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Feed-Forward ALINEA: A ramp metering control algorithm for nearby and distant bottlenecks

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***Abstract*—This paper proposes a new ramp metering control algorithm, Feed-Forward ALINEA (FF-ALINEA), for bottlenecks located both nearby on an on-ramp and further away from it (i.e. more than just a few hundred meters). The formulation of the controller is based on a feed-forward modification of the well-known control algorithm for ramp metering, ALINEA. The feed-forward structure allows to anticipate the future evolution of the bottleneck density in order to avoid or reduce traffic breakdowns.**

The proposed controller is tested, using the macroscopic traffic flow model METANET, for 9 scenarios and the results are compared with the ones obtained with ALINEA, PI-ALINEA, and with the optimal solution.

The simulations show that FF-ALINEA is able to approach the optimal behavior, thereby outperforming ALINEA and PI-ALINEA. Moreover, results indicate that FF-ALINEA is quite robust in cases where different demands are considered, there is a limited number of available detectors, or there are errors in the estimation of the capacity and/or the critical density of the bottleneck.

***Index Terms*—Ramp Metering, ALINEA, PI-ALINEA, FF-ALINEA, Feed-forward control, Freeway traffic control.**

I. INTRODUCTION

TRAFFIC jams on freeways cause many social and economic problems in daily life, such a waste of fuel and time, an increase in pollution, and greater accident risk. Much research has been focused on solving these problems without constructing new infrastructure, because that choice is not always a viable option or it cannot be afforded. Ramp metering is the most successfully implemented and widely used freeway control measure among the most promising dynamic traffic control measures (such as variable speed limits [1], reversible lanes [2], route guidance [3], . . .). Ramp metering has already been successfully implemented in practice in France, United States, Germany, Australia, and several countries [4], [5].

Over a period of more than 30 years, a wide range of local and coordinated ramp metering algorithms have been proposed. Literature reviews about the most relevant of these control algorithms for ramp metering can be found in [6] (for algorithms proposed before 2002) and [7] (for more recent advancements). Among all these algorithms, ALINEA [8] is the most widely deployed ramp metering strategy. ALINEA is based on a feedback structure and is derived by use of classical automatic control methods. ALINEA is a simple, robust, and easy-to-implement strategy for ramp metering.

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ALINEA is effective and efficient in handling merging congestion [4], [9]. However, as stated in some references such as [10], [11] and as it can be observed in the numerical results for the case study in Section IV, ALINEA is not effective (i.e. performs quite suboptimally) if the bottleneck is located far away from the on-ramp (more than just a few hundred meters).

In order to deal with this problem, PI-ALINEA was proposed in [12] and integrated with the control of variable speed limits in [13]. PI-ALINEA improves the performance given by ALINEA for a distant bottleneck. However, the obtained behavior can still be substantially improved, especially in terms of robustness. Moreover, PI-ALINEA has two parameters that have to be calibrated, which complicates the implementation compared with ALINEA, which only has one parameter.

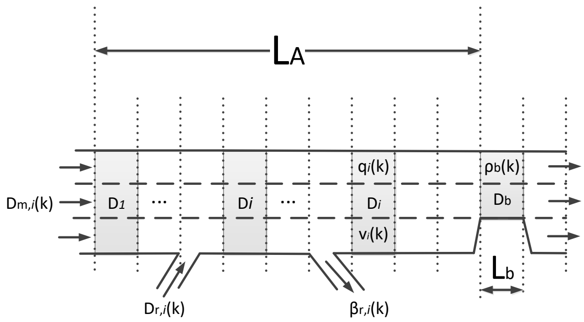

Fig. 1. Freeway stretch with one bottleneck due to a decrease in the number of lanes. In the stretch, there are flow and speed detectors (D_i) located at the segments in grey (upstream of the bottleneck), there is also one detector located at the bottleneck measuring density, $D_{\mathrm{m},i}(k)$ and $D_{\mathrm{r},i}(k)$ are the mainline and on-ramp demands, and $\beta_{\mathrm{r},i}(k)$ are off-ramp split ratios.

This paper proposes a feed-forward controller (FF-ALINEA) based on ALINEA in order to improve the performance when the main congestion is created on a downstream bottleneck located far away from the on-ramp while keeping the performance for nearby locations. The paper is organized as follows: Section II introduces the previously proposed algorithms ALINEA and PI-ALINEA. Section III proposes, explains, motivates and analyzes the FF-ALINEA controller. Section IV-A shows the model used for simulation (METANET), the scenarios that have been considered, the characteristic of the optimization overtaken, and the simulation results obtained for these scenarios. Finally, the conclusions are presented in Section V.

II. ALINEA AND PI-ALINEA

A. ALINEA

The feedback control law applied by ALINEA for a ramp metering installation located at segment i at time step k is:

$$r_i(k+1) = r_i(k) + K_{\mathrm{A}}(\bar{\rho} - \rho_{\mathrm{b}}(k)) \tag{1}$$

where $r(k)$ is the ramp metering rate applied over $[(k-1)T_{\mathrm{c}}, kT_{\mathrm{c}}]$, T_{c} is the length of the control time step interval, $\bar{\rho}$ is the desired set-point, $\rho_{\mathrm{b}}(k)$ is the lane-averaged mainstream density measurement collected during the control time interval $[(k-1)T_{\mathrm{c}}, kT_{\mathrm{c}}]$ at a bottleneck downstream of the controlled on-ramp, and K_{A} is a positive parameter.

B. PI-ALINEA

PI-ALINEA is a feedback ramp metering strategy similar to ALINEA but using a proportional-integral (PI) controller structure:

$$\begin{aligned} &r_i(k+1) = \\ &r_i(k) + K_{\mathrm{R}}\left(\bar{\rho} - \rho_{\mathrm{b}}(k)\right) - K_{\mathrm{P}}(\rho_{\mathrm{b}}(k) - \rho_{\mathrm{b}}(k-1)) \end{aligned} \tag{2}$$

where K_{R} and K_{P} are positive parameters.

C. Selection of the set point:

Both ALINEA and PI-ALINEA use a density set-point that is typically set equal to the critical density of the bottleneck ($\bar{\rho} = \rho_{\mathrm{b,c}}$). The value of this critical density can be easily estimated from real data by analyzing the flow/density measurements provided by a detector at the bottleneck.

D. Limitations of ALINEA and PI-ALINEA

The main limitation of ALINEA and PI-ALINEA, when applied to distant bottlenecks, is that the feedback is only based on the density of the bottleneck (and its previous values) while any change of the control action will need a certain amount of time to influence the bottleneck density.

As a consequence, if the bottleneck is in the same segment as the on-ramp, or nearby, the time needed to influence the bottleneck is short and, therefore, ALINEA is usually able to reduce the density of the bottleneck in time. However, if the bottleneck is far away from the on-ramp, the effects of ramp metering will need a longer time in order to affect the bottleneck. When the bottleneck density is then actually affected by a ramp metering action, it may be too late because, e.g., the density of the bottleneck may be already too high (over the critical density) and so a significant reduction of the capacity is already delaying traffic flows.

On the other hand, PI-ALINEA is able to anticipate the activation of ramp metering due to the integral term. However, if the bottleneck density is increased faster (or slower) than for the nominal case (used for the identification of the control parameters), the activation of the ramp metering will occur sooner (or later) than the optimal activation time. This will cause that the traffic jam is not avoided (late activation) or that ramp metering is unnecessarily activated (early activation).

III. FEED-FORWARD ALINEA (FF-ALINEA)

A. Control structure

The goal of this paper is to propose a modification of ALINEA that is able to anticipate the future evolution of the bottleneck density in order to avoid or reduce traffic breakdowns in cases where the on-ramp is far away from the bottleneck (such as, e.g., the freeway stretch shown in Figure 1). This can be achieved by the use of the "Feed-Forward ALINEA (FF-ALINEA)" control structure shown in Fig. 2.

As can be seen in the figure, FF-ALINEA makes use of the available measurements of speeds and flows upstream the bottleneck ($q_i(k)$, $v_i(k)$) in order to adjust the time-varying density set point $\hat{\rho}(k)$ (which, in case of ALINEA and PI-ALINEA, is constant and usually equal the critical density) for each control time step k:

$$r_i(k+1) = r_i(k) + K_{\mathrm{FF}}(\hat{\rho}(k) - \rho_{\mathrm{b}}(k)) \tag{3}$$

where K_{FF} is a positive parameter. The computation of the time-varying density set-point $\hat{\rho}(k)$ is justified and explained in the following subsections.

B. Simplified modeling

In order to define a convenient equation for $\hat{\rho}(k)$, a simplified model to predict the evolution of bottleneck density is used (because the goal is to propose an easy-to-implement linear controller, similar to ALINEA).

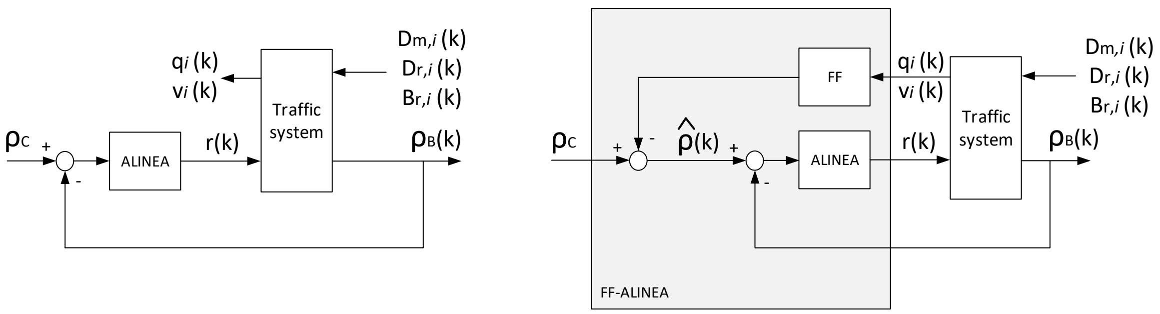

Fig. 2. Control structure for ALINEA (left) and FF-ALINEA (right), where $\hat{\rho}(k)$ is a time-varying density set-point used by FF-ALINEA.

Firstly, the conservation of vehicles is used to predict the value of the density of the bottleneck after a given period of time T_{A} (for the sake of simplicity, in this subsection it is assumed that T_{A} is a multiple integer of the simulation time step T):

$$\rho_{\mathrm{b}}(k+T_{\mathrm{A}}/T)=\rho_{\mathrm{b}}(k)+\frac{T_{\mathrm{A}}}{\lambda_{\mathrm{b}}L_{\mathrm{b}}}(Q_{\mathrm{ib}}(k)-Q_{\mathrm{ob}}(k)) \quad (4)$$

where $Q_{\mathrm{ib}}(k)$ is the flow over all lanes (veh/h) entering the bottleneck during the considered period T_{A}, λ_{b} is the number of lanes of the bottleneck, L_{b} is the length of the section of the bottleneck where the congestion is created (decreasing the corresponding outflow due to the capacity drop), and $Q_{\mathrm{ob}}(k)$ is the flow leaving the bottleneck during T_{A}.

Subsequently, the previous equation is simplified using the following assumptions:

- The traffic upstream of the bottleneck (i.e. within L_{A}) is assumed to be uncongested, implying that the speed of flow propagation equals the vehicle propagation speed.
- The period of time T_{A} will be chosen such as all the vehicles located at time step k within certain distance L_{A} upstream of the bottleneck, and not more, are able to reach the bottleneck.
- It is assumed that the vehicles entering the bottleneck between time step k and time step $k+T_{\mathrm{A}}/T$ have been traveling during this period at a mean speed $\hat{v}_{\mathrm{A}}(k)$ before they reach the bottleneck.
- The flow leaving the bottleneck is bounded by the current capacity C_{b} of the bottleneck.

With these assumptions, (4) can be rewritten as:

$$\rho_{\mathrm{b}}(k+T_{\mathrm{A}}/T)\geq\rho_{\mathrm{b}}(k)+\frac{L_{\mathrm{A}}}{\lambda_{\mathrm{b}}L_{\mathrm{b}}\hat{v}_{\mathrm{A}}(k)}(Q_{\mathrm{ib}}(k)-C_{\mathrm{b}}) \quad (5)$$

C. Modification of the density set-point

The goal of a controller designed to maximize the outflow of a bottleneck (and, therefore, to locally minimize travel times) is to keep the density of the bottleneck around or below the critical density (i.e. $\rho_{\mathrm{b}}(k+T_{\mathrm{A}}/T)\leq\rho_{\mathrm{b,c}}$) [6].

Consequently, and considering equation (5), the following bound can be considered within the formulation of the controller:

$$\rho_{\mathrm{b,c}}\geq\rho_{\mathrm{b}}(k)+\frac{L_{\mathrm{A}}}{\lambda_{\mathrm{b}}L_{\mathrm{b}}\hat{v}_{\mathrm{A}}(k)}(Q_{\mathrm{ib}}(k)-C_{\mathrm{b}}) \quad (6)$$

This is equivalent to:

$$\rho_{\mathrm{b}}(k)\leq\rho_{\mathrm{b,c}}-\frac{L_{\mathrm{A}}}{\lambda_{\mathrm{b}}L_{\mathrm{b}}\hat{v}_{\mathrm{A}}(k)}(Q_{\mathrm{ib}}(k)-C_{\mathrm{b}}) \quad (7)$$

Therefore, since the goal of the controller is to respect inequality (7), the time-varying density set-point also has to respect its corresponding constraint:

$$\hat{\rho}(k)\leq\rho_{\mathrm{b,c}}-\frac{L_{\mathrm{A}}}{\lambda_{\mathrm{b}}L_{\mathrm{b}}\hat{v}_{\mathrm{A}}(k)}(Q_{\mathrm{ib}}(k)-C_{\mathrm{b}}) \quad (8)$$

ALINEA and PI-ALINEA (for which $\hat{\rho}(k)$ is set equal to ρ_{c}) do not respect this constraint in cases where the arriving flow is larger than the capacity of the bottleneck.

On the other hand, FF-ALINEA modifies the set-point in real time as follows in order to respect inequality (8):

$$\hat{\rho}(k)=\rho_{\mathrm{b,c}}-\max\left(\frac{L_{\mathrm{A}}}{\lambda_{\mathrm{b}}L_{\mathrm{b}}\hat{v}_{\mathrm{A}}(k)}(Q_{\mathrm{ib}}(k)-C_{\mathrm{b}}),0\right) \quad (9)$$

where $\hat{v}_{\mathrm{A}}(k)$ and $Q_{\mathrm{ib}}(k)$ have to be estimated for each time step based on real-time data (see Section III-E below).

D. FF-ALINEA

Using (3) and (9), the control law for the implementation of FF-ALINEA is obtained:

$$\begin{aligned} r_i(k+1)=r_i(k)+ \qquad\qquad\qquad\qquad\qquad\qquad\qquad (10)\\ K_{\mathrm{FF}}\left(\rho_{\mathrm{b,c}}-\max\left[\frac{L_{\mathrm{A}}}{\lambda_{\mathrm{b}}L_{\mathrm{b}}\hat{v}_{\mathrm{A}}(k)}(Q_{\mathrm{ib}}(k)-C_{\mathrm{b}}),0\right]-\rho_{\mathrm{b}}(k)\right)\end{aligned}$$

where L_{b}, and λ_{b} are based on the network topology, L_{A} is chosen based on the available detectors upstream of the bottleneck, $Q_{\mathrm{ib}}(k)$ and $\hat{v}_{\mathrm{A}}(k)$ have to be estimated on-line using measurements available from detectors located upstream of the bottleneck (see the following subsection), $\rho_{\mathrm{b,c}}, C_{\mathrm{b}}$ and K_{FF} have to be estimated off-line (or in an adaptive way), and $\rho_{\mathrm{b}}(k)$ has to be measured (or estimated) every control time step.

E. Entering flow and mean speed estimation

The implementation of (10) requires the online estimation of $Q_{\mathrm{ib}}(k)$ and $\hat{v}_{\mathrm{A}}(k)$. The method used for this estimation can be adapted according to the number of detectors available and the topology of the network.

We could consider 4 different cases:

- If we have measurements available in many detectors upstream the bottleneck, an easy and accurate way to estimate $Q_{\mathrm{ib}}(k)$ and $\hat{v}_{\mathrm{A}}(k)$ is to use the weighted summation of all the flows and speeds:

$$\begin{aligned} Q_{\mathrm{ib}}(k)&=\frac{\sum_{i\in D_A}(q_i(k)L_i)}{L_{\mathrm{A}}} \qquad (11)\\ \hat{v}_{\mathrm{A}}(k)&=\frac{\sum_{i\in D_A}(v_i(k)L_i)}{L_{\mathrm{A}}}\end{aligned}$$

  where q_i is the flow measured at detector i, L_i is the distance between detector i and detector $i+1$, A is the stretch of the freeway between the first detector and the bottleneck, D_A is the set of detectors in freeway stretch A, and L_{A} is the length of this stretch.
- If there is only one detector available upstream the bottleneck, $Q_{\mathrm{ib}}(k)$ and $\hat{v}_{\mathrm{A}}(k)$ can be estimated by taking the temporal mean of the measurements during the last period T_{A} (using the current value of the speed measurements in order to predict T_{A}):

$$\begin{aligned} T_{\mathrm{A}}&=L_{\mathrm{A}}/v_m(k) \qquad (12)\\ \hat{v}_{\mathrm{A}}(k)&=\sum_{l=0}^{[T_{\mathrm{A}}/T]}\frac{v_m(k-l)}{T_{\mathrm{A}}/T}\\ Q_{\mathrm{ib}}(k)&=\sum_{l=0}^{[T_{\mathrm{A}}/T]}\frac{q_m(k-l)}{T_{\mathrm{A}}/T}\end{aligned}$$

where $q_m(k)$ and $v_m(k)$ are flow and speed measurements on time step k for the available detector and L_{A} is the distance between this detector and the bottleneck.
- If there are no speed measurements available (or if the estimation of $\hat{v}_{\mathrm{A}}(k)$ is avoided in order to simplify the controller formulation), the free-flow speed can be used for the estimation ($\hat{v}_{\mathrm{A}}(k) = v_{\mathrm{f}}$).
- If there are on-ramps or off-ramps between the first considered detector and the bottleneck, the flows entering/leaving the freeway by the ramps have to be taken into account during the estimation of $Q_{\mathrm{ib}}(k)$.
  For example, if there were one off-ramp just upstream of the bottleneck (but downstream of the detectors used for the estimation of $Q_{\mathrm{ib}}(k)$), the estimated flow would have to be adapted using the following equation:
  $$Q_{\mathrm{ib}}(k) = (1 - \beta(k)) \frac{\sum_{i \in D_A} (q_i(k) L_i)}{L_{\mathrm{A}}} \tag{13}$$
  where $\beta(k)$ is the split ratio of the off-ramp at time step k, which has to be measured or estimated online.

F. Theoretical behavior of FF-ALINEA

In order to theoretically compare the behavior of FF-ALINEA with ALINEA and PI-ALINEA, this subsection analyzes the behavior of the density set-point for the 4 cases arising when comparing the bottleneck density with the critical density and the entering flow with the capacity of the bottleneck. It has to be pointed out that these 4 cases just analyze the response of FF-ALINEA (proposed in Sections III-D and III-E above) without affecting its formulation.

- **Case 1:** $\rho_{\mathrm{b}}(k) \leq \bar{\rho}_{\mathrm{c}}$ and $Q_{\mathrm{ib}}(k) \leq C_{\mathrm{b}}(k)$. Under these conditions, the FF-ALINEA set-point is constant and equal to the critical density and, therefore, the behavior of FF-ALINEA is the same as that of ALINEA (both ALINEA and FF-ALINEA keep the ramp open under these conditions). In fact, if the estimated flow entering the bottleneck during the period T_{A} is lower than its capacity and the bottleneck is not congested, there is no need to apply any traffic control action.
- **Case 2:** $\rho_{\mathrm{b}}(k) \leq \bar{\rho}_{\mathrm{c}}$ and $Q_{\mathrm{ib}}(k) > C_{\mathrm{b}}(k)$. In this case, the new set-point $\hat{\rho}(k)$ used by FF-ALINEA is lower than the critical density. The new value of the set-point allows to activate ramp metering before the bottleneck reaches congestion.
  On the other hand, ALINEA has to wait until the bottleneck density has reached a value larger than the critical density causing an unavoidable capacity drop that cannot be compensated until the activation ramp metering affects the bottleneck.
  Under these conditions, PI-ALINEA is also able to activate ramp metering before the bottleneck reaches congestion using the integral term of the controller. However, its behavior highly depends on how fast the bottleneck density is increasing (i.e. it will depend on the scenario).
- **Case 3:** $\rho_{\mathrm{b}}(k) > \bar{\rho}_{\mathrm{c}}$ and $Q_{\mathrm{ib}}(k) \leq C_{\mathrm{b}}$. Again, the new set-point $\hat{\rho}(k)$ used by FF-ALINEA is equal to the one used by ALINEA.
  Ideally, the value of the set-point $\hat{\rho}(k)$ should to be higher than the critical density if the bottleneck density is going to decrease during the following minutes due to low flows arriving to the bottleneck. However, this case is not considered within FF-ALINEA for two reasons. Firstly, without using a calibrated macroscopic model, it is more difficult to predict the evolution of the density of a congested bottleneck compared to an uncongested one (because the capacity drop of a bottleneck is time-varying during congestion). Moreover, it is less important, in terms of Total Time Spent (TTS) reductions, to anticipate the activation of ramp metering compared to anticipate the deactivation of the ramp metering because a late activation of ramp metering can create or increase a new traffic jam that remains during a certain period of time while a late deactivation of ramp metering only delays the disappearance of an already existing traffic jam).
- **Case 4:** $\rho_{\mathrm{b}}(k) > \bar{\rho}_{\mathrm{c}}$ and $Q_{\mathrm{ib}}(k) > C_{\mathrm{b}}$. Under these conditions, the new set-point $\hat{\rho}(k)$ is lower than the critical density. Therefore, the proposed ramp metering rate using FF-ALINEA is lower than the one given by ALINEA (or equal if the ramp metering rates of both FF-ALINEA and ALINEA are saturated). This lower ramp metering rate allows to partially compensate the density increase that will be caused by the high flows.
  In other words, FF-ALINEA estimates that the already congested bottleneck is going to get more congested in the future and, consequently, FF-ALINEA decreases the ramp metering rate (with respect to the one obtained with ALINEA).

G. Advantages and Disadvantages of the controller

The main advantages of FF-ALINEA compared with ALINEA and PI-ALINEA are:

- The controller is able to activate ramp metering before the bottleneck is congested if the flow arriving at the bottleneck is higher than the capacity of the bottleneck. In many scenarios, this anticipation will allow to avoid or reduce the congestion created at the bottleneck and, therefore, to substantially decrease the TTS.
- The controller is able to activate ramp metering before the bottleneck is congested if the capacity of the bottleneck is suddenly decreased (e.g., due to a lane closure caused by an accident). Again, this will allow to avoid or reduce congestion created at the bottleneck created by the incident.
- As for ALINEA, only one control parameter has to be calibrated. The rest of the constant parameters can be easily found or chosen by considering the topology of the network ($\lambda_{\mathrm{b}}, L_{\mathrm{b}}, L_{\mathrm{A}}$).

The main disadvantages are:

- Tuning FF-ALINEA is more complex than for ALINEA because for ALINEA only two parameters ($\rho_{\mathrm{b,c}}$ and K_{A}) have to be estimated. On the other hand, fine-tuning of PI-ALINEA is similarly hard as or even harder than for FF-ALINEA:

- The critical density ($\rho_{\mathrm{b,c}}$) has to be estimated for both controllers.
- C_{b} (needed for FF-ALINEA) can be easily is estimated based on bottleneck detector data (such as $\rho_{\mathrm{b,c}}$).
- L_{A}, and L_{b} (needed for FF-ALINEA) can be found easily by just inspecting the network topology.
- $Q_{\mathrm{ib}}(k)$ and $\hat{v}_{\mathrm{A}}(k)$ (needed for FF-ALINEA) can be easily estimated on-line by just having one detector upstream of the bottleneck (where the estimation is improved if more detectors are available).
- On the other hand, only one control parameter (K_{FF}) has to be tuned for FF-ALINEA while two control parameters (K_{R} and K_{P}) have to tuned for PI-ALINEA.

• For real implementations of ALINEA and PI-ALINEA, at least 3 detectors are needed: one occupancy detector at the bottleneck and two detectors on the on-ramp (due to the limitation for the maximum number of vehicles waiting on the on-ramp queue). On the other hand, FF-ALINEA needs to use data from at least 4 detectors (the previous ones plus one flow detector upstream of the on-ramp). The higher the number of additional detectors (for flow and speed), which are currently installed in many segments of congested freeways, the better the performance that is obtained (as can be seen in Section IV-E).

IV. Simulation Results

A. Considered scenarios

A hypothetical 12 km long freeway stretch, shown in Fig. 3, is used in order to simulate the proposed FF-ALINEA controller and to compare its performance with ALINEA, PI-ALINEA and the optimal solution:

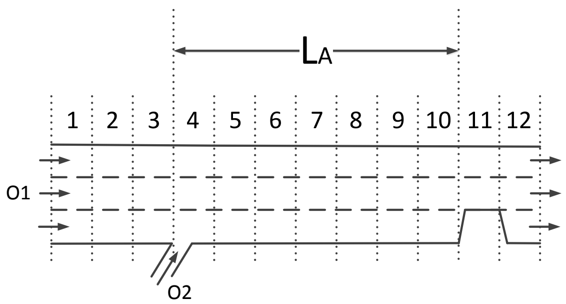

Fig. 3. Freeway stretch considered.

The freeway has $N = 12$ segments with $\lambda_i = 3$ lanes and with a length of $L_i = 1$ km for each segment, one controlled on-ramp at the beginning of segment 4 and one lane drop in segment 11 (i.e. segment 11 has only 2 lanes). Because of the lane drop, segment 11 is a bottleneck that will create congestion if the demands are high enough.

In order to simulate the considered freeway stretch, the METANET model [14] has been used. All the METANET parameters are considered to be the same for all the segments. The simulation time chosen is three hours corresponding to 180 controller sample steps ($T_{\mathrm{c}} = 60$ s) and 1080 simulation steps ($T = 10$ s). The on-ramp has a capacity of $C_{\mathrm{r},4} = 2000$ veh/h, the free-flow speed v_{f} is 110 km/h, the critical density ρ_{c} is 32 veh/(km·lane), the maximum density ρ_{m} is 180 veh/(km·lane), and the time constant τ is 18 s. The rest of the model parameters can be seen in Table I. As proposed in [15], the model takes different values for μ_i (μ_{H} and μ_{L}) depending on the downstream density.

TABLE I
METANET PARAMETERS

a	μ_{H}	μ_{L}	ϕ	K	δ
2	40 km^2/h	80 km^2/h	0.1	40	0.01

The ramp metering installation, the only traffic control measure within the freeway stretch, is located 7 kilometers upstream the bottleneck. Therefore, any change of the control action will need at least $7/v_{\mathrm{f}} = 3.82$ minutes to influence the bottleneck density (assuming that the vehicles are driving at the free-flow speed). If the speeds are lower than the free-flow speed, ramp metering will need more time to influence the bottleneck (e.g., if the vehicles have a mean speed of 40 km/h between segments 4 and 11, a change in the ramp metering rate will only affect the bottleneck after 10.5 minutes).

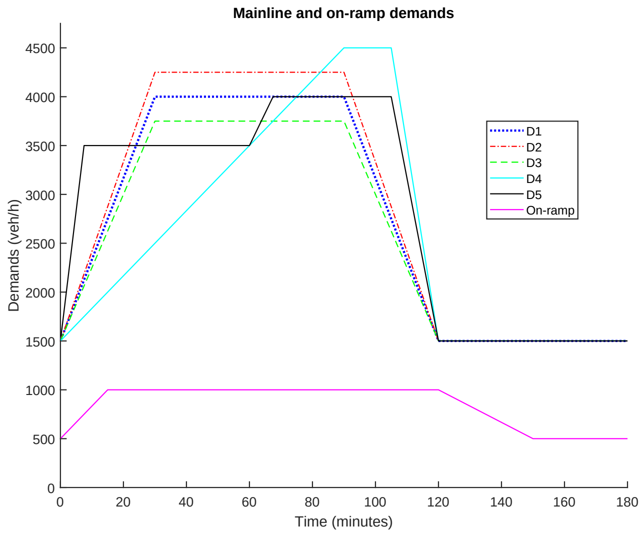

Fig. 4. Mainline and on-ramp demands

Five different mainline demands (shown in Fig. 4) and two maximum values for the number of vehicles waiting on the queue ($w_{\max}$) are considered. Combining the demands and the queue restrictions as shown in Table II, nine scenarios, with different levels of congestion, are considered. The on-ramp demand used is the same for the 9 scenarios and it is also shown in Fig. 4. Since the demand D_3 does not create congestion, only one scenario has been considered for D_3 because a queue constraint does not modify the obtained behavior.

TABLE II
CONSIDERED SCENARIOS

Scenario	1	2	3	4	5	6	7	8	9
Demand	D_1	D_1	D_2	D_2	D_3	D_4	D_4	D_5	D_5
$w_{\max}$	-	200	-	200	-	-	200	-	200

For the implementation of FF-ALINEA, it has been considered that there are flow and speed detectors available for all the segments between the on-ramp and the bottleneck (segments 4 to 11).

The critical density of the bottleneck (used by ALINEA, PI-ALINEA and FF-ALINEA) and the capacity of the bottleneck (used by FF-ALINEA) have been estimated using the flows and densities obtained by simulating METANET for Scenario 1 without any activation of ramp metering. As in previous references [11], [12], the obtained critical density and capacity ($\rho_{\mathrm{c,b}} = 36,78$ veh/(km·lane) and $C_{\mathrm{b}} = 4782$ veh/h) are larger than the one given by the METANET fundamental diagram (32 veh/(km·lane) and 4270 veh/h).

In order to ensure that the controllers respect the queue constraint ($w_4(k) < w_{\max}\ \forall\ k$), the following equation has been used after any controller time step for ALINEA, PI-ALINEA and FF-ALINEA.

$$r(k) = \begin{cases} \frac{D_r(k)}{C_r} + \frac{w_4(k)-w_{\max}}{T_{\mathrm{c}}C_r} & \text{if } (D_r(k) - r(k)C_r) > \frac{w_{\max}-w_4(k)}{T_{\mathrm{c}}} \\ r(k) & \text{otherwise} \end{cases} \tag{14}$$

The optimal solution for each scenario is computed in order to have a estimation of the highest TTS reduction that can be achieved for each scenario. The computation of the optimal ramp metering solution has been analyzed in many previous references either using a rolling prediction horizon [1], [15] or optimizing over the entire simulation horizon [16]. In this work, we use the second choice because we will not compute any optimization on-line so the computation load is not a key factor.

The optimal solution between time steps k_o and k_e for a given demand can be found by solving the optimization problem with cost function J, which is used to measure the performance of the system with respect to the Ramp Metering sequence. The cost function contains one term for the TTS, another term that limits (using a soft constraint in order to make the optimization faster) the maximum value of the queues, and a third term penalizing the ramp metering rate variations:

$$J = \sum_{k=k_o}^{k=k_e} \Bigg[T\Big(\sum_{i\in \mathrm{O}} w_i(k) + \sum_{i\in I} \rho_i(k) L_i \lambda_i \Big) + \psi\Big(\max(w_4(k) - w_{\max}, 0)\Big)^2 + \epsilon\Big(r(k) - r(k-1)\Big)^2 \Bigg] \tag{15}$$

where O is the set of all the segments with a queue (on-ramp and mainline origin), ψ and ϵ are tuning parameters, and I is the set of all the segments. For this work, ψ and ϵ have been set equal to 1. If lower values of ϵ are used, the TTS is slightly reduced but higher oscillations appear.

In this work, the optimizations have been computed continuously using the gradient-based optimization algorithms RPROP [16], [17] and Sequential Quadratic Programming (SQP) [18]. It has to be pointed out that, in general, it is necessary to run the algorithm many times (with different initial points) in order to avoid ending up in local minima (because the problem is highly non-convex). More concretely, 15 initial points have been used for each computation of the optimal solution, 110 initial points for the computation of the optimal values of K_{A} and K_{FF} for each scenario, and 900 initial points for the computation of K_{R} and K_p for each scenario.

B. Numerical results

In this subsection, FF-ALINEA is tested for the 9 scenarios considered in subsection IV-A. and the results are compared with the ones obtained with ALINEA and PI-ALINEA and with the optimal solution for each scenario.

The values of the controller parameters (K_{A}^i, K_{FF}^i, K_{R}^i, and K_{P}^i) have been found by minimizing the cost function ((15)) for the corresponding scenario i. For the estimation of $Q_{\mathrm{ib}}(k)$ and $\hat{v}_{\mathrm{A}}(k)$, the flows and speeds from segments 4 to 11 have been taken as measurements for equation (11). The obtained numerical results are shown in Table III.

Analyzing the results, it can be seen that the proposed controller (FF-ALINEA) is able to approach the optimal performance for the entire set of considered scenarios. In fact, the highest difference between the TTS reduction of FF-ALINEA and the optimal TTS reduction occurs for Scenario 2 (with a TTS reduction of 44.3% for the optimal case and 41.7% for FF-ALINEA). As a result, the mean TTS reduction for the 9 scenarios using FF-ALINEA is also quite close the optimal one (31.1% versus 31.8%).

PI-ALINEA is also able to substantially improve the behavior of the traffic system with a 28.2% mean TTS reduction for the 9 scenarios. However, even taking account that PI-ALINEA has two parameters that have been optimized for each scenario (allowing to better adapt the controller performance to each scenario), the performance is worse than using FF-ALINEA.

Finally, it can be seen that ALINEA performance is far away from the other controllers (with a mean TTS reduction of 14.3%). In the worst case, for Scenario 3, ALINEA is almost not able to improve traffic behavior (with a TTS reduction of 0.04%), while the other controllers have a huge impact on traffic behavior (49.2%, 52.3%, and 52.8% for PI-ALINEA, FF-ALINEA, and the optimal solution, respectively).

C. Graphical results

The graphical results for a representative scenario with an intermediate mainline demand (D1) and without queue constraints (Scenario 1) can be seen in Fig. 5, 6, 7, and 8.

In Fig. 5, the speed contour plots obtained using each controller are shown. It can be seen that ALINEA is able to reduce the traffic jam, but it is not able to totally eliminate the congestion. On the other hand, PI-ALINEA, and FF-ALINEA are able to avoid traffic breakdown. The oscillating behavior

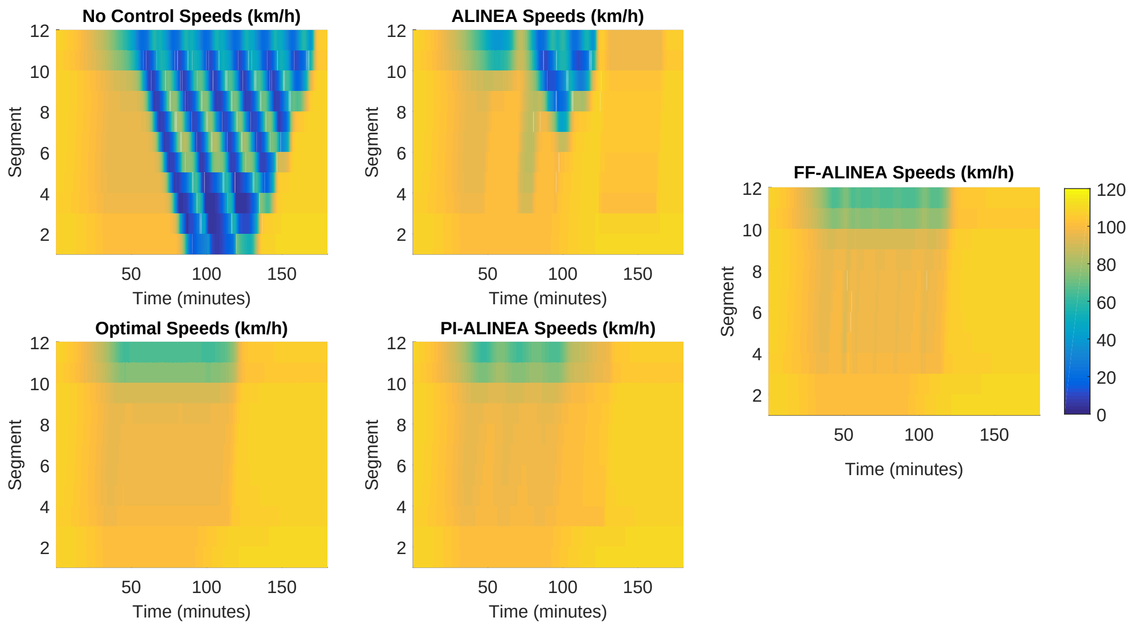

Fig. 5. Contour plots for the speeds obtained for Scenario 1

obtained for the no-control case is related with shock wave phenomena, also observed in real field data, which implies that a bottleneck can create oscillations in speeds and flows (which create shock waves upstream of the bottleneck).

The limited reduction of the traffic jam obtained with ALINEA can be explained by analyzing the ramp metering rates shown in Fig. 6. As can be seen in the figure, the ramp metering installation is closed later using ALINEA because the controller is not able to anticipate the congestion of the bottleneck. Once ramp metering is applied (at minute 46), it is already too late to totally eliminate congestion but, obviously, a reduction is obtained compared to the no-control case.

On the other hand, it can also be seen in Fig. 6 that PI-ALINEA and FF-ALINEA anticipate the activation of ramp metering:

- FF-ALINEA anticipates the activation of ramp metering because, at minute 37, the flow between segments 4 and 11 is already larger than the capacity so the system can estimate that the bottleneck will be congested during the following minutes if no measures are applied. In fact, FF-ALINEA starts to influence on-ramp flow at minute 39 (only one minute later than the optimal solution) and, during the remainder of the simulation, the ramp metering rates obtained with FF-ALINEA are similar to the optimal ones, but with a higher oscillation. These oscillations of the ramp metering rate do not have negative effects related with traffic safety or congestion. Nevertheless, these oscillations can be reduced, if desired, by decreasing parameter K_{FF}, entailing a slightly worse performance in terms of TTS reduction."
- PI-ALINEA is also able to anticipate the traffic jam, but its behavior is quite scenario-dependent. In the figure, it can be seen that the ramp metering rate starts to decrease from 1 sooner than needed (according to the optimal solution). However, the first time that ramp metering is affecting the system (because for high values of $r(k)$, all the ramp flow can enter the freeway so the ramp metering rate is not influencing the system behavior) is at minute 38 (like the optimal solution). However, because of the activation of ramp metering is mainly based on the

TABLE III
TTS FOR DIFFERENT CONTROLLERS AND SCENARIOS

Scenario	Uncontrolled	Optimal	ALINEA	PI-ALINEA	FF-ALINEA
1	2860.7	1455.2 (-49.1 %)	2290.7 (-19.9 %)	1506.3 (-47.3 %)	1458.1 (-49.0 %)
2	2860.7	1594.4 (-44.3 %)	2258.2 (-21.1 %)	1673.9 (-41.5 %)	1666.8 (-41.7 %)
3	3820.1	1804.7 (-52.8 %)	3818.5 (-0.04 %)	1940.1 (-49.2 %)	1821.3 (-52.3 %)
4	3820.1	2846.0 (-25.5 %)	3655.7 (- 4.3 %)	2956.1 (-22.6 %)	2890.2 (-24.3 %)
5	1215.6	1215.6 (0.0 %)	1215.6 (0.0 %)	1215.6 (0.0 %)	1215.6 (0.0 %)
6	2464.8	1591.9 (-35.4 %)	1728.7 (-29.9 %)	1673.4 (-32.1 %)	1604.0 (-34.9 %)
7	2464.7	1989.4 (-19.3 %)	2086.4 (-15.4 %)	2026.1 (-17.8 %)	2033.7 (-17.5 %)
8	2490.4	1600.8 (-35.7 %)	1922.6 (-22.8 %)	1839.2 (-26.1 %)	1606.6 (-35.5 %)
9	2490.4	1845.8 (-25.9 %)	2114.1 (-15.1 %)	2067.8 (-17.0 %)	1889.3 (-24.1 %)
Mean		-31.8 %	-14.3 %	-28.2 %	-31.1 %

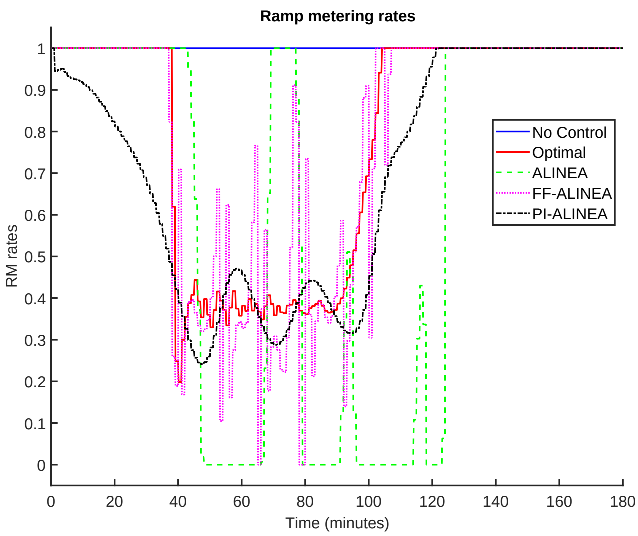

Fig. 6. Ramp metering rates for Scenario 1

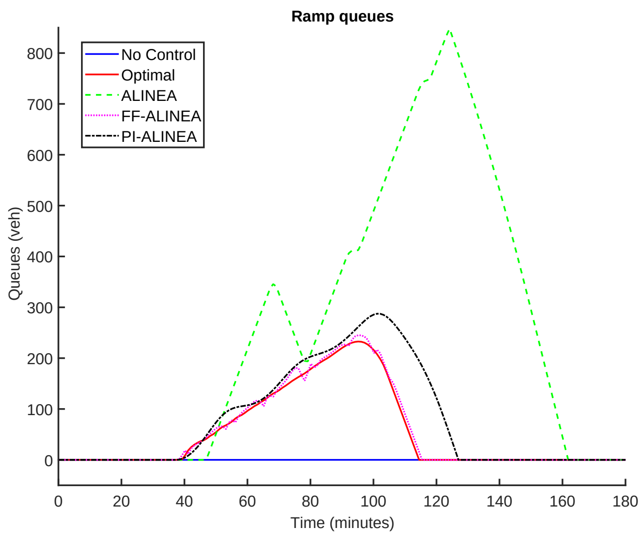

Fig. 7. Ramp queues for Scenario 1

increase of the bottleneck density, and not on bottleneck density itself, ramp metering will not be activated in advance if, e.g., the bottleneck density increases slower than in this scenario.

The ramp queues created using each controller can be seen in Fig. 7. Again, it can be seen that the behavior obtained with FF-ALINEA is quite close to the optimal one while ALINEA creates quite long (and suboptimal) queues. The queue lengths created by PI-ALINEA are also close to the optimal ones but with higher values than the ones obtained with FF-ALINEA and with the optimal solution.

Finally, in Fig. 8 the bottleneck densities (i.e. the densities of segment 11) are shown. It can be seen that the optimal solution keeps the density of the bottleneck around the critical density of 36.78 veh/(km·lane). This behavior is again approached by FF-ALINEA and PI-ALINEA but with a higher accuracy using for FF-ALINEA.

D. Cross-validation

In real applications, the values of the controller parameters will be usually computed for one case (generally, the typical demand) and applied to different scenarios. Therefore, it is important that the controllers tuned for one scenario, also perform properly in other circumstances. In other words, it is necessary to have a robust controller, especially against different demand profiles.

This section analyzes the robustness, against different mainline demands and ramp queue constraints, of the considered controllers (ALINEA, PI-ALINEA and FF-ALINEA) by a cross-validation (i.e. by analyzing the TTS reduction for scenario j when using the parameters computed for scenario i).

The optimal value of the controller parameters (K_{A}^{*}, K_{FF}^{*}, K_{R}^{*}, and K_{P}^{*}) that minimize the summation of the cost functions (15) for the 9 scenarios have been also computed and included in the comparison (in the second-to-last column of the tables).

It can be seen that the behaviors of ALINEA and PI-ALINEA are much more dependent on the value of the parameters. In fact, as can be seen in Tables IV and V, there are no values of the parameters that are able to perform properly (in terms of TTS reduction) for the entire set of scenarios.

Moreover, for some scenarios, PI-ALINEA and ALINEA increase the TTS if incorrect values of the parameters are used. For example, for Scenario 5 (for which congestion is

TABLE IV

CROSS-VALIDATION: TTS REDUCTION WITH RESPECT TO THE NO-CONTROL CASE FOR ALINEA WITH K_i OPTIMIZED FOR SCENARIO i

	$K_{\mathrm{A}}^{1}=$ 0.0612	$K_{\mathrm{A}}^{2}=$ 0.0663	$K_{\mathrm{A}}^{3}=$ 0.0005	$K_{\mathrm{A}}^{4}=$ 00118	$K_{\mathrm{A}}^{6}=$ 0.2837	$K_{\mathrm{A}}^{7}=$ 1.1020	$K_{\mathrm{A}}^{8}=$ 0.1636	$K_{\mathrm{A}}^{9}=$ 0.2606	$K_{\mathrm{A}}^{*}=$ 0.2837	Mean for the 10 values of K_{A}
Scenario 1	**19.9**%	18.3%	−1.90%	−3.5%	13.9%	8.7%	13.2%	14.2%	13.9%	10.8%
Scenario 2	9.8%	**21.1**%	−1.41%	−0.6%	15.1%	13.2%	17.5%	15.1%	15.1%	11.6%
Scenario 3	−1.9%	−1.9%	**0.04**%	−3.4%	−0.6%	−1.9%	−1.3%	−0.8%	−0.6%	−1.4%
Scenario 4	0.8%	0.7%	−0.04%	**4.3**%	−0.7%	−0.3%	−0.6%	−0.7%	−0.7%	0.3%
Scenario 5	0.0%	0.0%	0.00%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Scenario 6	−1.2%	−1.4%	0.05%	−2.8%	**29.9**%	12.7%	−1.2%	4.4%	29.9%	7.8%
Scenario 7	−0.8%	−0.8%	0.05%	3.2%	5.8%	**15.3**%	−0.0%	5.1%	5.8%	3.7%
Scenario 8	−7.0%	−6.5%	−0.07%	−1.1%	14.7%	11.4%	**22.8**%	14.9%	14.7%	7.1%
Scenario 9	−2.1%	−2.1%	−0.06%	2.3%	14.7%	14.0%	2.3%	**15.1**%	14.7%	6.5%
Mean for the 9 scenarios	2.0%	3.0%	−0.4%	−0.2%	10.3%	8.1%	5.8%	7.5%	**10.3**%	

TABLE V
CROSS-VALIDATION: TTS REDUCTION WITH RESPECT TO THE NO-CONTROL CASE FOR PI-ALINEA WITH K_r AND K_p OPTIMIZED FOR SCENARIO i

	$K_{\mathrm{R}}^1 =$ 0.00050 $K_p^1 =$ 0.033	$K_{\mathrm{R}}^2 =$ $7.3{\cdot}10^{-6}$ $K_p^2 =$ 0.021	$K_{\mathrm{R}}^3 =$ 0.00078 $K_p^4 =$ 0.044	$K_{\mathrm{R}}^4 =$ 0.00009 $K_p^5 =$ 0.027	$K_{\mathrm{R}}^6 =$ 0.00128 $K_p^6 =$ 0.078	$K_{\mathrm{R}}^7 =$ 0.00069 $K_p^7 =$ 0.046	$K_{\mathrm{R}}^8 =$ 2.06061 $K_p^8 =$ 9.344	$K_{\mathrm{R}}^9 =$ 0.00229 $K_p^9 =$ 0.051	$K_r^* =$ 0.00034 $K_r^* =$ 0.032	Mean for the 10 values of K_{r} and K_{p}
Scenario 1	**47.3**%	46.0%	46.7%	43.3%	37.2%	44.8%	16.1%	18.8%	46.1%	38.5%
Scenario 2	40.7%	**41.5**%	37.1%	35.6%	12.0%	30.4%	18.6%	18.2%	39.4%	30.4%
Scenario 3	2.6%	2.1%	**49.2**%	47.2%	41.5%	48.4%	8.6%	0.2%	48.2%	27.5%
Scenario 4	1.6%	0.1%	20.3%	**22.6**%	8.0%	19.7%	8.2%	−0.8%	20.2%	11.1%
Scenario 5	−0.5%	−5.5%	−2.3%	−11.1%	−19.4%	−6.3%	0.0%	0.0%	−4.0%	−5.5%
Scenario 6	−0.2%	12.6%	1.0%	10.7%	**32.1**%	17.6%	5.4%	0.7%	11.4%	10.2%
Scenario 7	−0.4%	12.2%	−0.4%	11.3%	15.5%	**17.8**%	6.7%	−0.7%	12.2%	8.3%
Scenario 8	21.2%	17.1%	16.8%	9.4%	−9.2%	11.2%	**26.2**%	15.6%	17.1%	13.9%
Scenario 9	−7.2%	−10.3%	−17.4%	−17.2%	−20.7%	−18.9%	12.4%	**17.0**%	−16.0%	−8.7%
Mean for the 9 scenarios	11.7%	12.9%	16.8%	16.9%	10.8%	18.3%	11.4%	7.7%	**19.4**%	

TABLE VI
CROSS-VALIDATION: TTS REDUCTION WITH RESPECT TO THE NO-CONTROL CASE FOR FF-ALINEA WITH K_{FF} OPTIMIZED FOR SCENARIO i

	$K_{\mathrm{FF}}^1 =$ 0.234	$K_{\mathrm{FF}}^2 =$ 0.278	$K_{\mathrm{FF}}^3 =$ 0.120	$K_{\mathrm{FF}}^4 =$ 0.134	$K_{\mathrm{FF}}^6 =$ 0.329	$K_{\mathrm{FF}}^7 =$ 0.397	$K_{\mathrm{FF}}^8 =$ 0.403	$K_{\mathrm{FF}}^9 =$ 0.266	$K_{\mathrm{FF}}^* =$ 0.279	Mean for the 10 values of K_{FF}
Scenario 1	**49.0**%	48.9%	48.2%	47.3%	47.5%	47.4%	47.5%	48.2%	49.0%	48.1%
Scenario 2	41.3%	**41.7**%	39.9%	38.2%	35.7%	35.8%	38.0%	38.8%	41.4%	39.0%
Scenario 3	51.6%	50.4%	**52.3**%	51.1%	50.3%	50.2%	51.3%	51.3%	51.7%	51.1%
Scenario 4	24.0%	22.7%	23.7%	**24.3**%	22.7%	22.1%	22.8%	22.8%	22.7%	23.0%
Scenario 5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Scenario 6	33.8%	34.0%	33.4%	34.6%	**34.9**%	33.9%	32.3%	34.4%	34.6%	34.0%
Scenario 7	16.0%	17.1%	17.1%	17.3%	17.3%	**17.5**%	16.4%	16.7%	17.1%	16.9%
Scenario 8	34.2%	33.7%	34.5%	33.1%	33.6%	34.9%	**35.5**%	34.8%	34.8%	34.4%
Scenario 9	23.5%	24.1%	20.7%	21.7%	23.0%	24.0%	24.0%	**24.1**%	24.1%	23.3%
Mean for the 9 scenarios	30.4%	30.3%	30.0%	29.7%	29.4%	29.5%	29.7%	30.1%	**30.6**%	

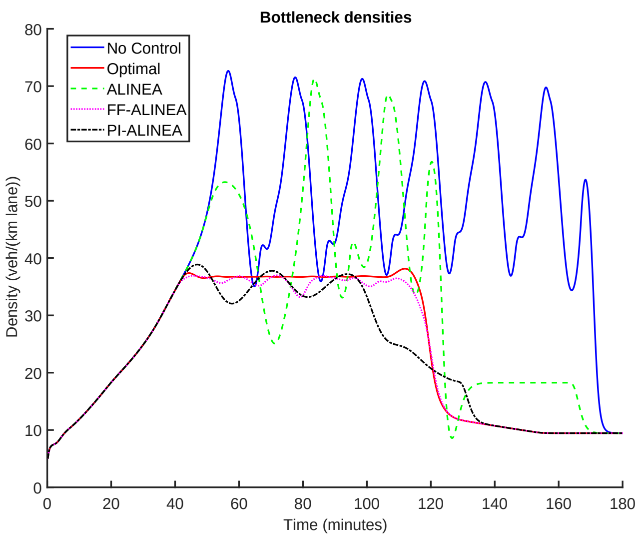

Fig. 8. Density of segment 11 for Scenario 1

not reached, but the bottleneck density reaches values between the FD critical density of 32 veh/(km·lane) and the estimated critical density of 36.78 veh/(km·lane)), the TTS is increased for most of the controller parameters using PI-ALINEA.

The best mean TTS reduction for the 9 scenarios that can be obtained using ALINEA and PI-ALINEA is 10.3% and 19.4%, respectively.

On the other hand, the results obtained for FF-ALINEA, which can be seen in Table VI, show that FF-ALINEA is quite robust for different traffic conditions: For the simulated scenarios, the performance obtained with different values of K_{FF} is always close the one obtained with the best value of K_{FF}. The biggest difference is for Scenario 2: 35.7% for K_{FF}^6 against 41.7% for K_{FF}^2. The best mean TTS reduction for the 9 scenarios using FF-ALINEA is 30.6%, slightly lower than the optimal one (31.8%).

E. Robustness

Finally, this section analyses the robustness of FF-ALINEA in other cases apart from demands and queue constraints. The following cases have been considered:

- Case 1: The capacity is overestimated with 5% (4542.9 veh/h versus 4782 veh/h).
- Case 2: The capacity is underestimated with 5% (5021.1 veh/h versus 4782 veh/h).
- Case 3: The critical density is underestimated with 5% (34.94 veh/(km·lane) versus 36.78 veh/(km·lane)).
- Case 4: The critical density is underestimated with 5% (38.62 veh/(km·lane) versus 36.78 veh/(km·lane)).
- Case 5: $\hat{v}_{\mathrm{A}}(k)$ is taken as the free-flow speed.
- Case 6: The flow $Q_{\mathrm{ib}}(k)$ is estimated by taking the mean

TABLE VII
ROBUSTNESS ANALYSIS: TTS REDUCTION WITH RESPECT TO THE NO-CONTROL CASE FOR EACH CASE

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
	$C_\mathrm{b}\downarrow$	$C_\mathrm{b}\uparrow$	$\rho_\mathrm{c}\downarrow$	$\rho_\mathrm{c}\uparrow$	$(\hat{v}_\mathrm{A}(k)=v_\mathrm{f})$	(16)	(17) + $(\hat{v}_\mathrm{A}(k)=v_\mathrm{f})$
Scenario 1	46.7%	43.8%	45.0%	48.3%	46.9%	47.5%	46.5%
Scenario 2	36.2%	30.7%	35.8%	38.9%	35.5%	38.3%	35.7%
Scenario 3	49.7%	47.6%	50.0%	51.1%	50.5%	50.6%	49.1%
Scenario 4	20.3%	18.8%	21.8%	22.4%	22.6%	20.7%	20.6%
Scenario 5	−2.4%	0.0%	−0.2%	0.0%	0.0%	0.0%	0.0%
Scenario 6	32.3%	9.5%	31.6%	33.3%	31.9%	33.1%	33.5%
Scenario 7	15.3%	15.4%	16.8%	16.5%	15.4%	15.2%	15.4%
Scenario 8	30.4%	29.5%	30.2%	35.0%	33.7%	33.3%	32.3%
Scenario 9	12.6%	15.3%	17.0%	21.6%	21.8%	20.6%	21.3%
Mean for the 9 scenarios	26.8%	23.4%	27.6%	29.7%	28.7%	28.8%	28.3%

value of $q_4(k)$ during the last period T_A:

$$Q_\mathrm{ib}(k) = \sum_{l=0}^{[L_\mathrm{A}/(T\hat{v}_\mathrm{A}(k))]} \frac{q_4(k-l)}{L_\mathrm{A}/(T\hat{v}_\mathrm{A}(k))} \tag{16}$$

where $\hat{v}_\mathrm{A}(k)$ is computed using the mean speed estimation based on the 7 detectors available.

- Case 7: The mean speed $\hat{v}_\mathrm{A}(k)$ is taken as the free-flow speed and the flow $Q_\mathrm{ib}(k)$ is estimated by taking the mean value of $q_4(k)$:

$$Q_\mathrm{ib}(k) = \sum_{l=0}^{[L_\mathrm{A}/(Tv_f)]} \frac{q_4(k-l)}{L_\mathrm{A}/(Tv_f)} \tag{17}$$

For this section, FF-ALINEA is simulated using the optimal value of the controller parameter $K^*_\mathrm{FF} = 0.279$. The corresponding result can be seen in Table VII.

Cases 1, 2, 3 and 4 show that an error in the estimation of the capacity and/or the critical density affects the performance of FF-ALINEA but the resulting TTS reduction is of the same order of magnitude.

In Case 7, the performance of FF-ALINEA using simpler estimation methods for $\hat{v}_\mathrm{A}(k)$ and $Q_\mathrm{ib}(k)$ (with only one additional detector measuring the flow of segment 4) is computed. In this case, the structure and external resources required by FF-ALINEA are similar as those required by PI-ALINEA. The differences between them are that FF-ALINEA uses one additional flow detector, and that for FF-ALINEA one has to estimate C_b, L_A, L_b, $v_\mathrm{f}(k)$ (which can be easily estimated based on the network layout and the detector data), and KFF (which does not need a calibrated model due to the inherently robust behavior). On the other hand, for PI-ALINEA one has to estimate K_R and K_p (for which a calibrated model of the network is necessary). However, for Case 7 the performance obtained for FF-ALINEA is still much more optimal and robust than using PI-ALINEA (i.e. mean TTS reduction of 28.3% versus 19.4%).

V. CONCLUSIONS

This paper has proposed a new ramp metering control algorithm (FF-ALINEA) for bottlenecks located far away from the on-ramp (i.e. more than just a few hundred meters). FF-ALINEA is based on a feed-forward modification of ALINEA, which allows to anticipate the future evolution of the bottleneck density in order to avoid or reduce traffic breakdowns. The main advantage of FF-ALINEA, comparing to ALINEA and PI-ALINEA, is that the proposed controller is able to activate ramp metering before the bottleneck is congested if the flow arriving to the bottleneck is higher than its capacity. In fact, in the scenarios simulated, FF-ALINEA has shown a significant increase in the TTS reduction compared to ALINEA and PI-ALINEA due to an earlier activation of ramp metering, which allows to avoid the congestion created on the bottleneck.

The simulation results have also shown that FF-ALINEA is able to approach the optimal behavior and that FF-ALINEA is quite robust if there is a limited number of available detectors or there are errors in the estimation of the capacity and/or the critical density of the bottleneck.

In a future work, FF-ALINEA will be tested for scenarios where the capacity of a segment is suddenly decreased, creating a bottleneck due to an incident. Moreover, FF-ALINEA will be integrated in the framework of a joint controller for ramp metering and variable speed limits and tested extensively in field implementations. Another interesting topic for future work is to perform a stability analysis for ALINEA and FF-ALINEA using a second-order traffic model.

REFERENCES

[1] J.R.D. Frejo, A. Núñez, B. De Schutter and E.F. Camacho, *Hybrid model predictive control for freeway traffic using discrete speed limit signals*, Transportation Research Part C: Emerging Technologies, vol. 46, pp. 309-325, 2014.

[2] J.R.D. Frejo, I. Papamichail, M. Papageorgiou and E.F. Camacho, *Macroscopic modeling and control of reversible lanes on freeways*, IEEE Transactions on Intelligent Transportation Systems, vol. 17, no. 4, pp 948-959, 2016.

[3] Y. Wang, M. Papageorgiou, G. Sarros and W.J. Knibbe, *Real-time route guidance for large-scale express ring-roads* IEEE Intelligent Transportation Systems Conference, pp. 224-229, 2006.

[4] M. Papageorgiou, H. Hadj-Salem and F. Middelham, *ALINEA local ramp metering: Summary of field results*, Transportation Research Record: Journal of the Transportation Research Board, vol. 1603, pp. 90-98, 1997.

[5] C. Taylor and D. Meldrum, *Evaluation of a Fuzzy Logic Ramp Metering Algorithm: A Comparative Study among Three Ramp Metering Algorithms Used in the Greater Seattle Area*, Washington State Department of Transportation, Report WA-RD 481.2.

[6] M. Papageorgiou and A. Kotsialos, *Freeway ramp metering: an overview*, IEEE Transactions on Intelligent Transportation Systems, vol. 3 (4), pp. 271-281, 2002.

[7] K. Shaaban, M. Asif Khan and R. Hamila, *Literature review of advancements in adaptive ramp metering*, Procedia Computer Science, vol. 83 (C), pp. 203 - 211, 2016.

[8] M. Papageorgiou, H. Hadj-Salem and J. M. Blosseville, *ALINEA: A local feedback control law for on-ramp metering*, Transportation Research Record: Journal of the Transportation Research Board, vol. 1320, pp 58-67,2001.

[9] M. Zhang, T. Kim, X. Nie, W. Jin, L. Chu and W. Recker, *Evaluation of On-ramp Control Algorithms*, UCB-ITS-PRR-2001-36, California PATH Research Report, 2001.

[10] Y. Kan, W. Yibing, M. Papageorgiou and I. Papamichail, *Local ramp metering with distant downstream bottlenecks: A comparative study*, Transportation Research Part C: Emerging Technologies, vol. 62, pp 149-170, 2016.

[11] Y. Wang, E.B. Kosmatopoulos, M. Papageorgiou and I. Papamichail, *Local ramp metering in the presence of a distant downstream bottleneck: Theoretical analysis and simulation study*, IEEE Transactions on Intelligent Transportation Systems, vol. 15 (5), pp. 2024 - 2039, 2014.

[12] Y. Wang and M. Papageorgiou, *Local ramp metering in the case of distant downstream bottlenecks*, IEEE Conference on Intelligent Transportation Systems, pp. 426-431, Toronto, Canada, 2006.

[13] R.C. Carlson, I. Papamichail and M. Papageorgiou, *Integrated feedback ramp metering and mainstream traffic flow control on motorways using variable speed limits*, Transportation Research Part C: Emerging Technologies, vol. 46, pp 209-221, 2014.

[14] M. Papageorgiou, I. Papamichail, A. Messmer and Y. Wang, *Traffic simulation with METANET*, Fundamentals of Traffic Simulation, Springer, 2010.

[15] A. Hegyi, B. De Schutter and H. Hellendoorn, *Model predictive control for optimal coordination of ramp metering and variable speed limits*, Transportation Research Part C: Emerging Technologies, vol 13, no. 3, pp. 185-209, 2005.

[16] A. Kotsialos, M. Papageorgiou, M. Mangeas and H. Haj-Salem, *Coordinated and integrated control of motorway networks via non-linear optimal control*, Transportation Research Part C: Emerging Technologies, vol. 10, no. 1, pp. 65-84, 2002.

[17] C. Pasquale, D. Anghinolfi, S. Sacone, S. Siri and M. Papageorgiou, *A comparative analysis of solution algorithms for nonlinear freeway traffic control problems*, IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), pp. 1773-1778, Rio de Janeiro, Brazil, 2016.

[18] J.R.D. Frejo and E. F. Camacho, *Global versus local MPC algorithms in freeway traffic control with ramp metering and variable speed limits*, IEEE Transactions on Intelligent Transportation Systems, vol. 13, no. 4, pp. 1556-1565, 2012.