also an interesting question. Certain investigations have revealed fractional order dynamics in the nature of freeway traffic [7]. Several models can be regarded as some mathematical approximations of continuum mechanical ones that use integer order partial derivatives (e.g. [8], [9], [10], [11], [12], [13], [14]) in which the time is kept as continuous variable but the space is treated as a discretized grid. This discretization can be realized by the use of various numerical approximations of the gradient operator that lead to models of various complexity. Either one-sided or centralized differences can be applied without deeper physical substantiation. Since the underlaying physics behind the hydrodynamic traffic models does not suggest unique mathematical formulation we need adaptive controllers that iteratively improve the forecasts obtained by a rough initial model without tuning the parameters of a particular mathematical structure.

For similar purposes various Model Reference Adaptive Controllers (MRAC) can be found in the literature applied in robotics (e.g. [15], [16], [17], [18]) that use Lyapunov's "direct" method (e.g. [19], [20]) which can be a difficult technique that requires good mathematical skills in some cases. Alternative, also effective techniques generating convergent sequences by the use of contractive maps in iterative learning control were also published (e.g. [21], [22], [23], [24], which is called Robust Fixed Point Transformations (RFPT).

In this paper a new approach is shown for determining the stationary solutions of emission control obtained from a hydrodynamic model for a realistic parameter range. The method is based on RFPT that needs only the main factors in the emission: the traffic density and velocity. For controlling it applies electric road signs for the prescribed velocities and allowed ingress rate from the ramp in the preceding sector. The method is less complex compared to the ones mentioned above. This is a new area for the RFPT, but as the simulations show it is successfully applyable to the problem.

The paper is organized as follows: the hydrodynamic models of freeway traffic are presented in Section II. The stationary solutions of the dynamic model under the particular boundary conditions applied are shown in III. The simulation results are detailed ins Section IV. Section V contains the discussion of the results and proposes further researches in this direction.

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II. Hydrodynamic models of freeway traffic

For our investigations, we use the model shown in Fig [**?**]. For simplicity let's assume a one dimensional state varible which has six segments, from 0 to 5. The road segments have equal lengths L. Segments 0 and 5 represent the *boundary conditions* determining the propagation of the *state variables* of segments 1 to 4 by *keeping time as continuous variable*, and applies discretized approximation of the –in this case one dimensional– space variable. The *state variables* are the *vehicle density* ρ (i.e. the number of vehicles over road segments of unit length), and the *velocity of traffic* v of a *compressible fluid model*. The quantity ρv $(1/s)$ denotes the *traffic current density* by the use of which *conservation of the vehicles* can be described by Eqs (2)-(5).

$$\dot{v}_i = \frac{\partial v_i}{\partial t} + \sum_{s=1}^{3} \frac{\partial v_i}{\partial x_s}\dot{x}_s = \frac{v_i}{\partial t} + \sum_{s=1}^{3} \frac{\partial v_i}{\partial x_s} v_s(x,t) \tag{1}$$

$$\dot{\rho}_1 = \frac{q_0 - \rho_1 v_1}{L\lambda} \tag{2}$$

$$\dot{\rho}_2 = \frac{\rho_1 v_1 - \rho_2 v_2 + r_2}{L\lambda} \tag{3}$$

$$\dot{\rho}_3 = \frac{\rho_2 v_2 - \rho_3 v_3}{L\lambda} \tag{4}$$

$$\dot{\rho}_4 = \frac{\rho_3 v_3 - \rho_4 v_4}{L\lambda} \tag{5}$$

$$\begin{aligned}\dot{v}_2 &= \frac{V(\rho_2) - v_2}{\tau} + \frac{v_2(v_1 - v_3)}{2L} - \\ &- \frac{\eta}{\tau 2L}\frac{\rho_3 - \rho_1}{\rho_2 + \kappa} - \frac{\delta}{L}\frac{r_2 v_2}{\rho_2 + \kappa}\end{aligned} \tag{6}$$

$$\dot{v}_1 = \frac{V(\rho_1) - v_1}{\tau} + \frac{v_1(v_0 - v_2)}{2L} - \frac{\eta}{\tau 2L}\frac{\rho_2 - \rho_0}{\rho_1 + \kappa} \tag{7}$$

$$\dot{v}_3 = \frac{V(\rho_3) - v_3}{\tau} + \frac{v_3(v_2 - v_4)}{2L} - \frac{\eta}{\tau 2L}\frac{\rho_4 - \rho_2}{\rho_3 + \kappa} \tag{8}$$

$$\dot{v}_4 = \frac{V(\rho_4) - v_4}{\tau} + \frac{v_4(v_3 - v_5)}{2L} - \frac{\eta}{\tau 2L}\frac{\rho_5 - \rho_3}{\rho_4 + \kappa} \tag{9}$$

According to Fig. 1 these equations apply the finest available spatial resolution and they can be regarded as an integral form in the Gauss Equation that relates the time derivative of the number of vehicles within a fixed road segment with the ingress and egress of traffic flow at the boundaries of this segment. The *dynamic behavior* of this system is described by Eqs (7)-(9) in which for the $V(\rho)$ functions various suggestions can be found in the literature as e.g. the *Greenshields* and the *Papageorgiou models* (10).

$$\begin{aligned} V(\rho) &:= v_{free}\left(1 - \tfrac{\rho}{2\rho_{cr}}\right) \quad \texttt{or} \\ V(\rho) &:= v_{free}\exp\left(-\tfrac{1}{b}\left[\tfrac{\rho}{\rho_{cr}}\right]^b\right)\end{aligned} \tag{10}$$

in which the first relationship established by Greenshields may provide even negative velocities that are not allowed under normal conditions in a real traffic, while the second one, the Papageorgiou model always results in interpretable nonnegative values. On this reason in the present paper we use this latter approach.

It worths noting that Eqs. (7)-(9) cannot unambiguously derived from the fluid mechanical model. For instance, in case of a 3D traffic model (that definitely has sense for aircrafts and submarines), be the use of the *3D tensor components* of the *velocity field of motion*, $v_i(x,t)$ *the acceleration along a flowpath* in (1) contains the gradient of this field that is approximated by central differences in (7)-(9).

However, we also could use *one-sided differences* for the approximation of the gradient $\frac{\partial v_i}{\partial x_s}$ as e.g. in the following equations. The complexity of the model using central differences evidently exceeds that of the one-sided models.

$$\dot{v}_1 = \frac{V(\rho_1) - v_1}{\tau} + \frac{v_1(v_0 - v_1)}{L} - \frac{\eta}{\tau L}\frac{\rho_2 - \rho_1}{\rho_1 + \kappa} \tag{11}$$

$$\begin{aligned}\dot{v}_2 &= \frac{V(\rho_2) - v_2}{\tau} + \frac{v_2(v_1 - v_2)}{L} - \\ &- \frac{\eta}{\tau L}\frac{\rho_3 - \rho_2}{\rho_2 + \kappa} - \frac{\delta}{L}\frac{r_2 v_2}{\rho_2 + \kappa}\end{aligned} \tag{12}$$

$$\dot{v}_3 = \frac{V(\rho_3) - v_3}{\tau} + \frac{v_3(v_2 - v_3)}{L} - \frac{\eta}{\tau L}\frac{\rho_4 - \rho_3}{\rho_3 + \kappa}. \tag{13}$$

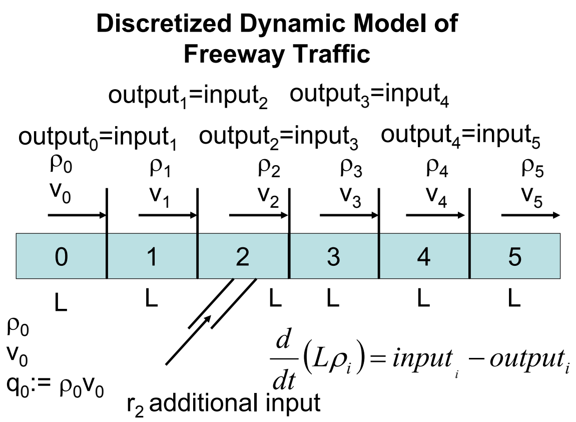

Fig. 1. The discretized hydrodynamic model of freeway traffic.

If the additional ingress rate from the ramp r_2 is applied at section 2 and we apply central differences the appropriate dynamic model is given by Eqs (2)-(9). If we use electronically controlled road signs the quantities ρ_0, v_0 (consequently $q_0 := \rho_0 v_0$), v_4 and v_5 can be set as *constant boundary conditions* which together with Eq (9) with $\dot{v}_4 = 0$ immediately determine the density in segment 5, ρ_5. Therefore the state variables remain only ρ_1, ρ_2, ρ_3, ρ_4, v_1, v_2, and v_3 for which we have coupled first order nonlinear differential equations.

We note that these equations describe a strongly "underactuated" system: we have only one time-varying control signal r_2 that influences the propagation of seven state variables. Therefore we can precisely control only one of these variables or a well defined complex expression calculated from them, or we can apply a kind of optimal controller in which a goal or cost function may describe weighted significance of the precision of controlling the individual variables so resolving the essentially contradiction-burdened task.

III. The idea of the adaptive controller using quasi-stationary approach

Further significant observation concerns the *stability of the stationary solutions of these differential equations*. Assume that for *fixed* $\hat{r}_2$ *stationary solutions* (i.e. $\hat{\rho}_1$, $\hat{\rho}_2$, $\hat{\rho}_3$, $\hat{\rho}_4$, $\hat{v}_1$, $\hat{v}_2$, and $\hat{v}_3$) for which $\dot{\hat{\rho}}_1 = 0, \dot{\hat{\rho}}_2 = 0, \dot{\hat{\rho}}_3 = 0, \dot{\hat{\rho}}_4 = 0, \dot{\hat{v}}_1 = 0$, $\dot{\hat{v}}_2 = 0$, and $\dot{\hat{v}}_3 = 0$, but these solutions are *unstable*. Such a dynamic system could require very fast feedback signal in r_2 to stabilize the stationary solutions that would be a very difficult, but its practical implementation would be dubious. But if the stationary solutions are stable, the control task can be approached in a far simpler and far more easily implementable manner. In this case small steps in the control signal can result in small modifications of the controlled quantities that automatically set themselves following a shorter or longer transient session. In this case the need for really dynamic control ceases. The system model can simply be used for determining the necessary small steps in r_2 and instead of fast dynamic feedback a simple iterative controller can be designed for the compensation of the modeling errors. This approach is traditional e.g. in Thermodynamics and Chemistry when the states of the thermal equilibrium are stable or at least metastable, i.e. they show stability at least against small perturbations. The quasi-stationary thermodynamic processes model the sate propagation as a sequence of stationary states (e.g. [26], [27]. The stationary solutions of certain multiple-compartment process models of the human glucose-insulin system (e.g. [29], [28]) also show stability that eases their control. In the next section the stationary solution of our model under the given boundary conditions are investigated.

A. The stationary solutions of the dynamic model

Under the boundary conditions $\hat{\rho}_0 = const.$, $\hat{v}_0 = const.$ (consequently $\hat{q}_0 := \hat{\rho}_0\hat{v}_0$=const.), $\hat{v}_4 = const.$ and $\hat{v}_5 = const.$ for constant control signal $\hat{r}_2 = const.$ the dynamic equations take the form of

$$0 = \frac{\hat{q}_0 - \hat{\rho}_1\hat{v}_1}{L\lambda} \tag{14}$$

$$0 = \frac{\hat{\rho}_1\hat{v}_1 - \hat{\rho}_2\hat{v}_2 + \hat{r}_2}{L\lambda} \tag{15}$$

$$0 = \frac{\hat{\rho}_2\hat{v}_2 - \hat{\rho}_3\hat{v}_3}{L\lambda} \tag{16}$$

$$0 = \frac{\hat{\rho}_3\hat{v}_3 - \hat{\rho}_4\hat{v}_4}{L\lambda} \tag{17}$$

$$0 = \frac{V(\hat{\rho}_1) - \hat{v}_1}{\tau} + \frac{\hat{v}_1(\hat{v}_0 - \hat{v}_2)}{2L} - \frac{\eta}{\tau 2L}\frac{\hat{\rho}_2 - \hat{\rho}_0}{\hat{\rho}_1 + \kappa} \tag{18}$$

$$\begin{aligned} 0 = {} & \frac{V(\hat{\rho}_2) - \hat{v}_2}{\tau} + \frac{\hat{v}_2(\hat{v}_1 - \hat{v}_3)}{2L} - \frac{\eta}{\tau 2L}\frac{\hat{\rho}_3 - \hat{\rho}_1}{\hat{\rho}_2 + \kappa} \\ & - \frac{\delta}{L}\frac{\hat{r}_2\hat{v}_2}{\hat{\rho}_2 + \kappa} \end{aligned} \tag{19}$$

$$0 = \frac{V(\hat{\rho}_3) - \hat{v}_3}{\tau} + \frac{\hat{v}_3(\hat{v}_2 - \hat{v}_4)}{2L} - \frac{\eta}{\tau 2L}\frac{\hat{\rho}_4 - \hat{\rho}_2}{\hat{\rho}_3 + \kappa} \tag{20}$$

with the explicit equation for $\hat{\rho}_5$ as

$$\hat{\rho}_5 = \hat{\rho}_3 - \tfrac{\tau 2L(\hat{\rho}_4 + \kappa)}{\eta} \times \left[\tfrac{V(\hat{\rho}_4) - \hat{v}_4}{\tau} + \tfrac{\hat{v}_4(\hat{v}_3 - \hat{v}_5)}{2L}\right]. \tag{21}$$

Due to nonlinearities in Eqs (14)-(20) the stationary solutions can be found by some numerical technique. Our solution is detailed in the next subsection.

B. Determination of the stationary solutions

For reducing complexity, we use a simple method. The occurrence of $(\hat{\rho}_i + \kappa)$ in the denominators may cause division by zero in numerical algorithms, so in the 1st step such divisions were eliminated via multiplication in Eqs 14-20 resulting the equations

$$0 = f_4 := \hat{q}_0 - \hat{\rho}_1\hat{v}_1 \tag{22}$$

$$0 = f_5 := \hat{\rho}_1\hat{v}_1 - \hat{\rho}_2\hat{v}_2 + \hat{r}_2 \tag{23}$$

$$0 = f_6 := \hat{\rho}_2\hat{v}_2 - \hat{\rho}_3\hat{v}_3 \tag{24}$$

$$0 = f_7 := \hat{\rho}_3\hat{v}_3 - \hat{\rho}_4\hat{v}_4 \tag{25}$$

$$\begin{aligned} 0 = f_1 := {} & 2L(\hat{\rho}_1\kappa)[V(\hat{\rho}_1) - \hat{v}_1] + \\ & + \tau(\hat{\rho}_1 + \kappa)\hat{v}_1(\hat{v}_0 - \hat{v}_2) - \eta(\hat{\rho}_2 - \hat{\rho}_0) \end{aligned} \tag{26}$$

$$\begin{aligned} 0 = f_2 := {} & 2L(\hat{\rho}_2 + \kappa)[V(\hat{\rho}_2) - \hat{v}_2] + \\ & + \tau(\hat{\rho}_2 + \kappa)\hat{v}_2(\hat{v}_1 - \hat{v}_3) - \eta(\hat{\rho}_3 - \hat{\rho}_1) - \\ & - 2\tau\delta\hat{r}_2\hat{v}_2 \end{aligned} \tag{27}$$

$$\begin{aligned} 0 = f_3 := {} & 2L(\hat{\rho}_3 + \kappa)[V(\hat{\rho}_3) - \hat{v}_3] + \\ & + \tau(\hat{\rho}_3 + \kappa)\hat{v}_3(\hat{v}_2 - \hat{v}_4) - \eta(\hat{\rho}_4 - \hat{\rho}_2). \end{aligned} \tag{28}$$

A formal possibility is to consider Eqs (22)-(28) as subjects of some optimization task. According to the classification of the optimization tasks published in [30] our task corresponds to the most general case in which both the goal function as well as the possible constraints are nonlinear. However, the number of the independent variables is not too big. With the help of MS Excel's Solver it can be proved that there is dependence of the coefficients of the $\hat{r}_2$-based polynomial on $\hat{q}_0$.

In the next section the main exhaust fume emission factors are briefly considered.

C. Introduction of the Emission Factor

For calculating the main factors (the emission rates), it is assumed that at high velocities in the freeway the most significant dissipative factor is the *drag force* generated by eddying air that is proportional to the square of the velocity: $F = Cv^2$ in which the C coefficient depends on the particular vehicles. At velocity v the power consumption of this drag force is $Fv = Cv^3$ which roughly determines its fuel consumption. On a road segment of length L and vehicle density ρ in a given moment $L\rho$ vehicles produces $L\overline{C}\rho v^3$ power consumption which roughly determines the emission rate of exhaust fume on this segment ($\overline{C}$ denotes some "average" for the various vehicles present on the segment). It is evident that it is very difficult to obtain information on $\overline{C}$, however, the emission for any car still strongly depends on the factor $E_f := \rho v^3$ that easily and quickly can be measured by cheap and simple inductive loop detectors (e.g. [31], [32]). On this reason we refer to this quantity as the "*emission factor*" which in the case of stationary flow in segment 3 can also be expressed as $E_f = (\hat{q}_0 + \hat{r}_2)v_3^2$ since $\hat{\rho}_3\hat{v}_3 = \hat{q}_0 + \hat{r}_2$. Independently of the actual (unknown) value of $\overline{C}$ this factor must be decreased if the contamination of air is too high, or it can be increased if the actual concentration of the exhaust in the air is under some prescribed threshold. On this reason we made direct polynomial fitting for E_f, too.

To sum up the stationary behavior of the system in the given parameter range can well be approximated by a few simple matrices containing the coefficients of the polynomial fitting. Simultaneous measurement of $\hat{\rho}_3$ and $\hat{v}_3$ guarantees not having drastic estimation errors.

The last question is the stability of the stationary states. Since the suggested method needs continuous observations in general it cannot promise "asymptotic stability" due to the principle of causality (any correction is possible only after the observation), but as the investigations revealed, it can guarantee stability.

IV. Simulation results

For the adaptive control of the *emission factor* at road segment 3 the 3rd order polynomial fitting of E_f is directly calculated. Utilizing the fact that it is found to be monotone increasing function of $\hat{r}_2$ for arbitrary positive $\hat{q}_0$ investigated a simple function is written in SCILAB to find a model-based $\hat{r}_2^{Des}$ value for a prescribed nominal $\hat{E}_f^{Nom} \equiv \hat{E}_f^{Des}$ emission factor. The *non-adaptive controller* immediately introduced this value to its available system model. The *adaptive controller* introduced this corrected value into function G of equation ([24], [25]) to calculate the deformed "*Required*" input into the rough system model. In the simulations the realistic $\delta t_{sampling} = 0.028\,h \approx 100.8\,s$ value is chosen. The control parameters are $K_{ctrl} = -1e10$, $A_{ctrl} = 5e-12$, and $B_{ctrl} = 1$. The allowed maximum discrete time step on the integrator was set to $\delta t_{sampling}/50$.

Simulation were made for the *exact* and the *approximate* models. The *approximate model parameters* were set as follows: the values marked by the tilde symbol $\tilde{()}$ represent the exact model values, and the original parameter set now corresponds to the rough approximation of the real data: $\tilde{v}_{free} = 1.20v_{free}$, $\tilde{b} = 1.2b$, $\tilde{L} = L$, $\tilde{\rho}_{cr} = 1.2\rho_{cr}$, $\tilde{\tau} = 1.2\tau$, $\tilde{\eta} = 1.2\eta$, $\tilde{\kappa} = 1.2\kappa$, $\tilde{\delta} = 1.2\delta$, and $\tilde{\lambda} = \lambda$. The trivially not available parameters' values were overestimated by 20%.

In the first set the applicability of the polynomially fitted exact model was checked for use in a common non-adaptive controller. In the simulations $\hat{q}_0$ was varied in drastic steps while E_f^{Nom} varied continuously. Figure 2 reveals that the fitted stationary approximation is in harmony with the output of the dynamic model. It can be observed that the sign of the tracking error in the great majority of the simulation time is identical, i.e. the approximation is a little bit biased.

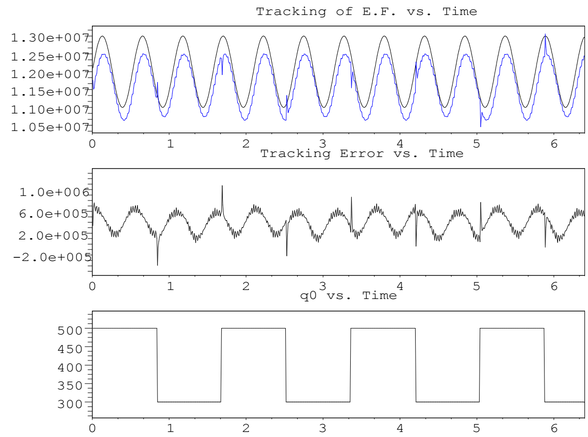

Fig. 2. Emission factor tracking of the *non-adaptive controller using the exact model parameters* of the controlled system: E_f^{Nom} vs. E_f, in km^2/h^3 units

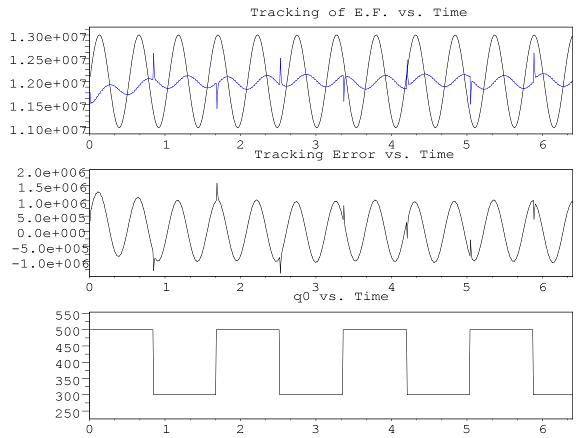

Fig. 3. Emission factor tracking of the *adaptive controller using the exact model parameters* of the controlled system: E_f^{Nom} vs. E_f, in km^2/h^3 units.

In the next step it was investigated to what extent disturbs the adaptive controller the use of the exact model. Figure 4 well demonstrates that instead of the bias, the adaptive controller produces an error that fluctuates around zero.

In the next step the operation of the adaptive controller was investigated for the case in which the polynomially fitted stationary values originate from the *approximate dynamic model*. The results are given in Figs. 4.

In the above simulations can well be seen that the sharp jumps in $\hat{q}_0$ generate jumps in the solutions. In the next investigations the variation of $\hat{q}_0$ was made continuous and smooth. The non-adaptive controller works with a huge error that means that the E_f very drastically depends on the model parameters that were modified to the tune of 20% only (Fig. 5).

The adaptive controller (results given in Fig. 6) yields precise tracking without sharp jumps.

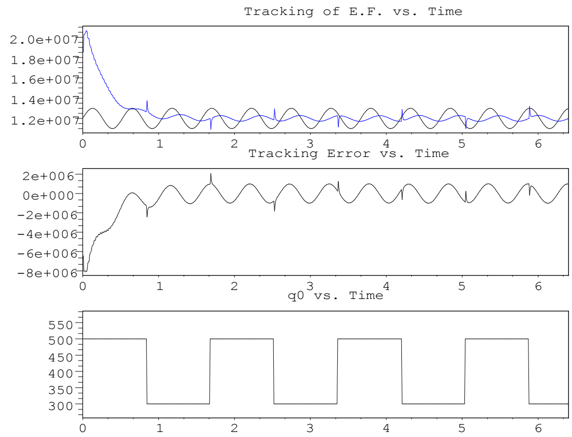

Fig. 4. Emission factor tracking of the *adaptive controller using the approximate model parameters* of the controlled system: E_f^{Nom} vs. E_f, in km^2/h^3 units.

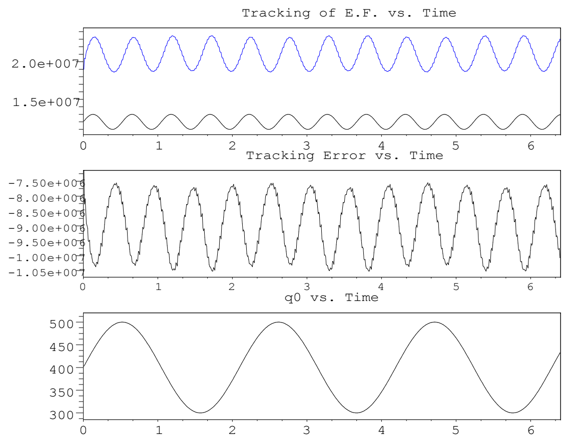

Fig. 5. Emission factor tracking of the *non-adaptive controller using the approximate model parameters* of the controlled system for smooth q_0 ingress rate: E_f^{Nom}:-black, E_f:-blue lines in km^2/h^3 units, time is given in h units.

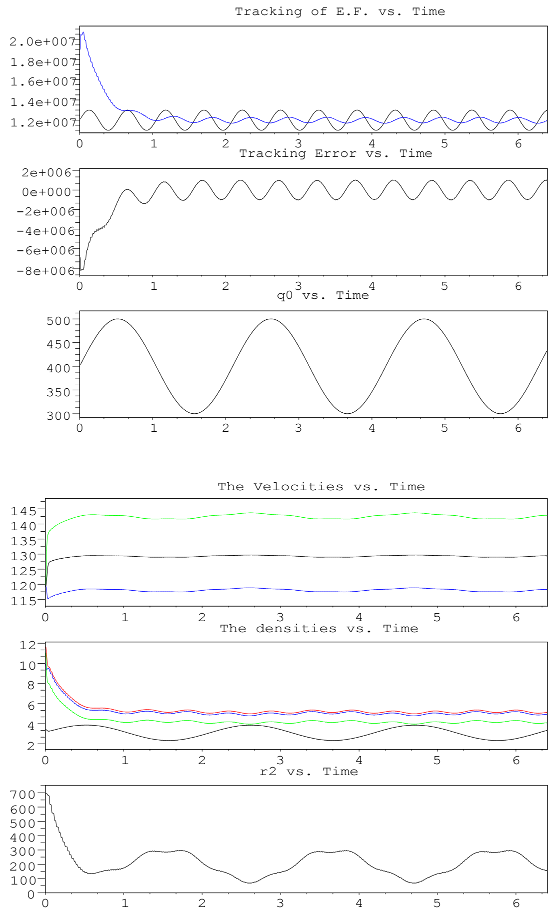

Fig. 6. Emission factor tracking of the *adaptive controller using the approximate model parameters* of the controlled system for smooth q_0 ingress rate: E_f^{Nom}:-black, E_f:-blue lines in km^2/h^3 units in the upper chart; v_1:-black, v_2:-blue, v_3:-green lines in km/h units, ρ_1:-black, ρ_2:-blue, ρ_3:-green, ρ_4:-red lines in $1/km$ units in the lower chart, time is given in h units.

In the above simulations the cycle time of the controller was very big ($\approx 100\,s$). In the practice in urban traffic the available time for crossing a street used to be about $10\,s$, so the best accuracy can be expected to this nice sampling time. According to Fig. 7 really very nice tracking precision can be achieved.

V. Conclusions

In this paper a new adaptive emission controller is shown and compared to a nonadaptive one. Its simple structure ensures low complexity. The adaptive controller that is based on the simple 3rd order polynomial approach of the quasi-stationary states of a given model and the RFPT transformations seems to be a prospective solution. It applies the ingress rate from the ramp in the preceding road segment as a control signal, and requires the measurement of the traffic velocity and vehicle density in the controlled segment. The adaptive controller applied iteratively learns by utilizing the recent value of the control signal and the recent observed behavior of the controlled system. The here applied "preliminary" or experimental version must be completed with safety limitations that prevent negative $\hat{r}_2$ at the ingress side that cannot be realized in an actual road. In similar manner, the occurrence of negative velocities has to be excluded on the same reason. From the theory of partial differential equations it is well known that the boundary conditions very significantly influence the behavior of the solutions. In the here considered example we applied a well defined boundary condition by prescribing constant ρ_0, v_0, and $v_4 = v_5$ values. For practical applications fitted polynomial packages could be prepared for several reasonable ρ_0, v_0, and $v_4 = v_5$ combinations depending on some "typical" traffic situations.

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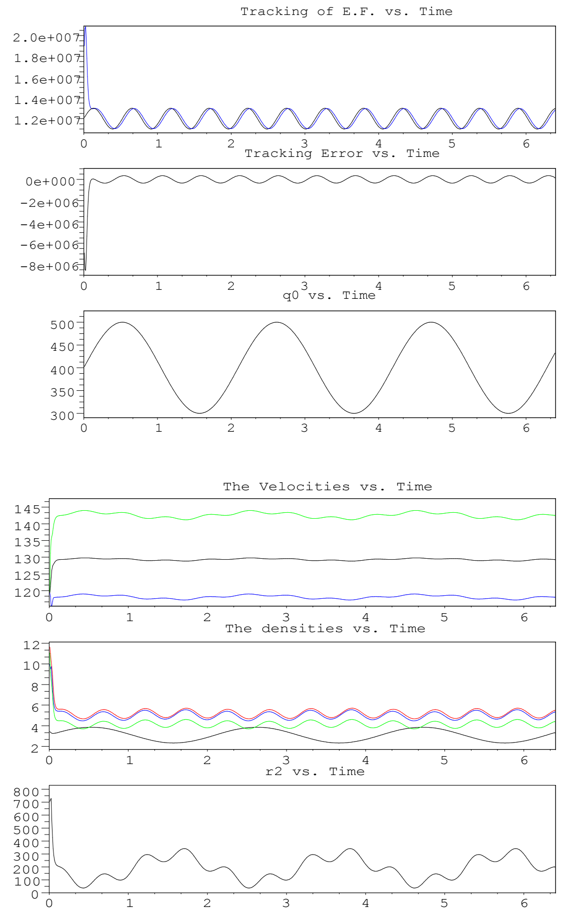

Fig. 7. Emission factor tracking of the *adaptive controller using the approximate model parameters* of the controlled system for smooth q_0 ingress rate and $10\,s$ cycle-time: E_f^{Nom}:-black, E_f:-blue lines in km^2/h^3 units in the upper chart; v_1:-black, v_2:-blue, v_3:-green lines in km/h units, ρ_1:-black, ρ_2:-blue, ρ_3:-green, ρ_4:-red lines in $1/km$ units in the lower chart, time is given in h units.

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