Mainstream traffic flow control at sags

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ABSTRACT

Sags are freeway sections along which the gradient changes significantly from downwards to upwards. The capacity of sags is considerably lower than the capacity of normal sections. Consequently, sags are often freeway bottlenecks. Recently, several control measures have been proposed to improve traffic flow efficiency at sags. Those measures generally aim to increase the capacity of the bottleneck and/or to prevent traffic flow perturbations in nearly-saturated conditions. This paper presents an alternative type of measure based on the concept of mainstream traffic flow control. The proposed control measure regulates the traffic density at the bottleneck area in order to keep it below the critical density, hence preventing traffic from breaking down while maximizing outflow. Density is regulated by means of a variable speed limit section that regulates the inflow to the bottleneck. Speed limits are selected based on a feedback control law. We evaluate the effectiveness of the proposed control strategy by means of a simple case study using microscopic traffic simulation. The results show a significant increase in bottleneck outflow, particularly during periods of high demand, which leads to a considerable decrease in total delay. This finding suggests that mainstream traffic flow control strategies using variable speed limits have the potential to substantially improve the performance of freeway networks containing sags.

INTRODUCTION

Sags are freeway sections along which the gradient changes significantly from downwards to upwards in the direction of traffic (*1*). The capacity of sags is considerably lower than the capacity of normal freeway sections (*2*, *3*). In general, the bottleneck is located 0.5–1 km downstream of the bottom of the sag (*4*). As a consequence of the reduced capacity, traffic often breaks down at sags in conditions of high demand. The formation of congestion results in a further decrease in bottleneck capacity (*2*). Recently, various control measures have been proposed to improve traffic flow efficiency at sags. Generally, those measures aim to increase the capacity of the bottleneck and/or to prevent traffic flow perturbations in nearly-saturated conditions.

This paper presents an alternative type of control measure and evaluates its potential effectiveness, performing a proof of principle. The proposed measure is based on the concept of mainstream traffic flow control (*5*). The traffic density at the bottleneck area is regulated in order to keep it below the critical density, hence preventing traffic from breaking down. The capacity drop due to congestion does not occur, so the outflow from the bottleneck can be higher. The density at the bottleneck area is regulated by means of a variable speed limit section that regulates the inflow to the bottleneck. Speed limits are selected based on a proportional feedback control law. The effectiveness of the proposed control measure is evaluated by means of a simple case study using microscopic traffic simulation. Traffic flow is simulated in a single-lane freeway stretch containing a sag, with and without implementing the control strategy. The results show that the control measure increases the bottleneck outflow significantly (particularly in periods of very high demand), which leads to a considerable decrease in total delay. This finding suggests that mainstream traffic flow control strategies using variable speed limits can considerably improve traffic flow efficiency in freeway networks containing sags.

The next section contains a literature review on the characteristics of traffic flow at sags and on types of control measures to mitigate congestion at that type of bottlenecks. Then, the proposed control strategy and the method used to evaluate its effectiveness are described. Next, the results of the evaluation (including a sensitivity analysis) are presented. The final section presents the conclusions of this study and some suggestions for future research.

BACKGROUND

Sags as freeway bottlenecks

Bottlenecks are freeway sections that have a lower capacity than the immediate upstream section. Generally, the causes of that lower capacity are spatial inhomogeneities (e.g., lane drops, ramps, tunnels), traffic conditions (e.g., slow vehicles, accidents), and/or environmental conditions (e.g., adverse weather) (*6*, *7*). When traffic demand exceeds the capacity of a bottleneck, congestion forms upstream of the bottleneck. The capacity of a bottleneck depends on the traffic state: the capacity in congested traffic conditions (queue discharge capacity) is generally lower than the capacity in uncongested traffic conditions (free flow capacity). The difference, which is called capacity drop, ranges from 3% to 20% according to different studies (*8*–*10*).

Several empirical studies show that the capacity of sags can be significantly lower than the capacity of flat sections (*2*, *3*). In general, the bottleneck is located 0.5–1 km downstream of the bottom of the sag (*4*). Xing *et al.* (*3*) present empirical measurements of free flow capacities and queue discharge capacities of various sag sections of Japanese freeways. Most of the measurements were taken on holidays, when traffic demand consists mainly of passenger cars and the percentage of heavy vehicles is relatively low. According to the data presented in that study, the average free flow capacity is 3150 veh/h at two-lane sags and 5340 veh/h at three-lane sags. The average queue discharge capacity is 2780 veh/h at two-lane sags and 4600 veh/h at three-lane sags, which means that the capacity drop is -12% and -14%, respectively. Similar capacity estimates have been reported by other authors (*2*, *11*).

If we compare the capacities of sags with those of flat sections, we observe that the free flow capacity and the queue discharge capacity of sags are considerably lower. At flat sections, free flow capacities are generally around 4000 pcu/h (two lanes) and 6000 pcu/h (three lanes) (*2*). Assuming a 10% capacity drop, we obtain queue discharge capacities for flat sections of 3600 pcu/h (two lanes) and 5400 pcu/h (three lanes). Therefore, the free flow capacity and the queue discharge capacity of two-lane freeways are around 20% lower at sags than at flat sections (10–15% lower in three-lane freeways).

The main cause of capacity reduction at sags seems to be related to the impact that the increase in freeway gradient has on the behavior of drivers. Several empirical studies show that two important changes in longitudinal driving behavior occur when vehicles go through a sag. First, drivers tend to reduce speed (*1*, *4*). Second, drivers tend to keep longer distance headways than expected given their speed (*12*, *13*). These local changes in driving behavior seem to be caused by the fact that drivers are unable to accelerate sufficiently and compensate for the increase in resistance force resulting from the increase in slope (*14*).

Control measures to mitigate congestion at sags

In the last two decades, several measures have been proposed to prevent or delay the formation of congestion at sags, and to reduce its severity. In general, those measures can be sorted into three categories: a) measures that aim to increase the free flow capacity of sag bottlenecks; b) measures that aim to prevent traffic flow perturbations at sag bottlenecks in nearly-saturated conditions; and c) measures that aim to increase the queue discharge capacity of active sag bottlenecks. An example of a measure from the first category is equipping vehicles with adaptive cruise control systems, which perform the acceleration task more efficiently than human drivers (*15*). Another example is distributing the traffic flow more evenly across lanes in order to use the bottleneck capacity more efficiently (*3*, *16*). The second category comprises measures such as preventing the formation of long vehicle platoons (*16*) and discouraging drivers from performing lane changes to the busiest lanes (*11*, *16*). The third category comprises measures such as giving information to drivers about the location of the head of the queue, encouraging them to recover speed after leaving congestion (*17*, *18*). Also, control measures belonging to the above-mentioned categories have been proposed for other types of bottlenecks besides sags, e.g., on-ramps (*19*) and weaving sections (*20*). The potential effectiveness of most of those measures has been demonstrated by means of empirical data analysis or simulation.

However, there is an additional category of measures that could improve traffic flow efficiency at sags but has received little attention in the recent literature, namely mainstream traffic flow control measures. In mainstream traffic flow control, the inflow to a bottleneck is regulated by creating a controlled section upstream. The traffic density at the bottleneck area is kept below the critical density. Consequently, even if demand gets very high, traffic does not break down at the bottleneck; the capacity drop does not occur, so the outflow from the bottleneck can be higher than its queue discharge capacity. Mainstream traffic flow control is a concept that was first applied in the 1950s (*21*). Recently, it has been presented as an effective measure to mitigate congestion at on-ramp bottlenecks (*5*). We argue that mainstream traffic flow control can also be used to improve traffic flow efficiency at sags, either by itself or in combination with other types of measures. It is important to note that this control concept can only result in relevant improvements in traffic flow efficiency if the queue discharge capacity of the bottleneck is significantly lower than the queue discharge capacity of the controlled section. This is usually the case with sag bottlenecks (*2*, *3*, *11*).

CONTROL STRATEGY

This section describes the characteristics of a mainstream traffic flow control strategy aimed at mitigating congestion at sags. The control goal is to minimize the total time spent by vehicles in the network over a certain time period. Note that if we assume that the flow entering the network cannot be influenced by any control measure, then minimizing the total time spent is equivalent to maximizing the time-weighted sum of exit flows (*22*). For the sake of simplicity, we consider a simple network consisting of a freeway stretch with a sag (bottleneck), without any on-ramps or off-ramps. Hence, the network that we aim to control has a single entry point and a single exit point. However, the control strategy described in this section could be generalized to more complex networks, possibly in combination with other control measures.

Control Concept: Mainstream Traffic Flow Control

The outflow from a sag bottleneck (q_b) is lower or equal to its capacity ($q_{b,\max}$) regardless of the traffic demand. Therefore, if there is no other bottleneck within the network or downstream of it, then the network exit flow (s) is mainly constrained by the capacity of the sag bottleneck.

$$s \simeq q_b \leq q_{b,\max} \qquad (1)$$

As mentioned above, the capacity of a bottleneck depends on the traffic state: the queue discharge capacity of the bottleneck ($q^c_{b,\max}$) is lower than its free flow capacity ($q^f_{b,\max}$).

$$q_{b,\max} = \begin{cases} q^f_{b,\max} & \text{in uncongested traffic conditions} \\ q^c_{b,\max} & \text{in congested traffic conditions} \end{cases} \qquad (2)$$

where:

$$q^c_{b,\max} < q^f_{b,\max} \qquad (3)$$

Since network exit flows (s) can be higher if traffic flow at the bottleneck is uncongested than if it is congested, a way to maximize the time-weighted sum of exit flows in our network (control goal) is to prevent traffic from breaking down at the sag bottleneck area. To that end, we propose a control strategy based on the concept of mainstream traffic flow control. The control strategy aims to regulate the traffic inflow to the sag bottleneck ($q_{b,\text{in}}$) in order to achieve a desired traffic state at the bottleneck that maximizes outflow. The inflow to the sag bottleneck is regulated by means of a controlled section upstream of the bottleneck (see Figure 1). On that controlled section, the speed limit is variable. Speed limits are set by the controller based on measurements of the traffic conditions (density) at the bottleneck. As a result of the fundamental relation between traffic speed and flow, the outflow from the controlled section (q_c) depends on the speed limit (assuming that drivers comply with it). The inflow to the bottleneck is approximately equal to the outflow from the controlled section ($q_{b,\text{in}} \simeq q_c$). By applying an appropriate speed limit on the controlled section, the inflow to the bottleneck can be kept slightly below its free flow capacity ($q_c \simeq q_{b,\text{in}} < q^f_{b,\max}$). Therefore, even in conditions of high demand, the density at the bottleneck does not go above the critical density and traffic does not break down at the bottleneck area (Figure 1). Note that congestion is not completely prevented: traffic flow becomes congested on the controlled section and upstream of it. However, if an appropriate speed limit is applied, the outflow from the controlled section can be higher than the queue discharge capacity of the bottleneck ($q_c > q^c_{b,\max}$). As a result, we can obtain higher exit flows (s) than if traffic flow becomes congested at the bottleneck area (Figure 1). This should result in a higher time-weighted sum of exit flows and a lower total time spent.

Control Law: Proportional Feedback

The controller determines the speed limits to be applied on the controlled section by means of a proportional feedback control law that is similar in nature to the one used by the ramp metering control algorithm ALINEA (*23*). The control law requires: a) a target traffic density at the sag bottleneck area; and b) real-time measurements of the density at the sag bottleneck area. As explained above, the target density should be slightly lower than the critical density of the bottleneck. The density at the bottleneck is measured in real time by means of loop detectors. The control law determines the speed limit to be applied on the controlled section (v_{lim}) based on the difference between the target density ($\rho_{b,0}$) and the measured density (ρ_b). The speed limit is re-evaluated each time that the controller receives a new density measurement; hence the control time step period (T_c) is equal to the sampling time period of the detector (T_s). However, there is a delay ($r \cdot T_c$) between the time when the detector time sampling period finishes and the time when the new speed limit is actually applied on the control section.

$$v_{\text{lim}}(k) = v_{\text{lim},0} + K_p \cdot \left(\rho_{b,0} - \rho_b(k-r)\right) \qquad (4)$$

where: k is the control time step index; K_p is the proportional gain; r is the control time step delay; and $v_{\text{lim},0}$ is the target speed limit when $\rho_b(k-r) = \rho_{b,0}$.

Additionally, we imposed three constraints on the speed limits displayed on the message signs in order to make it easier for drivers to comply with them. First, the speed limit is always rounded to a value multiple of 10. Second, the speed limit cannot be lower than a minimum threshold ($v_{\text{lim,min}}$). Third, the change in speed limit between two consecutive control steps cannot be higher than a maximum change rate (Δv_{lim}).

By means of the feedback control law described above, the controller should be able to dynamically regulate the speed limit on the controlled section so that the outflow from the bottleneck is maximized. In stationary high demand conditions, the controller maintains the density (ρ_b) near the target value ($\rho_{b,0}$) in order to prevent traffic from breaking down at the bottleneck. Furthermore, the controller should be able to react immediately to density deviations. If the measured density is significantly lower than the target density (e.g., because the demand is low), the controller will choose to apply a high speed limit (or even the regular speed limit) in order to maximize the inflow to the bottleneck. If the measured density is higher than the target density (e.g., because traffic has broken down at the bottleneck), the controller will choose to apply a lower speed limit in order to reduce the density at the bottleneck to the target value. The latter is very important, because traffic flow in nearly-saturated conditions can easily destabilize and become congested, and the controller must be able to react to that. Finally, note that the controller reacts to density deviations with a certain delay. This delay is due to the control delay ($r \cdot T_c$), but also to the time needed by drivers to cover the distance between the controlled section and the bottleneck.

PERFORMANCE EVALUATION METHOD

A case study was carried out to evaluate the performance of the proposed control strategy. A longitudinal driving behavior model that takes into account the influence of changes in gradient on vehicle acceleration (*24*) was used to simulate traffic flow on a sag in two scenarios: a) no-control scenario (no control measures are implemented); and b) control scenario (the proposed control measure is operative). The performance of the control strategy was assessed by comparing the total delay experienced by drivers in the two scenarios.

Longitudinal Driving Behavior Model

The longitudinal driving behavior model determines the acceleration of every vehicle at each simulation time step. Vehicle acceleration is assumed to stay constant over the period [t, $t+\Delta t$], where Δt is the simulation step period. The model determines vehicle acceleration ($\dot{v}$) by means of a two-term additive function:

$$\dot{v}(t) = f_r(t) + f_g(t) \tag{5}$$

The first term (f_r) describes regular car-following behavior. It accounts for the influence of vehicle speed (v), relative speed to the leading vehicle (Δv) and net distance headway (s) on vehicle acceleration. The formulation of f_r is based on the IDM+ model (*25*):

$$f_r(t) = a \cdot \min\left[1 - \left(\frac{v(t)}{v_{\text{des}}(x(t),t)}\right)^4,\ 1 - \left(\frac{s_{\text{des}}(v(t),\Delta v(t))}{s(t)}\right)^2\right] \tag{6}$$

where the dynamic desired net distance headway (s_{des}) is:

$$s_{\text{des}}(v(t),\Delta v(t)) = s_0 + v(t)\cdot\tau(v(t)) + \frac{v(t)\cdot\Delta v(t)}{2\sqrt{ab}} \tag{7}$$

The parameters in Equations 6–7 are: desired speed (v_{des}), maximum acceleration (a), maximum comfortable deceleration (b), net distance headway at standstill (s_0), and safe time headway (τ). The value of parameter τ depends on the traffic state. In congested traffic conditions (i.e., below the critical speed v_{crit}), the value of τ is higher than in uncongested conditions:

$$\tau\left(v(t)\right)=\begin{cases}\tau_f & \text{if } v(t)\geq v_{\text{crit}}\\ \gamma\cdot\tau_f & \text{if } v(t)<v_{\text{crit}}\end{cases} \tag{8}$$

where: τ_f is the safe time headway in uncongested conditions; and γ is a factor greater than 1.

The second term (f_g) accounts for the influence of changes in freeway gradient on vehicle acceleration. At a given time t, this influence is the gravity acceleration (g = 9.81 m/s^2) multiplied by the difference between the gradient at the location where the vehicle is at that time ($G(x(t))$) and the gradient compensated by the driver until that time ($G_c(t)$).

$$f_g(t)=-g\cdot\left(G\left(x(t)\right)-G_c(t)\right) \tag{9}$$

The compensated gradient (G_c) is a variable that accounts for the fact that drivers have a limited ability to accelerate on freeway sections where the slope increases. We assume that drivers compensate for positive changes in slope linearly over time (with a maximum gradient compensation rate defined by parameter c). Furthermore, we assume that drivers can fully compensate for negative changes in gradient.

$$G_c(t)=\begin{cases}G\left(x(t)\right) & \text{if } G\left(x(t)\right)\leq G(t_c)+c\cdot(t-t_c)\\ G(t_c)+c\cdot(t-t_c) & \text{if } G\left(x(t)\right)>G(t_c)+c\cdot(t-t_c)\end{cases} \tag{10}$$

where:

$$t_c=\max\left[t\mid G_c(t)=G\left(x(t)\right)\right] \tag{11}$$

If the rate at which the freeway slope increases over time is lower than the driver's maximum gradient compensation rate (c), then $G_c(t) = G(t)$ for all t. Therefore, $f_g(t) = 0$ for all t, which means that vehicle acceleration is not affected by the increase in gradient. However, if the rate at which the freeway slope increases over time is higher than the driver's maximum gradient compensation rate (c), then $G_c(t) < G(t)$ for a certain period of time. During that period, G_c increases linearly over time, but f_g is negative, which limits vehicle acceleration. This limitation in vehicle acceleration seems to be the main cause of the local changes in longitudinal driving behavior that reduce the capacity of sags (*14*). Note that the longitudinal driving behavior model generates the main bottleneck of sags at the end of the transition section (see Figure 2), because the maximum difference between $G_c(t)$ and $G(t)$ occurs at that location. This is in line with empirical observations (*2*, *4*). Also, note that the longitudinal driving behavior model is face-valid (*24*), but it has not been calibrated yet.

Simulation Settings

Network Characteristics

The simulated network is a 30 km long freeway stretch that contains a sag. The stretch has a constant-gradient downhill section that goes from location x = 0 to x = 27.7 km; a transition section that goes from x = 27.7 km to x = 28.3 km; and a constant-gradient uphill section that goes from x = 28.3 km to x = 30.0 km (see Figure 2). On the transition section, the freeway slope increases linearly over distance. The long length of the freeway stretch ensures that the flow entering the network is not influenced by the traffic conditions at the sag bottleneck area. The regular speed limit is 120 km/h. The network has only one lane (with no overtaking possibilities). There are no ramps or horizontal curves. There are four detectors in the network, which are used to monitor traffic conditions at key locations: i) network entry area (x = 0.3 km); ii) area where the controlled section is located in the control scenario (x = 27.0 km); iii) sag bottleneck area (x = 28.3 km); and iv) network exit area (x = 29.9 km).

Traffic Demand

The simulation period is 10000 s. At $t = 0$, there are no vehicles in the network. Network loading starts in the first simulation time step. The demand profile (i.e., flow at $x = 0$ over time) contains three periods that are relevant to test the proposed control strategy. First, from $t = 0$ to $t = 2000$ s, demand increases and goes above the capacity of the sag bottleneck. Second, from $t = 2000$ s to $t = 3000$ s, demand decreases considerably. Third, from $t = 3000$ s to $t = 7000$ s, demand increases again, goes above the capacity of the sag bottleneck and stays at that level. The controller should be able to control traffic adequately in periods of high and low demand, and it should be able to react adequately to demand fluctuations. Note that from $t = 9000$ s to $t = 10000$ s, demand is zero. This is necessary to ensure that all vehicles exit the network before the end of the simulation period, which allows us to compare the network performance in different scenarios. The demand profile can be seen in Figure 3, which shows the flows measured by the detector located at $x = 0.3$ km during the whole simulation period.

Longitudinal Driving Behavior

For the sake of simplicity, we assume homogeneous vehicle and driver characteristics. All vehicles are 4 m long. The parameters of the longitudinal driving behavior model are shown in Table 1.

Control

In the control scenario, a controlled section is added to the network. On that section, the speed limit is variable. The speed limit is displayed on message signs. The controlled section is 1.0 km long. That length gives sufficient time to drivers to adapt to the speed limit before leaving the controlled section. The controlled section is located between $x = 26.3$ km and $x = 27.3$ km. The downstream end of the controlled section is 1.0 km upstream of the end of the transition section (i.e., the bottleneck) in order to make sure that drivers have enough time to accelerate and the traffic speed at the bottleneck is not influenced by the speed limit on the controlled section. Three message signs are located in different points of the controlled section: i) upstream end ($x = 26.3$ km); ii) center point ($x = 26.8$ km); and iii) downstream end ($x = 27.3$ km). Only the first two message signs display the variable speed limits (v_{lim}). The sign at the downstream end of the controlled section always displays the regular speed limit of the freeway. The variable speed limits are selected based on the feedback control law described above. The controller uses density measurements from the detector located at the bottleneck ($x = 28.3$ km) as input. The values of the control parameters are shown in Table 1. Those parameter values were selected after analyzing the controller performance for different sets of values. No optimization method was used to tune the controller.

In the control scenario, the longitudinal driving behavior model is extended based on two assumptions. First, we assumed that drivers notice the message signs displaying the variable speed limits when the distance between driver and sign is 300 m or shorter. Second, we assumed that longitudinal driving behavior after noticing a message sign can be adequately reproduced by changing the value of the desired speed parameter (v_{des}) to the displayed speed limit (we assumed that all drivers fully comply with speed limits), keeping the remaining parameter values unchanged. Note that a change in the desired speed parameter does not result in an instantaneous change in the vehicle speed.

Performance Indicator: Total Delay

The performance of the proposed control strategy is evaluated by comparing the total delay in the no-control scenario and the control scenario. The total delay (TD) in a given scenario is defined as:

$$\mathrm{TD} = \mathrm{TTS} - \mathrm{TTS}_{\mathrm{ref}} \tag{13}$$

where: TTS is the total time spent in that scenario; and $\mathrm{TTS}_{\mathrm{ref}}$ is the total time spent in the reference scenario. The total time spent is calculated based on demand and exit flows (*22*). The demand flows are the flows measured by the detector located at $x = 0.3$ km; the exit flows are the flows measured by the detector located at x

= 29.9 km. The reference scenario is a hypothetical scenario in which the freeway vertical alignment is assumed to have no influence on the acceleration behavior of drivers, hence the sag is not a bottleneck. This is modeled by setting the value of the maximum gradient compensation rate parameter to a very high value: c = 999 s^{-1}.

RESULTS

Reference Scenario

In the reference scenario, traffic flow remains uncongested everywhere in the network during the whole simulation period. Thus, the exit flow profile over time is similar to the demand flow profile, with an offset of around 900 s (see Figure 3a). The total time spent is 1035 veh·h.

No-control Scenario

In the no-control scenario, traffic breaks down at the sag bottleneck when the inflow goes above 2050 veh/h (which can be considered as the free flow capacity of the bottleneck). When traffic breaks down, the outflow from the bottleneck decreases to around 1855 veh/h (which can be considered as the queue discharge capacity), reducing the network exit flow to 1855 veh/h as well (Figure 3a). During the simulation period, traffic breaks down two times. After the first breakdown, the demand flow decreases considerably, allowing the first queue to dissolve. Afterwards, the demand flow increases again above the free flow capacity of the bottleneck, causing a second breakdown (Figure 3a). In both cases, since the demand flow is higher than the exit flow, the number of vehicles within the network increases. This accumulation of vehicles results in a higher total time spent than in the reference scenario. The total time spent in the no-control scenario is 1237 veh·h, so the total delay is 202 veh·h.

Control Scenario

In the control scenario, the outflow from the controlled section is regulated so that it does not go above the free flow capacity of the bottleneck. Because of that, traffic does not break down at the bottleneck during the whole simulation period. In conditions of high demand, congestion forms on the controlled section; however, the outflow from the controlled section is higher (around 1985 veh/h) than the queue discharge capacity of the bottleneck (which is around 1855 veh/h) (Figure 3a). As a result, in the periods of high demand, network exit flows are around 1985 veh/h, i.e., 7% higher than in the no-control scenario (Figure 3a). Therefore, less vehicles accumulate in the network, which results in a considerably lower total delay. In the control scenario, the total time spent is 1177 veh·h (5% lower than in the no-control scenario), so the total delay is 142 veh·h (30% lower than in the no-control scenario).

The controller is able to react adequately to fluctuations in demand. Demand flows reach high levels before t = 2000 s (Figure 3a). When density at the bottleneck gets close to the target density, the controller sets a speed limit of 60–70 km/h on the controlled section (around t = 2700 s in Figure 3b). Between t = 2000 s and t = 3000 s, demand significantly decreases (Figure 3a), which results in low densities at the bottleneck. When such low densities are measured, the controller increases the speed limit on the controlled section (see Figure 3b). The reason is that the demand is too low to cause traffic to break down at the bottleneck, so there is less need to restrict the inflow. Afterwards, between t = 3000 s and t = 4000 s, the demand increases again (Figure 3a). The controller responds by decreasing the speed limit on the controlled section to 60–70 km/h again (Figure 3b), in order to prevent traffic from breaking down at the bottleneck. Note that due to the proportional structure of the controller, demand fluctuations result in speed limit oscillations (Figure 3b). However, in our case study, oscillations seem to dampen out with time, so the system does not become unstable.

SENSITIVITY ANALYSIS

We selected the values of the controller parameters (Table 1) to ensure high controller performance under the assumption that drivers behave according to our longitudinal driving behavior model. However, we also analyzed the performance of the controller assuming that drivers do not behave exactly as described by that model. More specifically, we investigated the sensitivity of the controller performance to two key parameters of the longitudinal driving behavior model that have a significant influence on the capacity of the sag bottleneck. Those parameters are the maximum gradient compensation rate (c) and the congestion factor on safe time headway (γ). First, we evaluated the performance of the controller assuming a lower and a higher value for parameter c (i.e., 0.00005 s^{-1} and 0.00015 s^{-1}, respectively), whereas the other parameters remained unchanged. Second, we evaluated the performance of the controller assuming a lower and a higher value for parameter γ (i.e., 1.12 and 1.18, respectively), whereas the other parameters remained unchanged.

The results indicate that the reduction in total delay resulting from the implementation of the proposed control strategy significantly depends on the value of parameter c. If c = 0.00010 s^{-1} (default value), the total delay in the control scenario is 30% lower than in the no-control scenario. If c = 0.00005 s^{-1}, that percentage is 36%, whereas if c = 0.00015 s^{-1}, that percentage is 23% (see Table 2). The main reason for those differences is that a higher (lower) value of c results in a higher (lower) queue discharge capacity of the sag bottleneck, hence it also results in higher (lower) exit flows in the no-control scenario. Instead, in the control scenario, exit flows are almost the same regardless of the value of c. Therefore, the controller reduces total delay to a larger extent if the value of c is lower.

The reduction in total delay resulting from the implementation of the controller does not significantly depend on the value of parameter γ. If γ = 1.15 (default value), the total delay in the control scenario is 30% lower than in the no-control scenario. If γ = 1.12, that percentage is 31%, whereas if γ = 1.18, that percentage is 29% (Table 2). The main reason why the percentages are similar is that a higher (lower) value of γ results in a lower (higher) queue discharge capacity of both the sag bottleneck and the controlled section. Therefore, a higher (lower) value of γ results in lower (higher) exit flows in both the no-control scenario and the control scenario.

To conclude, the sensitivity analysis shows that the results of the evaluation of the controller performance depend on the specification of the longitudinal driving behavior model. However, the sensitivity analysis also shows that the controller is able to significantly reduce total delay even after changing the values of key model parameters.

CONCLUSIONS

The capacity of sags is considerably lower than the capacity of normal freeway sections. Consequently, sags are often bottlenecks in freeway networks. This paper presented a new control strategy to mitigate congestion at sags, based on the concept of mainstream traffic flow control. By limiting the traffic speed (and hence the flow) on a controlled section upstream of the bottleneck, the proposed strategy regulates the density at the bottleneck area in order to keep it slightly below the critical density, hence preventing traffic from breaking down. The capacity drop due to congestion does not occur, so the outflow from the bottleneck can be higher. The speed limit on the controlled section is set using a proportional feedback control law. The performance of the proposed control strategy was evaluated by means of a simple case study using microscopic traffic simulation. The results show a considerable improvement in traffic flow efficiency. In periods of high demand, the flow exiting the network is around 7% higher in the control scenario than in the no-control scenario, which reduces the total delay by around 30%. A sensitivity analysis shows that the controller is able to considerably reduce total delay even if we assume different values for key parameters of the longitudinal driving behavior model. In spite of the simplicity of the case study, our findings show for the first time that mainstream traffic flow control strategies using variable speed limits have the potential to considerably improve traffic flow efficiency in freeway networks containing sags.

Further research is necessary to make a more thorough evaluation of the performance of the proposed control strategy. Such evaluation requires extending the case study to include a multi-lane network and heterogeneous traffic. In addition, the longitudinal driving behavior model should take into account the level of compliance of drivers to variable speed limits, which may have a strong influence on the performance of the control strategy. Also, the model should be calibrated and validated. Further research should be carried out to refine the controller design and improve its performance. For example, the oscillatory behavior of the controller could be mitigated by using an alternative type of control law (e.g., proportional-integral feedback). Also, other means to regulate the speed on the controlled section could be tested. An alternative to displaying variable speed limits on message signs could be to regulate the speed of vehicles equipped with cooperative adaptive cruise control systems (via infrastructure-to-vehicle communication). Finally, the controller design could be extended in order to make it operational in more complex networks (e.g., networks with ramps and/or other types of bottlenecks). This may require combining the control strategy presented in this paper with other types of control measures.

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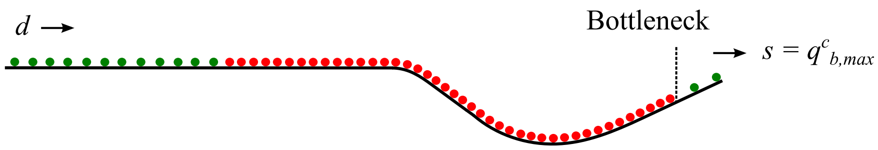
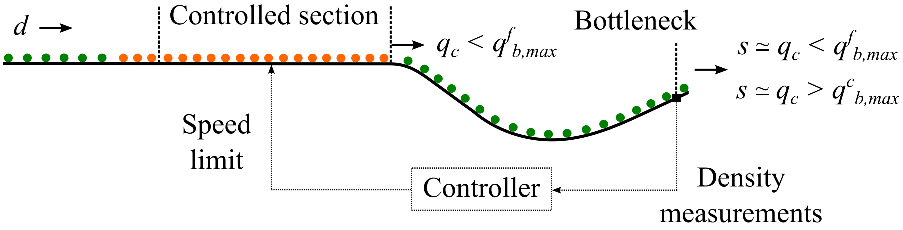
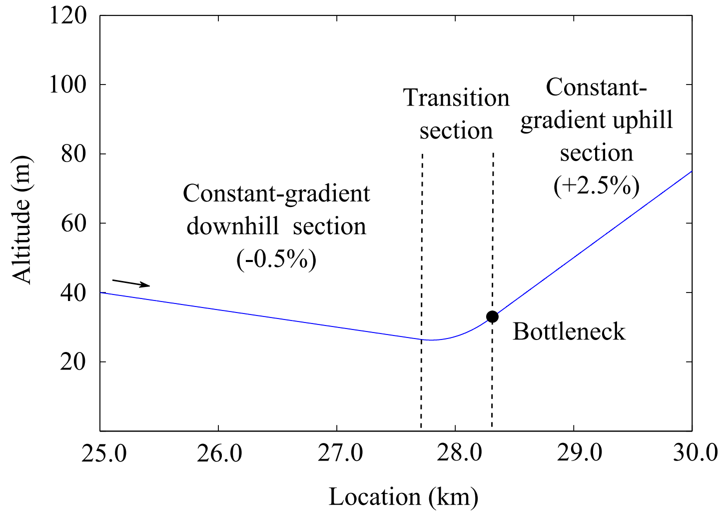


(a)

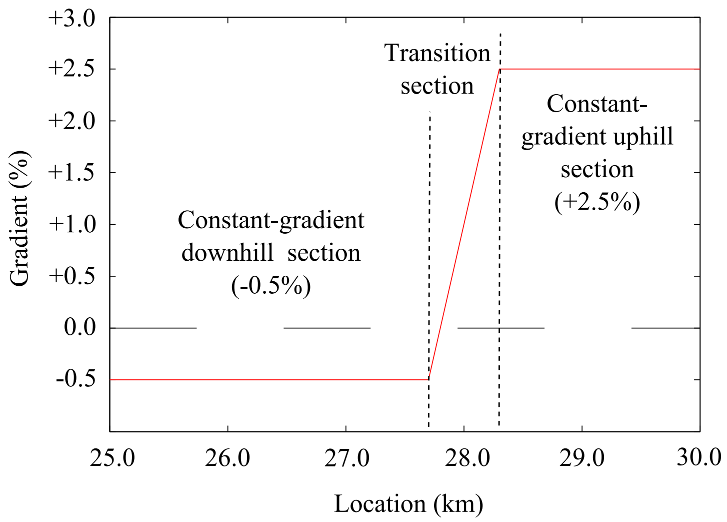


(b)

FIGURE 1 Flows within the network in two scenarios: (a) scenario without controlled section; (b) scenario with controlled section. In the figure: d is demand flow; s is exit flow; q_c is outflow from the controlled section; $q^f_{b,\max}$ is free flow capacity; $q^c_{b,\max}$ is queue discharge capacity; green circles represent vehicles in uncongested traffic conditions; red and orange circles represent vehicles in severe and less severe congested traffic conditions, respectively

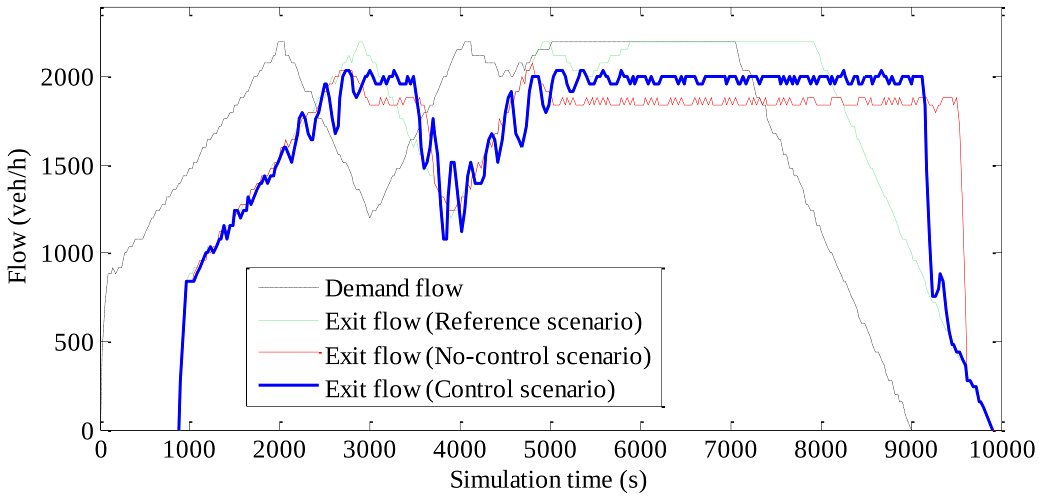


(a)

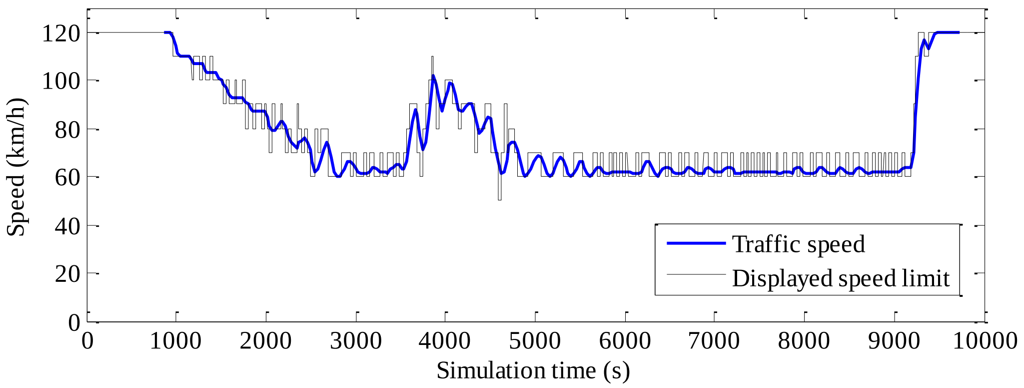


(b)

FIGURE 2 Vertical alignment of the network (from x = 25.0 km to x = 30.0 km): (a) altitude vs. location; (b) gradient vs. location



(a)



(b)

FIGURE 3 Simulation results: (a) demand and exit flows over time in all scenarios; (b) speed limit and traffic speed over time at location *x* = 27.0 km (i.e., within the controlled section) in the control scenario. Flows and speeds are smoothed by using a simple moving average method: the flow (speed) for a given sampling period is the unweighted mean of the measured flow (speed) on that sampling period and the measured flows (speeds) on the previous and next sampling period.

TABLE 1 Parameter values

	Parameter	Value
Longitudinal driving behavior model	v_{des} (km/h)	120
	a (m/s^2)	1.45
	b (m/s^2)	2.10
	τ_f (s)	1.20
	s_0 (m)	3
	v_{crit} (km/h)	65
	γ (-)	1.15
	c (s^{-1})	0.00010
	Δt (s)	0.5
Controller	T_s (s)	30
	T_c (s)	30
	$v_{\mathrm{lim},0}$ (km/h)	60
	K_p (h/veh)	4.8
	$\rho_{b,0}$ (veh/km)	18.0
	r (-)	2
	$v_{\mathrm{lim,min}}$ (km/h)	20
	Δv_{lim} (km/h)	20

TABLE 2 Performance of the controller (including sensitivity analysis)

	Model parameter values				
Parameter c (s^{-1})	0.00010	0.00005	0.00015	0.00010	0.00010
Parameter γ (-)	1.15	1.15	1.15	1.12	1.18
TD no-control scenario (veh·h)	202	227	177	157	244
TD control scenario (veh·h)	142	145	137	108	173
Absolute difference (veh·h)	- 60	- 82	- 40	- 49	- 71
Relative difference (%)	- 29.7	- 36.1	- 22.6	- 31.2	- 29.0