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Optimal flow metering and lane-changing control at motorway bottlenecks

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Abstract—In the near future, the appearance of vehicle automation and connectivity will revolutionise the features and capabilities of individual vehicles. Among the wide range of potentially introduced technology, some may be exploited to interfere with the driving behaviour via recommending, supporting, or even executing appropriately designed traffic control tasks, providing unprecedented opportunities to improve traffic control performance [1]–[3]. It has been shown that, particularly at bottleneck locations (e.g., lane-drops, on-ramp merges), human drivers usually perform suboptimal lane-changes based on erroneous perceptions, which may trigger congestion, and, thus, deteriorate the overall travel time (e.g., [4]–[7]). Furthermore, some of the mentioned empirical investigations indicate that, in conventional traffic, capacity flow is not reached simultaneously at all lanes, a feature that reduces the potentially achievable cross-lane capacity. For these reasons, a promising new feature that may be exploited for traffic management, independently or in combination with other strategies, is lane-changing control.

Index Terms—Optimal flow, ramp metering, lane-changing, control, bottleneck

I. INTRODUCTION

We address here the problem of maximising the outflow at motorway bottlenecks via a combined exploitation of flow metering and lane-changing control [8]. It is well known that a bottleneck, which is a location where the flow capacity upstream is higher than the flow capacity downstream of the bottleneck location, is activated when the arriving flow is higher than the overall capacity or when the lane-changing behaviour leads to exceeding the capacity in at least one lane. In conventional traffic, in order to avoid or delay the activation of a bottleneck, and the related capacity drop phenomenon, various traffic control measures have been proposed and applied [9]–[12]. In the context of automated and connected vehicles, only a limited number of works have considered to exploit optimal lane distribution (e.g., [13]–[16]). We presented in [17] an optimal feedback control strategy for lane-changing control, formulated as a linear quadratic regulator, which is highly efficient in real-time even for large-scale networks. The method has been extended in [18] in order to achieve different traffic density distribution for the various lanes at the bottleneck area.

We propose here a novel coordinated and integrated approach [19]–[21] that allows to jointly exploit mainstream or ramp flow metering together with lane-changing control, while accounting for unmeasured demand flows and incomplete

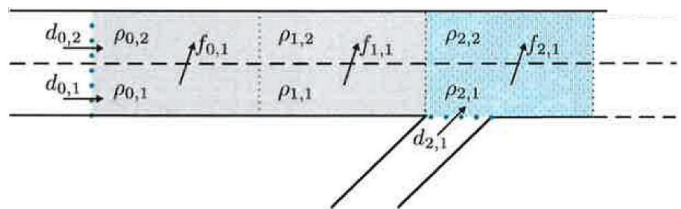


Fig. 1. Simple network example

measurements. The control strategy aims at regulating the on-ramp flow and the lane assignment of vehicles upstream of a bottleneck location so as to maximise the bottleneck throughput. Moreover, the proposed strategy is capable of handling efficiently the case of mixed traffic, where manual vehicles may not receive or may not follow the prescribed lane-changing commands. We first present the formulation of our strategy, which is based on a simplified linear macroscopic traffic flow model, with appropriate augmented dynamics to handle unmeasured flows. The model is employed to design a controller that aims at regulating the flow metered at an on-ramp together with the lane assignment of vehicles upstream of a bottleneck location in order to maximise the bottleneck throughput, targeting critical densities at bottleneck locations as set-points. Since the critical densities may be a-priori unknown and they may vary over time, we also employ a non-model-based real-time optimisation technique [22]–[25], namely, extremum seeking [26], to identify them, with the aim of minimising [27], [28] a performance index, namely the total time spent over a finite time horizon. Finally, we present simulation experiments, employing a first-order multi-lane macroscopic traffic flow model featuring the capacity drop phenomenon [29], in order to evaluate the effectiveness of the developed methodology and to highlight the different traffic behaviour in terms of generated queues and per-lane flow distribution.

II. PREVIOUS FORMULATION

Let us consider the network in Fig. 1. This system can be described as follows:

$$\underline{x}(k+1) = A\underline{x}(k) + B\underline{u}(k) + \underline{d} \quad (1)$$

$$\underline{x} = \begin{bmatrix} \rho_{0,1} \\ \rho_{0,2} \\ \rho_{1,1} \\ \rho_{1,2} \\ \rho_{2,1} \\ \rho_{2,2} \end{bmatrix}, \underline{u} = \begin{bmatrix} f_{0,1} \\ f_{1,1} \end{bmatrix}, \underline{d} = \begin{bmatrix} d_{0,1} \\ d_{0,2} \\ 0 \\ 0 \\ d_{2,1} \\ 0 \end{bmatrix} \quad (2)$$

$$\tilde{u} = -\tilde{K}\tilde{x}(k) \quad (8)$$

Equation (8) corresponds to the dynamic compensator

$$\underline{z}(k+1) = \underline{z}(k) + C\underline{x}(k) - \tilde{y} \quad (9)$$

$$A = \begin{bmatrix} 1 - \frac{T}{\Delta}v & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 - \frac{T}{\Delta}v & 0 & 0 & 0 & 0 \\ \frac{T}{\Delta}v & 0 & 1 - \frac{T}{\Delta}v & 0 & 0 & 0 \\ 0 & \frac{T}{\Delta}v & 0 & 1 - \frac{T}{\Delta}v & 0 & 0 \\ 0 & 0 & \frac{T}{\Delta}v & 0 & 1 - \frac{T}{\Delta}v & 0 \\ 0 & 0 & 0 & \frac{T}{\Delta}v & 0 & 1 - \frac{T}{\Delta}v \end{bmatrix}$$

$$B = \begin{bmatrix} -\frac{T}{\Delta}v & 0 \\ -\frac{T}{\Delta}v & 0 \\ 0 & -\frac{T}{\Delta}v \\ 0 & -\frac{T}{\Delta}v \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (3)$$

$$u^* = -Kx(k) - K_I z(k) \quad (10)$$

In practice, it may be not always possible to achieve the desired set-point y (e.g., due to lack of demand), therefore it is necessary to include an anti windup scheme in the controller. I selected the one proposed in [?] (see also [?], [?]), which, in our case, modifies the dynamic controller as

$$\underline{z}(k+1) = (I - MK_I)\underline{z}(k) + (C + MK)\underline{x}(k) + M\underline{u}_{sat}(k) - \tilde{y} \quad (11)$$

The controller is supposed to obtain the optimal (net) lateral flows u , given the set-points at the bottleneck area (i.e., $\rho_{2,1}$, $\rho_{2,2}$) and the external inflows d .

$$u^* = -Kx(k) - K_I z(k) \quad (12)$$

where

$$\underline{u}_{sat}(k) = sat(u^*(k)) \quad (13)$$

III. PROBLEM DESIGN WITH INTEGRAL CONTROL

We reformulate the problem, treating the flow entering from the ramp as controlled input and we introduce 2 integrators (one for each targeted cell). This allow to remove the need for measuring the external inflows d . The resulting augmented system is

Matrix M should be chosen in order that $I - MK_1$ has stable eigenvalues, for example, via an algorithm proposed in [3] or via classical pole placement. I tested both methods, obtaining no substantial differences (however some tuning of Q and R may be necessary).

IV. PROBLEM DESIGN WITH INPUT SATURATION OF BOTTLENECK AREA

The previous integral controller spends more effort on the inputs of segment 2 ($d_{2,1}$ and $f_{2,1}$) to eliminate the integral errors for the bottleneck area. As a result, the controller requests more flow from ramp and consequently send more vehicles to the adjacent line. Considering the saturation for ramp input, although the $f_{2,1}$ is under saturation $d_{10,1}$ is mostly saturated, thus the density of segment 11 at line 1 increases and the other decreases which indicates the first line will be congested. To avoid the saturation, we considered an upper limitation a as a constraint (section 5.3 of [30] also section 7.6 of [31]) for the $d_{2,1}$ and rewrite the Hamiltonian equation as following:

$$\tilde{x} = \begin{bmatrix} \underline{x} \\ z_1 \\ z_2 \end{bmatrix}, \tilde{u} = \begin{bmatrix} \underline{u} \\ d_{2,1} \end{bmatrix}, \underline{d} = \begin{bmatrix} d_{0,1} \\ d_{0,2} \\ 0 \\ 0 \\ 0 \\ 0 \\ -\hat{y} \end{bmatrix} \quad (4)$$

$$\tilde{A} = \begin{bmatrix} A & 0 \\ C & 1 \ 0 \\ & 0 \ 1 \end{bmatrix}, \tilde{B} = \begin{bmatrix} B & 0 \\ & 0 \\ & \frac{T}{\Delta} \\ & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (5)$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \hat{y} = \begin{bmatrix} -\rho_{2,1} \\ -\rho_{2,2} \end{bmatrix} \quad (6)$$

$$d_{2,1} \leq a \quad (14)$$

$$g(x) = a - d_{2,1} \geq 0 \quad (15)$$

$$f_{N+1} = H|g(x)| \quad (16)$$

$$H = \begin{cases} 0 & \text{if } g(x) \geq 0 \\ 1 & \text{if } g(x) < 0 \end{cases} \quad (17)$$

The system is observable and stabilisable, thus we may derive an LQR/LQI gain

$$\tilde{K} = [K \ K_I] \quad (7)$$

which can applied in the control law

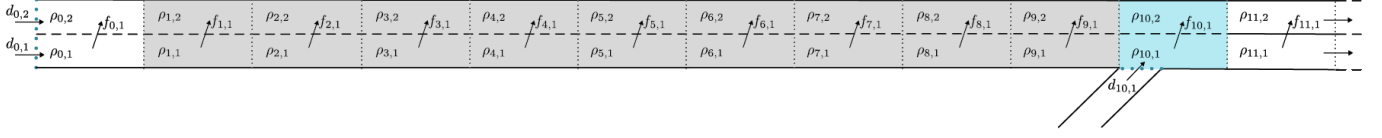


Fig. 2. Bigger network example

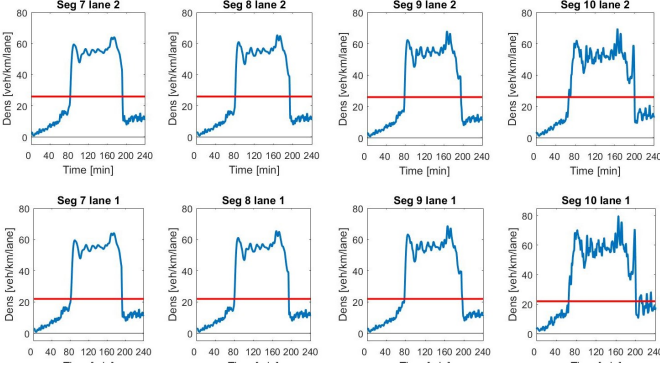


Fig. 3. Density, no-control case

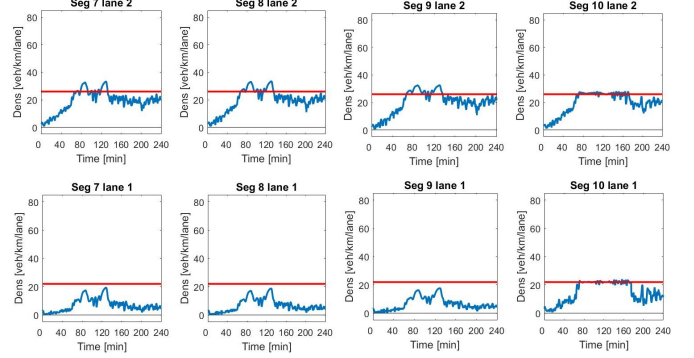


Fig. 4. Density, controlled case

A. Part 1- LQI

We apply the linear dynamic compensator (eq (11, 12)) to the non-linear traffic model, excluding segment 0 and segment 11. The operator sat u_m is defined as follows

$$\begin{cases} u_m^{min}, & u_m < u_m^{min} \\ u_m^{max}, & u_m > u_m^{min} \\ u_m, & otherwise \end{cases} \quad (29)$$

While bounds for the ramp accounts for the available flow entering from the ramp and a maximum ramp capacity (arbitrarily set as 1800 veh/h):

$$u_m^{min} = 0 \quad (30)$$

$$u_m^{max} = \min\left(\frac{\omega(k)}{T} + d_{2,1}, 1800\right) \quad (31)$$

Note that these bounds, in practice, do not need to be specified a priori, but may be measured as the ordered flow (lateral and/or ramp) that is successfully implemented. The optimal control values are directly implemented in the non-linear traffic model. Lateral flow in segment 1 is computed via the non-linear (nocontrol) formulation, while it is inhibited at segment 11.

Congestion fully disappears and the densities at the bottleneck area remain at their critical values (see Figure (4)). Consequently, no capacity drop is occurring.

A (quite long) queue is created at the on-ramp during the peak period. However, currently, the ramp flow has some sort of oscillatory behaviour, (see Figure (5)). The TTS improvement is about 33%.

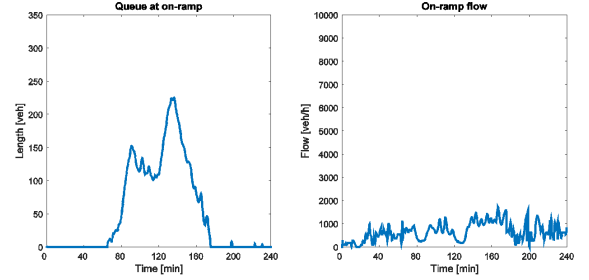


Fig. 5. Ramp queue (left) and ramp flow (right)

Although the system is controlled, the density at segment 10, line 2 didn't drop which shows that the controller request for more on-ramp demand and tries to send more flow to line 2 while the on-ramp input is saturated. Thus, the congestion of lane 2 doesn't drop.

B. Part 2- LQI considering the upper bound

To avoid the congestion on lane 2, we employ an upper constraint for the on-ramp input which expected to send more lateral flow to the lane 2. The results are indicated as the following.

And the performance of the controller for on-ramp input is mentioned as bellow.

According to the figure, the controller tries to eliminate the errors between demand and upper bound. A (quite long) queue is created at the on-ramp during the peak period. And the TTS improvement is about 33%.

VI. CONCLUSION

In this paper we investigated the optimal lanechanging and rampmetering control considering an upper bound for the

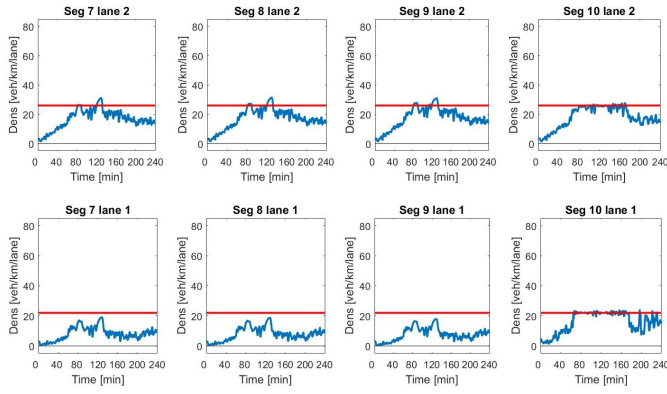


Fig. 6. Density, controlled considering the upper bound

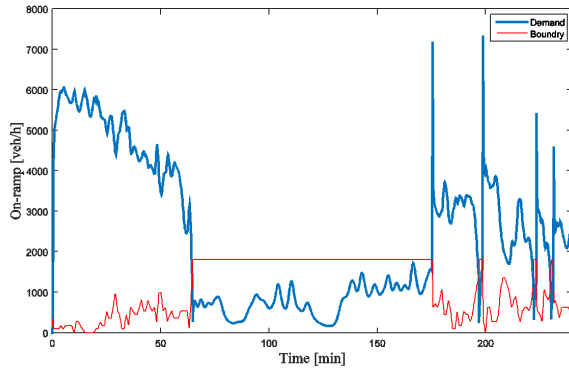


Fig. 7. Controller performance for input constraint.

ram-metering in the control methodology. Accordingly, we designed two sets of control gains in which the controller switches between them for the ramp-metering saturation and no-saturation conditions. The method is evaluated via simulation experiments, through a first-order, multi-lane, macroscopic traffic flow model featuring the capacity drop phenomenon, which allows to show the effectiveness of the developed methodology. We are currently investigating stability properties of the controller, as well as producing further simulation experiments to investigate robustness to parameter choices and to different type of disturbances, which are going to appear in a future publication.

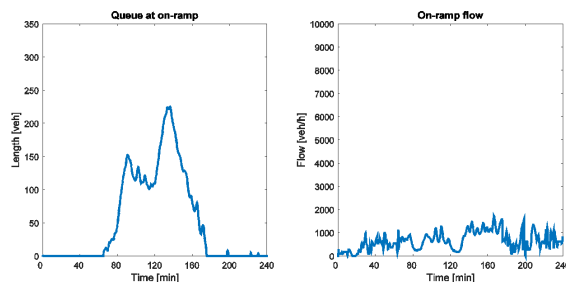


Fig. 8. Ramp queue (left) and ramp flow (right).

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