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*Published in:*

Proceedings of the 8th International Congress on Transportation Research in Greece (ICTR 2017)

Published: 01/01/2017

*Document Version*

Publisher's PDF, also known as Version of record

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*Please cite the original version:*

Papamichail, I., Iordanidou, G.-R., Roncoli, C., & Papageorgiou, M. (2017). Integrated motorway traffic flow control. In *Proceedings of the 8th International Congress on Transportation Research in Greece (ICTR 2017)* Technical University of Crete. <http://purl.tuc.gr/dl/dias/F2B54DCD-2A0F-4C25-8C0F-2EF1EE4E487F>

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## Integrated Motorway Traffic Flow Control

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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 has been proposed recently by the authors of 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 validated macroscopic traffic flow models for two case studies and for a number of different 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 & Kotsialos, 2002) 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 integration of different control measures are missed. 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 (Papamichail et al., 2010). Variable Speed Limits (VSL), on the other hand, can be used to enable Mainstream Traffic Flow Control (MTFC) (Carlson et al., 2010a, 2010b), 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 (see Iordanidou et al., 2017 for a more thorough review). 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 more measurements, demand prediction and model validation. In the last years, there was an effort for the design of feedback control approaches that integrate ramp metering and VSL and are more appropriate for field applications.

A generic integrated feedback-based motorway traffic flow control concept was proposed recently by the authors of this paper (Iordanidou et al., 2017). 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-enabled cascade-feedback MTFC, 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.

The present paper outlines the control algorithm and demonstrates its features using validated second-order macroscopic traffic flow models for two different case studies and a number of scenarios. The first case study concerns a stretch of the Kwinana Freeway in Perth, Australia, while the second case study concerns a motorway stretch in the United Kingdom.

## ***2. Integrated Traffic Flow Control for Multiple Bottlenecks with Balanced Delays***

Multiple bottlenecks along a relatively short motorway stretch 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 outlines the new feedback-based integrated motorway traffic flow control strategy for multiple bottlenecks with delay balancing. The concept is based on previous concepts addressing multiple bottlenecks, developed separately either for ramp metering (Wang et al., 2010) or for MTFC (Iordanidou et al., 2015); and it generalizes the delay balancing idea of Papamichail & Papageorgiou (2011) 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.

### ***2.1 Feedback Control Structure***

The feedback control structure proposed is depicted in Figure 1. A set of  $n$  Proportional-Integral (PI) controllers is used; each fed with a corresponding measurement from a potential bottleneck site, downstream of all actuators. The measured density  $\rho_{out,i}$  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 output of each regulator is truncated in order to remain within a range of admissible flow values.

An appropriately designed decision algorithm determines the overall action from all PI controller outputs. Specifically, the currently active (or most critical) bottleneck is determined, and the output of the corresponding PI controller is chosen for implementation. Specifically, the controller that corresponds to the smallest (smoothed) flow value is selected and is implemented. Smoothed flows are used to avoid frequent switching to different controllers, which may be caused by measurement noise.

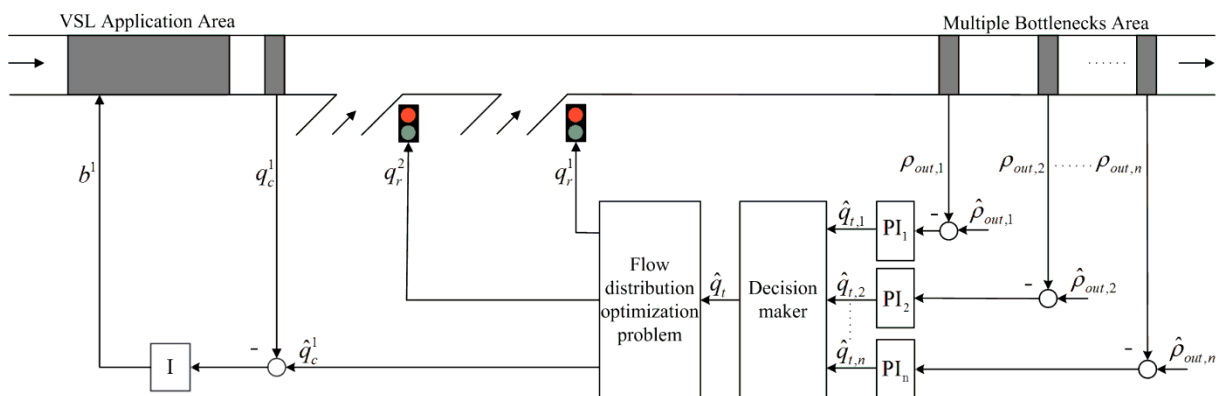
The specified total flow  $\hat{q}_t(k)$  must then be distributed to the available actuators so that the bounds of each actuator flow are respected. Such bounds exist due to operational and policy-related issues; for example, in case of ramp metering, a queue management policy may create lower bounds for the actuator and a low on-ramp demand may create upper bounds; while in case of MTFC, specific policy-dictated 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

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

$$q_{r,\min}^i(k) \leq q_r^i(k) \leq q_{r,\max}^i(k), \quad i = 1, \dots, n_r \quad (2)$$

$$\hat{q}_{c,\min}^i(k) \leq \hat{q}_c^i(k) \leq \hat{q}_{c,\max}^i(k), \quad i = 1, \dots, n_c \quad (3)$$

where  $n_r$  and  $n_c$  are the numbers of ramp metering and MTFC actuators available, respectively. In the example of Figure 1, 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 systems could be present. However, in order to avoid cases where drivers experience more than one piece of queue/delay, it is assumed that an MTFC system, if any, is always located upstream of all metered on-ramps that feed the mainstream section which includes the bottleneck locations.



**Figure 1:** Integrated control structure for multiple bottlenecks and balanced delays



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  $b^i$ . 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. 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 the I-controller are rounded to the closest discrete value to obtain the corresponding posted VSL rates. Furthermore, the difference between two consecutively posted VSL rates at the same gantry and the difference between the posted VSL rates at two consecutive gantries are limited, as often required in practice.

In general, there may be an infinite number of flow distributions that satisfy (1)-(3). Below, 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.

## 2.2 Delay Estimation

For the case of vehicles queuing 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 a linear function of the ramp flow (Papamichail & Papageorgiou, 2011):

$$\delta_r^i(k+1) = A_r^i - B_r^i q_r^i(k) \quad (4)$$

where  $A_r^i = w_i(k) / d_i^{sm}(k-1) + T$ ;  $B_r^i = T / d_i^{sm}(k-1)$ ;  $w_i(k)$  is an estimate of the queue on the on-ramp  $i$  at time instant  $k$ ;  $d_i^{sm}(k-1)$  is an exponentially smoothed value of the past demand measurements, which is used as an estimate of the demand for the next period; and  $T$  is the control period duration.

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 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:

$$\delta_c^i(k+1) = A_c^i - B_c^i q_c^i(k) \quad (5)$$

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 instant  $k$ ,  $L_i$  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.

### 2.3 Flow Distribution for Delay Balancing

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

$$\min \sum_{i=1}^{n_r} \frac{(A_r^i - B_r^i q_r^i(k))^2}{B_r^i} + \sum_{i=1}^{n_c} \frac{(A_c^i - B_c^i \hat{q}_c^i(k))^2}{B_c^i} \quad (6)$$

subject to the linear equality (1) and the bounds on the decision variables (2) and (3).

This problem is a convex optimization problem that is always feasible. 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 (6) 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 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 PI controller. Then, at the time periods that it is not necessary to update the flow to be implemented by some actuator, its two bounds 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).

### 3. Simulation Results

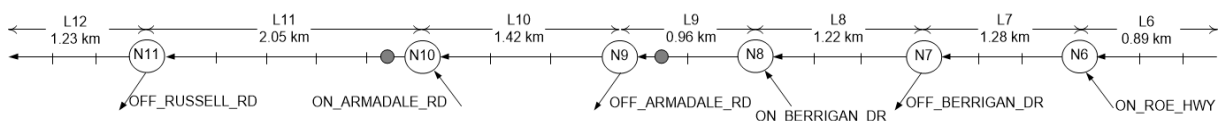
Simulation results, obtained with the aid of the METANET simulator (Messmer & Papageorgiou, 1990), are presented in this section for two case studies. The first case study concerns a stretch of the Kwinana Freeway in Perth, Australia, while the second case study concerns a motorway stretch in the United Kingdom. METANET applies a second-order macroscopic traffic flow model that was extended to incorporate VSL control measures (Papamichail et al., 2008). The motorway network is represented by a directed graph, whereby the links of the graph represent motorway stretches with uniform characteristics. The



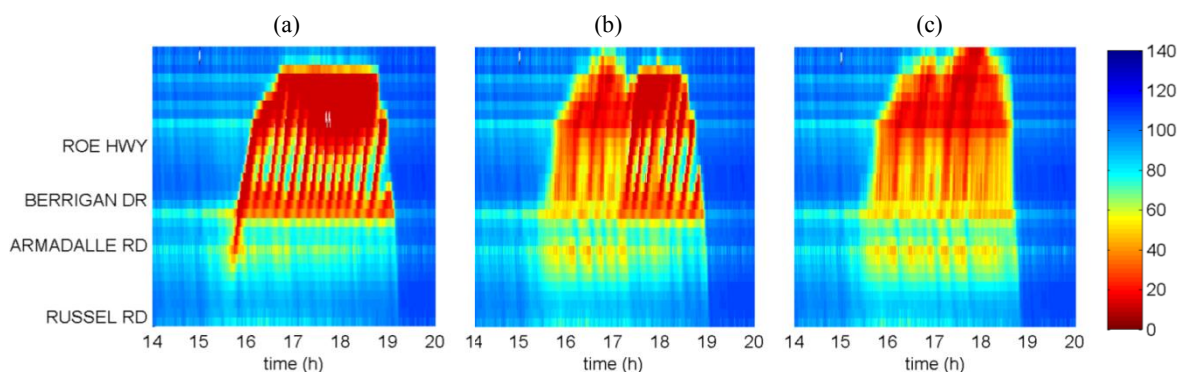
nodes of the graph are placed at locations where major changes in geometry occur, as well as at junctions and on-/off-ramps. The aggregate behavior of traffic at certain times and locations is defined by appropriate variables, whereby time and space arguments are discretized.

### 3.1 Case Study 1

A stretch of the Kwinana Freeway in Perth, Australia, is considered for the simulations. The considered stretch is about 19.8 km in length and extends from Leach Hwy to Anketell Rd. A part of this stretch, around the bottleneck areas, is shown in Figure 2. Arrows represent links divided into a number of segments, indicated by vertical lines, while circles represent nodes. The potentially active bottlenecks are located at links L9 and L11. While the METANET model has been calibrated for the stretch under consideration using real 2012 traffic data, the demand and exit rate profiles used for the investigations presented below are predictions of the 2015 profiles (Papamichail et al., 2013). A set of strategies are investigated, each for a time horizon of 6 h. Table 1 summarizes the strategies and the respective results. The total time spent (TTS) by all vehicles in the network (including the waiting time experienced at the ramp queues), i.e. the natural objective for the traffic system, is used as performance index. Figure 3 presents speed contour plots for all the strategies considered.



**Figure 2:** Case study 1 – Motorway stretch around the two bottleneck areas marked with dots



**Figure 3:** Case study 1 – Speed (km/h) contour plots for (a) No-control case; (b) Scenario 1; and (c) Scenario 2.



*Table 1: Case Study 1 – Summary of simulated scenarios and results*

Strategy	Description	TTS (veh·h)	%
No control	No-Control case	7,145	-
Scenario 1	MTFC for single bottleneck at L11	6,141	14.1
Scenario 2	MTFC for multiple bottlenecks at L9 and L11	5,924	17.1

### 3.1.1 No-Control Case

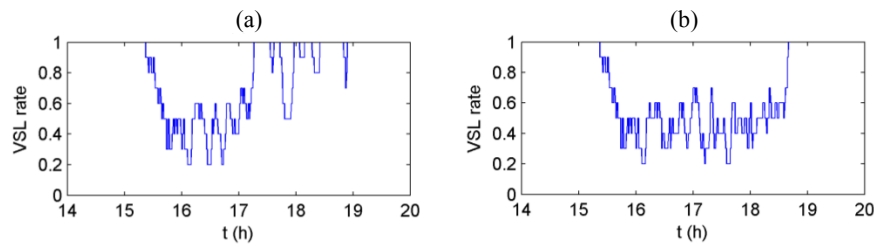
The case in which no control strategies are applied, is the base case that will be used to quantify any improvements arising from the use of control. The traffic situation displayed in Figure 3(a) is quite complex and can be explained as follows. At 15.6 h the merge area of the ON\_ARMADALE\_RD on-ramp (L11) reaches the factual capacity of 4000 veh/h. Mainstream congestion is created after 15.7 h, as the flow arriving at L11 continues to increase. As a result, the mainstream flow decreases due to the capacity drop phenomenon. This congestion propagates upstream but lasts only for 10 minutes. However, congestion insists at L9 and propagates upstream over 6.9 km and lasts for about 3.5 h. This second congestion is due to the lane drop at node N9, from three lanes on link L9 down to two lanes on link L10, while the trigger is the spillback of congestion from L11. When congestion is created at L9, the flow feeding L11 is reduced, causing resolution of congestion at links L10 and L11. The resulting TTS is equal to 7,145 veh·h.

### 3.1.2 Scenario 1

Feedback MTFC via VSL is applied in Scenario 1. The VSL application area is link L8, whereas upstream of L8 there are safety-related VSL, while downstream of L8, up to L11, a constant VSL rate  $b=0.9$  is applied whenever MTFC is active. Density measurements are taken from the first segment of L11, while flow measurements are taken from the first segment of L9; thus a single bottleneck is addressed in this scenario. The set-point for the primary controller is set to 38 veh/km/lane. The activation threshold is set equal to 28 veh/km/lane, while the deactivation threshold is set equal to 21 veh/h/lane.

The resulting TTS is 6,141 veh·h, which is a 14.1% improvement compared to the no-control case. The feedback VSL rate trajectory is shown in Figure 4(a). The VSL rate departs from 1.0 and is varied appropriately, at times reaching 0.2 (the lowest limit for VSL). This results in the creation of a controlled mainstream congestion upstream of the acceleration area. After some 2 h, the flow at the bottleneck area (second segment) of L9 is higher than what can be accommodated by L10, and, as a result, congestion is created there (Figure 3(b)) which is not visible at the density measurement location farther downstream and can therefore not be addressed by the single-bottleneck feedback MTFC scheme. In other words, congestion is created between the VSL and the addressed L11 bottleneck, and this result indicates the necessity for a logic that can treat multiple bottlenecks.





**Figure 4:** Case study 1 – VSL rate given by the feedback controller for (a) Scenario 1 - single bottleneck; and (b) Scenario 2 – multiple bottlenecks

### 3.1.3 Scenario 2

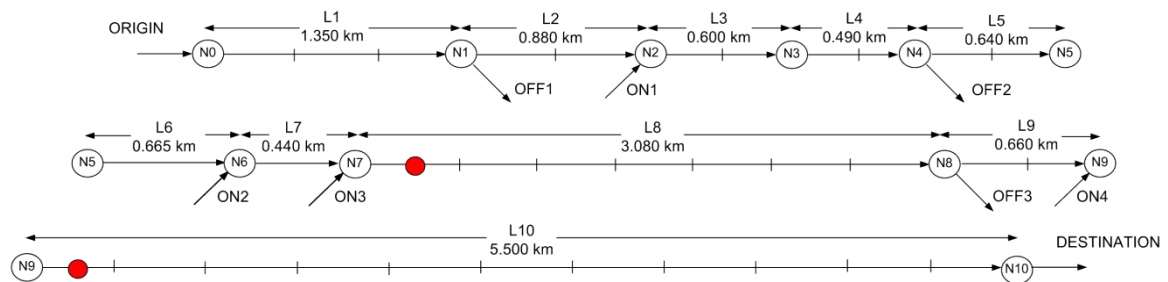
Feedback MTFC for multiple bottlenecks is applied in Scenario 2 to control both known bottleneck locations (L9 and L11); of course, additional downstream measurements, corresponding to farther potential bottlenecks, could be used, however this would not alter the presented results as no other bottlenecks are actually activated.

VSL is applied at L8; upstream of L8 there are safety-related VSL, while downstream of L8, up to L11, there is a constant VSL rate  $b = 0.9$  whenever MTFC is active. The set-point for the primary controller of L9 is set to 36 veh/km/lane and for the primary controller of L11 is set to 38 veh/km/lane. The activation threshold is set equal to 28 veh/km/lane while the deactivation threshold is set equal to 21 veh/h/lane.

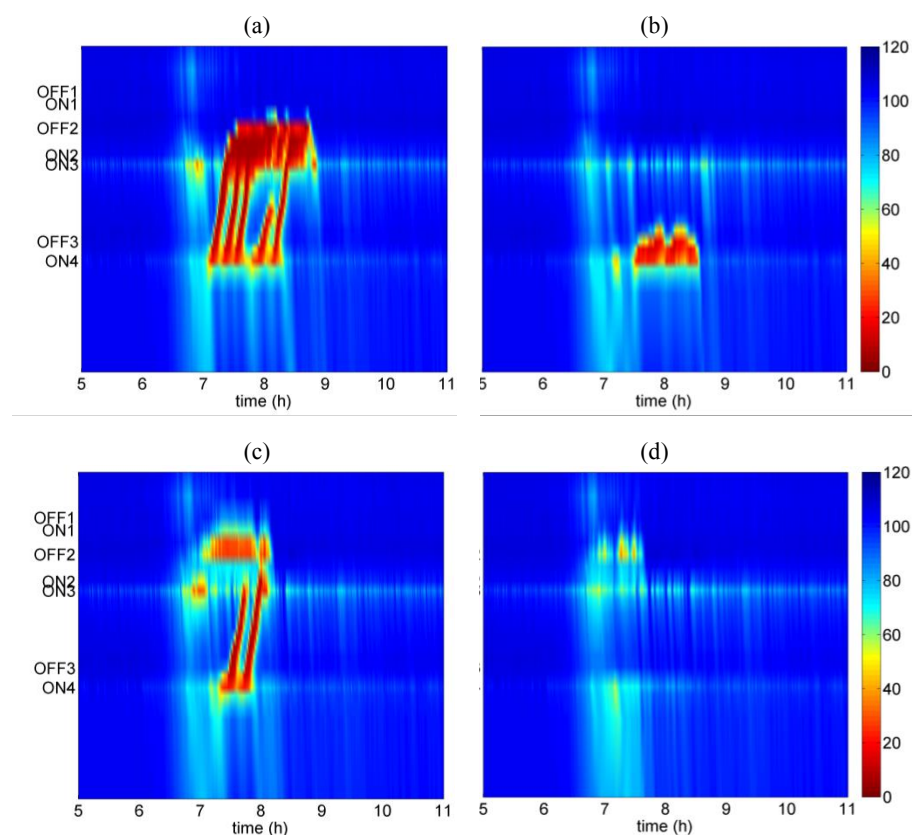
The resulting TTS is 5,924 veh·h, which is a 17.1% improvement compared to the no-control case, clearly better than Scenario 1. The feedback VSL rate trajectories are shown in Figure 4(b). Up to 16.23 h, the primary controller that receives measurements from the bottleneck area at L11 is active, which means that up to this point the situation is identical to Scenario 1; after this, the decision logic switches to the upstream bottleneck whenever necessary to avoid its activation. The VSL rate at L8 (see Figure 4(b)) is gradually decreasing to 0.2 (the lowest limit for VSL). The congestion extends over some 6 km for 2.5 h, which is smaller (in space and time) than in the no-control case and Scenario 1, having also a higher internal speed (see Figure 3).

### 3.2 Case Study 2

A stretch of a motorway in the United Kingdom is now considered for testing. The length of this stretch is 11.3 km. Figure 5 depicts the graph for the motorway stretch. 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 (Highways Agency, 2007) for the AM peak of September 9, 2014. 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. A set of strategies are investigated, each for a time horizon of 6 h. Table 2 summarizes the strategies and the respective TTS results. Figure 6 presents speed contour plots for all the strategies considered.



**Figure 5:** Case study 2 – The motorway stretch considered - two bottleneck areas marked with dots



**Figure 6:** Case study 2 – Speed (km/h) contour plots for (a) No-control case; (b) Scenario 1; (c) Scenario 2; and (d) Scenario 3.

**Table 2:** Case Study 2 – Summary of simulated scenarios and results

Strategy	Description	TTS (veh·h)	%
No control	No-Control case	3,949	-
Scenario 1	Coordinated ramp metering for multiple bottlenecks at L8 and L10	3,539	10.4
Scenario 2	MTFC enabled via VSL for multiple bottlenecks at L8 and L10	3,408	13.7
Scenario 3	Integrated control for multiple bottlenecks at L8 and L10	3,139	20.5



### 3.2.1 No-Control Case

No control is again the base case that will be used to quantify any efficiency improvements arising from the use of control actions. Figure 6(a) presents the no-control speed contour plot for the time horizon under consideration. At 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 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 9 h. The resulting TTS in the network is equal to 3949 veh·h.

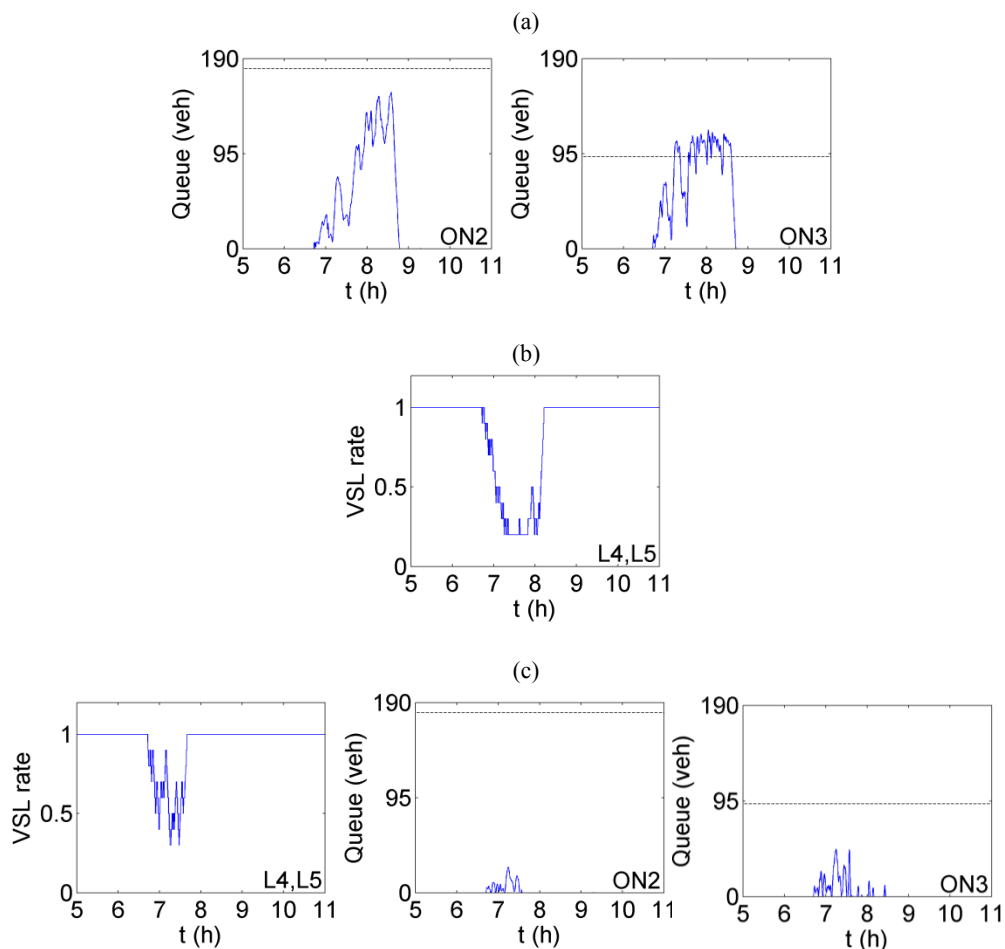
### 3.2.3 Scenario 1

Coordinated ramp metering is applied in Scenario 1 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 (with maximum admissible queues of 180 veh for ON2 and 92 veh for ON3) that are situated upstream of both bottlenecks, with a control period of 20 sec. The utilized density set-points are set equal to the respective factual critical densities, namely  $\hat{\rho}_{out,1} = 35$  veh/km/lane for L8 and  $\hat{\rho}_{out,2} = 29$  veh/km/lane for L10.

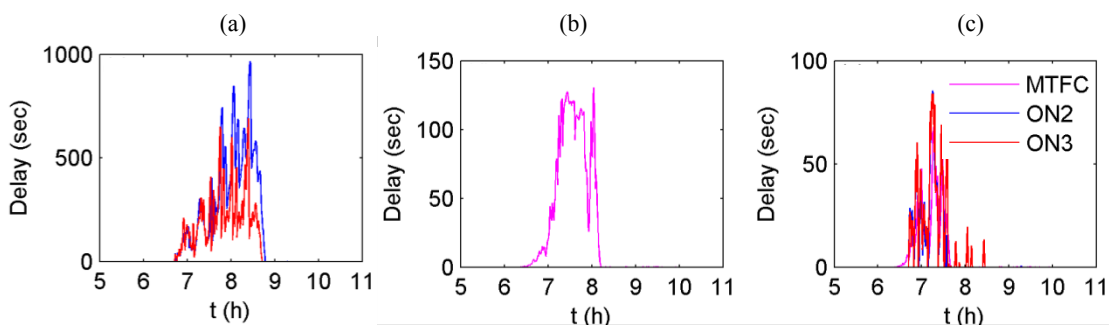
Compared to the no-control case, the resulting TTS is reduced by 10.4%. The speed contour plot for Scenario 1 is presented in Figure 6(b), while the queues created on the on-ramps due to ramp metering actions are shown in Figure 7(a).

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 Figure 8(a) 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 due to full ramp. However, the ordered metering does not materialize, because the arriving demand at ON2 has meanwhile fallen to low levels (lower than the lower bound applied on the ramp metering flow), hence 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; see Papamichail & Papageorgiou, (2011)), rather than balancing of the respective time-delays. This would enable a full exploitation of the available storage space in both on-ramps, before queue management actions are activated. For the present infrastructure and demand configuration, that approach would lead to an improvement in the TTS value of 18.9% and to an accordingly smaller mainstream congestion.



**Figure 7:** Case study 2 – (a) Queue profiles for Scenario 1; (b) VSL rate given for Scenario 2; and (c) VSL rate and queue profiles for Scenario 3



**Figure 8:** Case study 2 – Real delay profiles for (a) Scenario 1; (b) Scenario 2; and (c) Scenario 3



### 3.2.3 Scenario 2

Scenario 2 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 are the same with those used for Scenario 1.

Compared to the no-control case, the resulting TTS is reduced by 13.7%. The speed contour plot for Scenario 2 is presented in Figure 6(c) while the VSL rate trajectory is shown in Figure 7(b). 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 Figure 8(b).

### 3.2.4 Scenario 3

Integrated control is applied in Scenario 3 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 2. Both bottleneck locations are considered using the integrated concept aiming at delay balancing for the three actuators.

Compared to the no-control case, the resulting TTS is now reduced by 20.5%. The speed contour plot for Scenario 3 is presented in Figure 6(d), 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 Figure 7(c). Density values are maintained around the corresponding set-point each time a bottleneck is active, thus capacity flow is achieved at either L8 or L10 as appropriate. The additional benefits obtained thanks to the synergy created by integrated control actions are reflected by multiple aspects:

- Both ramp queues are now much smaller than in Scenario 1.
- The employed VSL are much higher than in Scenario 2; hence the created mainstream controlled congestion is much smaller (in space and time), having also much higher speed, than in Scenario 2.
- The delays experienced by drivers (displayed in Figure 8(c)) are balanced, as requested. In addition, more drivers are now experiencing much less (and balanced) delay, which improves the equity properties of the system.
- Last but most importantly, the total delay (experienced by all drivers) takes the smallest value among all scenarios, as reflected by the (lowest) obtained TTS value, which indicates highest efficiency for this scenario.

## 4. Conclusions

A feedback-based integrated motorway traffic flow control concept for multiple bottlenecks has been proposed recently by the authors of 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 couple of real infrastructures and has been compared to other control structures. The feedback controller is robust, as there is no need, neither for any predictions of the demand nor for any online model use. Practical and safety constraints 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. In addition, the design of cooperative systems is a very interesting and rapidly developing issue that will be taken forward.

## 5. Acknowledgements

The research leading to these results has been conducted in the frame of the project TRAMAN21 which has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 321132.

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