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 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 maximisation. The approach enables a pre-specified (desired) balancing of the incurred delays upstream of the employed actuators, via a suitably designed knapsack algorithm. Despite the multitude of the offered configurations, options and possibilities, the overall control algorithm remains simple, efficient and suitable for field implementation. The control algorithm is evaluated and demonstrated using a validated macroscopic traffic flow model for a number of scenarios.

Keywords: traffic management; integrated motorway traffic flow control; ramp metering; mainstream traffic flow control; variable speed limits; feedback control; delay balancing

1. INTRODUCTION

Congestion on motorways is a major and continuously growing problem that is known to reduce the nominal capacity of the infrastructure (Papageorgiou and Kotsialos, 2002) causing degradation in terms of travel times, traffic safety, fuel consumption and environmental pollution.

Different traffic management measures have been proposed to alleviate motorway traffic congestion, but each one of them considered individually may face some limitations. Ramp metering, for example, is the most direct and efficient measure for motorway traffic flow control, but it 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 (Papamichail et al., 2010). Variable Speed Limits (VSL), on the other hand, can be used in order to enable Mainstream Traffic Flow Control (MTFC) (Carlson et al., 2010a), but very low VSL values may not be deemed acceptable for long periods by the responsible road authority or the drivers.

The integration of control actions has been considered in the past in order to overcome some of these limitations. For example, ramp metering was integrated with VSL (Hegyi et al., 2005; Zhang et al., 2006; Chang et al., 2007; Carlson et al., 2010a, b; Lu et al., 2010; Zegeye et al., 2012). However, most of these approaches are based on sophisticated methods that may be cumbersome in field applications. 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 the work by Carlson et al. (2014), a quite specific layout is considered without accounting for the delays experienced by drivers; while the work of Mahajan et al. (2015) can be applied only in case of moving jams.

A new 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 (Wang et al., 2010) and for MTFC enabled by VSL (Iordanidou et al., 2015). Integration of an arbitrary number and type of such actuators is achieved through an optimisation algorithm that balances the delays experienced by drivers behind each actuator in a desired pre-specified way. The concept is simple and robust. Many practical aspects 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 demand flows.

The paper is structures as follows. In Section 2, the concepts of ramp metering, MTFC and their integration are briefly outlined. Section 3 presents the proposed integrated feedback control strategy. The efficiency of this strategy is evaluated in Section 4, while the conclusions as well as some ideas for future research are presented in Section 5.

2. MOTORWAY TRAFFIC MANAGEMENT

This section contains a brief description of two motorway traffic management methods, ramp metering (Papageorgiou and Kotsialos, 2002) and MTFC enabled by VSL (Carlson et al., 2010a, b), as well as their integration.

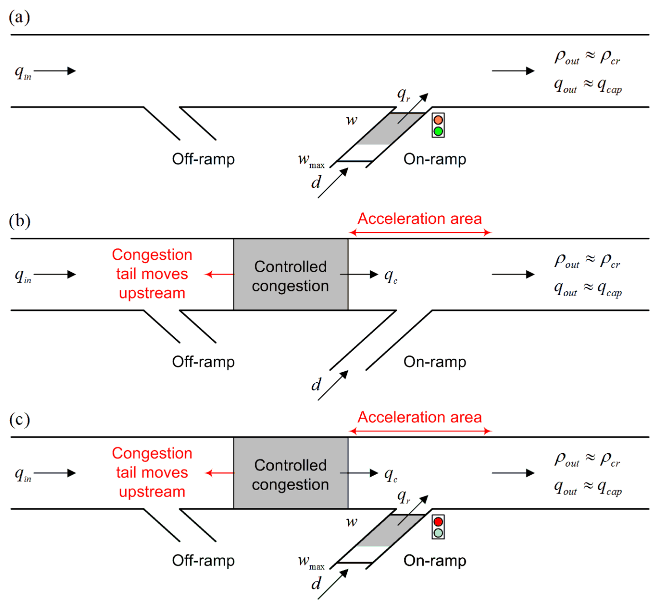

Fig. 1. (a) Ramp metering; (b) mainstream traffic flow control (MTFC); (c) integrated ramp metering and mainstream traffic flow control.

2.1 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 (Papageorgiou and Papamichail, 2008) 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, this 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.

2.2 Mainstream Traffic Flow Control

MTFC, enabled by VSL in this paper, 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 controlled 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 Carlson et al. (2010a, 2011a).

2.3 Integrated Motorway Traffic Flow Control

In the case of integrated motorway traffic flow control, two or more traffic control measures are combined (Papageorgiou et al., 2003). 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 and 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 (Papamichail and Papageorgiou, 2011) or merging motorways (Carlson et al., 2011b).

3. INTEGRATED TRAFFIC FLOW CONTROL FOR MULTIPLE BOTTLENECKS

This section presents the proposed feedback-based integrated motorway traffic flow control strategy for multiple bottlenecks. It is based on previous concepts for multiple bottlenecks developed either for ramp metering (Wang et al., 2010) or for MTFC (Iordanidou et al., 2015). The new generic integrated controller remains simple yet efficient and suitable for field implementation. It enables the integration of ramp metering and variable speed limit actions, balancing the delays caused by the different actuators.

Multiple bottlenecks may appear due to various reasons, e.g. uncontrolled on-ramps, bad weather, strong lane changing, lane drops, etc. Each potential bottleneck location should be equipped with a corresponding density measurement.

3.1 Feedback Control Structure

The feedback control structure proposed is depicted in Fig. 2. A set of Proportional-Integral (PI) controllers is used, each fed with a corresponding measurement from a potential bottleneck site, downstream of all actuators. The measured density $\rho_{out,i}(k)$ 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, at which capacity flow is achieved. The PI-type regulator for the bottleneck location i is given by:

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

where $\hat{q}_{t,i}(k)$ represents the output of the i-th regulator, 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 at the end of this sub-section. The truncated values are used at the next time-step as the $k-1$ values in (1) to avoid the well-known windup phenomenon for PI regulators.

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 (Iordanidou et al., 2015) in the following way:

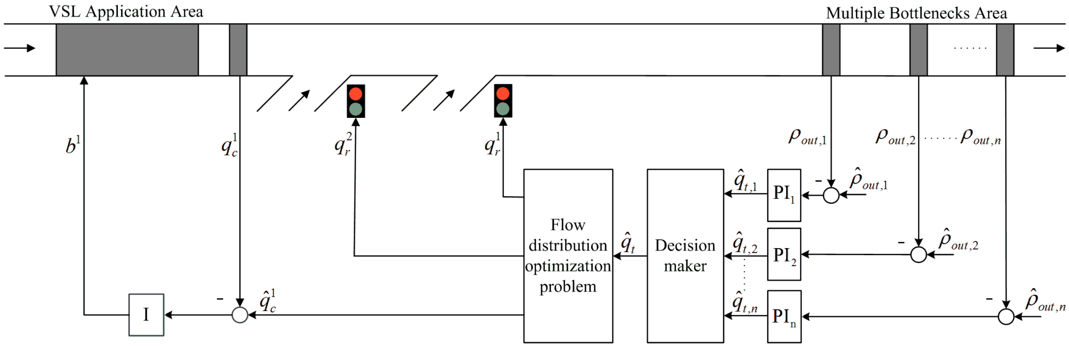

Fig. 2. Integrated control structure for multiple bottlenecks.

$$\hat{q}_t(k) = \hat{q}_{t,j}(k) \tag{2}$$

with

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

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

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 of the controllers 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. 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 instant k, then the total flow distribution should satisfy

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

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

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

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 (Carlson et al., 2011b)), more than one MTFC system could be present. Inequalities (6) and (7) reflect bounds for each actuator that will be determined in Sections 3.2 and 3.3. In general, there may be an infinite number of flow distributions that satisfy (5)-(7); Section 3.5 presents an appropriate approach that leads to a desired delay balancing. 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:

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

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

3.2 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 by inequality (6) can be determined by the queue management policy used. A Proportional (P) controller with feed-forward on-ramp demand may be used (Smaragdis and Papageorgiou, 2003)

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

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 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 step. The values obtained from (11) should be truncated in order to respect an infrastructure related upper bound $\bar{q}_{r,\max}^i$ and a policy related lower bound $\bar{q}_{r,\min}^i$. In the field, an estimate of the on-ramp queue can be obtained using the Kalman filter estimator by Vigos et al. (2008).

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

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

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).

3.3 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 (Carlson et al., 2011a) 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 by use of the I-controller

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

where K_I^i is the integral gain of the controller.

Some practical VSL implementation aspects are then taken into account. Posted VSL rates can only be 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 $\bar{b}^i(k) \in \{\hat{b}_{\min}^i, \hat{b}_{\min}^i + \Delta b, ..., \hat{b}_{\max}^i\}$, 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:

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

and the upper bound is given by:

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

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

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

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

In addition, for safety reasons, VSL is also applied upstream of the controlled congestion. In particular, the difference between the posted VSL rate at two consecutive gantries is limited to $\delta b_{\max}$. Furthermore, a constant VSL rate equal to 0.9 is applied in the acceleration area whenever MTFC is active (Carlson et al., 2011a).

3.4 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. 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, we denote $\delta_r^i(k+1)$ the estimated delay to be experienced by drivers exiting the ramp at the next time step 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 (Papamichail and Papageorgiou, 2011):

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

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 free flow speed travel time is subtracted from the experienced travel time. Based on similar assumptions for vehicles travelling within the controlled congestion with a speed smaller that the free flow speed v_f, an estimate of the delay is given by:

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

where $A_c^i = N_i(k) / q_{in,i}^{sm}(k-1) + T - L_i / v_f$, $N_i(k)$ is an estimate of the number of vehicles within the considered motorway stretch at time k, L_i is the length of the stretch i, $q_{in,i}^{sm}(k-1)$ is an exponentially smoothed value of the past inflow measurements, and $B_c^i = T / q_{in,i}^{sm}(k-1)$.

3.5 Flow Distribution for Delay Balancing

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

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

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

This problem is a convex optimisation problem that is always feasible due to (8) that has been taken into account. 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 (1984) 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 relations among the delays of different actuators, i.e. other than delay equalization.

The application of the ramp flows and the VSL rates delivered by the control strategy begins when the measured density at a bottleneck area becomes higher than an activation threshold and ends when the measured density at all bottleneck areas becomes lower than a deactivation threshold (which is lower than the activation threshold).

4. 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 (Messmer and Papageorgiou, 1990; Carlson et al., 2010a) is used. 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 behaviour of traffic at certain times and locations is defined by appropriate variables, whereby time and space arguments are discretized.

4.1 Network Model

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

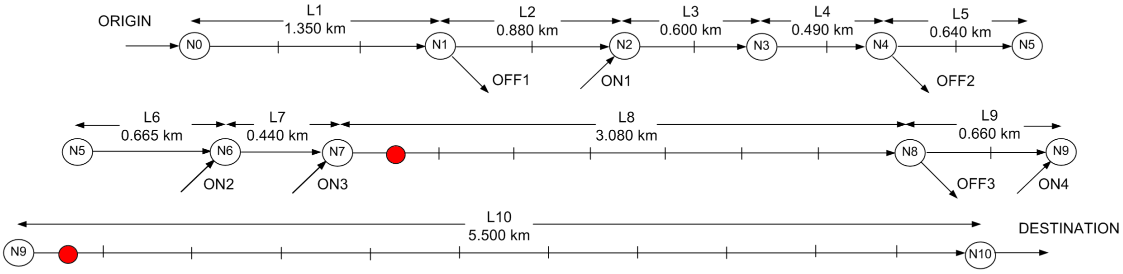

Fig. 3. The motorway stretch considered. The two bottleneck areas are marked with red dots.

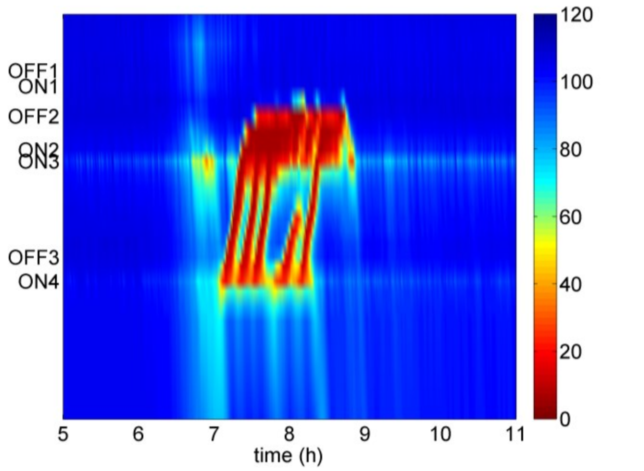

Fig. 4. Speed (km/h) contour plots for the no-control case.

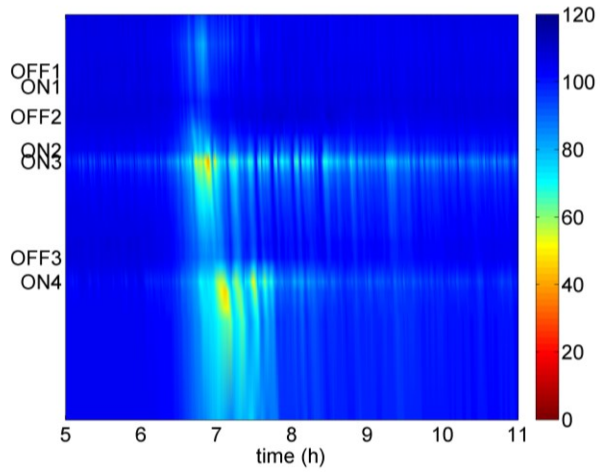

Fig. 5. Speed (km/h) contour plots for the Scenario 1.

to-motorway connections, modelled here as on-ramps. The METANET model has been calibrated using MIDAS data (www.midas-data.org.uk) for the AM peak of September 9, 2014. The active bottlenecks are located at links L8 and L10. A set of strategies is investigated, each for a time horizon of 6 hours (5-11 AM). The model time step used is 5 sec.

4.2 No-Control Case

The no-control is the base case that will be used to quantify any efficiency improvements arising from the use of control. Figure 4 presents the speed contour plot for the time period 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 which 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 Total Time Spend (TTS) in the network is equal to 3949 veh·h while the Total Delay (TD) is equal to 1178 veh·h.

4.3 Scenario 1

Scenario 1 applies local ramp metering actions using two 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 the on-ramp ON4. In both cases the P-term gain value in (1) was set to zero and the I-term gain value was set to 60 km·lane/h (which corresponds to the well-known ALINEA regulator, see (Papageorgiou et al., 1991)). 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, respectively. No queue management actions are considered in order to investigate what is the upper bound of efficiency that can be achieved. This can be implemented by setting a very high set-point for the queue in (11). Finally, the control period is set to 60 sec.

Compared to the no-control case, the resulting TTS is reduced by 20.1% while the resulting TD is reduced by a remarkable 67.5%. The speed contour plot for Scenario 1 is presented in Fig. 5 while the queues created on the on-ramps due to ramp metering actions are shown in Fig. 6. 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 delays experienced by drivers queueing at on-ramps ON3 and ON4 are displayed in Fig. 7(a) and are, as expected, completely unbalanced.

4.4 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

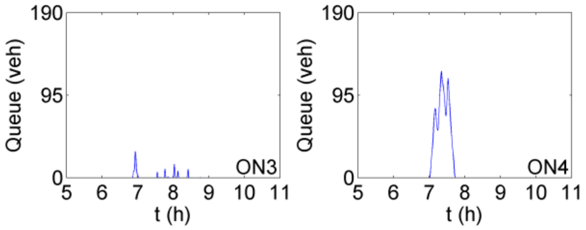

Fig. 6. Queue profiles for Scenario 1.

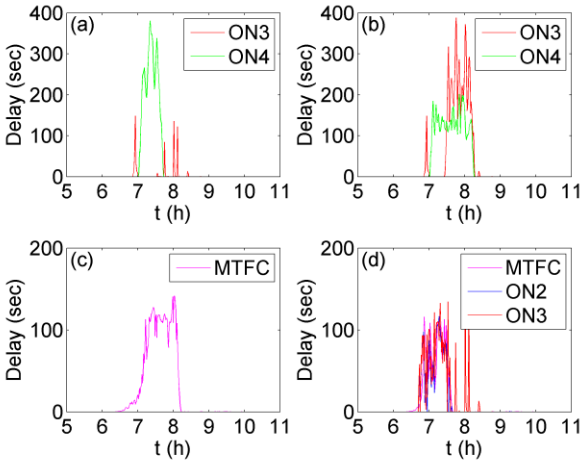

Fig. 7. Delay profiles for (a) Scenario 1; (b) Scenario 2; (c) Scenario 3; (d) Scenario 4.

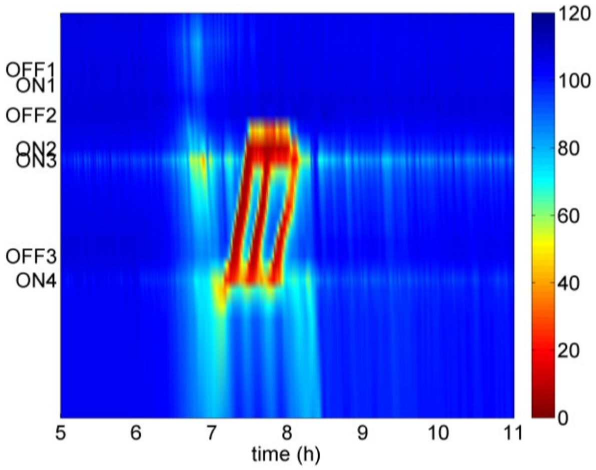

Fig. 8. Speed (km/h) contour plots for Scenario 2.

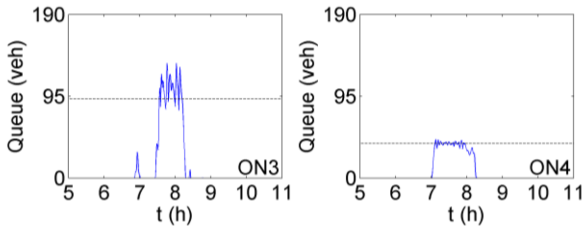

Fig. 9. Queue profiles for Scenario 2.

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 8.5% while the resulting TD is reduced by 28.4%. The speed contour plot for Scenario 2 is presented in Fig. 8 while the queues created on the on-ramps due to ramp metering actions are shown in Fig. 9.

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 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 delays are displayed in Fig. 7(b).

4.5 Scenario 3

Scenario 3 applies feedback MTFC for two bottleneck locations, L8 and L10. The parameter α_{sm} is set to 0.5. The VSL application area comprises links L4 and L5, whereas upstream of L4 there are safety limits; the acceleration area comprises links L6 and L7. 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 $\hat{K}_{I,1} = \hat{K}_{I,2} = 4$ km·lane/h and $\hat{K}_{P,1} = \hat{K}_{P,2} = 30$ km·lane/h. The following values are used for various parameters required by the secondary controller (the i index has 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 12.9% while the resulting TD is reduced by 52.1%. The speed contour plot for Scenario 3 is presented in Fig. 10 while the VSL rate trajectory is shown in Fig. 11. Note that no queues are created as no ramp metering is applied.

The VSL rate is gradually decreasing 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. The delay experienced by drivers within the controlled congestion is displayed in Fig. 7(c).

4.6 Scenario 4

Integrated control is applied in Scenario 4 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) and an MTFC enabled by VSL applied using the gains and the settings of Scenario 3. Both bottleneck locations are considered using the integrated concept presented in Section 3 aiming at delay balancing for the three actuators.

Compared to the no-control case, the resulting TTS is now reduced by 18.9% while the resulting TD is reduced by

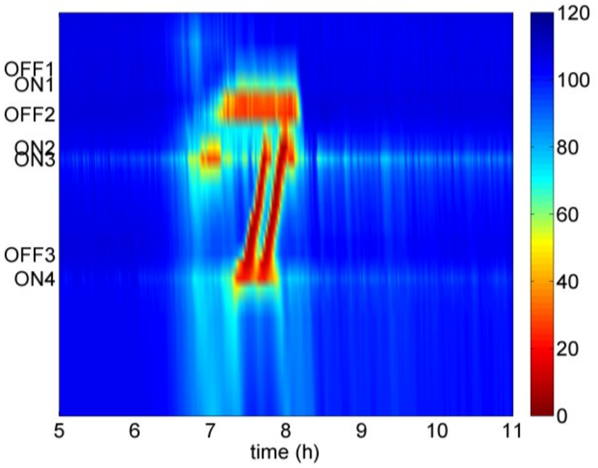

Fig. 10. Speed (km/h) contour plots for Scenario 3.

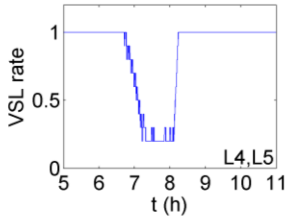

Fig. 11. VSL rate for Scenario 3.

69.0%. The speed contour plot for Scenario 4 is presented in Fig. 12, 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. 13. 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 with only occasional saturations 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.

Finally, the delays experienced by drivers are displayed in Fig. 7(d). It can be concluded that the (highest) efficiency of Scenario 1 is virtually reached while delay balancing is achieved.

5. CONCLUSION

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. The feedback controller is robust as there is no need for model predictions of the demand. Practical and safety constrains have been considered, and, as a result, the concept is appropriate for field implementations.

Future research activities will focus on the stability analysis of the proposed controller as well as on extensions of the proposed concept at a network level.

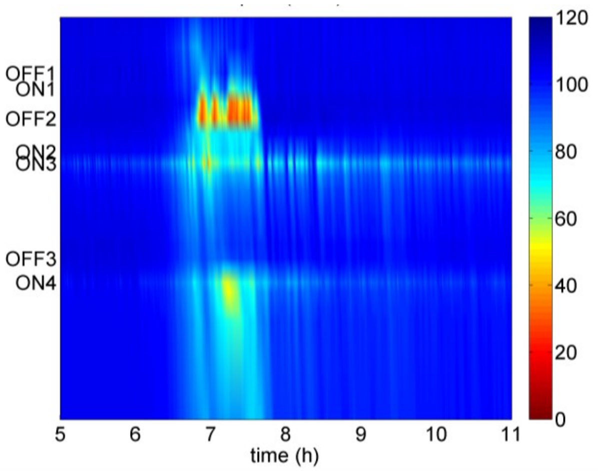

Fig. 12. Speed (km/h) contour plots for Scenario 4.

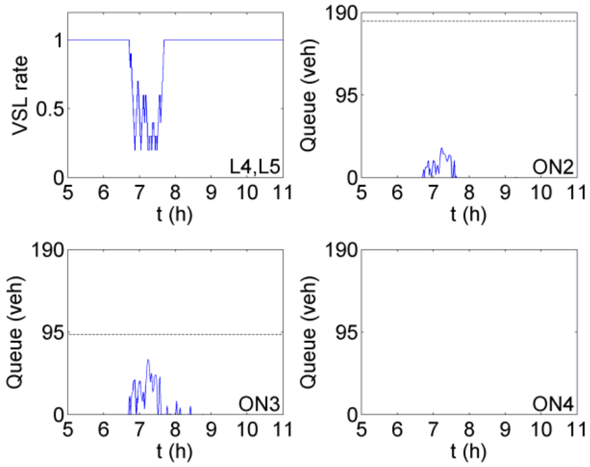

Fig. 13. VSL rate and queue profiles for Scenario 4.

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