Feedback-Based Integrated Motorway Traffic Flow Control with Delay Balancing

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***Abstract*—The development and deployment of simple, yet efficient, coordinated and integrated control tools for motorway traffic control remains a challenge. A generic integrated feedback-based motorway traffic flow control concept is proposed in this paper. It is based on the combination and suitable extension of control algorithms and tools proposed or deployed in other studies, such as ramp metering or VSL (Variable Speed Limit)-enabled cascade-feedback mainstream traffic flow control, and allows for consideration of multiple bottlenecks. The new controller enables coordination of ramp metering actions at a series of on-ramps, as well as integration with VSL control actions, towards a common control goal, which is bottleneck throughput maximization. While doing this, the approach considers a pre-specified (desired) balancing of the incurred delays upstream of the employed actuators, via a suitably designed knapsack problem. Despite the multitude of the offered configurations, options and possibilities, the generic control algorithm remains simple, efficient and suitable for field implementation. The control algorithm is demonstrated and evaluated using a validated macroscopic traffic flow model for a number of scenarios.**

***Index Terms*—traffic management, integrated motorway traffic flow control, ramp metering, mainstream traffic flow control, variable speed limits, feedback control, delay balancing.**

I. Introduction

CONGESTION on motorways is a major and continuously growing problem that is known to reduce the nominal capacity of the infrastructure [1] causing degradation in terms of travel time, traffic safety, fuel consumption and environmental pollution.

Different traffic management measures have been proposed and implemented to alleviate motorway traffic congestion, but, if each one of them is considered independently, surplus benefits that would result from synergy (integration) of different control measures are missed; while the respective control actions by individually designed control algorithms may even be contradictory under certain circumstances. Ramp metering, for example, is a direct and efficient measure for motorway traffic flow control, but the metered flow may be actually released whenever queue management strategies are activated in order to avoid the creation of over-long on-ramp queues that spill over to the adjacent network [2]. Variable Speed Limits (VSL), on the other hand, can be used to enable Mainstream Traffic Flow Control (MTFC) [3], [4], but very low VSL values may not be deemed acceptable for long time periods by the responsible road authority or the drivers.

The integration of control actions has been considered in previous works in order to overcome some of these limitations. For example, ramp metering was integrated either with route guidance [5], [6] or with VSL [3], [4], [7]-[13]. However, most of these approaches are based on sophisticated methods, e.g. nonlinear optimal control approaches, that may turn out to be cumbersome in field applications due to their black-box character and their requirement for many more measurements, demand prediction and model validation. Recently, there was an effort for the design of feedback control approaches that integrate ramp metering and VSL and are more appropriate for field applications. However, for example in [14], a quite specific layout is considered without accounting for the delays experienced by drivers; while the algorithm in [15] can be applied only in case of limited-length moving jams.

A new simple and generic control concept is presented in this paper using feedback controllers that can handle multiple bottlenecks, as addressed in the past for ramp metering [16] and for MTFC enabled by VSL [17]. The new concept aims at throughput maximization while integrating an arbitrary number and type of such actuators, located upstream of all bottlenecks, through an optimization algorithm that balances the delays experienced by drivers behind each actuator in a desired pre-specified way. Many practical aspects, related to ramp metering and VSL implementation constraints, have been considered, and simulation results are presented for a real motorway stretch in the United Kingdom using a validated second-order macroscopic traffic flow model and real demands.

In Section II, the concepts of ramp metering, MTFC and their integration are briefly outlined. Section III presents the proposed integrated feedback control strategy, whose efficiency is evaluated in Section IV for a number of different scenarios. Conclusions as well as some ideas for future research are

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presented in Section V.

II. Motorway Traffic Management

Activation of a motorway bottleneck due to increased upstream demand is known to lead to reduced throughput (capacity drop) [1]. This section contains a brief outline of countermeasures, specifically of two motorway traffic management methods, ramp metering [1] and MTFC enabled by VSL [3],[4], as well as their integration.

A. Ramp Metering

Whenever an on-ramp merging bottleneck is close to activation, ramp metering (Fig. 1(a)) can be used to regulate the ramp flow q_r (veh/h) via traffic lights [18] so as to keep the outflow of the system q_{out} (veh/h) around its capacity q_{cap}. This can be achieved if the density ρ_{out} (veh/km/lane) at the bottleneck location is maintained around its critical value ρ_{cr} via the ramp metering actions. On-ramp flow regulation leads to the creation of a queue w (veh) at the on-ramp. As long as the available queue storage space $w_{\max}$ is sufficient, the congestion creation and its consequences (capacity drop) can be avoided. However, the storage space is usually limited, and a queue management strategy may have to be activated in order to avoid the spillback of the queue on the adjacent infrastructure. As a result, ramp metering actions are then overridden. The available storage space may be increased via coordination of control actions at multiple upstream on-ramps with significant benefits [19]. However, ramp metering coordination also reaches its limits if the considered on-ramps are located far upstream of the bottleneck and the corresponding ramp demands are only partially bound for the bottleneck location.

B. Mainstream Traffic Flow Control

MTFC, enabled by VSL, can be used to regulate the flow q_c (veh/h) upstream of a bottleneck location (Fig. 1(b)) in order to avoid its activation. As a result, a controlled congestion is created on the mainstream. An acceleration area downstream of the control point ensures that vehicles have enough space to accelerate from low speeds to the critical speed. The capacity drop at the bottleneck is avoided as long as the regulated flow is arranged such that the outflow of the system q_{out} is around its capacity q_{cap}. As in ramp metering, this can be achieved if the density ρ_{out} at the bottleneck location is maintained around its critical value ρ_{cr}. Since the outflow of the system in the MTFC case is higher compared to the uncontrolled congested case, the controlled congestion has a higher internal speed and is space-time shorter than in the uncontrolled case, leading to less blocking of upstream off-ramps. For more details see [3], [4], [20].

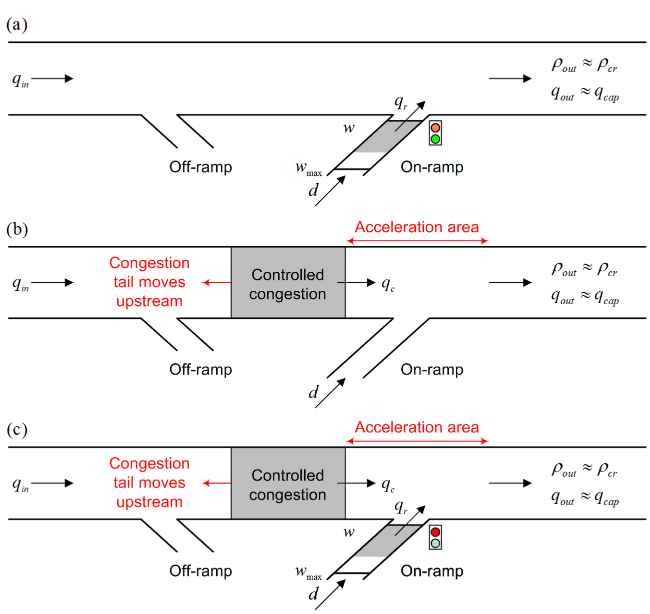

Fig. 1. (a) Ramp metering; (b) mainstream traffic flow control (MTFC); (c) integrated ramp metering and mainstream traffic flow control.

C. Integrated Motorway Traffic Flow Control

In the case of integrated motorway traffic flow control, two or more traffic control measures are combined [21]. For example, integration of ramp metering and MTFC enabled via VSL (Fig. 1(c)) can be used to maintain ρ_{out} at the bottleneck location around its critical value ρ_{cr}. A suitable combination of a ramp flow q_r and a mainstream flow q_c should then be specified, while the remaining degree of freedom may be exploited to achieve some secondary criteria, for example, delay balancing, as done in case of dual-branch on-ramps [22] or merging motorways [23].

III. Integrated Traffic Flow Control for Multiple Bottlenecks with Balanced Delays

Multiple bottlenecks may appear due to various reasons, e.g. high demand of consecutive uncontrolled on-ramps, bad weather, strong lane changing, lane drops, speed limit changes etc. In several earlier works, it is assumed that feedback control actions taken for treating different bottleneck locations do not interfere with each other and can be independently handled. This is sometimes not possible, e.g., when potentially active bottlenecks are in close proximity or interact with each other or are uncertain due to a number of possible reasons.

This section presents the proposed feedback-based integrated motorway traffic flow control strategy for multiple bottlenecks with delay balancing. Each potential bottleneck location should be equipped with a corresponding device providing the necessary real-time measurements. The concept is based on previous concepts addressing multiple bottlenecks, developed either for ramp metering [16] or for MTFC [17]; and it generalizes the delay balancing idea of [21], [22] to apply to an arbitrary number of ramp metering or VSL actuators via appropriate definition of a knapsack optimization problem. The new generic integrated controller remains simple yet efficient and suitable for field implementation. It enables the integration of ramp metering and VSL actions, balancing the delays caused by the different actuators.

A. Feedback Control Structure

The feedback control structure proposed is depicted in Fig. 2. A set of n Proportional-Integral (PI) controllers is used; each fed with a corresponding measurement from a potential

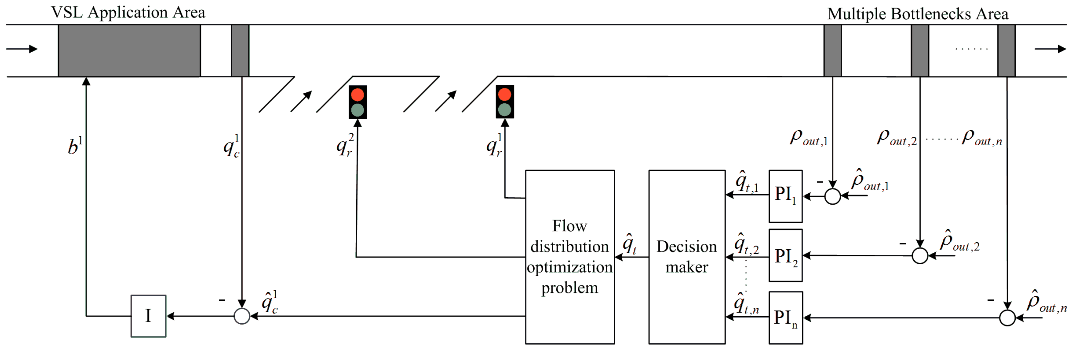

Fig. 2. Integrated control structure for multiple bottlenecks and balanced delays.

bottleneck site, downstream of all actuators. The measured density $\rho_{out,i}$ at the bottleneck location i at time instant k is compared with the set-point $\hat{\rho}_{out,i}$, usually set around the critical density value, at which capacity flow is achieved at that location. The PI-type regulator for the bottleneck location i is given by:

$$\hat{q}_{t,i}(k) = \hat{q}_{t,i}(k-1) + \hat{K}_{I,i}(\hat{\rho}_{out,i} - \rho_{out,i}(k)) + \hat{K}_{P,i}(\rho_{out,i}(k-1) - \rho_{out,i}(k)), \quad i = 1,...,n \tag{1}$$

where $\hat{q}_{t,i}(k)$ represents the output of the *i*-th regulator (i.e. the flow to be implemented by all actuators), while $\hat{K}_{I,i}$ and $\hat{K}_{P,i}$ are the integral and proportional gains, respectively. The output of each regulator is truncated in order to remain within a range of flow values $\left[\hat{q}_{t,\min}(k), \hat{q}_{t,\max}(k)\right]$. These time-varying bounds are determined as explained later. The truncated values are used at the next time-period as the $k-1$ values in (1) to avoid the well-known windup phenomenon for PI regulators.

It should be noted that the stability of the closed-loop ramp metering system with a PI-type regulator has been rigorously proved by both linearized system analysis and by Lyapunov stability arguments [24]. In fact, with its control parameters appropriately tuned, the regulator was found to be universally applicable to a range of distances between the on-ramp and downstream bottlenecks. The latter was also an empirical observation found in [25]. Studying the stability of the specific control concept presented in this section is out of the scope of this paper. Additional research on this issue may be useful.

An appropriately designed decision algorithm determines the overall action from all PI controller outputs. Specifically, the currently active bottleneck is determined, and the output of the corresponding PI controller is chosen for implementation. This is done in the following way [17]:

$$\hat{q}_t(k) = \hat{q}_{tj}(k) \tag{2}$$

with

$$j = \arg\min_{i=1,...,n} \left\{\hat{q}_{t,i}^{sm}(k)\right\} \tag{3}$$

$$\hat{q}_{t,i}^{sm}(k) = \alpha_{sm} \cdot \hat{q}_{t,i}(k) + (1-\alpha_{sm}) \cdot \hat{q}_{t,i}^{sm}(k-1), \quad i = 1,...,n \tag{4}$$

where $\hat{q}_{t,i}^{sm}(k)$ in (4) represents the exponential smoothing of $\hat{q}_{t,i}(k)$ with α_{sm} a parameter within $[0,1]$. The controller that corresponds to the smallest (smoothed) flow value is selected and is implemented in the time interval $\left(kT,(k+1)T\right]$, where T is the control period. The smoothed flow is used to avoid frequent switching to different controllers, which may be caused by measurement noise.

The specified total flow $\hat{q}_t(k)$ must then be distributed to the available actuators so that the bounds of each actuator flow are respected. Such bounds exist due to operational and policy-related issues; for example, in case of ramp metering a queue management policy may create lower bounds for the actuator; while in case of MTFC specific VSL lower and upper bounds are present. If $q_r^i(k)$ is the flow to be implemented by the *i*-th ramp metering system and $q_c^i(k)$ is the flow to be implemented by the *i*-th MTFC system, both at time period k, then the total flow distribution should satisfy

$$\hat{q}_t(k) = \sum_{i=1}^{n_r} q_r^i(k) + \sum_{i=1}^{n_c} \hat{q}_c^i(k) \tag{5}$$

$$q_{r,\min}^i(k) \le q_r^i(k) \le q_{r,\max}^i(k), \quad i = 1,...,n_r \tag{6}$$

$$\hat{q}_{c,\min}^i(k) \le \hat{q}_c^i(k) \le \hat{q}_{c,\max}^i(k), \quad i = 1,...,n_c \tag{7}$$

where n_r and n_c are the numbers of ramp metering and MTFC actuators available, respectively. In the example of Fig. 2, two ramp metering and a single MTFC actuator are utilized. Note that, in case of merging motorways (as in [23]), more than one MTFC systems could be present. However, in order to avoid cases where drivers experience more than one piece of queue/delay, it is assumed that a MTFC system, if any, is always located upstream of all metered on-ramps that feed the mainstream section which includes the bottleneck locations. The actuator bounds (6) and (7) will be specified in Sections III.B and III.C. Based on (5)-(7), the following can be derived:

$$\sum_{i=1}^{n_r} q_{r,\min}^i(k) + \sum_{i=1}^{n_c} \hat{q}_{c,\min}^i(k) \le \hat{q}_t(k) \le \sum_{i=1}^{n_r} q_{r,\max}^i(k) + \sum_{i=1}^{n_c} \hat{q}_{c,\max}^i(k) \tag{8}$$

and, as a result, the bounds used to truncate the outputs of (1) are given by:

$$\hat{q}_{t,\min}(k) = \sum_{i=1}^{n_r} q_{r,\min}^i(k) + \sum_{i=1}^{n_c} \hat{q}_{c,\min}^i(k) \tag{9}$$

$$\hat{q}_{t,\max}(k) = \sum_{i=1}^{n_r} q_{r,\max}^i(k) + \sum_{i=1}^{n_c} \hat{q}_{c,\max}^i(k) . \tag{10}$$

In general, there may be an infinite number of flow distributions that satisfy (5)-(7); Section III.D presents an approach that leads to a desired delay balancing across the involved actuators.

B. Ramp Metering

In the case of ramp metering, the ramp flows determined by the flow distribution algorithm can be implemented directly using traffic lights. The lower bounds required in inequality (6) can be determined by the queue management policy applied. A Proportional (P) controller with feed-forward on-ramp demand may be used [26] to limit the on-ramp queue:

$$q_{qm}^i(k) = (w_i(k) - \hat{w}_i)/T + d_i^{sm}(k-1) \tag{11}$$

where $w_i(k)$ is an estimate of the queue on the on-ramp i at time instant k; $\hat{w}_i$ is the utilized set-point, which is usually the maximum admissible on-ramp queue length for the on-ramp i; and $d_i^{sm}(k-1)$ is an exponentially smoothed value of the past demand measurements, which is used as an estimate of the demand for the next period. The values obtained from (11) should be truncated in order to respect an infrastructure-related upper bound $\overline{q}_{r,\max}^i$ and a policy-related lower bound $\overline{q}_{r,\min}^i$. In the field, an estimate of the on-ramp queue can be obtained using a Kalman filter estimator [27].

On the other hand, the upper bounds required by inequality (6) can be determined by the available demand:

$$q_d^i(k) = w_i(k)/T + d_i^{sm}(k-1) + c_i, \quad c_i \geq 0 \tag{12}$$

where the constant c_i is used to ensure that the bound is not conservative in case of an underestimation of demand through smoothing. Truncation of the values obtained by (12) is finally applied using the bounds used earlier for (11).

C. MTFC enabled by VSL

In the case of MTFC enabled by VSL, a secondary loop with an Integral (I) controller is used for each MTFC system (see [20] for details). This secondary loop compares the flow measurement q_c^i, collected downstream of VSL's i application area, with the corresponding desired flow $\hat{q}_c^i(k)$, delivered by the flow distribution algorithm, to calculate the VSL rate b^i. The VSL rate b^i is defined as the VSL-induced free speed divided by the non-VSL free speed and is approximately equal to the displayed VSL divided by the legal speed limit without VSL. The I-controller reads

$$b^i(k) = b^i(k-1) + K_I^i\left[\hat{q}_c^i(k) - q_c^i(k)\right] \tag{13}$$

where K_I^i is the integral gain of the controller. As an alternative to this I-type controller, a look-up table of VSL rates versus desired flows could be used [28].

Some practical VSL implementation aspects are then taken into account. Posted VSL rates can only take predefined discrete values. As a result, the VSL rates delivered by (13) are rounded to the closest discrete value to obtain the corresponding posted VSL rates $\overline{b}^i(k) \in \left\{\hat{b}_{\min}^i, \hat{b}_{\min}^i + \Delta b, ..., \hat{b}_{\max}^i\right\}$, where Δb is the practiced discrete VSL increment, e.g. $\Delta b = 0.1$. Furthermore, the difference between two consecutively posted VSL rates at the same gantry is limited to $\Delta b_{\max}$, as often required in practice. As a result, the lower bound for the VSL rate that can be implemented is given by:

$$b_{\min}^i(k) = \max\left\{\hat{b}_{\min}^i, \overline{b}^i(k-1) - \Delta b_{\max}\right\} \tag{14}$$

and the upper bound is given by:

$$b_{\max}^i(k) = \min\left\{\hat{b}_{\max}^i, \overline{b}^i(k-1) + \Delta b_{\max}\right\} . \tag{15}$$

Appling these bounds to (13), one can determine the bounds required by inequality (7) as:

$$\hat{q}_{c,\min}^i(k) = q_c^i(k) + \left[b_{\min}^i(k) - b^i(k-1)\right]/K_I^i \tag{16}$$

$$\hat{q}_{c,\max}^i(k) = q_c^i(k) + \left[b_{\max}^i(k) - b^i(k-1)\right]/K_I^i . \tag{17}$$

In addition, for safety reasons, VSL may also be applied upstream of the controlled congestion. Then, the difference between the posted VSL rate at two consecutive gantries is limited to $\delta b_{\max}$. Finally, a constant VSL rate equal to 0.9 is applied in the acceleration area whenever MTFC is active [20].

D. Delay Estimation

As mentioned earlier, the flow distribution to the available actuators will be determined so as to balance the delays experienced by the respective groups of drivers upstream of each actuator. In order to achieve this goal, an estimation of these delays is necessary.

For the case of vehicles queueing on an on-ramp i due to ramp metering actions, $\delta_r^i(k+1)$ denotes the estimated delay to be experienced by drivers exiting the ramp at the next time period if a ramp flow $q_r^i(k)$ is implemented. Assuming no internal vehicle sinks and sources, and that vehicles enter and exit according to the first-in-first-out rule, an estimate of the delay is [22]:

$$\delta_r^i(k+1) = A_r^i - B_r^i q_r^i(k) \tag{18}$$

where $A_r^i = w_i(k)/d_i^{sm}(k-1) + T$ and $B_r^i = T/d_i^{sm}(k-1)$.

For the case of vehicles delayed by the controlled congestion due to MTFC actions, the delay can be estimated if the travel time under free flow conditions is subtracted from the currently experienced travel time for all the freeway segments located upstream of the control point that experience a speed smaller than the free flow speed v_f. This delay can be considered as having two components. The first component is the

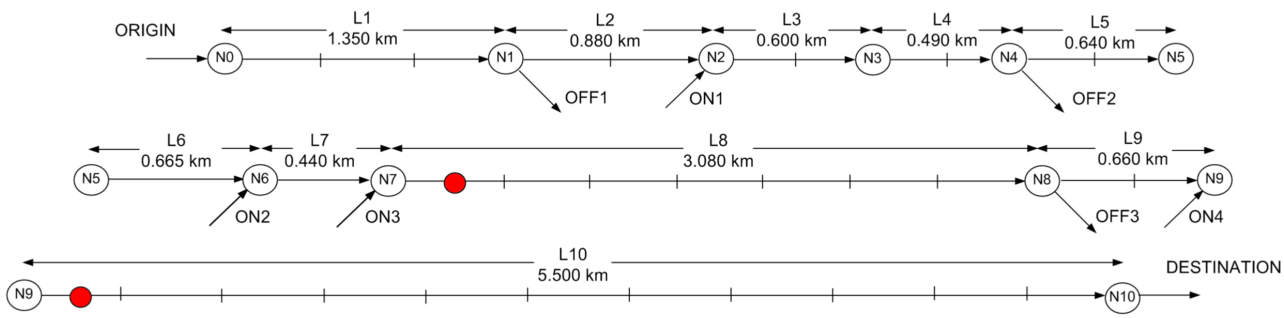

Fig. 3. The motorway stretch considered. The two bottleneck areas are marked with red dots.

delay experienced within the most downstream part of the controlled congestion, where no on-/off-ramps are present, hence there are no internal sinks and sources, and vehicles enter and exit according to the first-in-first-out rule as at on-ramp queues; while the second component considers the delay experienced farther upstream and is estimated by use of available speed measurements. Thus, the estimate of the delay due to *i*-th MTFC system is given by:

$$\delta_c^i(k+1) = A_c^i - B_c^i q_c^i(k) \tag{19}$$

where $A_c^i = A_c^{i*} + N_i(k)/q_{in,i}^{sm}(k-1) + T - L_i/v_f$, $N_i(k)$ is an estimate of the number of vehicles within the most downstream (ramp-free) motorway segment at time k, L_i is the length of that segment, $q_{in,i}^{sm}(k-1)$ is an exponentially smoothed value of the past inflow measurements at the entrance of this motorway segment, and $B_c^i = T/q_{in,i}^{sm}(k-1)$. Finally, A_c^{i*} is the second component of the delay that can be calculated based on speed measurements for all the segments that experience a speed smaller than the free flow speed v_f and are located further upstream.

E. Flow Distribution for Delay Balancing

The solution of the following knapsack optimization problem delivers the flows to be applied for each actuator:

$$\min \sum_{i=1}^{n_r} \frac{\left(A_r^i - B_r^i q_r^i(k)\right)^2}{B_r^i} + \sum_{i=1}^{n_c} \frac{\left(A_c^i - B_c^i \hat{q}_c^i(k)\right)^2}{B_c^i} \tag{20}$$

subject to the linear equality (5) and the bounds on the decision variables (6) and (7).

This problem is a convex optimization problem that is always feasible due to the fact that the bounds defined by (8) are taken into account for the truncation of the values calculated by (1). By applying the first-order optimality conditions, it can be easily seen that delay equalization is achieved as long as none of the bounds is active. If some bounds are active (for some actuators) then delay equalization is achieved for the rest of the actuators. This knapsack problem can be solved using the computationally efficient algorithm developed by Brucker [29] within a finite number of iterations. Note that the cost criterion (20) can be readily extended with additional weights so as to lead to any desired linear relations among the delays of different actuators, i.e. other than delay equalization.

Different actuators may feature different control periods. For example, ramp metering may be most efficient with a period of 20 sec; while VSL cannot switch more frequently than each 1 min to avoid driver irritation. In such cases, the different control periods must be multiples of an equal-smaller common divisor, which is the period employed for the controller (1). Then, at the time periods that it is not necessary to update the flow to be implemented by some actuator, its two bounds required by (6) and (7) are both set equal to the last decided flow value for the same actuator. Since both bounds are set equal to the same value, the corresponding inequalities are acting as equalities. As a result, the solution of the knapsack problem is such that the flows of all actuators that are not updated remain indeed the same as in the last controller period, while all other flows are decided so as to guarantee delay equalization for all other actuators.

The application of the ramp flows and the VSL rates delivered by the control strategy begins when the measured density $\rho_{out,i}$ at a bottleneck location i becomes higher than an activation threshold, and ends when the measured densities at all bottleneck areas become lower than a deactivation threshold (which is lower than the activation threshold).

IV. Simulation Results

This section presents a number of different control scenarios simulated for a real motorway stretch. The well-known second-order macroscopic traffic flow model included in the METANET simulator [30] is used. This model was extended to incorporate VSL measures in [3]. The motorway network is represented by a directed graph, whereby the links of the graph represent motorway stretches with uniform characteristics. The nodes of the graph are placed at locations where major changes in geometry occur, as well as at junctions and on-/off-ramps. The aggregate behavior of traffic at certain times and locations is defined by appropriate variables, whereby time and space arguments are discretized.

A. Network Model

A stretch of a motorway in the United Kingdom is consid-

TABLE I
DESCRIPTION OF SCENARIOS AND ACHIEVED RESULTS

	Description	TTS (veh·h)	Improvement (%)	TD (veh·h)	Improvement (%)
No-Control	Calibrated no-control case	3949	-	1178	-
Scenario 1	Local ramp metering with two separate controllers (no queue constraints)	3133	20.7	361	69.4
Scenario 2	Local ramp metering with two separate controllers (queue constraints)	3437	13.0	665	43.5
Scenario 3	Coordinated ramp metering for multiple bottlenecks	3539	10.4	767	34.9
Scenario 4	MTFC enabled via VSL for multiple bottlenecks	3408	13.7	540	54.2
Scenario 5	Integrated control for multiple bottlenecks	3139	20.5	340	71.1

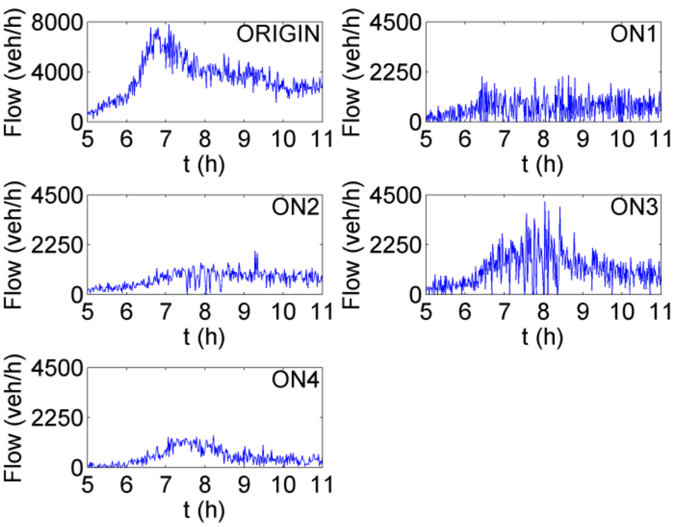

Fig. 4. Demand profiles for all the origins of the network.

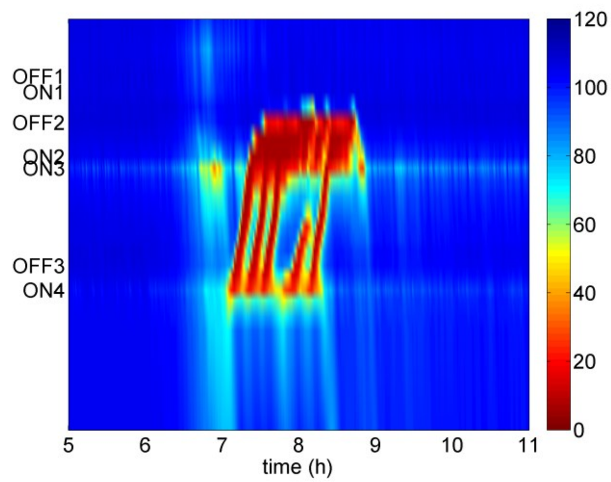

Fig. 5. Speed (km/h) contour plot for the no-control case.

ered for the simulations. The length of this stretch is 11.3 km. Figure 3 depicts the graph for the motorway stretch. Arrows represent links divided into a number of segments, indicated by vertical lines. Links ON2 and ON3 are in fact motorway-to-motorway connections, modelled here as on-ramps. The METANET model has been calibrated using MIDAS data [31] for the AM peak of September 9, 2014. The model time step used is set to 5 sec. The demand profiles for all the origins of the network are presented in Fig. 4. The active bottlenecks are located at links L8 and L10, i.e. a multiple bottleneck case exists if the on-ramp ON4 is not controlled. After discussing the no-control case, a set of control scenarios is investigated (see Table I), each for a time horizon of 6 hours (5-11 AM). A different control structure is used per scenario in order to show the increased efficiency achieved by the proposed approach. The efficiency measures considered (see Table I) are the Total Time Spent (TTS) in the network, which is the sum of the Total Travel Time (TTT) and the Total Waiting Time (TWT) at the origins, as well as the Total Delay (TD), which is given as the sum of the Mainstream Delay and the TWT at the origins.

B. No-Control Case

No-control is the base case that will be used to quantify any efficiency improvements arising from the use of control actions. Figure 5 presents the no-control speed contour plot for the time horizon under consideration. At $t = 6.75$ h, the merge area of the ON3 on-ramp reaches its factual capacity of about 6000 veh/h. A short-lived congestion is created, lasting for about 15 min, without any major propagation of the phenomenon further upstream. At $t = 7$ h, congestion is created at the merge area of the ON4 on-ramp because the demand is exceeding capacity (around 6200 veh/h) at the specific area. A capacity drop of around 15% is created and congestion propagates upstream over 6.6 km triggering more severe congestion phenomena at the merge area of ON3 that last till about $t = 9$ h. The resulting TTS in the network is equal to 3949 veh·h, while TD is equal to 1178 veh·h.

C. Scenario 1

Scenario 1 applies local ramp metering actions using two

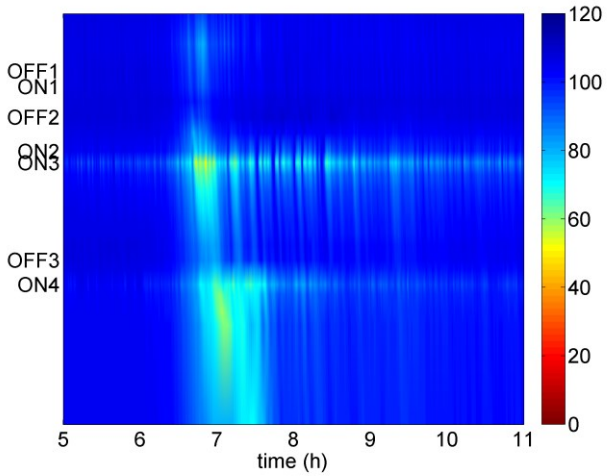

Fig. 6. Speed (km/h) contour plot for the Scenario 1.

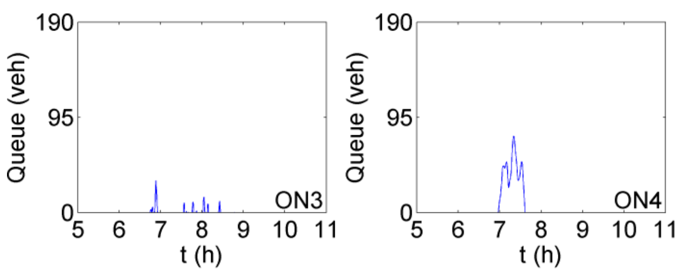

Fig. 7. Queue profiles for Scenario 1.

separate controllers; a first controller receives measurements from the first segment of link L8 and acts using ramp metering at on-ramp ON3; a second controller receives measurements from the first segment of link L10 and acts using ramp metering at on-ramp ON4. In both cases the control period was set to 20 sec while the P-term gain value in (1) was set to zero and the I-term gain value was set to 90 km·lane/h (which corresponds to the well-known ALINEA regulator [32]). The set-points of the controllers are set equal to the respective factual critical densities, namely 35 veh/km/lane and 29 veh/km/lane. No queue management actions are considered in order to investigate what is the upper bound of efficiency that can be achieved for the case of the most direct control measure, i.e. local ramp metering. This is implemented by setting a very high value for the maximum admissible on-ramp queue length in (11).

Compared to the no-control case, the resulting TTS is reduced by 20.7% while the resulting TD is reduced by a remarkable 69.4%. The speed contour plot for Scenario 1 is presented in Fig. 6, while the queues created on the on-ramps due to ramp metering actions are shown in Fig. 7. At both bottlenecks, density values are maintained around the corresponding set-points; thus capacity flow is achieved at L8 and L10, which leads to minimization of TTS. The real delays experienced by drivers queueing at on-ramps ON3 and ON4 are displayed in Fig. 8(a) and are, as expected, completely unbalanced.

D. Scenario 2

Scenario 2 applies local ramp metering actions as in Scenario 1. The only difference is that queue management actions are now considered. The maximum admissible queues (based on an estimate of the real storage space of the infrastructure) are 92 veh for ON3 and 40 veh for ON4.

Compared to the no-control case, the resulting TTS is now reduced by 13.0%, while the resulting TD is reduced by 43.5%. The speed contour plot for Scenario 2 is presented in Fig. 9, while the queues created on the on-ramps due to ramp metering actions are shown in Fig. 10.

As expected, ramp metering actions are now just delaying the onset of congestion because the applied queue controller releases the ON4 on-ramp flow in order to maintain the queue around its maximum admissible value. Congestion propagates upstream causing further ramp metering actions at the ON3 on-ramp. However, due to queue management actions there, the ON3 on-ramp flow is also released leading to congestion propagation up to the area of the OFF2 off-ramp, which is a major connection to another motorway. The quite unbalanced on-ramp queue delays are displayed in Fig. 8(b).

E. Scenario 3

Coordinated ramp metering is applied in Scenario 3 utilizing the proposed new approach. Both bottleneck locations, L8 and L10, are considered by a single control structure, and ramp metering is applied at on-ramps ON2 and ON3, i.e. the two on-ramps that are situated upstream of both bottlenecks, (with maximum admissible queues of 180 veh for ON2 and 92 veh for ON3) with a control period of 20 sec. The utilized density set-points remain the same as in the previous scenarios, i.e. $\hat{\rho}_{out,1} = 35$ veh/km/lane for L8 and $\hat{\rho}_{out,2} = 29$ veh/km/lane for L10, while the gain values are $\hat{K}_{I,1} = \hat{K}_{I,2} = 5$ km·lane/h and $\hat{K}_{P,1} = \hat{K}_{P,2} = 30$ km·lane/h.

Compared to the no-control case, the resulting TTS is reduced by 10.4% while the resulting TD is reduced by 34.9%. The speed contour plot for Scenario 3 is presented in Fig. 11, while the queues created on the on-ramps due to ramp metering actions are shown in Fig. 12.

At both bottlenecks, density values are maintained around the corresponding set-points up to 7:45 AM, i.e. up to the point that queue management actions are applied at on-ramp ON3. The delays experienced by drivers queueing at on-ramps ON2 and ON3 are displayed in Fig. 8(c) and are, as expected, balanced up to 7:45 AM. Later on, the optimizer asks for stronger ramp metering actions to be applied at on-ramp ON2, since metering at on-ramp ON3 is practically inactive. However, because the arriving demand at ON2 has meanwhile fallen to low levels (lower than the lower bound applied on the ramp metering flow), the ordered metering does not materialize, and congestion at L10 cannot be avoided. This low demand after 7:45 AM is the reason why the queue created at on-ramp ON2 is never reaching the maximum storage capacity.

It is interesting to note that this coordinated ramp metering scenario can be readily modified to act towards balancing of the relative on-ramp queues (as in the well-known HERO system [22]), rather than balancing of the respective time-delays. This would enable a better exploitation of the available storage

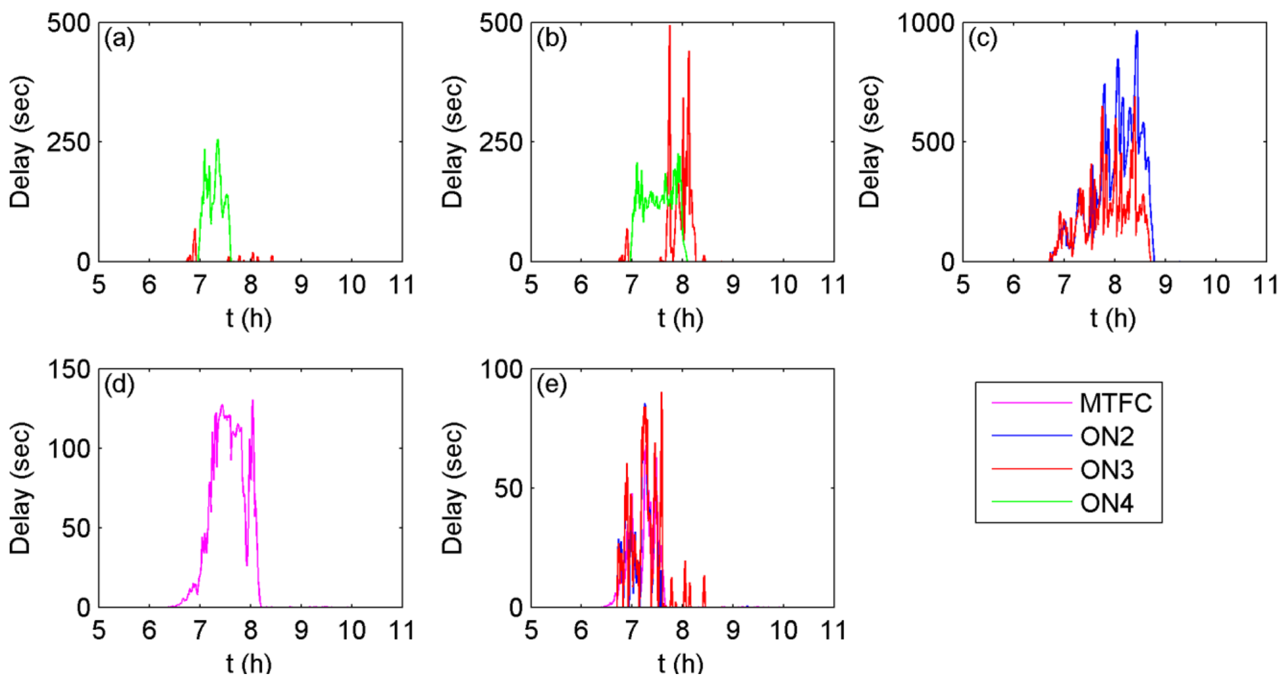

Fig. 8. Real delay profiles for (a) Scenario 1; (b) Scenario 2; (c) Scenario 3; (d) Scenario 4; (e) Scenario 5.

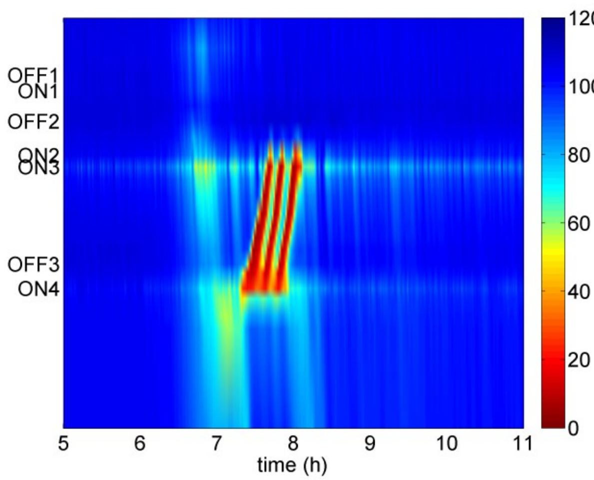

Fig. 9. Speed (km/h) contour plot for Scenario 2.

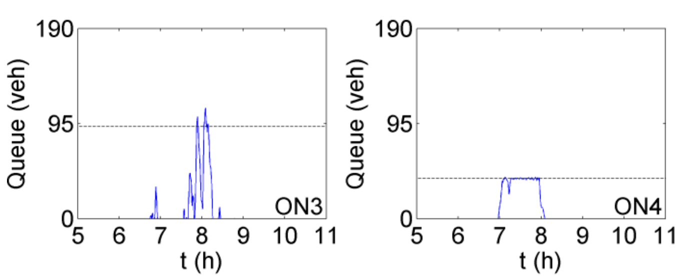

Fig. 10. Queue profiles for Scenario 2.

space in both on-ramps, before queue management actions are activated. For the present infrastructure and demand configuration, this approach leads to an improvement in the TTS value of 18.9% and to an accordingly smaller mainstream congestion.

F. Scenario 4

Scenario 4 applies feedback MTFC for two bottleneck locations, L8 and L10. The VSL application area comprises links L4 and L5, whereas upstream of L4 there are safety-related VSL; the acceleration area comprises links L6 and L7. The control period was set to 60 sec. The utilized density set-points as well as the gain values are the same with those used for Scenario 3. The following values are used for various parameters required by the secondary controller (the $i=1$ index has

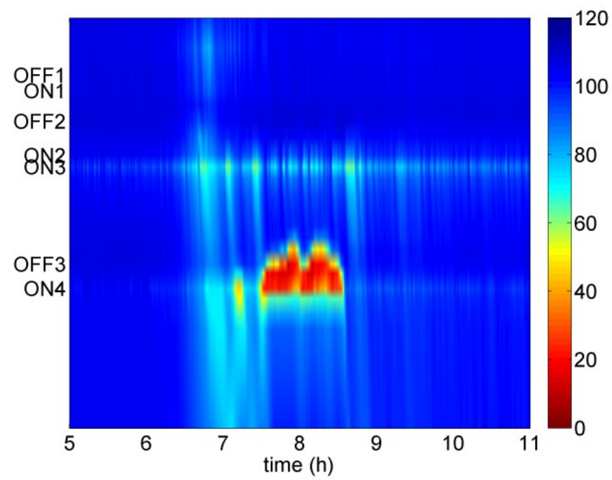

Fig. 11. Speed (km/h) contour plot for Scenario 3.

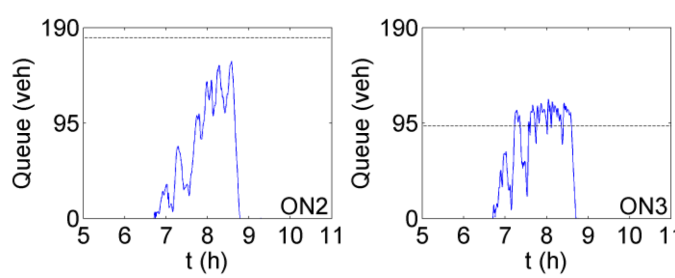

Fig. 12. Queue profiles for Scenario 3.

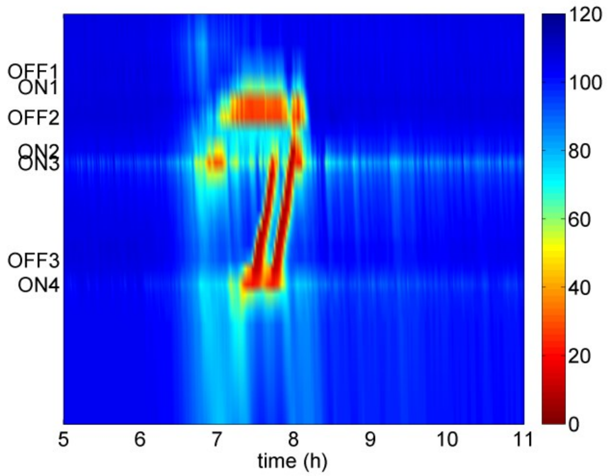

Fig. 13. Speed (km/h) contour plot for Scenario 4.

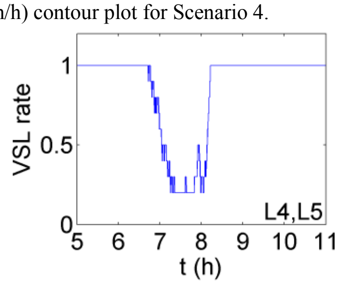

Fig. 14. VSL rate for Scenario 4.

been dropped for simplicity): $\hat{b}_{\min} = 0.2$, $\hat{b}_{\max} = 1.0$, $\Delta b = 0.1$, $\Delta b_{\max} = 0.1$, $\delta b_{\max} = 0.3$ and $K_I = 0.0015$ h·lane/veh.

Compared to the no-control case, the resulting TTS is reduced by 13.7% while the resulting TD is reduced by 54.2%. The speed contour plot for Scenario 4 is presented in Fig. 13 while the VSL rate trajectory is shown in Fig. 14. Note that no queues are created as no ramp metering is applied.

The VSL rate is gradually decreased from 1 (no speed limit) to 0.2 (the lowest admissible limit for VSL), and a controlled congestion is created at the VSL application area. The onset of congestion at the merging area of the ON4 on-ramp is delayed up to a few minutes after 7 AM, i.e. up to the point at which the secondary I-regulator is saturated due to reaching the lower admissible VSL rate bound of 0.2. The delay experienced by drivers within the controlled congestion is displayed in Fig. 8(d).

G. Scenario 5

Integrated control is applied in Scenario 5 using three actuators, i.e. two ramp meters applied at on-ramps ON2 and ON3 (with maximum admissible queues of 180 veh for ON2 and 92 veh for ON3) with a control period of 20 sec; and a VSL-enabled MTFC with a control period of 60 sec as in Scenario 4. The same gains and the settings as in Scenario 4 are used. Both bottleneck locations are considered using the integrated concept presented in Section III aiming at delay balancing for the three actuators.

Compared to the no-control case, the resulting TTS is now reduced by 20.5% while the resulting TD is reduced by a remarkable 71.1%. The speed contour plot for Scenario 5 is presented in Fig. 15, while the VSL rate trajectory due to MTFC actions, as well as the queues created on the on-ramps due to ramp metering actions, are shown in Fig. 16. At both bottlenecks, density values are maintained around the corresponding set-points, thus capacity flow is achieved at L8 and L10. This is done without any queue saturation for the two on-ramps and without any saturation of the VSL rates. The created mainstream controlled congestion is much smaller (in space and time) than in the no control case, having also higher internal speed.

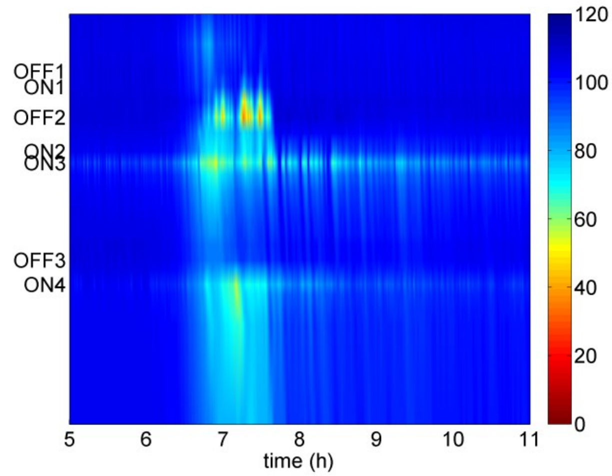

Fig. 15. Speed (km/h) contour plot for Scenario 5.

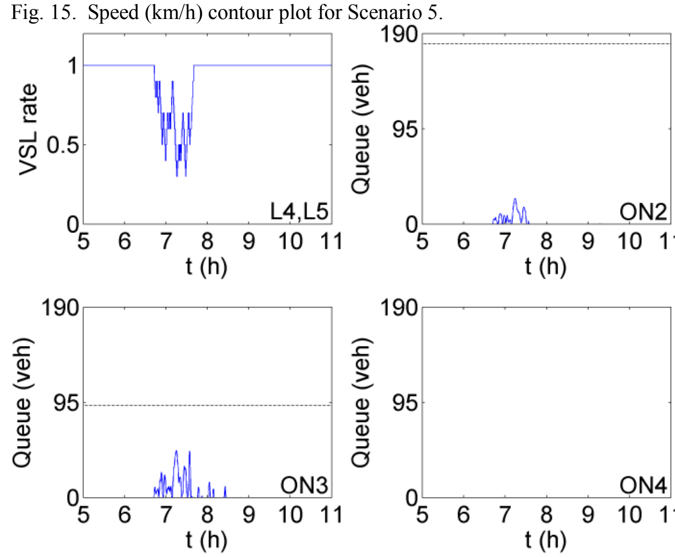

Fig. 16. VSL rate and queue profiles for Scenario 5.

Finally, the delays experienced by drivers are displayed in Fig. 8(e). It can be concluded that the (highest) efficiency of Scenario 1 is virtually reached, while delay balancing is achieved for the utilized actuators. As no ramp meter is applied at on-ramp ON4, there are no queues created there (Fig. 16), and as a result there is no delay experienced by the drivers on this ramp.

V. Conclusions

A feedback-based integrated motorway traffic flow control concept for multiple bottlenecks is proposed in this paper. Integration is achieved subject to balancing of delays experienced by drivers. The suggested concept has been evaluated using the validated METANET macroscopic traffic flow simulator for a real infrastructure and has been compared to other control structures. The integrated controller presented in Scenario 5 is shown to be superior as it takes advantage of all the available storage capacity required for queueing upstream of the bottlenecks. The feedback controller is robust as there is no need, neither for any predictions of the demand nor for any model calibration or parameter identification. Practical and safety constrains have been considered, and, as a result, the concept is appropriate for field implementations.

Future research activities will focus on further extensions of the proposed concept at a network level so as to apply coordination between different integrated controllers. Safety impact of the control strategy under various traffic scenarios will be also considered using microscopic simulation.

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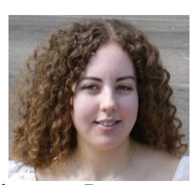

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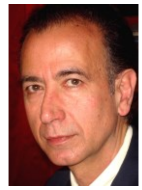

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