Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Two-class emission traffic control for freeway systems

Cecilia Pasquale, Simona Sacone, Silvia Siri

Department of Informatics, Bioengineering, Robotics and Systems Engineering, University of Genova, Italy.

Abstract: In the paper a traffic control strategy based on ramp metering is proposed in order to reduce traffic emissions in freeway stretches. Such strategy is devised to take into account that two vehicle classes are present in the freeway (cars and trucks) and that they are separately controlled. The simulation analysis developed in the paper shows, first of all, that the proposed control strategy is able not only to reduce traffic emissions in the freeway but also to reduce the congestion, by decreasing the total time spent by vehicles in the system. Moreover, the effectiveness of the two-class ramp metering control is shown on different traffic scenarios, that are deeply analysed and discussed in the paper.

1. INTRODUCTION

Road transport is one of the main sources of air pollution, and for this reason it has become more and more important to estimate traffic emissions precisely in order to design appropriate pollution-reduction measures [1]. One of the most widespread traffic emission models used within the European context is the COPERT model, which represents the vehicle emissions as functions of the vehicle mean travel speed. Hence COPERT belongs to the class of the so-called average-speed models that have been progressively updated on the basis of real measured data obtained from different sources. COPERT will be used in this paper to compute the traffic emissions, since the aim of this work is to propose a two-class traffic control scheme in order to reduce traffic emissions in freeway systems.

The traffic control approaches for freeway systems present in the literature consider different control objectives. The most of them are devoted to reduce congestion, often measured in terms of total time spent by the drivers in the traffic network [2], but there are also some recent results considering other goals, such as the decrease in fuel consumptions or the minimization of traffic emissions [3, 4, 5]. In our case, we propose a two-class local ramp metering strategy to control the traffic flow entering the mainstream; in [6] we have shown that, adopting such a control strategy, the two objectives of minimizing the total time spent and of minimizing the total emissions are not conflicting. In the simulation analysis provided in the present work we will confirm this result and we will show different scenarios in which the controlled system is characterized by a reduction of both the total time spent and the total emissions with respect to the open-loop case.

The control strategy considered in this work is based on the feedback traffic controller ALINEA [7], which has been successfully implemented in many real cases. Other more sophisticated traffic control approaches can be found in the literature, such as for instance those based on Model Predictive Control [8, 9]. However, these control approaches are not taken into account in this work since we aim at designing a local ramp metering strategy that is simple and flexible, and ALINEA has shown, also in real applications, to present these characteristics [10].

One of the peculiarities of our work stands in considering a two-class traffic model in order to separately control cars and trucks. Generally speaking, it is useful to adopt a two-class model whenever the considered freeway system is characterized by a significant presence of slow vehicles: in that case classical macroscopic models are not completely adequate since vehicles do not form a homogeneous flow, but two different flows can be identified. Besides explicitly modeling different classes, it seems useful to define the control measures specifically for different vehicle classes, cars and trucks in particular. Devising ramp-metering control strategies specific for each vehicle class means that different lanes in the on-ramps, with different traffic lights, are assigned to different vehicle typologies. Some multiclass models can be found in the literature, such as for instance [11] and [12].

The two-class model and the local ramp metering strategy adopted in this work are an extended version of the work [5] and are, instead, the same adopted in [6]. However, the objective of the present work is quite different from the one in [6]: in [6] we have analysed how the performance of the controlled system (in terms of emissions and total time spent) changes while varying the set-point value of the occupancy to be set in the local control strategy, both in the one-class and in the two-class case. In the present work, instead, the simulation analysis is completely different and devoted to analyse the behaviour of the traffic densities and the queue lengths, for each vehicle category, in different traffic scenarios, in order to show the effectiveness of the proposed two-class control strategy.

The paper is organized as follows. Section 2 describes the two-class macroscopic traffic model adopted in this work, whereas Section 3 describes the proposed ramp metering strategy to reduce traffic emissions. Then, in Section 4 the results of the developed simulation analysis are reported and discussed in detail. Finally, in Section 5 some conclusive comments are drawn.

2. THE TWO-CLASS TRAFFIC MODEL

The two-class traffic model adopted in this paper is obtained by extending the macroscopic traffic flow model Metanet [13] to the case in which two classes of vehicles are explicitly taken into account, as in [6]. The two-class model is motivated by the fact that cars and trucks constitute two traffic flows which share the same freeway stretch. Obviously, distinguishing trucks from cars is much more required if the percentage of trucks in the overall traffic flow is quite high. Moreover, in our work we suppose that different control actions can be actuated for cars and trucks.

The macroscopic traffic flow model is based on the subdivision of the freeway stretch in N sections and the discretization of the time horizon in K time steps. In this paper, $k = 0, \dots, K$, denotes the time step, $i = 1, \dots, N$, indicates the section of the freeway stretch, and $c = 1, 2$, represents the vehicle class ($c = 1$ represents the class of cars whereas $c = 2$ indicates the class of trucks). T is the sample time interval and Δ_i is the length of section i. Referring to section i and time step k, the main aggregate variables to be considered are:

- $\rho_{i,c}(k)$ is the traffic density of class c (expressed in vehicles of class c per space unit);
- $\rho_i^{\text{tot}}(k)$ is the total traffic density (expressed in vehicles of class 1 per space unit);
- $v_{i,c}(k)$ is the mean traffic speed of class c (expressed in space unit per time unit);
- $q_{i,c}(k)$ is the traffic volume of class c (expressed in vehicles of class c per time unit);
- $l_{i,c}(k)$ is the queue length of vehicles of class c waiting on the on-ramp (expressed in vehicles of class c);
- $d_{i,c}(k)$ is the traffic volume of class c requiring to enter the freeway from the on-ramp (expressed in vehicles of class c per time unit);
- $r_{i,c}(k)$ is the on-ramp traffic volume of class c (expressed in vehicles of class c per time unit);
- $r_i^{\text{tot}}(k)$ is the total on-ramp traffic volume (expressed in vehicles of class 1 per time unit);
- $s_{i,c}(k)$ is the off-ramp traffic volume of class c (expressed in vehicles of class c per time unit).

In case a certain section i is not provided with on-ramps and off-ramps, the corresponding variables $r_{i,c}(k)$, $s_{i,c}(k)$, $l_{i,c}(k)$ and $d_{i,c}(k)$, $k = 0, \dots, K$, $c = 1, 2$, are fixed equal to 0. In the considered model, the following quantities are also defined: the free-flow speed $V_{\text{f},c}$, for each class $c = 1, 2$, the critical density ρ_{cr} (expressed in vehicles of class 1 per space unit), the jam density $\rho_{\max}$ (expressed in vehicles of class 1 per space unit), the on-ramp capacity $r_{\max,c}$ for each class $c = 1, 2$ (expressed in vehicles of class c per time unit) and the parameter η, that is a conversion factor between cars and trucks. The meaning of parameter η, that in this paper is assumed to be a constant value, is analogous to the definition of passenger car equivalents (PCE), that are considered as the number of passenger cars displaced by a single heavy vehicle.

The two-class dynamic model is given by the following equations

$$\rho_{i,c}(k+1) = \rho_{i,c}(k) + \frac{T}{\Delta_i}\Big[q_{i-1,c}(k) - q_{i,c}(k) + r_{i,c}(k) - s_{i,c}(k)\Big]$$
$$c = 1,2, \quad i = 1, \dots, N, \quad k = 0, \dots, K-1 \quad (1)$$

$$v_{i,c}(k+1) = v_{i,c}(k) + \frac{T}{\tau_c}\Big[V_{i,c}(k) - v_{i,c}(k)\Big] + \frac{T}{\Delta_i} v_{i,c}(k)\big(v_{i-1,c}(k) - v_{i,c}(k)\big) - \frac{\nu_c T\big(\rho_{i+1}^{\text{tot}}(k) - \rho_i^{\text{tot}}(k)\big)}{\tau_c \Delta_i\big(\rho_i^{\text{tot}}(k) + \chi_c\big)} - \delta_{\text{on},c} T \frac{v_{i,c}(k) r_i^{\text{tot}}(k)}{\Delta_i(\rho_i^{\text{tot}}(k) + \chi_c)}$$
$$c = 1,2, \quad i = 1, \dots, N, \quad k = 0, \dots, K-1 \quad (2)$$

$$l_{i,c}(k+1) = l_{i,c}(k) + T\big[d_{i,c}(k) - r_{i,c}(k)\big]$$
$$c = 1,2, \quad i = 1, \dots, N, \quad k = 0, \dots, K-1 \quad (3)$$

$$V_{i,c}(k) = V_{\text{f},c} \cdot \left[1 - \left(\frac{\rho_i^{\text{tot}}(k)}{\rho_{\max}}\right)^{l_c}\right]^{m_c}$$
$$c = 1,2, \quad i = 1, \dots, N, \quad k = 0, \dots, K-1 \quad (4)$$

$$q_{i,c}(k) = \rho_{i,c}(k) \cdot v_{i,c}(k)$$
$$c = 1,2, \quad i = 1, \dots, N, \quad k = 0, \dots, K-1 \quad (5)$$

$$\rho_i^{\text{tot}}(k) = \rho_{i,1}(k) + \eta \rho_{i,2}(k)$$
$$i = 1, \dots, N, \quad k = 0, \dots, K-1 \quad (6)$$

$$r_i^{\text{tot}}(k) = r_{i,1}(k) + \eta r_{i,2}(k)$$
$$i = 1, \dots, N, \quad k = 0, \dots, K-1 \quad (7)$$

where τ_c, ν_c, χ_c, $\delta_{\text{on},c}$, l_c, m_c, $c = 1, 2$, are suitable model parameters.

In case the freeway system is not controlled, the on-ramp entering flow can be computed as follows

$$r_{i,c}(k) = \min\left\{d_{i,c}(k) + \frac{l_{i,c}(k)}{T}, r_{\max,c}, r_{\max,c} \cdot \frac{\rho_{\max} - \rho_i^{\text{tot}}(k)}{\rho_{\max} - \rho_{cr}}\right\}$$
$$i = 1, \dots, N, \quad c = 1,2, \quad k = 0, \dots, K-1 \quad (8)$$

If the on-ramps are controlled via ramp metering and denoting with $\bar{r}_{i,c}(k)$ the actuated on-ramp flow for ramp of section i at time step k for class c, (8) is substituted by

$$r_{i,c}(k) = \min\left\{d_{i,c}(k) + \frac{l_{i,c}(k)}{T}, \bar{r}_{i,c}(k), r_{\max,c}, r_{\max,c} \cdot \frac{\rho_{\max} - \rho_i^{\text{tot}}(k)}{\rho_{\max} - \rho_{cr}}\right\}$$
$$i = 1, \dots, N, \quad c = 1,2, \quad k = 0, \dots, K-1 \quad (9)$$

It is worth noting that the two-class model can be easily used to represent the one-class case by considering $c = 1$, $\rho_i^{\text{tot}}(k) = \rho_{i,1}(k)$ and $r_i^{\text{tot}}(k) = r_{i,1}(k)$ $i = 1, \dots, N, \quad k = 0, \dots, K-1$.

3. THE PROPOSED CONTROL SCHEME

In this work we adopt a local ramp metering strategy with the objective of minimizing the traffic emissions of cars and trucks in the freeway system. Different emission models can be found in the literature but in this work we are interested in considering the class of average-speed emission models since they are quite aggregate and then are easy to be adopted in our control approach. These models assume that the average emissions for a certain pollutant and for a certain type of vehicle only depend on the average speed during a trip. In particular, we rely on the COPERT model proposed in [14]. In this paper we consider a simplified traffic composition: we suppose that all the cars are gasoline cars, split in four legislation emission categories (from Euro 1 to Euro 4), and only the case of roads with no slope and half loaded trucks is considered for the truck emission models. Note that the methodology proposed in this paper could be easily adapted to the case of more complex traffic compositions.

According to COPERT, the hot emissions for gasoline passenger cars, referred to the emission legislation category $j = 1, \ldots, 4$ (from Euro 1 to Euro 4), are calculated as

$$E_1^j(v) = \frac{a_1^j + e_1^j v + f_1^j v^2}{1 + b_1^j v + d_1^j v^2} \tag{10}$$

where v represents the mean speed, whereas a_1^j, b_1^j, d_1^j, e_1^j and f_1^j, $j = 1, \ldots, 4$, are parameters which depend on the considered pollutant, the vehicle type and the engine capacity. Note that the index 1 is used to indicate that this is the model for class 1, i.e. for cars. As regards instead trucks, many formulations for the emission factors of heavy duty vehicles can be found in the literature. In [14] some of these formulations are reported, and in this work we refer in particular to the case of roads with no slope and half loaded trucks, i.e.

$$E_2(v) = a_2 + \frac{b_2}{1 + exp(-c_2 + d_2 \ln(v) + e_2 v)} \tag{11}$$

where v represents again the mean speed, and the parameters a_2, b_2, c_2, d_2 and e_2 depend on the considered load and slope conditions, according with the emission legislation. Analogously to the notation adopted before, in (11) the index 2 stands for class 2, i.e. trucks.

The ramp metering strategy adopted in this paper is based on the controller ALINEA [7] and in particular on its extended version of proportional integral type, called PI-ALINEA [15], properly adapted to the two-class case. Let us introduce PI-ALINEA for the one-class case, reminding that its main aim is to maximize the flow throughput at the merging area, considering both a proportional and an integrative logic. According to PI-ALINEA, the on-ramp flow for section i at time step k is computed as

$$\begin{aligned}\bar{r}_i(k) = \max\big\{ & r_{\min}, r_i(k-1) - K_P[o_i(k-1) - o_i(k-2)] \\ & + K_R[\hat{o} - o_i(k-1)]\big\}\end{aligned} \tag{12}$$

where $o_i(k-1)$ is the freeway occupancy measurement downstream of the ramp collected during the interval $[(k-1)T, kT)$, $o_i(k-2)$ is the same measurement during the interval $[(k-2)T, (k-1)T)$, $\hat{o}$ is a desired value for the downstream occupancy (normally set equal to the critical occupancy at which the freeway flow becomes maximum), $r_{\min}$ is the minimum on-ramp traffic volume, $K_R > 0$ and $K_P > 0$ are regulator parameters.

According to the two-class PI-ALINEA, the on-ramp flow of class c for section i at time step k is computed as

$$\begin{aligned}\bar{r}_{i,c}(k) = \max\big\{ & r_{\min,c}, r_{i,c}(k-1) \\ & - K_{Pc}[o_{i,c}(k-1) - o_{i,c}(k-2)] \\ & + K_{Rc} \cdot f_{i,c}(k-1)[\hat{o} - o_i^{\mathrm{tot}}(k-1)]\big\} \\ & c = 1,2, \quad i = 1,\ldots,N, \quad k = 0,\ldots,K-1\end{aligned} \tag{13}$$

In (13) $f_{i,c}(k)$ indicates the ratio of the occupancy of class c over the entire occupancy (referred to both the mainstream and the queues) computed as

$$f_{i,1}(k) = \frac{o_{i,1}(k)\Delta_i + l_{i,1}(k)}{o_{i,1}(k)\Delta_i + l_{i,1}(k) + \eta \cdot [o_{i,2}(k)\Delta_i + l_{i,2}(k)]} \quad i = 1,\ldots,N, \quad k = 0,\ldots,K-1 \tag{14}$$

$$f_{i,2}(k) = \frac{\eta \cdot [o_{i,2}(k)\Delta_i + l_{i,2}(k)]}{o_{i,1}(k)\Delta_i + l_{i,1}(k) + \eta \cdot [o_{i,2}(k)\Delta_i + l_{i,2}(k)]} \quad i = 1,\ldots,N, \quad k = 0,\ldots,K-1 \tag{15}$$

whereas the total occupancy $o_i^{tot}(k)$ is obtained as

$$o_i^{tot}(k) = o_{i,1}(k) + \eta o_{i,2}(k) \quad i = 1,\ldots,N, \quad k = 0,\ldots,K-1 \tag{16}$$

In (13) $r_{\min,c}$ is the minimum on-ramp traffic volume for class c, $c = 1,2$, while K_{Pc} and K_{Rc}, $c = 1,2$, are suitable parameters for the considered regulators. When the two-class PI-ALINEA is adopted to minimize traffic emissions, as in the present work, the set-point value for the occupancy in (13) must be properly set, as it has been shown in [6].

The adoption of a ramp metering control action can imply, in some cases, the formation of long queues, in particular when the mainstream is very congested. Such a situation is often undesirable, both because of physical limitations of the queues and because it implies a high concentration of polluting emissions due to the wait of vehicles at the on-ramp. Taking into account such a motivation, a constraint on the maximum queue length is added to the two-class PI-ALINEA defined above, according to the following logic. Suppose that the computed on-ramp flow to be actuated according to PI-ALINEA gives rise to a queue length that is too high, then such on-ramp flow should be increased in order to reduce the queue length to be almost equal to its maximum value. Let us denote with $l_{\max,i,c}$ the maximum queue length for section i and class c. First of all, a temporary value $\bar{r}_{i,c}^*(k)$ for the actuated on-ramp volume is computed as in (13), i.e.

$$\begin{aligned}\bar{r}_{i,c}^*(k) = \max\big\{ & r_{\min,c}, r_{i,c}(k-1) \\ & - K_{Pc}[o_{i,c}(k-1) - o_{i,c}(k-2)] \\ & + K_{Rc} \cdot f_{i,c}(k-1)[\hat{o} - o_i^{\mathrm{tot}}(k-1)]\big\} \\ & c = 1,2, \quad i = 1,\ldots,N, \quad k = 0,\ldots,K-1\end{aligned} \tag{17}$$

that would correspond to the on-ramp volume $r_{i,c}^*(k)$ and queue length $l_{i,c}^*(k+1)$, computed as in (3) and (9), i.e.

$$\begin{aligned}r_{i,c}^*(k) = \min\Big\{ & d_{i,c}(k) + \frac{l_{i,c}(k)}{T}, \bar{r}_{i,c}^*(k), r_{\max,c}, \\ & r_{\max,c} \cdot \frac{\rho_{\max} - \rho_i^{\mathrm{tot}}(k)}{\rho_{\max} - \rho_{cr}}\Big\} \\ & c = 1,2, \quad i = 1,\ldots,N, \quad k = 0,\ldots,K-1\end{aligned} \tag{18}$$

$$l_{i,c}^*(k+1) = l_{i,c}(k) + T\big[d_{i,c}(k) - r_{i,c}^*(k)\big] \quad c = 1,2, \quad i = 1,\ldots,N, \quad k = 0,\ldots,K-1 \tag{19}$$

Then, $l^*_{i,c}(k+1)$ represents the queue length that would be obtained if the flow $\bar{r}^*_{i,c}(k)$ were actuated. If such a queue exceeds the maximum length, this flow is actuated; otherwise, the flow is increased such that the queue does not exceed the maximum value, i.e.

$$\begin{aligned}
&\text{If} \quad l^*_{i,c}(k+1) \leq l_{\max,\mathrm{i,c}} \\
&\text{then} \\
&\bar{r}_{i,c}(k) = \bar{r}^*_{i,c}(k) \\
&\text{else} \\
&\bar{r}_{i,c}(k) = \bar{r}^*_{i,c}(k) + \frac{l^*_{i,c}(k+1) - l_{\max,\mathrm{i,c}}}{T}
\end{aligned} \tag{20}$$

4. SIMULATION RESULTS

The control strategy and the two-class dynamic model have been implemented with Matlab. The considered freeway stretch is composed of $N = 12$ sections, each one with a length $\Delta_i = 500$ [m], $i = 1, \ldots, 12$; this stretch is characterized by three on-ramps, that are present in sections 3, 5, 8. The sample time $T = 10$ [s] has been chosen and a total time horizon of 2 hours (corresponding to $K = 720$) has been considered for the simulation tests. Three traffic scenarios corresponding to decreasing congestion levels have been considered (scenario 1 is the most congested one). The traffic demands relative to cars and trucks for the three on-ramps in scenario 1 are reported, respectively, in Fig. 1 and in Fig. 2. The demands of scenarios 2 and 3 present similar behaviours but are characterized by lower values. The initial and boundary conditions are the same for the three scenarios and have been set equal to 40 [cars/km] and to 2.5 [trucks/km].

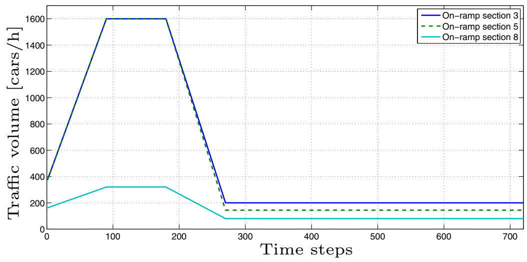

Fig. 1. Traffic demand of cars, scenario 1.

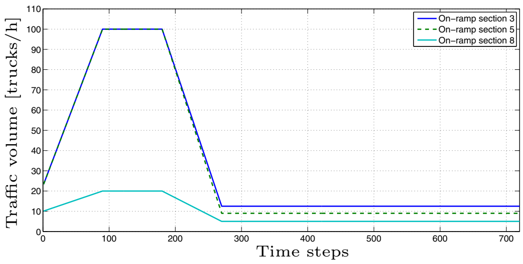

Fig. 2. Traffic demand of trucks, scenario 1.

Let us start analysing scenario 1, that is the most congested one. The behaviour of the traffic density in the open-loop case, for the two vehicle classes, is reported in Fig. 3 and in Fig. 4, showing a rather high congestion level.

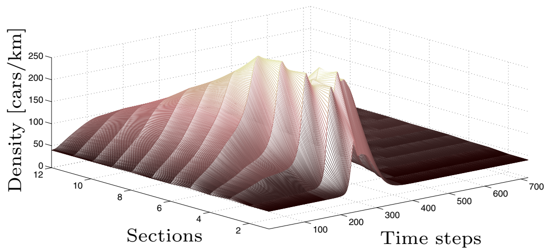

Fig. 3. Traffic density of cars, scenario 1 (open-loop).

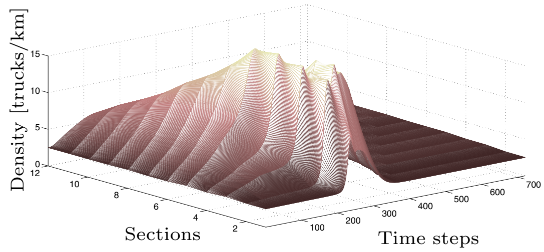

Fig. 4. Traffic density of trucks, scenario 1 (open-loop).

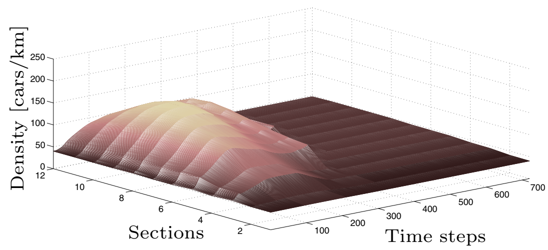

Fig. 5. Traffic density of cars, scenario 1 (without constraints).

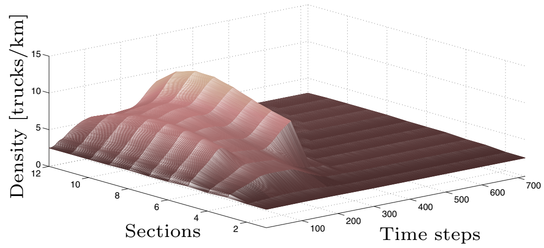

Fig. 6. Traffic density of trucks, scenario 1 (without constraints).

In this case the queue lengths at the on-ramps are null over the entire time horizon.

By applying the ramp metering control strategy, setting $\hat{o} = 127$ [veh/km] and without constraining the queue lengths at on-ramps, the congestion is strongly reduced, as shown by the density behaviours, for cars and trucks, reported in Fig. 5 and in Fig. 6. The resulting queue lengths at on-ramps are shown in Fig. 7 and in Fig. 8, for cars and trucks respectively. Note that the the queue of the first on-ramp is almost null and this is due to the local nature of the considered controller.

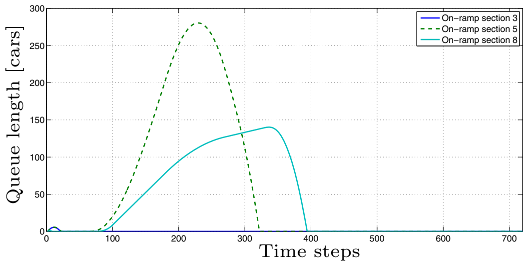

Fig. 7. Queue of cars, scenario 1 (without constraints).

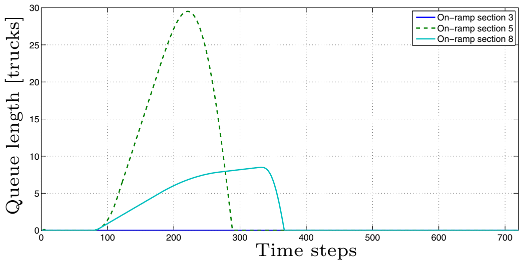

Fig. 8. Queue of trucks, scenario 1 (without constraints).

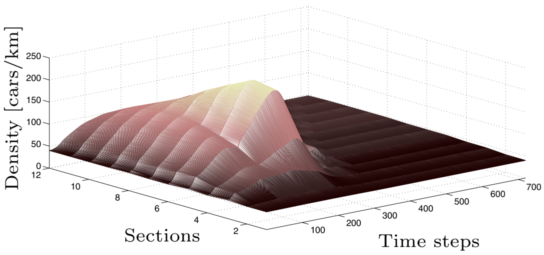

Fig. 9. Traffic density of cars, scenario 1 (with constraints).

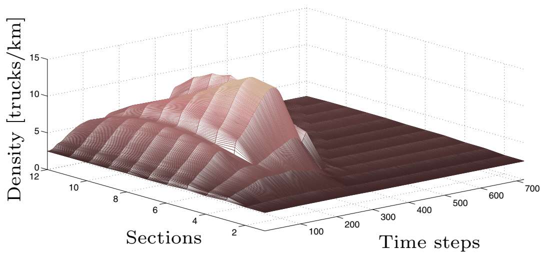

Fig. 10. Traffic density of trucks, scenario 1 (with constraints).

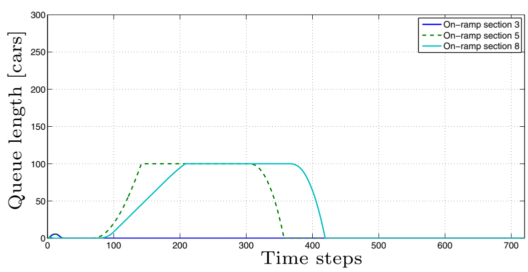

Fig. 11. Queue of cars, scenario 1 (with constraints).

The evolutions of the traffic densities, for cars and trucks, in case a limit on the queue lengths is set, are shown in Fig. 9 and in Fig. 10, whereas the queue lengths for each vehicle category are reported in Fig. 11 and in Fig. 12. In the considered case we have set a maximum queue length equal to 100 for cars and equal to 10 for trucks. Obviously, when setting a queue limit, the queue lengths are lower and consequently the traffic densities are higher (but much lower than in the open-loop case).

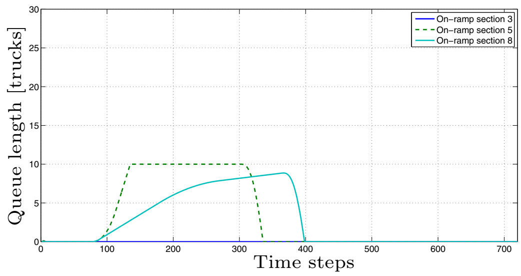

Fig. 12. Queue of trucks, scenario 1 (with constraints).

In order to compare the different scenarios, some performance indexes have to be introduced. First of all, the emissions in the mainstream can be computed separately for each vehicle class, as follows

$$E_1^{\text{main}} = \sum_{k=1}^{720} \sum_{i=1}^{12} \sum_{j=1}^{4} \Delta_i \cdot \rho_{i,1}(k) \cdot \gamma_1^j \cdot E_1^j\big(v_{i,1}(k)\big) \quad (21)$$

$$E_2^{\text{main}} = \sum_{k=1}^{720} \sum_{i=1}^{12} \Delta_i \cdot \rho_{i,2}(k) \cdot E_2\big(v_{i,2}(k)\big) \quad (22)$$

where $E_1^j\big(v_{i,1}(k)\big)$ and $E_2\big(v_{i,2}(k)\big)$ are computed respectively according to (10) and (11). In (21) γ_1^j represents the composition rate for cars related to legislation emission j. These composition rates must be such that $\sum_{j=1}^{4} \gamma_1^j = 1$ and in this case they are $\gamma_1^1 = 0.21$, $\gamma_1^2 = 0.19$, $\gamma_1^3 = 0.20$, $\gamma_1^4 = 0.40$. Moreover, in this analysis the considered pollutant is carbon monoxide.

Analogously, the emissions at the on-ramps can be computed separately for each vehicle class, as follows

$$E_1^{\text{ramp}} = \sum_{k=1}^{720} \sum_{i=1}^{12} \sum_{j=1}^{4} \gamma_1^j \cdot \alpha_1^j \cdot l_{i,1}(k) \quad (23)$$

$$E_2^{\text{ramp}} = \sum_{k=1}^{720} \sum_{i=1}^{12} \alpha_2 \cdot l_{i,2}(k) \quad (24)$$

where α_1^j, $j = 1, \ldots, 4$, are constant emission factors obtained from (10) in case of $v = 10$ [km/h] and α_2 is obtained from (11) with $v = 12$ [km/h].

The total mainstream emissions are $E^{\text{main}} = E_1^{\text{main}} + E_2^{\text{main}}$, the total on-ramp emissions are $E^{\text{ramp}} = E_1^{\text{ramp}} + E_2^{\text{ramp}}$ and the total emissions are $E^{\text{tot}} = E^{\text{main}} + E^{\text{ramp}}$. It is also possible to compute the emissions referred to class c, i.e. $E_c^{\text{tot}} = E_c^{\text{main}} + E_c^{\text{ramp}}$, $c = 1, 2$.

Besides the emissions in the freeway, other important indexes regard the capability of the control scheme to reduce the congestion. Such indexes are the Total Time Spent (TTS) and the Total Travelled Distance (TTD), computed as

$$TTS = T \cdot \sum_{k=1}^{720} \sum_{i=1}^{12} \Delta_i \Big(\rho_{i,1}(k) + \eta \cdot \rho_{i,2}(k) \Big) + \Big(l_{i,1}(k) + \eta \cdot l_{i,2}(k) \Big) \quad (25)$$

$$TTD = \sum_{k=1}^{720} \sum_{i=1}^{12} \Delta_i \cdot T \Big(q_{i,1}(k) + \eta \cdot q_{i,2}(k) \Big) \quad (26)$$

Finally, the Mean Speed (MS) is obtained as $MS = TTD/TTS$.

Table 1. Performances (without constraints).

Scenario	ΔE_1^{main}	ΔE_1^{tot}	ΔE_2^{main}	ΔE_2^{tot}	ΔE^{main}	ΔE^{tot}
1	-45.53	-16.92	-49.56	-13.51	-46.41	**-16.18**
2	-28.66	-7.30	-36.36	-1.47	-30.37	**-6.00**
3	-24.89	-5.45	-32.35	+0.81	-26.53	**-4.07**

Scenario	ΔTTD	ΔTTS^{tot}	ΔMS
1	0.00	-9.90	10.99
2	0.00	-6.56	7.02
3	0.00	-5.42	5.74

In Table 1 the performances of the three considered scenarios are evaluated in the case without queue constraints. In particular, each column reports the percentage improvement of the previously cited indexes with respect to the open-loop case. The same percentage improvement indexes are reported in Table 2 for the case with queue constraints.

Table 2. Performances (with constraints).

Scenario	ΔE_1^{main}	ΔE_1^{tot}	ΔE_2^{main}	ΔE_2^{tot}	ΔE^{main}	ΔE^{tot}
1	-33.64	-12.61	-33.77	-4.59	-33.67	**-10.87**
2	-25.06	-6.34	-31.54	-6.47	-26.50	**-6.37**
3	-22.78	-5.03	-29.47	-4.62	-24.25	**-4.94**

Scenario	ΔTTD	ΔTTS^{tot}	ΔMS
1	0.00	-4.62	4.85
2	0.00	-5.83	6.19
3	0.00	-5.25	5.54

By analysing these percentage improvement indexes with respect to the open-loop case, it can be seen that the system performance gets better when the proposed ramp metering control strategy is applied, both in terms of traffic emission reduction and in terms of total time spent reduction (or total mean speed increase). Hence, it can be concluded that adopting the proposal control scheme yields an improvement of the considered system performance also in the case in which queue constraints are imposed.

5. CONCLUSION

A two-class ramp metering strategy for freeway stretches has been designed in the paper. By extending the METANET model and the PI-ALINEA regulator to the two-class case, it is possible to improve the freeway system performance both in terms of pollutant emissions and in terms of traffic behaviour. Such results have been described and shown in the paper through a detailed simulation analysis.

REFERENCES

[1] R. Smit, L. Ntziachristos and P. Boulter. Validation of road vehicle and traffic emission models - A review and meta-analysis. *Atmospheric Environment*, 44: 2943–2953, 2010.

[2] M. Papageorgiou, A. Kotsialos. Freeway Ramp Metering: An Overview. *IEEE Trans. on Int. Transp. Systems*, 3:271–281, 2002.

[3] S.K. Zegeye, B De Schutter, J. Hellendoorn, E.A. Breunesse, A. Hegyi. Integrated macroscopic traffic flow, emission, and fuel consumption model for control purposes. *Transp. Res. C*, 31:158-171, 2013.

[4] A. Csikós, T. Luspay, I. Varga. Modeling and optimal control of travel times and traffic emission on freeways. *Proc. of the 18th IFAC World Congress*, 13058–13063, 2011.

[5] C. Pasquale, S. Sacone, S. Siri. Multi-class local ramp metering to reduce traffic emissions in freeway systems. *Proc. of the IFAC Workshop ACATTA*, 43–48, 2013.

[6] C. Pasquale, S. Sacone, S. Siri. Ramp metering control for two vehicle classes to reduce traffic emissions in freeway systems. *Proc. of the European Control Conference*, to appear, 2014.

[7] M. Papageorgiou, H. Hadj-Salem, J.-M. Blosseville. ALINEA: A local feedback control law for on-ramp metering. *Transp. Res. Record*, 1320:58–64, 1991.

[8] A. Hegyi, B. De Schutter, H. Hellendoorn. Model predictive control for optimal coordination of ramp metering and variable speed limits. *Transp. Res. C*, 13:185–209, 2005.

[9] A. Ferrara, A. Nai Oleari, S. Sacone, S. Siri. An event-triggered Model Predictive Control scheme for freeway systems. *Proc. of 51th IEEE Conf. on Decision and Control*, 6975–6982, 2012.

[10] M. Papageorgiou, E. Kosmatopoulos, I. Papamichail, Y. Wang. ALINEA maximises motorway throughput - an answer to flawed criticism. *TEC Magazine*, 271–276, 2007.

[11] S.P. Hoogendoorn, P.H.L. Bovy. Platoon-Based Multiclass Modeling of Multilane Traffic Flow. *Networks and Spatial Economics*, 1:137–166, 2001.

[12] G.C.K. Wong, S.C. Wong. A multi-class traffic flow model - an extension of LWR model with heterogeneous drivers. *Transp. Res. A*, 36:827–841, 2002.

[13] M. Papageorgiou, J.-M. Blosseville, H. Hadj-Salem. Modelling and realtime control of traffic flow on the southern part of Boulevard Périphérique in Paris: Part I: Modelling. *Transp. Res. A*, 24:345–359, 1990.

[14] L. Ntziachristos, C. Kouridis. Road transport emission chapter of the EMEP/CORINAIR Emission Inventory Guidebook *European Environment Agency Techn. Report 16/2007*, Copenhagen, Denmark, 2007.

[15] Y. Wang, M. Papageorgiou, J. Gaffney, I. Papamichail, J. Guo. Local ramp metering in the presence of random-location bottlenecks downstream of a metered on-ramp. *Proc. of 13th IEEE Conf. on Int. Transp. Systems*, 1462–1467, 2010.