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A Feedback-Based Approach for Mainstream Traffic Flow Control of Multiple Bottlenecks on Motorways

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Abstract: Mainstream traffic flow control (MTFC) enabled via variable speed limits (VSLs) has been investigated in previous studies, utilizing various control strategies. In this paper a new feedback control strategy is proposed for MTFC enabled via VSLs, considering multiple bottleneck locations. Results are evaluated using a validated macroscopic model. The feedback concept is robust and can be immediately implemented in the field as it considers practical and safety constraints.

Keywords: Feedback control, Mainstream traffic flow control, Multiple bottlenecks, Variable speed limits.

1. INTRODUCTION

Congestion on motorways is a major community problem which leads to a sensible reduction of the motorway infrastructure capacity (Papageorgiou and Kotsialos, 2002). This reduction occurs during the peak periods, causing degradation in terms of travel times, traffic safety, fuel consumption, and environmental pollution. With the purpose of alleviating traffic congestion, various control strategies have been suggested. However, some of them face limitations; e.g., ramp metering suffers from the limited number of vehicles that can be stored while route guidance is most valuable under non-recurrent traffic congestion.

Mainstream traffic flow control (MTFC) regulates the flow upstream of a bottleneck location in order to maximize throughput at the specific location. This control action has been proposed by Carlson et al. (2010a, b) and was shown to lead to a remarkable improvement of the traffic flow efficiency indicators. In early research, Gazis and Foote (1969) had proposed a traffic-responsive control system for a tunnel flow control. Real-time traffic measurements from the bottleneck location were used by the system to make decisions on the tunnel's flow control. Crowley and Greenberg (1965) and Foote and Crowley (1967) suggested the first simple feedback control strategy, while Foote (1968) and Gazis and Foote (1969) proposed a more sophisticated heuristic feedback algorithm. Another MTFC-like system is the traffic-light based entrance control system of the San Francisco-Oakland Bay Bridge, which was introduced by McCalden (1984) and has been in operation for more than 35 years. The algorithm used (Chen et al., 1990) appears to have important similarities with the algorithm proposed by Spiliopoulou et al. (2010). Finally, some fix-time mainline strategies have been investigated by Jacobson and Landsman (1994), and Haboian (1995) using traffic lights as a new traffic management tool for motorways.

So far, the use of traffic lights is generally not acceptable on motorways. As a result, researchers have considered MTFC enabled by use of Variable Speed Limits (VSLs) with various control strategies and traffic application settings. In the work by Carlson et al. (2010b), it has been shown that ramp-metering and MTFC can have a similar impact on bottleneck locations, while an optimal control problem has been proposed by Carlson et al. (2010a) showing the benefits of MTFC, applied to a large-scale motorway. It is obvious from these papers that MTFC applied upstream of an active bottleneck location is able to avoid the capacity drop. Nevertheless, the optimal control approach used may be cumbersome for use in real field implementation. Zhang et al. (2006) proposed an ALINEA-like feedback controller for MTFC, based on VSLs, and performed tests via microscopic simulation. The obtained improvements were marginal probably because of the absence of an acceleration area, as proposed by Carlson et al. (2010a, b).

This paper proposes an extension of the feedback controller presented by Carlson et al. (2011) for the case of multiple bottlenecks. The issue of multiple bottlenecks was addressed by Wang et al. (2010) for the case of ramp metering control; hence this paper combines the concepts developed by Carlson et al. (2011) and Wang et al. (2010) to derive a feedback law for VSL-based MTFC addressing multiple downstream bottlenecks. The new feedback control strategy is simple and robust and can be directly applied in the field. Many practical aspects of VSL operations are also considered in the simulation-based tests using a validated second-order macroscopic traffic flow model.

In Section 2, the MTFC concept is reviewed and the implementation aspects are presented. In Section 3, the MTFC strategy for multiple bottlenecks is described, taking into account practical application aspects. The efficiency of the proposed control strategy is evaluated in Section 4, while the conclusion of this paper and some ideas for further research on the subject are presented in Section 5.

2. MAINSTREAM TRAFFIC FLOW CONTROL

In the current section, basic and new MTFC concepts are described, while some implementation aspects related to the design of the proposed feedback algorithm are discussed.

2.1 Congestion Triggers and Effects

The location where the upstream flow capacity q_{cap}^{up} is higher than the downstream flow capacity q_{cap}^{down} is called latent bottleneck (see Fig. 1). The activation of a bottleneck can occur due to various causes, i.e., on-ramps merging, lane drop, curvature, strong grade, strong weaving, fixed speed limits, overspilling of off-ramps, and road incidents.

If the traffic flow q_{in} arriving upstream of the bottleneck location is equal to q_{cap}^{down}, then the nominal bottleneck capacity q_{cap}^{down} , which is the maximum traffic flow that the bottleneck can accommodate, is obtained. In case the arriving flow q_{in} (which naturally verifies $q_{in} \leq q_{cap}^{up}$) is higher than q_{cap}^{down}, the bottleneck is activated causing congestion. The head of the congestion appears at the location of the bottleneck, whereas the tail of the congestion keeps moving upstream until the incoming flow is decreased sufficiently (see Fig. 1). Two detrimental effects occur when a congestion is formed at an active bottleneck: capacity drop and blocking of off-ramps.

Capacity drop appears at the congestion head because vehicles must accelerate from the reduced speed upstream of the bottleneck location to a higher speed. This action leads to a capacity drop, i.e., a 5%-20% reduction of the active bottleneck outflow q_{out} compared to the nominal capacity q_{cap}^{down} (see Fig. 1).

Another consequence of traffic congestion is the reduction of flow exiting from the off-ramps, due to the upstream propagation of the congestion tail (see Fig. 1) that causes a diminished flow in the congested area with respect to the upstream arrivals: this phenomenon is called blocking of off-ramps (BOR). Moreover, vehicles that are bound for exits upstream of the active bottleneck are also delayed due to the congestion.

2.2 MTFC Concept

The basic idea of MTFC is to regulate mainstream traffic flow upstream of a bottleneck location with an appropriate control strategy in order to avoid capacity drop and BOR, having optimal traffic conditions for any appearing demand. This is shown in Fig. 2 for a local example. As long as $q_{in} \leq q_{cap}^{down}$ the bottleneck of Fig. 2 is not activated (and no MTFC is needed): in that case $q_{out} \approx q_{in}$. The bottleneck would be activated if q_{in} becomes bigger than q_{cap}^{down}, causing the reduction of q_{out}. Using MTFC, the controlled outflow q_c is kept equal to q_{cap}^{down} (or a smaller value in case the bottleneck is caused by an on-ramp). For sure, MTFC cannot avoid completely mainstream congestion because $q_{in} > q_{cap}^{down}$, however it has some advantages such as:

1) Since the capacity drop is avoided, the flow leaving the bottleneck is higher when MTFC is applied.

2) Due to the increased outflow when applying MTFC, the resulting congestion is characterized by a higher internal speed, and it is shorter in space and time. This leads to a potential improvement for the detrimental effects of BOR, due to the reduction of blocked off-ramps.

Nevertheless, BOR effects cannot be fully avoided with MTFC because this strategy leads anyway to a (controlled) mainstream congestion. For this reason MTFC performance is theoretically worse than ramp metering (assuming that a sufficient storage is available at the on-ramp), that is theoretically able to completely avoid congestion. However, the simulation results reported by Carlson et al. (2010a, b) show that the difference in terms of cost function may be small.

2.3 MTFC for Multiple Bottlenecks

Multiple bottlenecks may sometimes appear, due to various causes, e.g. high demand of consecutive uncontrolled on ramps, bad weather, strong lane changing, lane drops, speed limit changes, etc. In the previous works with MTFC, it has been assumed that feedback control actions taken for treating different bottleneck locations do not interfere with each other. This is often unrealistic, thus an extension of the MTFC concept is proposed in this paper for the case of multiple bottlenecks that have to be treated using a single controlled area. In this case, the outflow q_c is equal to the smallest outflow computed for the different bottlenecks. This idea was inspired from a control strategy applicable to local ramp metering in presence of random-location bottlenecks that was studied by Wang et al. (2010).

A significant issue that must be addressed is the identification of the bottleneck locations. For this purpose, the availability of sufficiently dense measurements from the mainstream is required.

2.4 Implementation Aspects of MTFC

VSLs are utilized in this paper as an MTFC actuator.

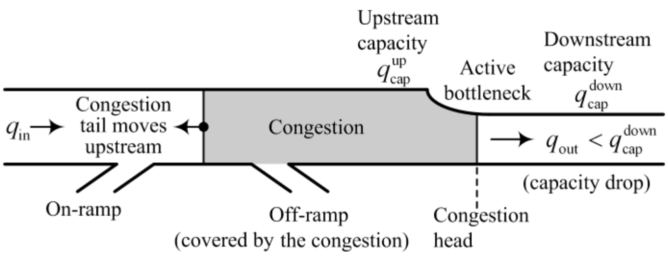

Fig. 1. Active bottleneck notions.

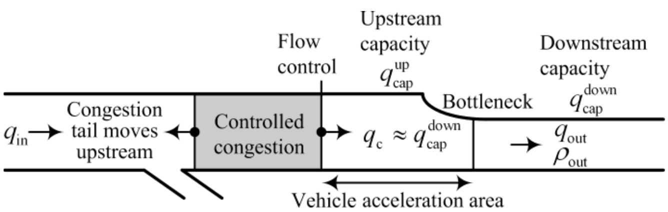

Fig. 2. Local aspect of MTFC.

Mainstream congestion will be formed upstream of the MTFC location. The vehicles exiting the congested area will be characterized by a speed lower than the critical speed that is needed to achieve bottleneck capacity flow q_{cap}^{down}. In order to avoid that, vehicles should be allowed (and encouraged) to reach the critical speed v_{cr}, that allows the maximum flow to pass through the bottleneck (about 70 km/h). This is realized by placing the head of the created congestion upstream enough of the addressed bottleneck so as the vehicles have the ability to accelerate from low speeds to the critical speed. In Fig. 2.7 of Hall (2001) a 700 m distance is considered to be appropriate for vehicles acceleration. In the case of absence of an acceleration area, the capacity drop phenomenon may not be avoided (Carlson et al., 2010a, b).

Acceleration of vehicles in the acceleration area and in the downstream bottleneck area depends on q_c and on their individual speed. The goal would be to have vehicles that adopt the critical speed which leads to q_{cap}^{down}. Thus, appropriate VSLs should be imposed to vehicles travelling in the acceleration area and the downstream bottleneck area.

In the mainstream controlled section vehicles move slower than in the upstream sections; this is dangerous for vehicles with a high speed approaching the congestion tail. The computation of VSLs must also take into account a gradual reduction of speed for the arriving vehicles in order to reach the minimum speed reducing the safety risk.

When using VSLs as an MTFC actuator, some restrictions are defined for the posted speed limits. The first restriction has to do with the accepted VSL values: speed limits can take only discrete values within a predefined range of permitted VSLs (e.g., multiples of 10 km/h). A second restriction takes into account the speed limit difference between two consecutive VSLs at the same gantry that is not allowed to be greater than a predefined value (e.g. 20 km/h). Moreover, the difference of speed limits between two consecutive gantries is considered. At the end, speed limits are not permitted to change their values more frequently than a predefined time interval (e.g., 1 min). This time interval could be used as the control period of the control strategy.

2.5 METANET

A validated macroscopic second-order traffic flow model included in the METANET freeway traffic flow simulator (Messmer and Papageorgiou, 1990; Carlson et al., 2010a, b) is used in this work. In METANET the freeway network is represented by a directed graph, whereby the links of the graph represent freeway stretches with uniform characteristics. The nodes of the graph are placed at locations where a major change in road geometry occurs, as well as at junctions and on-/off-ramps. Adequate variables express the aggregate behaviour of traffic at certain times and locations, while the time and space arguments are discretized.

3. MTFC CONTROL FOR MULTIPLE BOTTLENECKS

The cascade feedback MTFC controller that was developed by Carlson et al. (2011) is presented in this section with an appropriate extension for the case of multiple bottlenecks.

3.1 Feedback Controller

The feedback controller developed by Carlson et al. (2011) regulates the traffic density ρ_{out} (Fig. 2) via appropriate real-time changes of the mainstream flow q_c. This is performed via appropriate VSL actions upstream of the bottleneck location. The flow q_{out} is maximized when ρ_{out} equals to the critical density ρ_{cr}, thus the density set point $\hat{\rho}_{out}$ of the control loop has to be set equal to ρ_{cr}. The problem to be controlled is represented by a single-input-single-output (SISO) system with the VSL rate b (defined as the displayed VSL divided by the legal speed limit without VSL) as the control input and ρ_{out} as the control output.

Figure 3 depicts the MTFC feedback cascade controller structure designed by Carlson et al. (2011). An integral (I) controller is included in the secondary loop while a Proportional-Integral (PI) controller is included in the primary loop. The secondary loop is affected by the VSL rate b delivered by the secondary controller that will determine the outflow q_c. Downstream of the VSL application area, q_c is measured, fed back, and compared to the desired flow $\hat{q}_c$ delivered by the primary controller. The measured density ρ_{out} (or occupancy) at the bottleneck area is used by the primary loop that compares it with the set-point $\hat{\rho}_{out}$. The I controller for the secondary loop is described by:

$$b(k) = b(k-1) + K_I(\hat{q}_c(k) - q_c(k)), \qquad (1)$$

where K_I is the controller's integral gain. The PI controller for the primary loop is described by:

$$\hat{q}_c(k) = \hat{q}_c(k-1) + K_I'\big(\hat{\rho}_{out}(k) - \rho_{out}(k)\big) + K_P'(\rho_{out}(k-1) - \rho_{out}(k)) \qquad (2)$$

where K_I' and K_p' are the integral and proportional gains of the controller, respectively. In case of multiple bottleneck locations, a set of PI controllers is now used in the control strategy (Fig. 4). Each controller takes measurements from a separate detector site, downstream of the acceleration area. An appropriately designed decision device determines the overall MTFC action from all PI controllers' outputs. This strategy is similar to the strategy used by Wang et al. (2010) for ramp metering. The active bottleneck can be picked-up by at least one bottleneck location and the output of the PI controller corresponding to the bottleneck location should be chosen for determining the overall MTFC action. The bottleneck locations are determined from the beginning of the process.

The equation for the primary controller (2) is now replaced by:

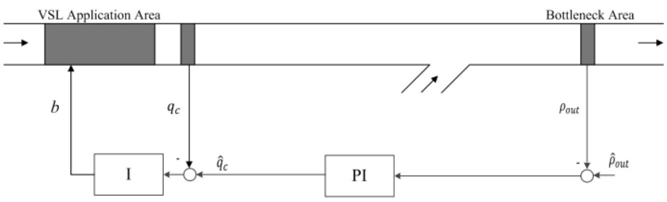

Fig. 3. MTFC feedback controller structure using VSLs as actuator.

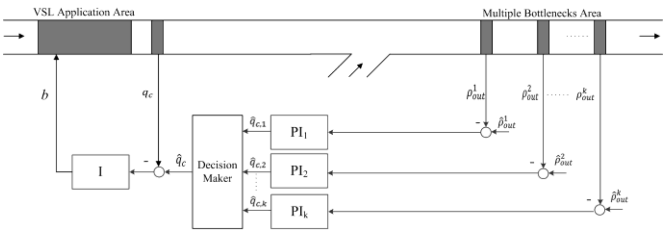

Fig. 4. MTFC feedback controller structure for multiple bottlenecks using VSLs as actuator.

$$\hat{q}_{c,i}(k) = \hat{q}_{c,i}(k-1) + K'_{I,i}\left(\hat{\rho}_{out,i}(k) - \rho_{out,i}(k)\right)$$
$$+K'_{P,i}\left(\rho_{out,i}(k-1) - \rho_{out,i}(k)\right),\ i = 1, \dots, n \quad (3)$$

where $\hat{q}_{c,i}(k)$ represents the output of the i-th PI controller at time instant k.

The chosen decision policy is simply:

$$\hat{q}_c(k) = \hat{q}_{cj}(k) \quad (4)$$

with

$$j = \arg\min_{i=1,\dots,n}\{\hat{q}_{c,i}^{sm}(k)\} \quad (5)$$

$$\hat{q}_{c,i}^{sm}(k) = \alpha_{sm} \cdot \hat{q}_{c,i}(k) + (1-\alpha_{sm}) \cdot \hat{q}_{c,i}^{sm}(k-1),$$
$$i = 1, \dots, n \quad (6)$$

where $\hat{q}_{c,i}^{sm}(k)$ represents the exponential smoothing of $\hat{q}_{c,i}(k)$ computed through Equation (6) in which α_{sm} is a parameter within $[0,1]$. The controller that corresponds to the smallest (smoothed) flow value is selected. The smoothed flow is used for avoiding fast switching of the controllers.

The methodologies applied for tuning the controllers are the zone-based procedure, as described by Ellis (2004), and the SIMC PID tuning method (Skogestad, 2003), for the secondary and primary controller, respectively. The gain values that emerged and were used in the simulations of Section 4 are the following: $K_I = 0.0006$ h·lane/veh for the secondary controller, and $K'_I = 1.5$ km/h/lane and $K'_p = 13.0$ km/h/lane for the primary controllers.

3.2 *Practical Application Aspects*

This section summarizes some practical VSL implementation aspects detailed by Carlson et al. (2011). Firstly, VSL can only take discrete values via a set of admissible discrete VSL rates $b\epsilon\{0.2, 0.3, \dots, 1.0\}$. The VSL rate $b(k)$ delivered by the control strategy is rounded off to obtain the applied VSL rate. In addition, as was mentioned in Section 2.4, VSL is applied also upstream of the controlled congestion. In particular, the difference between two consecutive posted VSL rates at the same gantry is limited to 0.2, and also the same limit applies to the difference between the posted VSL rates at two consecutive gantries. A last constraint is that a constant VSL rate equal to 0.9 is applied in the acceleration and bottleneck areas, only when MTFC is active. All the above constraints are considered only in feedback control and not in the optimal control case.

The control period is set to $T_c = 60$ s. This value is appropriate for practical purposes, as it is used in current VSL installations in various countries.

4. SIMULATION RESULTS

Simulation results, obtained with the aid of the METANET simulator, are presented in this section for some representative cases.

4.1 *Network Model*

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 Fig. 5. Arrows represent links divided into a number of segment using vertical lines, while circles represent nodes. The nodes are placed mainly at locations where on-ramps and off-ramps are connected to the mainstream. The potentially active bottlenecks are located at links L9 and L11. While the METANET model has been validated, for the stretch under consideration, using real 2012 data, the demand and exit rate profiles used for the investigations presented below are a prediction of the 2015 profiles (Papamichail et al., 2013). The model time step used is $T = 5$ s. A set of strategies are investigated, each for a time horizon of 6 h.

4.2 *No-Control case*

The no-control strategy is the base case that will be used to quantify any improvements arising from the use of control. Figure 6 depicts the density, speed, and flow profiles for the two bottleneck areas from $t = 14$ h until $t = 20$ h, that is the time interval in which congestion appears.

At $t = 15.6$ h the merge area of the ON_ARMADALLE_RD on-ramp (L11) reaches the factual capacity of 4000 veh/h. Mainstream congestion is created after $t = 15.7$ h, as the flow arriving at L11 continues to increase. As a result, the mainstream flow is obviously decreasing due to the capacity drop phenomenon. This congestion lasts only for 10 minutes and propagates upstream. Immediately after, another congestion is created at L9 at around $t = 15.8$ h which propagates upstream over 6.9 km and last for about 3.5 h. The onset of this second congestion is due to a lane drop at

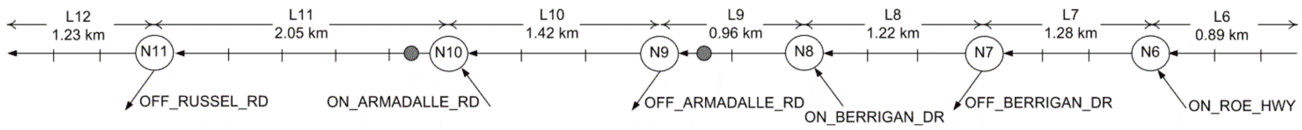

Fig. 5. Motorway stretch around the two bottleneck areas marked with dots.

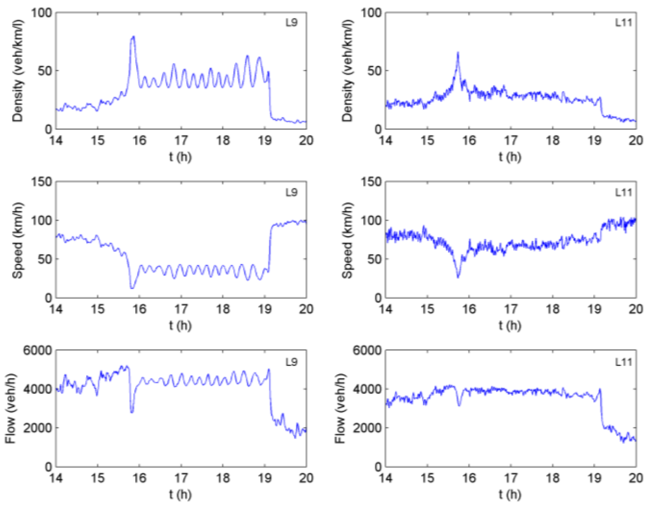

Fig. 6. No control: Traffic conditions at the bottleneck areas.

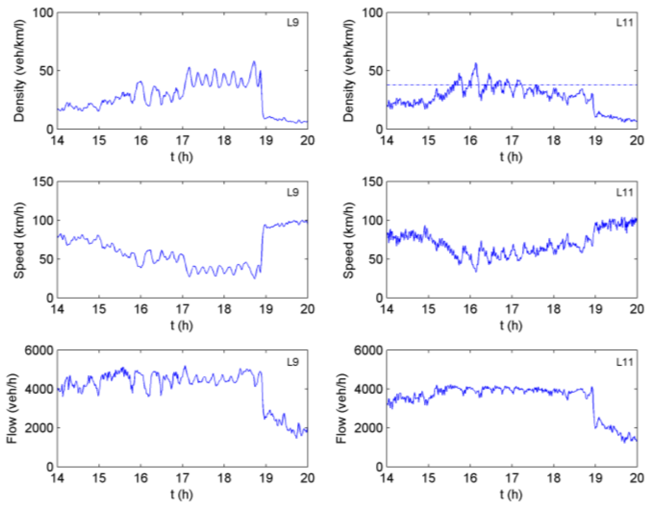

Fig. 7. Scenario 1: Traffic conditions at the bottleneck areas.

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.

4.3 Scenario 1

Scenario 1 applies feedback MTFC via VSL, with the constraints described in Section 3.2. The VSL application area is link L8, whereas upstream of L8 there are safety limits, and downstream of L8, up to L11, a constant VSL rate $b = 0.9$ is applied. Density measurements are taken from the first segment of L11, while flow measurements are taken from the first segment of L9. The primary controller's set-point is set to $\hat{\rho}_{out} = 38$ veh/km/lane.

The resulting TTS is 6,200 veh·h, which is a 13.23% improvement compared to the no-control case. The density, speed and flow profiles for both bottleneck locations are shown in Fig. 7. The dashed line shows the density set-point utilized by the primary controller for L11. The feedback VSL rate and flow trajectories are shown in Fig. 8(a-b).

The VSL rate at L8 [see Fig. 8(a)] is gradually decreasing from 1 to 0.2 (the lowest limit for VSL). The flow decrease at the first segment of L9 [see Fig. 8(b)] shows the impact of VSL on the controlled variable q_c. On the same figure, the dotted line indicates the primary controller's output $\hat{q}_c$. The secondary controller uses this flow as a reference and, at most time, it is narrowly tracked by the controlled variable. However, the flow at the bottleneck area (second segment) of L9 (Fig. 7) is higher than what can be accommodated by L10, and as a result, congestion is created that spills back. The results of this scenario shows the necessity for a logic that can treat multiple bottlenecks.

4.4 Scenario 2

The proposed feedback MTFC for multiple bottlenecks is now applied. Both bottleneck locations (L9 and L11) are thus controlled. VSL is applied at L8, whereas upstream of L8 there are safety limits, and downstream of L8, up to L11, there is a constant VSL rate $b = 0.9$. The set-point for the primary controller of L9 is set to $\hat{\rho}_{out} = 36$ veh/km/lane and for the primary controller of L11 is set to $\hat{\rho}_{out} =$ 38 veh/km/lane.

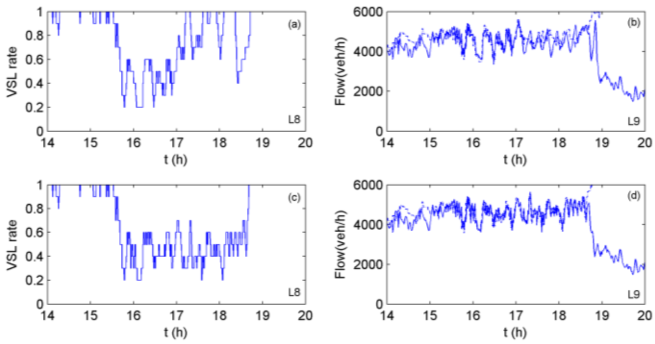

Fig. 8. VSL rate and flow given by the feedback controllers for Scenario 1 (a, b) and Scenario 2 (c, d).

The resulting TTS is 5,977 veh·h, which is a 16.35% improvement compared with the no-control case, quite better than scenario 1. The density, speed and flow profiles for both bottleneck locations are shown in Fig. 9. The dashed line shows the density set-point utilized by the primary controller for L11, while the red lines show the periods for which each one of the primary controllers is selected by the decision policy defined by Equations (4-6). The feedback VSL rate and flow trajectories are shown in Fig. 8(c-d).

The VSL rate at L8 [see Fig. 8(c)] is gradually decreasing from 1 to 0.2, as in the previous scenario. The flow decrease at the first segment of L9 [see Fig. 8(d)] shows the impact of VSL on the controlled variable q_c. This decrease manages to avoid the bottleneck at L11 and the second segment of L9 (Fig. 9), whereas a controlled mainstream congestion upstream of the acceleration area is created. The extension of the congestion is over some 6 km for 2.5 h, and, compared

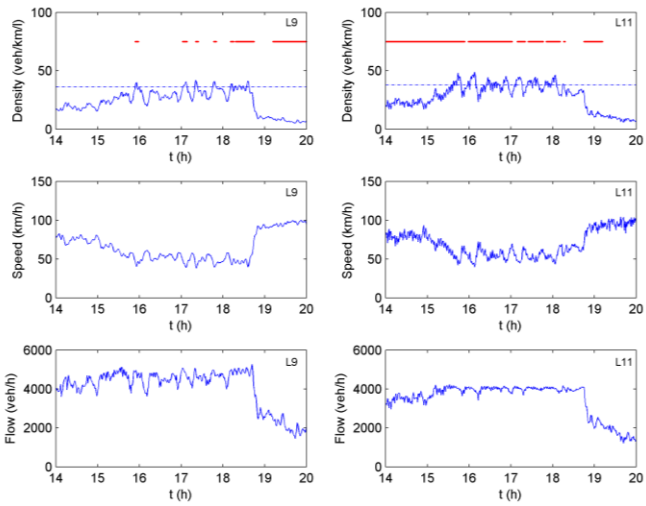

Fig. 9. Scenario 2: Traffic conditions at the bottleneck areas.

with the no-control scenario and scenario 1, is shorter (in space and time), having also a higher internal speed.

5. CONCLUSIONS

Feedback MTFC enabled via VSLs for multiple bottlenecks on motorways has been proposed in this paper. The assessment of the suggested control strategy, utilizing the METANET simulator for a real network, demonstrates its efficiency. The feedback concept is robust because there is no need for a model and predictions of the demand and can be immediately implemented in the field as it considers practical and safety constraints as well as the case of multiple bottlenecks.

Future research will be focused on the integration of feedback MTFC via VSL with feedback ramp metering at the local and global levels. In addition, the design of cooperative systems is a very interesting and rapidly developing issue that will be taken forward.

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