Microscopic Simulation Analysis of Mainstream Traffic Flow Control with Variable Speed Limits

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***Abstract*— Mainstream Traffic Flow Control (MTFC) with Variable Speed Limits (VSL) is a freeway traffic control method which aims to maximize throughput by regulating the mainstream flow upstream from a bottleneck. Recent studies in a macroscopic simulator have shown optimal and feedback MTFC potential to improve traffic conditions. In this paper, local feedback MTFC is applied in microscopic simulation for an on-ramp merge bottleneck. Traffic behavior reveals important aspects that had not been previously captured in macroscopic simulation. Mainly, the more realistic VSL application at specific points instead of along an entire freeway section produces a slower traffic response to speed limit changes. In addition, the nonlinear speed limit-flow relation observed in the microscopic model is more pronounced than what was observed at the macroscopic level. After appropriate modifications in the control law significant improvements in traffic conditions were obtained.**

I. INTRODUCTION

Traffic congestion is a main issue in metropolitan areas. Congestion is known to reduce the capacity of freeways [1], with consequences such as increased vehicular delays, reduced traffic safety, driver stress, and environmental pollution.

Appropriate control measures can improve traffic conditions. Mainstream Traffic Flow Control (MTFC) on freeways by use of Variable Speed Limits (VSL) [2]–[5] aims to maximize throughput by regulating the mainstream flow upstream from a bottleneck and has shown promising results in a second-order macroscopic simulation environment. Those results are refined here with a microscopic traffic simulator, since in a macroscopic simulator:

- speed limit changes affect a whole freeway section, while in reality the change usually affects vehicles that are passing by the point where the speed limit is posted;
- as used in previous studies, traffic is deterministic, whereas real traffic systems are stochastic;
- space and time are discretized in the form of segments with a given length and simulation time step, which may restrict admissible lengths for control application.

Indeed, applying feedback MTFC-VSL to a freeway stretch in a microscopic traffic simulator revealed important aspects of the control method that were not considered in previous studies. This paper presents the following findings:

- for the studied scenario, the relation between speed limits and flow shows a stronger nonlinearity than what was observed in previous studies, see, e.g., [5];
- when speed limit changes do not affect a whole section, i.e., affect only vehicles passing by the posted speed limit, a slower traffic response results, especially for increasing speed limits;
- the length of the section where VSL is applied and the distance between this section and the bottleneck to be controlled affect the speed of the traffic response to VSL changes;
- overall, the microscopic simulations confirmed that MTFC-VSL can successfully avoid the capacity drop and the onset of congestion, thereby increasing the performance of a freeway bottleneck.

Previous works about VSL control strategies in microscopic simulation environments [6]–[8] focused mainly on system performance whereas the present study focuses also on features that affect control design and, as such, anticipates practical aspects that may appear in reality.

The next section briefly reviews the MTFC concept and presents an I-type MTFC feedback controller. Section III elaborates on practical control aspects that are unveiled in our microscopic simulation studies. The control setup is further discussed in Section IV. Section V presents simulation results. Conclusions are presented in Section VI.

II. MAINSTREAM TRAFFIC FLOW CONTROL

This section presents a brief outline of the MTFC concept and the feedback MTFC controller (see [3], [4] for details).

A. The MTFC Concept

MTFC is a freeway traffic control method which aims to maximize freeway throughput by controlling the mainstream traffic flow. The idea is to maintain the mainstream traffic flow upstream from a bottleneck at a sufficiently low level to avoid congestion and capacity drop at the bottleneck location, establishing maximum flow.

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It is inevitable that by doing so, MTFC induces a controlled congestion at the MTFC application area. This congestion, however, is located upstream of the bottleneck, avoiding the capacity drop, and has higher outflow and speed than in the no-control case. In this work we consider VSL as an MTFC actuator, based on the principle that lower speed limits induce lower capacity flows [2].

The area subject to VSL is the *application area*. Vehicles may leave this area with low speeds, so for them to reach the critical speed $v_{\rm cr}$ (corresponding to the bottleneck capacity flow and critical occupancy $o_{\rm cr}$) at the bottleneck, the end of the area should be sufficiently upstream of the bottleneck. The section between the application area and the bottleneck is denoted the *acceleration area*. Fig. 1 depicts both areas.

B. Feedback MTFC-VSL

The control problem is to regulate the occupancy $o_{\rm out}$ of the bottleneck at a reference value (set-point) $\hat{o}_{\rm out}$ by controlling the mainstream flow upstream of the bottleneck with VSL ($\hat{o}_{\rm out}$ is chosen near $o_{\rm cr}$ for maximum flow). We define a VSL rate $0 < b \leq 1$ as the ratio of the current speed limit by the nominal speed limit. This is a single-input-single-output control problem where the VSL rate b and occupancy $o_{\rm out}$ are the control input and output, respectively. A discrete-time linear model for this system is given by [4]:

$$\frac{\Delta o_{\rm out}(z)}{\Delta b(z)} = K \frac{\tau}{z + \tau - 1} \cdot \frac{z - \alpha}{z - \beta} \tag{1}$$

with α, β, $\tau > 0$, and $K > 0$ model parameters, and $0 < \beta < \alpha \leq 1$; z is the discrete-time complex variable; $\Delta o_{\rm out}$ is the occupancy variation caused by VSL rate variation Δb.

Based on model (1) an I-type control structure can be used to calculate the VSL rate b at instant k:

$$b(k) = b(k-1) + K_{\rm I} e_o(k) \tag{2}$$

with $K_{\rm I}$ the integral gain of the controller and $e_o(k) = \hat{o}_{\rm out} - o_{\rm out}(k)$ the occupancy error, with occupancy in %. We set $\hat{o}_{\rm out}$ equal to the critical occupancy $o_{\rm cr}$.

It should be noted that in [5] only a cascade and a PI control structure were applied, possibly because of the long acceleration areas used. In [9] an I-controller was used to relocate congestion away from populated areas; performance was also a concern but capacity drop did appear.

III. MTFC-VSL IN MICROSCOPIC SIMULATION

A. The Aimsun Microscopic Traffic Simulator

Aimsun is a software application that offers, among other tools, a microscopic traffic simulator [10]. This tool consists basically of two vehicle behavior models: car-following and lane-changing, both of which can be considered as developments of the respective Gipps models [11], [12]. The Aimsun

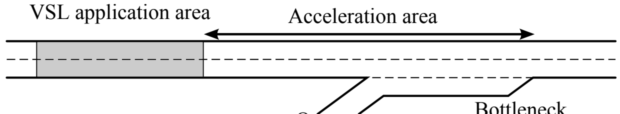


Fig. 1. MTFC-VSL application and acceleration areas

implementation allows a non-deterministic range of values to be set for several vehicle parameters (i.e., each vehicle can have its own acceleration, deceleration, etc., randomly sampled from customizable probability distributions).

Although studies [13], [14] question the ability of current microscopic lane-change models to accurately capture merging behavior in a congested regime, we consider that:

- appropriate application of MTFC can prevent the onset of congestion at the bottleneck, therefore establishing a regime where lane-change models are more accurate;
- a controlled congestion in the application area far upstream from the bottleneck will not be affected by lane-changing behavior at the merge area;
- despite the microscopic merging behavior, the model was adjusted to give a capacity drop in the aggregate traffic behavior similar to practical values [15].

B. Control Aspects Found in Microscopic Simulation

This section elaborates on the findings made while applying MTFC-VSL for an on-ramp bottleneck in Aimsun as supported by the simulation results presented in Section V.

1) Nonlinearity of the speed limit-flow relation: for the microscopic simulation model and the modeled network, the speed limit-flow relation is nonlinear, being more sensitive at low speed limits. Thus, to be able to induce low flow rates, very low speed limits are needed, e.g., 20 km/h for 1500 veh/h/lane. Since traffic response at very different speed regimes (e.g., 80 km/h and 20 km/h) is significantly different, it is difficult to control the system. In [5] the speed limit-flow relation is approximated as linear with good results, but here the pronounced nonlinearity requires a different approach.

The nonlinear speed limit-flow relation makes a linear control strategy such as (2) inadequate to maintain stability at all allowed speed limits, unless a slow control at high speed limits is tolerated. To circumvent this problem, gain scheduling [16] is adopted as discussed in Section IV.

2) Ways of applying VSL: we examine two possible ways of applying VSL. In Section Level VSL (S-VSL), VSL is applied to a whole freeway section; i.e., all vehicles within the application area immediately adjust their speeds to the new speed limit. At the macroscopic level, only S-VSL is possible. In reality S-VSL requires vehicle-infrastructure integration systems or tightly spaced VSL signs.

In contrast, Point Level VSL (P-VSL) considers a more typical sparse distribution of VSL signs, whereby vehicles adjust their speed when passing by the VSL sign and maintain this speed until a new sign indicates a different speed limit further downstream. Hence, with P-VSL a change in the speed limit affects only vehicles arriving at the application area with no effect on vehicles already inside it.

Testing in Aimsun revealed that with P-VSL:

- as could be expected, traffic response to speed limit changes is slower than with S-VSL, i.e., it takes longer for changes to have an effect on the merging area;
- the effects on traffic of a VSL increase take longer to appear than when VSL is decreased; it should be noted

that in the modeling of [17], a similar behavior can be observed but the authors did not elaborate on its cause;
- a temporary ‘void’ of vehicles may be formed in the mainstream when VSL is decreased.

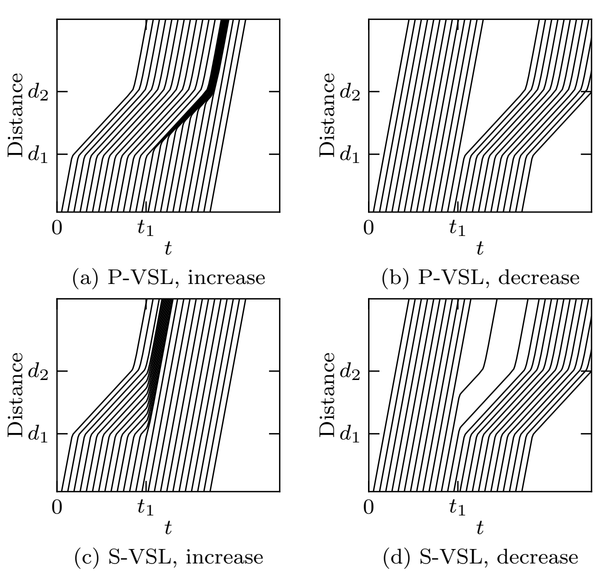
The time-space diagrams in Fig. 2 illustrate these findings for a 4 km long freeway section with an application area from d_1 to d_2. In a microscopic simulation, VSL changes between v and v', with $v > v'$. The speed limit upstream and downstream of the application area is v.

For the P-VSL case (Fig. 2(a–b)), a VSL sign is placed at the entrance of the application area. Fig. 2(a) depicts a VSL increase from v' to v at time t_1. Vehicles entering the VSL application area are unable to maintain speed v because of the presence of slower vehicles ahead moving at speed v' (dark area). The delay between increasing the VSL and observing vehicles at the desired speed leaving the application area varies according to the difference between v and v' and the length of the application area.

Fig. 2(b) depicts a VSL decrease from v to v' at time t_1. Vehicles in the application area at the time of the speed limit change maintain speed v, while new ones enter the application area with speed v'. Thus, the distance between the rear of the faster platoon and the front of the slower one increases over time, leading to a temporary ‘void’ of vehicles. If the application area is sufficiently long and the new speed limit v' is sufficiently smaller than v, this leads to a temporary and significant decrease in flow (and occupancy) downstream until vehicles traveling at speed v' reach the bottleneck.

Fig. 2(c–d) depict the corresponding cases for S-VSL. Clearly, traffic response is faster in these cases and, consequently, easier to control. Although currently not feasible from a practical standpoint, the use of S-VSL in field applications would give the best performance.

3) Length of the application area: The discussion about P-VSL and S-VSL in the previous section indicates that if P-VSL is used, longer VSL application areas lead to longer delays and a slower system, which is undesirable. Indeed, simulations conducted with different lengths for the application area have confirmed this indication. Shorter application areas improve performance.



(a) P-VSL, increase (b) P-VSL, decrease

(c) S-VSL, increase (d) S-VSL, decrease

Fig. 2. Time-space diagrams for point (P) and section (S) VSL application

4) Length of the acceleration area: longer acceleration areas lead to higher delays in both forms of VSL application, since vehicles leaving the VSL application area have to cover a longer distance to reach the bottleneck. Simulations give best results with an acceleration area around 175 m long. Longer areas increase delay, while shorter ones are not sufficient for vehicles to accelerate to v_{cr}. A similar study [18] for the case of merging control with traffic lights at work zones found better results for an acceleration area of 150 m for a section with 80 km/h speed limit.

IV. Control Setup

This section elaborates on the control setup. For the use of the integral control law (2) it is necessary to choose its parameters, namely the integral gain K_{I} and the set-point o_{cr}, and the measurement of occupancy o_{out} at the point of congestion onset.

A. Controller Parameters

1) Integral gain: the controller was first tuned for a fixed integral gain. A gradual increase of K_{I} for the best performance (and output) resulted in $K_{\text{I}} = 0.005$.

However, for an adequate performance of the nonlinear traffic control system we use gain scheduling, in which different integral gains are assigned for different operation points. The VSL rate b is used to determine the current point of operation and then the appropriate gain is selected. Fig. 3 shows the speed limit-flow relation obtained through simulation. Using piecewise linear regression we obtained the minimum quadratic error with the three line segments shown in the figure.

For a nominal speed limit of 100 km/h, the resulting ranges for the three segments and respective gains are: $0 < b \leq 0.15$ and $K_{\text{I}} = 0.002$; $0.15 < b \leq 0.4$ and $K_{\text{I}} = 0.0052$; and $0.4 < b \leq 1$ and $K_{\text{I}} = 0.02$. The gains are proportional to the ratios between the slopes of the respective line segments. With these, the control strategy is fast at high speed limits and remains stable at low ones, providing sufficiently good performance.

2) Set-point: a critical occupancy o_{cr} of 19% was found from the no-control scenario (see Section V). This became the set-point $\hat{o}_{\text{out}}$ in all control scenarios (except for short acceleration areas). The critical speed is around 85 km/h.

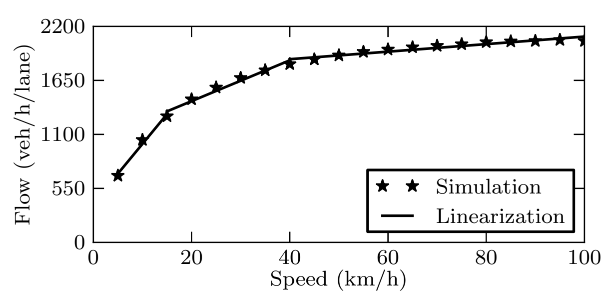


Fig. 3. Piecewise linearization of the speed limit-flow relation

B. Measurement

The merge point of on-ramp and mainstream vehicles in simulation changes according to the flows. When traffic is low, merging is closer to the on-ramp. Near breakdown merging is usually closer to the lane drop. For a proper occupancy measurement, more than one detector is needed as sometimes congestion may start forming downstream or upstream from a given detector. Four detectors spaced 50 m apart were placed around the lane drop. The highest measured occupancy at each interval is taken as the control measurement. The exception is when acceleration areas shorter than 200 m are used. In this case, vehicles approach the first detectors somewhat slowly when control is active, leading to higher occupancy. Then, in such scenarios only the last three detectors are used.

Flow measurements show the total for all three lanes, while occupancy and speeds consider only the mainstream.

V. Simulation Results

This section presents the modeled network and simulation results that support the conclusions presented in Section III.

A. Simulation Setup

1) Network Model and Demand: Fig. 4 shows the simulated 4.3 km hypothetical freeway stretch with two lanes and an on-ramp 300 m upstream of its end. A 200 m acceleration lane creates the merge area with a lane drop where the bottleneck is formed. The nominal speed limit is 100 km/h.

The demand profiles in Fig. 5 extending over a 3-hour simulation period are used as traffic inputs. A normal distribution with standard deviation of 10% from the mean is used to sample entrance times.

2) Simulator parameters: traffic is comprised of passenger cars. Default values of the simulator were used for most parameters, except for reaction time (0.5 s), vehicle acceleration (1.5 m/s^2) and parameters for the two-lane car following model, adjusted for a maximum speed difference of 30 km/h between mainstream lanes and 50 km/h between the rightmost and middle lanes in the three-lane section. These values give a nominal capacity of 3700 veh/h and a capacity drop of around 17% for the studied demands, in line with field observations [15].

Simulation results correspond to the mean of 10 replications using different random seeds.

B. Base Scenarios

Table I, rows 1–3, summarizes the base scenarios with flows, occupancies, speeds, and VSL rates shown in Fig. 6(a–c). Dotted lines denote the set-point. Application and acceleration areas are fixed and P-VSL is used for MTFC-VSL.

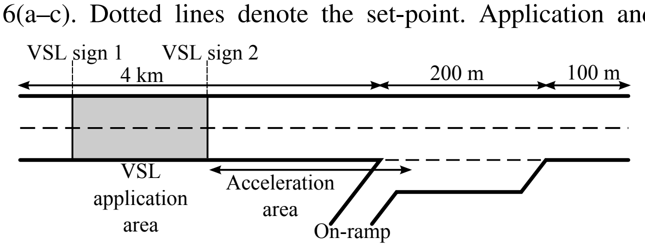


Fig. 4. Hypothetical network (not in scale)

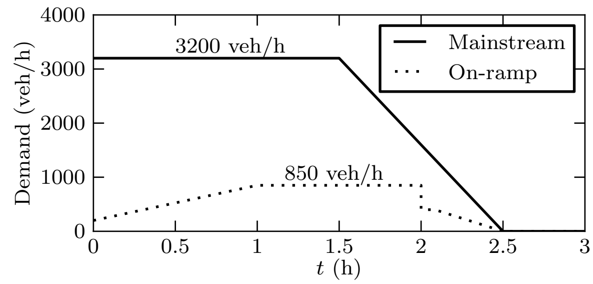


Fig. 5. Simulated demand

1) No Control: the congestion formed at $t = 0.7$ h leads gradually from a capacity flow of 3700 veh/h to an outflow of 3070 veh/h, a drop of 17%. Despite the decreasing demand entering the network after $t = 1.5$ h, it takes until $t = 2.5$ h before congestion is dissolved. The Total Time Spent (TTS) by all vehicles during simulation is equal to 1137 veh·h.

2) Integral control with fixed gain: the slow reaction of the controller causes a peak in occupancy at around $t = 0.8$ h. The peak is followed by large oscillations in flow and occupancy (and in the control action b) around the set-point, which is undesirable despite the decrease in TTS of 30.8%. Gain increases for faster reaction would turn the system unstable at low speed limits.

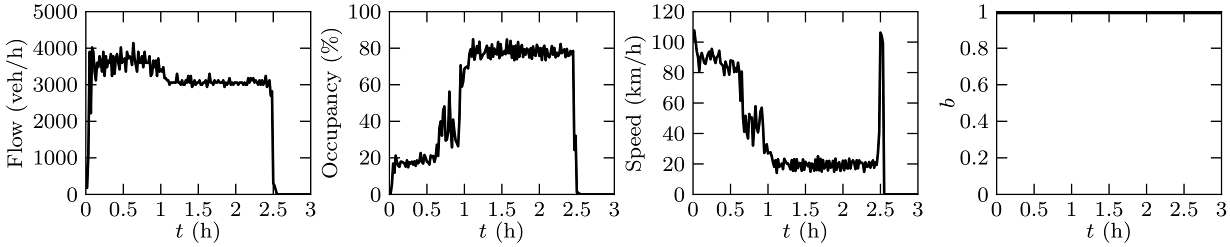
3) Integral control with gain scheduling: the controller reacts faster at high speed limits with smoother action at low speed limits when compared to the previous scenario. Capacity flow and critical occupancy are maintained most of the time with an improvement in TTS of 37.1%. The flow dip at $t = 1.0$ h reflects the control reaction to a sudden increase in occupancy. From Section IV, the value of K_{I} for b between 1.0 and 0.4 is four times the fixed gain, allowing the earlier reaction seen for t between 0.5 and 1 h.

C. Point versus Section VSL Application

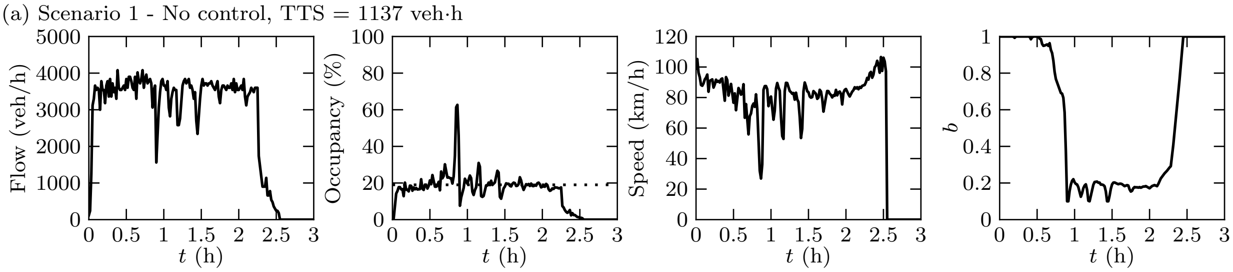
Scenario 4 in Table I is analogous to Scenario 3 but with S-VSL instead of P-VSL. Corresponding plots are shown in Fig. 6(d). TTS in this case is further improved to 42.9% less than in the no-control case. Control reaction is even faster than in the P-VSL case and smoother. Capacity flow and critical occupancy are maintained most of the time as well. The decrease in flow at around $t = 0.8$ h has a much shorter duration than in the P-VSL case, since with S-VSL there is a temporary reduced flow, not a proper 'void'.

TABLE I. Summary of Simulated Scenarios

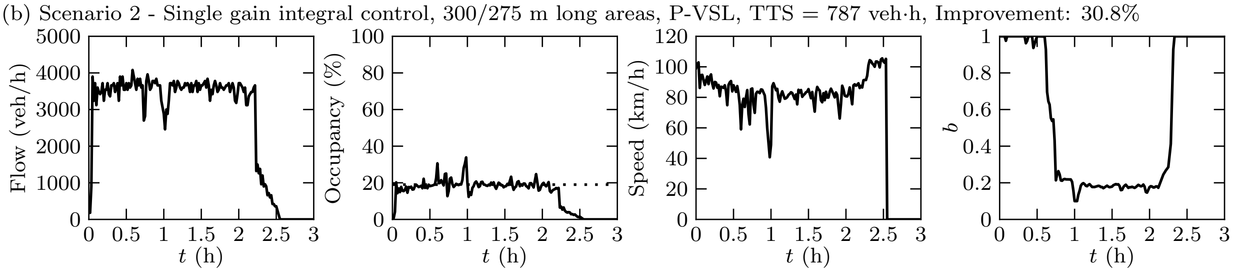
Scn.	Gain Sched.	App/Acc. areas lengths (m)	VSL type	TTS (veh·h)	%
1	–	–	–	1137	–
2	No	300/275	P-VSL	787	−30.8
3	Yes	300/275	P-VSL	716	−37.1
4	Yes	300/275	S-VSL	650	−42.9
5	Yes	100/275	P-VSL	613	−46.1
6	Yes	300/175	P-VSL	627	−44.9



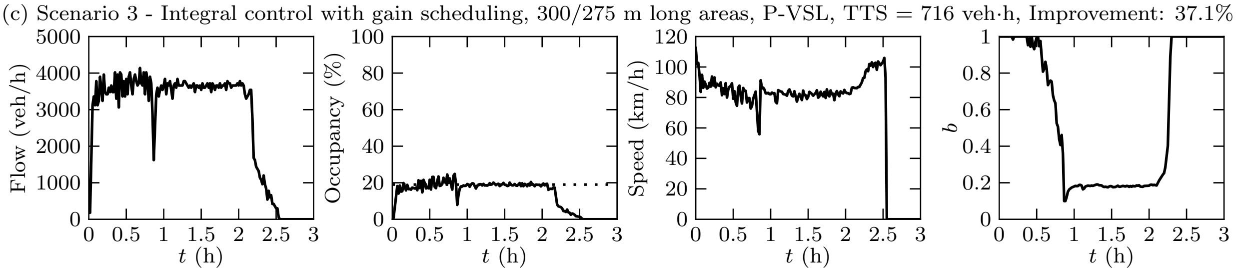
(a) Scenario 1 - No control, TTS = 1137 veh·h



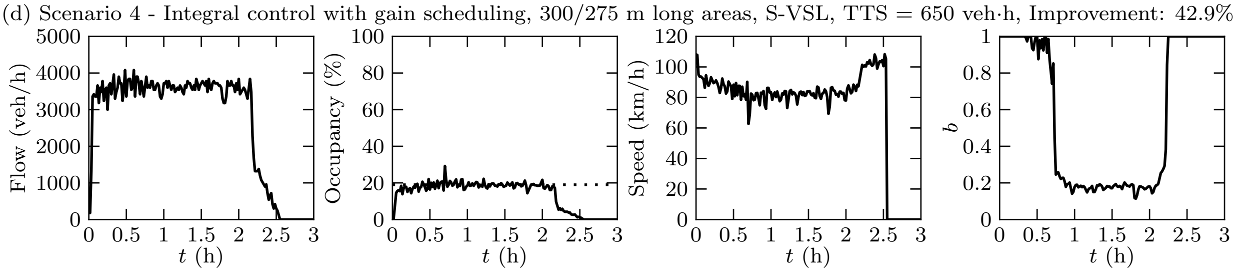
(b) Scenario 2 - Single gain integral control, 300/275 m long areas, P-VSL, TTS = 787 veh·h, Improvement: 30.8%



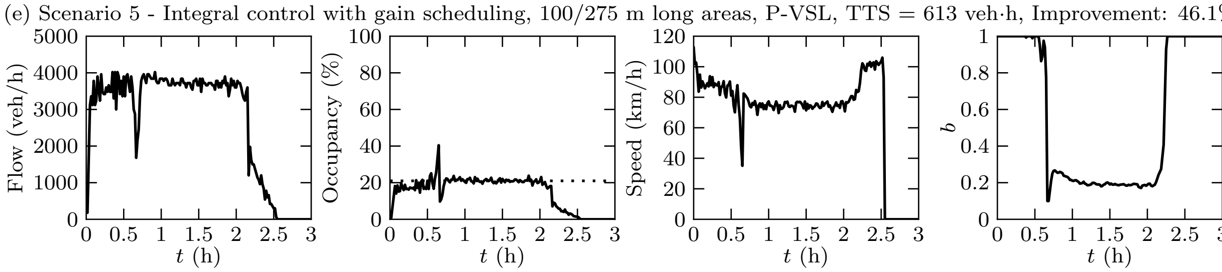
(c) Scenario 3 - Integral control with gain scheduling, 300/275 m long areas, P-VSL, TTS = 716 veh·h, Improvement: 37.1%



(d) Scenario 4 - Integral control with gain scheduling, 300/275 m long areas, S-VSL, TTS = 650 veh·h, Improvement: 42.9%



(e) Scenario 5 - Integral control with gain scheduling, 100/275 m long areas, P-VSL, TTS = 613 veh·h, Improvement: 46.1%



(f) Scenario 6 - Integral control with gain scheduling, 300/175 m long areas, P-VSL, TTS = 627 veh·h, Improvement: 44.9%

Fig. 6. Flow, occupancy and speed measured in a detector placed at the bottleneck for six different scenarios

D. Effect of the Length of the Application and Acceleration Areas

To evaluate the effect of the length of the acceleration and application areas, several scenarios with P-VSL were simulated for both areas varying one length while the other was kept fixed. Fig. 7 summarizes the TTS results, with best values for an application area of 50 m and an acceleration area of 175 m, as discussed in Section III. The visible degradation for increasing length of either area is expected due to the introduced delay, which is more pronounced when

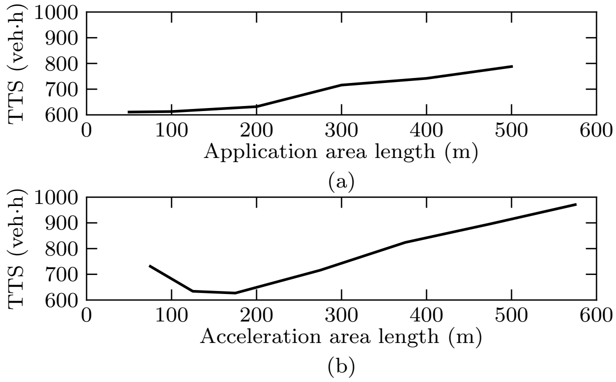


Fig. 7. Variation of TTS with the length of the (a) application and (b) acceleration areas

increasing the length of the application area; and also due to the the change of vehicle speed at the bottleneck when altering the length of the acceleration area.

Scenarios 5 and 6 were chosen as representative scenarios easily comparable with Scenario 3. Flows, occupancies, speeds, and VSL rates are shown in Fig. 6(e) and (f), respectively. In Fig. 6(e) the transitory effect ('void') is not noticeable because of the short application area. Also, the shorter delays lead to a faster traffic response and better performance. A 46.1% reduction in TTS is obtained, and overall all curves for Scenario 5 are smoother than for Scenario 3.

In Scenario 6 there is also a (less pronounced) reduction in delay, leading to a faster traffic response, although not as fast as in Scenario 5 (see Fig. 6(f)). It is noteworthy that with an acceleration area this short vehicles are unable to reach critical speed at the bottleneck when very low speed limits are applied. This slower traffic leads to an occupancy that is higher than the critical one. Controller design must account for that in the form of an increased occupancy reference. This means, however, that the controller only reacts when occupancy is at a higher level, allowing traffic to deteriorate more before taking action, which can be seen as the peak in occupancy at approximately $t = 0.6$ h in Fig. 6(f). Still, a 44.9% reduction in TTS was obtained.

VI. Conclusions

Mainstream Traffic Flow Control (MTFC) was applied upstream from an on-ramp merge bottleneck in a microscopic simulation environment. Several control aspects not addressed in previous works based on macroscopic simulation were observed. Applying speed limits in a specific location (P-VSL) rather than along an entire section (S-VSL) makes the system considerably slower and introduces transitory effects, which makes S-VSL desirable if possible. Simulation results show that shorter application and acceleration areas decrease delay, and an application area as short as 50 m is sufficiently long for control purposes in the simulated scenario. Even with a highly nonlinear relation and P-VSL, improvements in the order of 40% in total time spent by traffic were achieved. These were obtained for a capacity drop of around 17%, so in scenarios with lower drops the benefits will not be so pronounced. The speed limit-flow relation is a vital part of the MTFC concept and should be further investigated. As is, large reductions in speed limit are necessary to induce the intended flows to avoid congestion and may affect acceptance of the method.

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