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Sags are freeway sections along which the gradient changes significantly from downward to upward. 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, to prevent traffic flow perturbations in nearly saturated conditions, or both. This paper presents an alternative type of measure based on the concept of mainstream traffic flow control. The proposed control measure regulates traffic density at the bottleneck area to keep it below the critical density and hence prevent 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 on the basis of a feedback control law. The authors evaluate the effectiveness of the proposed control strategy by means of a simple case study by 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 that use variable speed limits have the potential to improve substantially the performance of freeway networks containing sags.

Sags are freeway sections along which the gradient changes significantly from downward to upward in the direction of traffic (*1*). The capacity of sags is considerably lower than that of normal freeway sections (*2, 3*). In general, a bottleneck is located 0.5 to 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, to prevent traffic flow perturbations in nearly saturated conditions, or both.

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 to keep it below the critical density and hence prevent traffic from breaking down. The capacity drop caused by 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 on the basis of a proportional-feedback control law. The effectiveness of the proposed control measure is evaluated by means of a simple case study by 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 extremely high demand), and this increase in flow leads to a considerable decrease in total delay (TD). 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 for mitigating congestion at that type of bottleneck. 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 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, 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 to 1 km downstream of the bottom of the sag (*4*). Xing et al. present empirical measurements of free-flow capacities and queue discharge capacities of various sag sections of Japanese freeways (*3*). 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 3,150 vehicles per hour (vph) at two-lane sags and 5,340 vph at three-lane sags. The average queue discharge capacity is 2,780 vph at two-lane sags and 4,600 vph 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*).

In a comparison of the capacities of sags with those of flat sections, one observes that the free-flow capacity and the queue discharge capacity of sags are considerably lower. At flat sections, free-flow capacities are generally around 4,000 passenger car units per hour

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(pcu/h) (for two lanes) and 6,000 pcu/h (for three lanes) (*2*). If a 10% capacity drop is assumed, queue discharge capacities for flat sections of 3,600 pcu/h (for two lanes) and 5,400 pcu/h (for three lanes) are obtained. 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% to 15% lower in three-lane freeways).

The main cause of capacity reduction at sags seems to be related to the impact of the increase in freeway gradient 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 inability of drivers to accelerate sufficiently and compensate for the increase in the 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: measures that aim (*a*) to increase the free-flow capacity of sag bottlenecks, (*b*) to prevent traffic flow perturbations at sag bottlenecks in nearly saturated conditions, and (*c*) 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 distribution of the traffic flow more evenly across lanes 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 and encouraging them to recover speed after leaving congestion (*17, 18*). In addition, 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, an additional category of measures could improve traffic flow efficiency at sags, but it has received little attention in the recent literature, namely measures of mainstream traffic flow control. 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 extremely 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*). The current authors 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. This control concept can result in relevant improvements in traffic flow efficiency only if the queue discharge capacity of the bottleneck is significantly lower than the queue discharge capacity of the controlled section. This relationship is usually the case with sag bottlenecks (*2, 3, 11*).

CONTROL STRATEGY

This section describes the characteristics of a strategy for mainstream traffic flow control aimed at mitigating congestion at sags. The control goal is to minimize the total time spent by vehicles in the network over a certain period. If one assumes 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, the authors consider a simple network consisting of a freeway stretch with a sag (bottleneck) without any on- or off-ramps. Hence, the network designated for 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 than or equal to its capacity ($q_{b,\max}$) regardless of the traffic demand. Therefore, with no other bottleneck in or downstream of the network, the network exit flow (s) is mainly constrained by the capacity of the sag bottleneck:

$$s \simeq q_b \leq q_{b,\max} \tag{1}$$

As noted earlier, 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 ($q^f_{b,\max}$):

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

where

$$q^c_{b,\max} < q^f_{b,\max} \tag{3}$$

Because 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 the network (control goal) is to prevent traffic from breaking down at the sag bottleneck area. To that end, the authors propose a control strategy that is based on the concept of mainstream traffic flow control. The control strategy aims to regulate the traffic inflow to the sag bottleneck ($q_{b,\text{in}}$) 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 (Figure 1). On that controlled section, the speed limit is variable. Speed limits are set by the controller on the basis of 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 (if one assumes 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). Yet congestion is not completely prevented: traffic flow becomes congested on the controlled section and upstream of it. However, if an appropriate

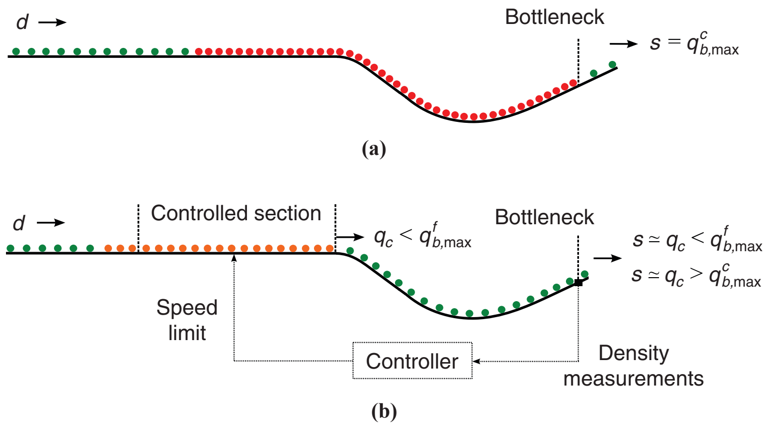


FIGURE 1 Flows within network in two scenarios: (*a*) without controlled section and (*b*) with controlled section (*d* = demand flow).

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, higher exit flows (s) can be obtained than if traffic flow becomes congested at the bottleneck area (Figure 1). This condition 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 earlier, 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 reevaluated each time that the controller receives a new density measurement; hence, the control time step period (T_c) is equal to the sampling period of the detector (T_s). However, a delay ($r \cdot T_c$) occurs between the time the detector time sampling period finishes and the time the new speed limit is actually applied on the control section.

$$v_{\lim}(k) = v_{\lim,0} + K_p\big(\rho_{b,0} - \rho_b(k-r)\big) \quad (4)$$

where

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

Furthermore, three constraints are imposed on the speed limits displayed on the message signs 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 ($v_{\lim,\min}$). Third, the change in speed limit between two consecutive control steps cannot be higher than a maximum change rate ($\Delta v_{\lim}$).

By means of the feedback control law described earlier, the controller should be able to regulate dynamically 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 ($\rho_{b,0}$) 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) 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 to reduce the density at the bottleneck to the target value. The latter process is extremely important because traffic flow in nearly saturated conditions can easily destabilize and become congested, and the controller must be able to react to that possibility. Finally, the controller reacts to density deviations with a certain delay. This delay is the result of the control delay ($r \cdot T_c$) but also of the time needed by drivers to cover the distance between the controlled section and the bottleneck.

METHOD OF PERFORMANCE EVALUATION

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

Model of Longitudinal Driving Behavior

The model of longitudinal driving behavior 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:

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

where f_r describes regular car-following behavior and f_g is the freeway gradient. The term f_r 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

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

and

s_{des} = dynamic desired net distance headway,
v_{des} = desired speed,
x = position along the highway,
t = time,
a = maximum acceleration,
b = maximum comfortable deceleration (b),
s_0 = net distance headway at standstill, and
τ = safe time headway.

The desired speed depends on the position along the freeway x and on time t because some freeway sections may have variable speed limits. Also, the value of 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:

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

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

The second term (f_g) in Equation 5 accounts for the influence of changes in freeway gradient on vehicle acceleration. At a given time t, this influence is gravity acceleration ($g = 9.81$ m/s^2) multiplied by the difference between the gradient at the location of the vehicle at that time ($G(x(t))$) and the gradient compensated by the driver until that time ($G_c(t)$):

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

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

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

where

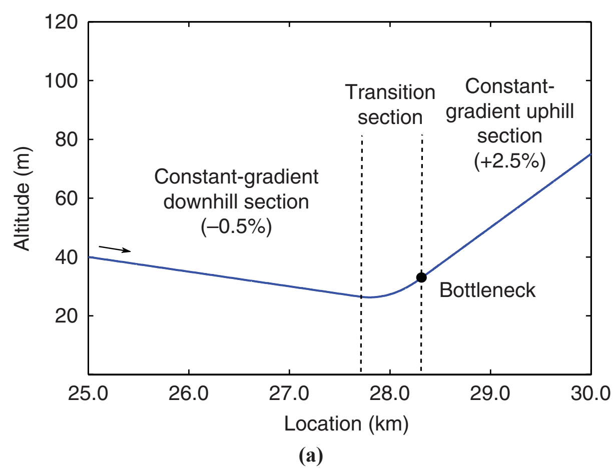
$$t_c = \max\left[t \mid G_c(t) = G(x(t))\right] \tag{11}$$

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 rate of gradient compensation (c), then $G_c(t) < G(t)$ for a certain period. 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 local changes in longitudinal driving behavior that reduce the capacity of sags (*14*). The model of longitudinal driving behavior generates the main bottleneck of sags at the end of the transition section (Figure 2) because the maximum difference between $G_c(t)$ and $G(t)$ occurs at that location. This situation is in line with empirical observations (*2, 4*). In addition, the model of longitudinal driving behavior is face valid, but it has not yet been calibrated (*24*).

Simulation Settings

Network Characteristics

The simulated network is a freeway stretch 30 km long that contains a sag. The stretch has a constant-gradient downhill section



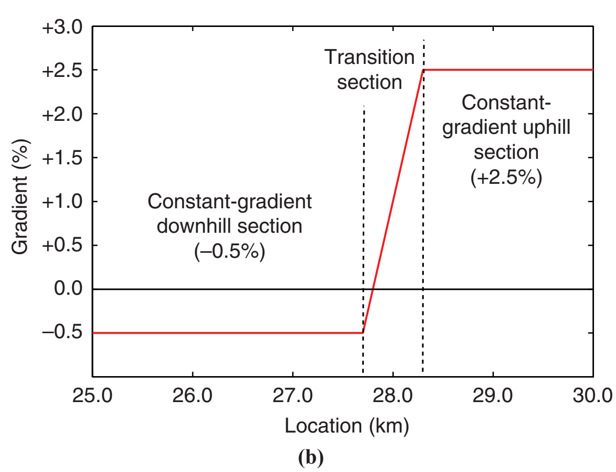


FIGURE 2 Vertical alignment of network (from x = 25.0 km to x = 30.0 km): (*a*) altitude versus location and (*b*) gradient versus location.

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 (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) and no ramps or horizontal curves. Four detectors are in the network, and they are used to monitor traffic conditions at key locations: (*a*) network entry area ($x = 0.3$ km), (*b*) the area where the controlled section is located in the control scenario ($x = 27.0$ km), (*c*) the sag bottleneck area ($x = 28.3$ km), and (*d*) the network exit area ($x = 29.9$ km).

Traffic Demand

The simulation period is 10,000 s. At $t = 0$, no vehicles are 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 for testing the proposed control strategy. First, from $t = 0$ to $t = 2{,}000$ s, demand increases and goes above the capacity of the sag bottleneck. Second, from $t = 2{,}000$ s to $t = 3{,}000$ s, demand decreases considerably. Third, from $t = 3{,}000$ s to $t = 7{,}000$ 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. From $t = 9{,}000$ s to $t = 10{,}000$ s, demand is 0. This period of no demand is necessary to ensure that all vehicles exit the network before the end of the simulation period and to allow comparison of network performance in different scenarios. Figure 3 shows the demand network, including the flows measured by the detector at $x = 0.3$ km, during the whole simulation period.

Longitudinal Driving Behavior

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

TABLE 1 Parameter Values

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

NOTE: veh = vehicles.

Control

In the control scenario, a controlled section is added to the network. In that section, the speed limit is variable and is displayed on message signs. The controlled section is 1.0 km long. That length gives drivers sufficient time to adapt to the speed limit before leaving the controlled section. The controlled section is 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) to ensure that drivers have sufficient time to accelerate and that the traffic speed at the bottleneck is not influenced by the speed limit on the controlled section. Three message signs are located at different points of the controlled section: (*a*) upstream end ($x = 26.3$ km), (*b*) center point ($x = 26.8$ km), and (*c*) 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 freeway's regular speed limit. The variable speed limits are selected on the basis of the feedback control law described earlier. The controller uses density measurements from the detector at the bottleneck ($x = 28.3$ km) as input. The values of the control parameters, shown in Table 1, were selected after the controller performance for different sets of values was analyzed. No optimization method was used to tune the controller.

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

Performance Indicator: TD

The performance of the proposed control strategy is evaluated by comparing the TD in the no-control scenario with that in the control scenario. The TD in a given scenario is defined as

$$\mathrm{TD} = \mathrm{TTS} - \mathrm{TTS}_{ref} \tag{12}$$

where TTS is the total time spent in that scenario and TTS_{ref} is the total time spent in the reference scenario. The total time spent is calculated on the basis of both demand flows 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 one 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 situation is modeled by setting the value of the maximum gradient compensation rate parameter c to an extremely high value: $c = 999$ s^{-1}.

RESULTS

Reference Scenario

In the reference scenario, traffic flow remains uncongested everywhere in the network during the entire simulation period. Thus, the exit flow profile over time is similar to the demand flow profile, with

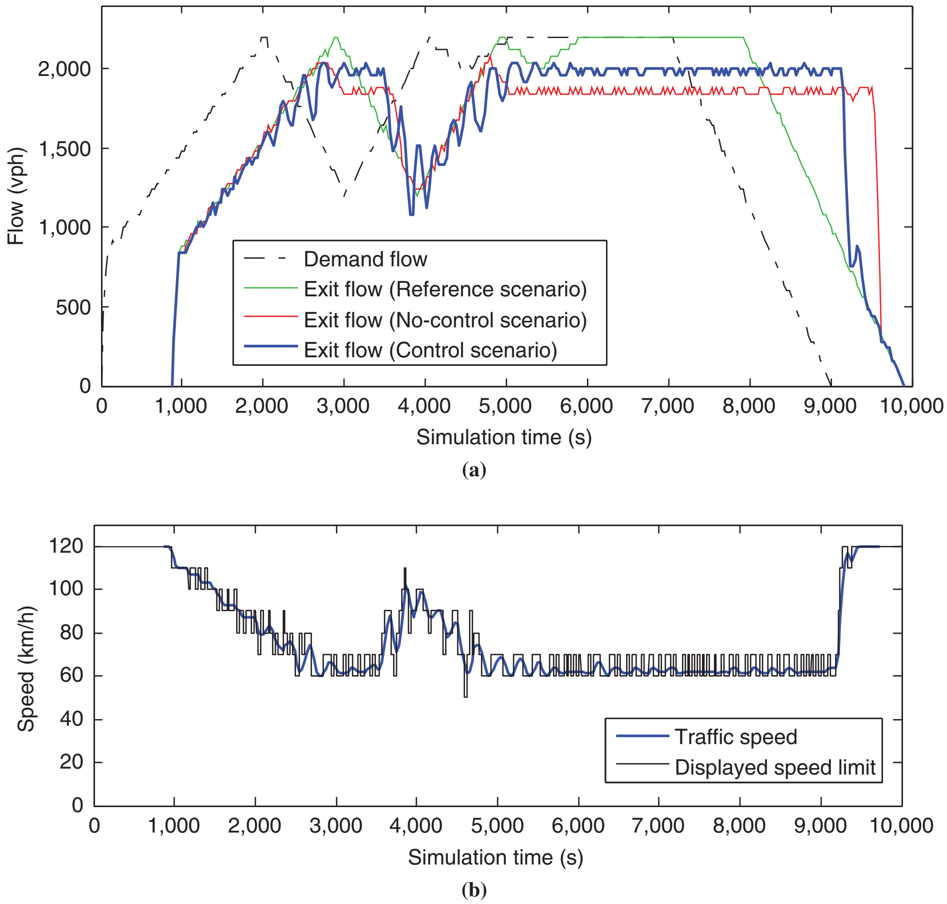


FIGURE 3 Simulation results: (*a*) demand and exit flows over time in all scenarios and (*b*) speed limit and traffic speed over time at location x = 27.0 km (i.e., within the controlled section) in the control scenario.

an offset of around 900 s (Figure 3*a*). The total time spent is 1,035 vehicle hours (veh-h).

No-Control Scenario

In the no-control scenario, traffic breaks down at the sag bottleneck when the inflow goes above 2,050 vph (which can be considered the free-flow capacity of the bottleneck). When traffic breaks down, the outflow from the bottleneck decreases to around 1,855 vph (which can be considered the queue discharge capacity) and reduces the network exit flow to 1,855 vph as well (Figure 3*a*). During the simulation period, traffic breaks down twice. After the first breakdown, the demand flow decreases considerably and allows the first queue to dissolve. Afterward, the demand flow again increases above the free-flow capacity of the bottleneck, causing a second breakdown (Figure 3*a*). In both cases, because 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 TTS than the TTS_{ref}. The TTS in the no-control scenario is 1,237 veh-h, so the TD 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 limit, traffic does not break down at the bottleneck during the entire simulation period. In conditions of high demand, congestion forms in the controlled section; however, the outflow from the controlled section is higher (around 1,985 vph) than the queue discharge capacity of the bottleneck (which is around 1,855 vph) (Figure 3*a*). As a result, in periods of high demand, network exit flows are around 1,985 vph (i.e., 7% higher than in the no-control scenario) (Figure 3*a*). Therefore, fewer vehicles accumulate in the network, and the result is a considerably lower TD. In the control scenario, the TTS is 1,177 veh-h (5% lower than in the no-control scenario), so the TD 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 $t = 2{,}000$ s (Figure 3*a*). When density at the bottleneck gets close to the target density, the controller sets a speed limit of 60 to 70 km/h in the controlled section (around $t = 2{,}700$ s, Figure 3*b*). Between $t = 2{,}000$ s and $t = 3{,}000$ s, demand significantly decreases (Figure 3*a*), and this decrease results in low densities at the bottleneck. When such low densities are measured, the controller increases the speed limit in the controlled section (Figure 3*b*). The reason for the speed limit increase is that demand is too low to cause traffic to break down at the bottleneck, so the need to restrict inflow is lower. Afterward, between $t = 3{,}000$ s and $t = 4{,}000$ s, the demand increases again (Figure 3*a*). The controller responds by decreasing the speed limit in the controlled section to 60 to 70 km/h again (Figure 3*b*) to prevent traffic from breaking down at the bottleneck. Because of the proportional structure of the controller, demand fluctuations result in speed limit oscillations (Figure 3*b*). However, in this case study, oscillations seem to dampen out with time, so the system does not become unstable.

SENSITIVITY ANALYSIS

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

The results indicate that the reduction in TD 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 TD 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% (Table 2). The main reason for those differences is that a higher (or lower) value of c results in a higher (or lower) queue discharge capacity of the sag bottleneck; hence, it also results in higher (or lower) exit flows in the no-control scenario. In contrast, in the control scenario, exit flows are almost the same regardless of the value of c. Therefore, the controller reduces TD to a larger extent if the value of c is lower.

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

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

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 on the basis of the concept of mainstream traffic flow control. By limiting the traffic speed (and hence the flow) in a controlled section upstream of the bottleneck, the proposed strategy regulates the density at the bottleneck area to keep it slightly below the critical density and hence prevents traffic from breaking down. The capacity drop attributable to congestion does not occur, so the outflow from the bottleneck can be higher. The speed limit on the controlled section is set by using a proportional feedback control law. The performance of the proposed control strategy was evaluated by means of a simple case study by using microscopic traffic simulation. The results show a considerable improvement in the efficiency of traffic flow. In periods of high demand, the flow exiting the network is around 7% higher in the control scenario than in the no-control scenario, and this higher exiting flow reduces the TD by around 30%. A sensitivity analysis shows that the controller is able to reduce TD considerably, even if different values for key parameters of the model of longitudinal driving behavior are assumed. Despite the simplicity of the case study, the findings here show for the first time that mainstream traffic flow control strategies using variable speed limits have the potential to improve traffic flow efficiency considerably 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 multilane network and heterogeneous traffic. In addition, the model of longitudinal driving behavior should take into account the level of compliance of drivers with variable speed limits, because driver compliance may have a strong influence on the performance of the control strategy. In addition,

TABLE 2 Performance of Controller, Including Sensitivity Analysis

	Value, by Scenario				
		Varied C		Varied γ	
Model Parameter	Reference	A	B	C	D
c (s^{-1})	0.00010	0.00005	0.00015	0.00010	0.00010
γ (unitless)	1.15	1.15	1.15	1.12	1.18
TD (veh-h)					
No-control scenario	202	227	177	157	244
Control scenario	142	145	137	108	173
Difference (veh-h)					
Absolute	–60	–82	–40	–49	–71
Relative	–29.7	–36.1	–22.6	–31.2	–29.0

the model should be calibrated and validated. Further research should be performed 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). Furthermore, other means to regulate speed in 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 to make it operational in more-complex networks (e.g., networks with ramps or other types of bottlenecks). This extension may require combining the control strategy presented in this paper with other types of control measures.

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