Local Ramp Metering with Distant Downstream Bottlenecks: A Comparative Study

Yibing Wang, Yuheng Kan, Markos Papageorgiou, Ioannis Papamichail

Abstract—**The well-known feedback ramp metering algorithm ALINEA can be applied for local ramp metering or included as a key component in a coordinated ramp metering system. ALINEA uses real-time occupancy measurements from the ramp flow merging area that may be at most few hundred meters downstream of the metered on-ramp nose. In many practical cases, however, bottlenecks with smaller capacity than the merging area may exist further downstream for various reasons, which suggests using measurements from those further downstream bottlenecks. Recent theoretical and simulation studies indicate that ALINEA may lead to a poorly damped closed-loop behavior in this case, but PI-ALINEA, a suitable Proportional-Integral (PI) extension of ALINEA, can lead to satisfactory control performance. This paper addresses the same local ramp-metering problem in the presence of downstream bottlenecks, with a particular focus on the general capacity of PI-ALINEA with three distinct types of bottleneck that may often be encountered in practice, i.e. (1) an uphill case; (2) a lane-drop case; (3) an un-controlled on-ramp case. Extensive simulation studies are conducted using a macroscopic traffic flow model to demonstrate that the performance of ALINEA indeed deteriorates in each of these bottleneck cases, while significant improvement is obtained using PI-ALINEA in all cases. Moreover, with its control parameters appropriately tuned beforehand, PI-ALINEA is found to be universally applicable, with little fine-tuning required for field applications.**

***Index Terms*—local ramp metering, distant downstream bottleneck, ALINEA, PI-ALINEA.**

I. Introduction

Ramp metering is a major means for freeway traffic control [1]. The significance of ramp metering has been demonstrated in the past three decades [1]. ALINEA is a popular and efficient local ramp metering strategy, developed on the basis of feedback control theory [1-3]. Since its design philosophy was developed in the late 1980s [2], ALINEA has been successfully applied to hundreds of freeway sites worldwide [1]. Despite its local operation nature, it may also be combined with coordinated ramp metering strategies [4]. In principle, ALINEA aims to maximize freeway throughput in the ramp merging area (e.g. location *A* in Fig. 1) and, to this end, it requires that occupancy measurements fed to ALINEA be collected from this area. In some cases, however, a bottleneck with lower capacity than the merging area may be present further downstream, due to the existence of e.g. slope, curvature, lane drop, a tunnel, or a downstream un-controlled on-ramp. It was recently demonstrated with rigorous theoretical investigations [3] that occupancy measurements in such cases have to be obtained around the bottleneck (e.g. location *B* in Fig. 1). Moreover, ALINEA is not sufficient any more in handling ramp metering in the case of a downstream bottleneck; while PI-ALINEA, an extended version of ALINEA, can instead serve the need satisfactorily. As a follow-up of [3], this paper aims to explore further the ramp metering capacity of PI-ALINEA with fixed distant downstream bottlenecks. To this end, three distinct bottleneck cases are considered: an uphill road section, where lower capacity per lane is the cause for the bottleneck; a lane drop, where capacity per lane is actually maintained; and an un-controlled on-ramp, where the bottleneck is caused by uncontrolled entering flow, rather than an infrastructure change. In all cases, the respective bottleneck is located at the far downstream of a metered on-ramp.

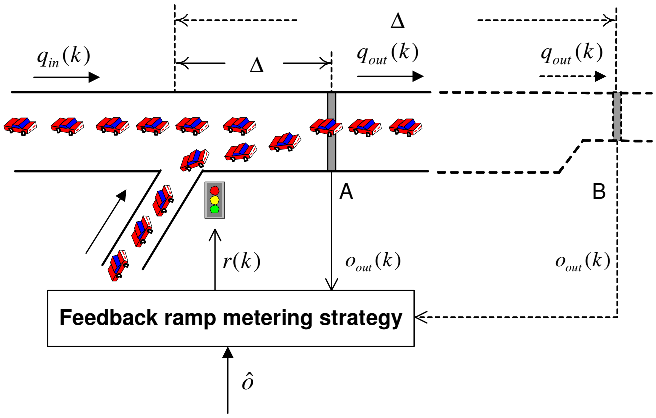

Fig. 1. Isolated ramp metering with feedback control strategy.

The paper is organized as follows. Section II reviews the ALINEA and PI-ALINEA algorithms. Section III introduces the simulation model and simulation setup. Simulation study of the ALINEA and PI-ALINEA performances is presented in Section IV. The main conclusions are delivered in Section V.

II. ALINEA and PI-ALINEA

ALINEA [1-3] aims to prevent merging congestion and maximize flow throughput in the merging area. Based on the fundamental diagram (Fig. 2), this can be achieved by maintaining traffic occupancy o_{out} (or density ρ_{out}) in the

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merging area (or shortly downstream of the merging area, see [2, 3]), around the critical occupancy o_{cr} (or the critical density ρ_{cr}) so as to maximize the mainstream flow q_{out}. For this purpose, ALINEA is designed to be:

$$r(k) = r(k-1) + K_{\mathrm{R}}[\hat{o} - o_{\mathrm{out}}(k)], \quad (1)$$

where k is the discrete time index; $o_{\mathrm{out}}(k)$ denotes lane-averaged mainstream occupancy measurements collected during the control time interval $((k-1)T,\ kT]$; T is within the range 20-60 s; $r(k)$ represents the on-ramp inflow applied over $[kT, (k+1)T)$; $\hat{o}$ is a set (desired) value for the occupancy and, to the end of flow maximization, typically selected to equal o_{cr}; $K_{\mathrm{R}} > 0$ is a regulator parameter. Note also that a similar value of K_{R} has been successfully used in all known simulation or field applications of ALINEA, without any need for fine-tuning [1-4]. $r(k)$, determined with (2), is truncated if it exceeds a range $[r_{\min},\ r_{\max}(k)]$ [3].

By its design philosophy, ALINEA operates with occupancy measurements collected at most a few hundred meters downstream of the metered on-ramp. If, however, a bottleneck with lower capacity than the merging area is present further downstream, the used occupancy measurements should be collected at the bottleneck (e.g. B in Fig. 1). It has been shown in [3] with detailed theoretical analysis and a preliminary simulation study that:

(i) ALINEA is not efficient in maintaining the maximum throughput at the distant downstream bottleneck.

(ii) PI-ALINEA, with an extended structure:

$$r(k) = r(k-1) - K_{\mathrm{P}}[o_{\mathrm{out}}(k) - o_{\mathrm{out}}(k-1)] + K_{\mathrm{R}}[\hat{o} - o_{\mathrm{out}}(k)], \quad (2)$$

can do a good job, both for a merging bottleneck and for a far downstream bottleneck. The rest of the paper focuses on extensive simulation studies to demonstrate and materialize the above conclusions.

III. Simulation Model and Setup

A. *Simulation Model*

The utilized macroscopic traffic flow model is briefly introduced here, and the interested reader is referred to [5, 6] for details. The model emulates traffic flow hydrodynamics along a freeway stretch by use of appropriate aggregate traffic flow variables. Any considered freeway stretch is sub-divided into a number of segments and the time is discretized with a model time step (around 5-10 s). The aggregated traffic flow variables are then defined for each segment and updated for each model time step. The model involves for each segment the transport equation, conservation equation, and dynamic speed equation. The last one includes the fundamental diagram as a key component.

Fig. 3 displays two fundamental diagrams FD 1 and FD 2 that are used in the simulation study. As shown, the free-flow speeds v_{f1} and v_{f2} are determined with the slope of the tangent of the $Q(\rho)$-curve at $\rho = 0$; the capacities q_{cap1} and q_{cap2} are the attainable maximum flow (per lane) achieved at the critical density ρ_{cr}. As shown, FD 1 and FD 2 have the same critical density, but different free speeds and capacities. Occupancy is directly related to traffic density. For physical reasons, our simulation model uses density (rather than occupancy) as a key variable. Therefore, density is used in (1) and (2) in place of occupancy.

The simulation or model time step T_s and control time step T are 5 s and 30 s, respectively, while the minimum admissible ramp flow $r_{\min}$ and the ramp's flow capacity r_{MAX} are set equal to 300 veh/h and 2000 veh/h, respectively.

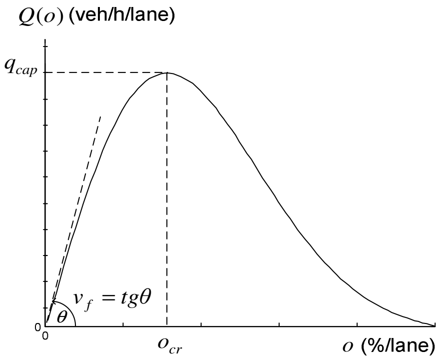

Fig. 2. Fundamental Diagram.

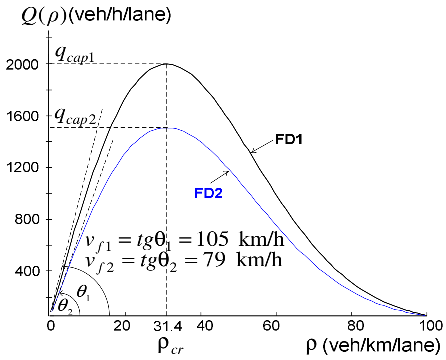

Fig. 3. Fundamental diagrams considered.

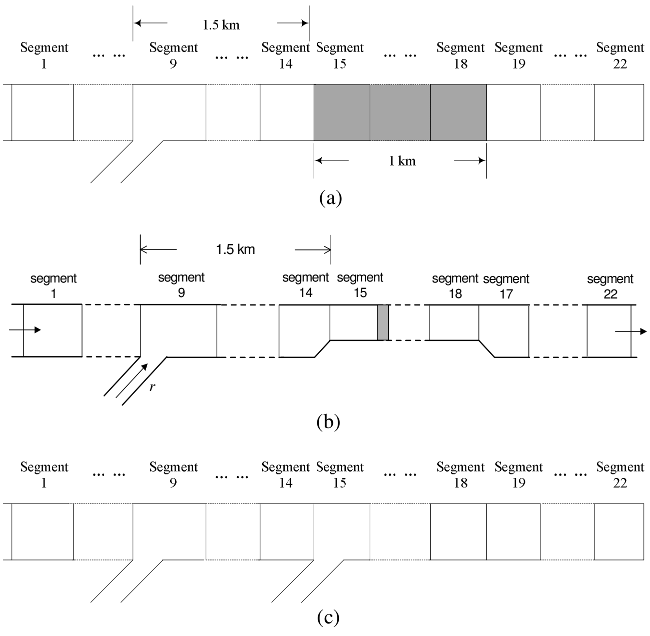

Fig. 4. A freeway stretch with a downstream bottleneck: (a) an uphill or tunnel case; (b) a lane drop case; (c) an un-controlled downstream on-ramp case.

B. Simulation Setup

Three types of bottlenecks: Three freeway stretches of 5.5 km involving three distinct types of bottleneck are considered in this work. Each bottleneck of 1 km starts 1.5 km downstream of an on-ramp. In the first case (Fig. 4a), the bottleneck is present due to an uphill or curved road section or a tunnel, which changes the traffic characteristics and leads to lower capacity. The second case (Fig. 4b) addresses a bottleneck caused by a lane-drop section of road, whereby the reduced capacity is due to less (equal-capacity) lanes. The third case (Fig. 4c) emulates a bottleneck caused by an un-controlled on-ramp at the far downstream of a metered on-ramp; thus, the bottleneck is due to uncontrolled inflow rather than infrastructure change as in the previous cases. Except for the bottleneck of 2 lanes in the second case, the freeway stretch in either Cases 1 or 3 has three lanes. The (upstream) on-ramp is located at 2 km from the start of the stretch. Setting the segment length equal to 0.25 km, each stretch is subdivided into 22 segments, with the (upstream) on-ramp located in segment 9 and the bottleneck starting in segment 15. In Case 1, the bottleneck section differs from a non-bottleneck section in traffic flow characteristics. More specifically, the fundamental diagram FD 1 (Fig. 3) is included in the simulation model to emulate each non-bottleneck segment, while FD 2 is considered for each bottleneck segment. Moreover, ρ_{cr} = 31.4 veh/km/lane, v_{f1} = 105 km/h, v_{f2} = 79 km/h, q_{cap1} = 2000 veh/h/lane, q_{cap2} = 1500 veh/h/lane. On the other hand, all segments in Cases 2 and 3 are characterized only by FD1.

Factual critical densities and capacities: Due to the complex nonlinear dynamics of the macroscopic simulation model, the factual critical densities and capacities of the three simulated freeway stretches are not fully determined by the considered fundamental diagrams [3]. With exhaustive simulation checking, the critical density for a no-bottleneck segment is found to be around 38 veh/km/lane (rather than 31.4 as given in Fig. 3), while the total capacity for 3 lanes is indeed around 6000 veh/h (as indicated by FD1). The corresponding density and total capacity values for the bottlenecks in Cases 1-3 (Fig. 4) are 42 veh/km/lane and 5270 veh/h, 41 veh/km/lane and 4300 veh/h, and 38 veh/km/lane and 5980 veh/h, respectively. Note that Case 3 is created with the un-controlled downstream on-ramp, and the mainstream is homogeneous in traffic flow dynamics. Hence, it is not surprising that the factual critical density and capacity are found to be the same as those in the case of no bottleneck.

Demand profiles: Trapezoidal demand scenarios are defined such that during the peak period the mainstream demand (at the upstream of any on-ramp) is sufficiently lower than the capacity of any considered downstream bottleneck (else there is no role for ramp metering), and the sum of the mainstream and on-ramp demands is higher than the bottleneck capacity (else there is no necessity for ramp metering), but lower than the merging area capacity so that congestion (if any) appears first at the downstream bottleneck. Specifically for Case 3 (Fig. 4c), the sum of the upstream demand and the first on-ramp demand and the sum of the upstream demand and the second on-ramp demand are both lower than the mainstream capacity, but the total demand reaching the merging area of the second on-ramp should be higher than the mainstream capacity. Specific to Fig. 5, "mainstream demand 1" is considered for the no-bottleneck case [3] and "mainstream demand 2" is considered for Case 1. The demand profiles considered for Cases 2 and 3 are omitted due to limited paper length.

IV. Simulation Investigations

Three configurations of ramp metering controllers are considered for each bottleneck case: no ramp metering (referred to as "no control" hereafter), ramp metering with ALINEA, and ramp metering with PI-ALINEA. Except for Case 1, only ALINEA and PI-ALINEA results are presented. It was demonstrated in [3], in the light of both theoretical analysis and simulation testing, that ALINEA with its K_{R} parameter set equal to 40 km∗lane/h operates efficiently if there exists no downstream bottleneck; while PI-ALINEA, with its K_{R} and K_{P} parameters set equal to 4 km∗lane/h and 100 km∗lane/h, respectively, performs satisfactorily, regardless of the distance of the merging or farther downstream bottleneck from the metered on-ramp. In addition, these parameters were found universally applicable, and not sensitive to the location of a downstream bottleneck. Comparative simulation studies are extensively conducted in the remainder of this paper to verify the above conclusions and also demonstrate PI-ALINEA's performance with different types of bottlenecks.

A. Bottleneck Case 1

No-Control: As previously mentioned, the factual maximum throughput (of 3 lanes) for the bottleneck section in Case 1 are found to be 5270 veh/h. The total demand reaching the bottleneck (i.e. "mainstream demand 2" + "on-ramp demand") during the peak period exceeds this capacity level. Fig. 6a displays the density trajectories in the case of no control, showing that the congestion occurs first in the bottleneck section (see the sudden rise of the black curve for segment 15 at 1.3 h). Congestion spills back quickly to reach the on-ramp and further upstream segments. Congestion persists at the upstream of the bottleneck until the total demand decreases sufficiently. It is also noted in Figs. 6a and 6b that, during the whole peak period:

- No segment downstream of the bottleneck is congested due to the upstream-propagation of the shockwave (see e.g. the yellow curve in Fig. 6a for segment 18).
- The outflow of the on-ramp segment as well as of all downstream segments drops to around 5180 veh/h (<5270 veh/h) due to capacity drop incurred by congestion.
- The peak-period throughputs of all segments upstream of the on-ramp are the same (due to flow conservation) and lower than the mainstream demand (i.e. 3830 veh/h < 4400 veh/h). In other words, the mainstream demand at the upstream of the on-ramp cannot be adequately served in the case of no-control because of the congestion.
- The uncontrolled on-ramp inflow is equal to the on-ramp demand (1350 veh/h), which is exactly the observed flow difference between segment 9 and segment 8 in Fig. 6b.

ALINEA: ALINEA aims to keep the bottleneck flow around the bottleneck capacity. For this reason, ALINEA is fed with the density of segment 15 (Fig. 1). The results of ALINEA are presented in Figs. 6c and 6d. Congestion is seen to initially form in segment 15 but its propagation towards upstream is prevented, as no other segment is ever congested. On the other hand, the resulting density profile of segment 15 as well as those of the neighboring segments is strongly oscillating, while the average throughput downstream of the on-ramp is lower than the total bottleneck capacity (5270 veh/h), which is nevertheless sufficient to serve the mainstream demand (4400 veh/h). To obtain these results, the parameter K_{R} of ALINEA was reduced to 10 km∗lane/h from its standard value of 40 km∗lane/h (because much stronger oscillations result otherwise). Note that the presented ALINEA results are the best possible results for this test example, out of a trade-off between the density/flow oscillation amplitude and the mean of the downstream flow throughput. Apparently, the ALINEA performance in this bottleneck case is satisfactory. The observed little-damped behavior is due to the significant distance (time delay) between the ramp flow change and its impact on the traffic flow dynamics at the downstream bottleneck [3].

PI-ALINEA: In striking contrast, the ramp metering results with PI-ALINEA using the same measurements are very satisfactory (Figs. 6e and 6f). The response trajectory of the density in segment 15 is very smooth, with a short transient period and a small overshoot. In the steady state, the density of segment 15 is kept exactly at the set value, while the capacity level of the bottleneck section is achieved and the mainstream demand is well served. Except for segment 15, where the critical density prevails, all other segments are under free-flow conditions. The utilized K_{R} and K_{p} parameters were set to 4 km∗lane/h and 100 km∗lane/h, respectively, but, moderately different values were found to have little impact on the quality of the control results.

PI-ALINEA was also tested with a more realistic stochastic scenario, whereby the traffic demand is involved with noise and the model equations include appropriate stochastic terms (see [6] for the details). Again, the density in segment 15 is kept around the set value (Fig. 6g) and the bottleneck throughput is around capacity (Fig. 6h).

B. Bottleneck Cases 2 and 3

Simulation investigations on the performance of ALINEA and PI-ALINEA are also conducted with respect to Bottleneck Cases 2 and 3 (Figs. 4b and 4c). First of all, the results from the no-control case are very similar to those presented in Figs. 6a and 6b, and therefore we omit the corresponding figures. The ALINEA results from both cases are displayed in Figs. 7a-7d. In spite of different mechanisms in creating bottlenecks, ALINEA delivers very similar results (at large) in three bottleneck cases (see Figs. 6c, 6d, 7a-7d). For the convenience of comparison, the utilized K_{R} parameter of ALINEA is the same for all cases. Though ALINEA can manage to get the upstream demand towards segment 9 well served in each case (Figs. 6d, 7b, 7d), it can neither stabilize the density in the segment 15 (the target segment) nor maximize the flow throughput there. On the other hand, very consistent results are obtained with PI-ALINEA in all cases (see Figs. 6e, 6f, 7e-7h). For Case 3, the flow in segment 15 is maximized to be around the mainstream capacity of 6000 veh/h (for 3 lanes), though the on-ramp demand at segment 15 is unknown and uncontrolled. Thus, the flow difference between Segments 12 and 15 in Fig. 7h is actually the un-controlled demand of the second on-ramp while that between segments 8 and 9 is actually the controlled inflow at the first on-ramp. It should again be emphasized that PI-ALINEA with the same K_{R} and K_{P} parameters was applied to get the above results. This again indicates the universal applicability of PI-ALINEA in the case of a far downstream bottleneck.

V. Conclusions

The reported simulation studies demonstrate that ALINEA leads to low-damped behavior and is not capable of maintaining the maximum throughput in the presence of distant downstream bottlenecks of various types. On the other hand, PI-ALINEA is universally efficient in handling the local ramp-metering task in such bottleneck cases. In addition, the utilization of the same PI-ALINEA parameters for various bottleneck circumstances and distances indicates that little fine-tuning will be necessary in field applications. It should be stressed that the proposed PI-ALINEA structure is currently only applicable if the downstream bottleneck location is known beforehand so as to have traffic sensors deployed there.

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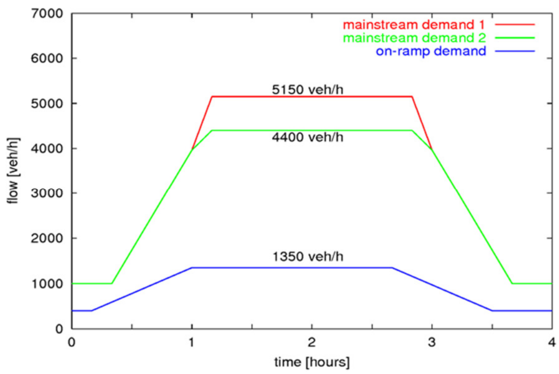

Fig. 5. The mainstream and on-ramp traffic demands in Bottleneck Case 1.

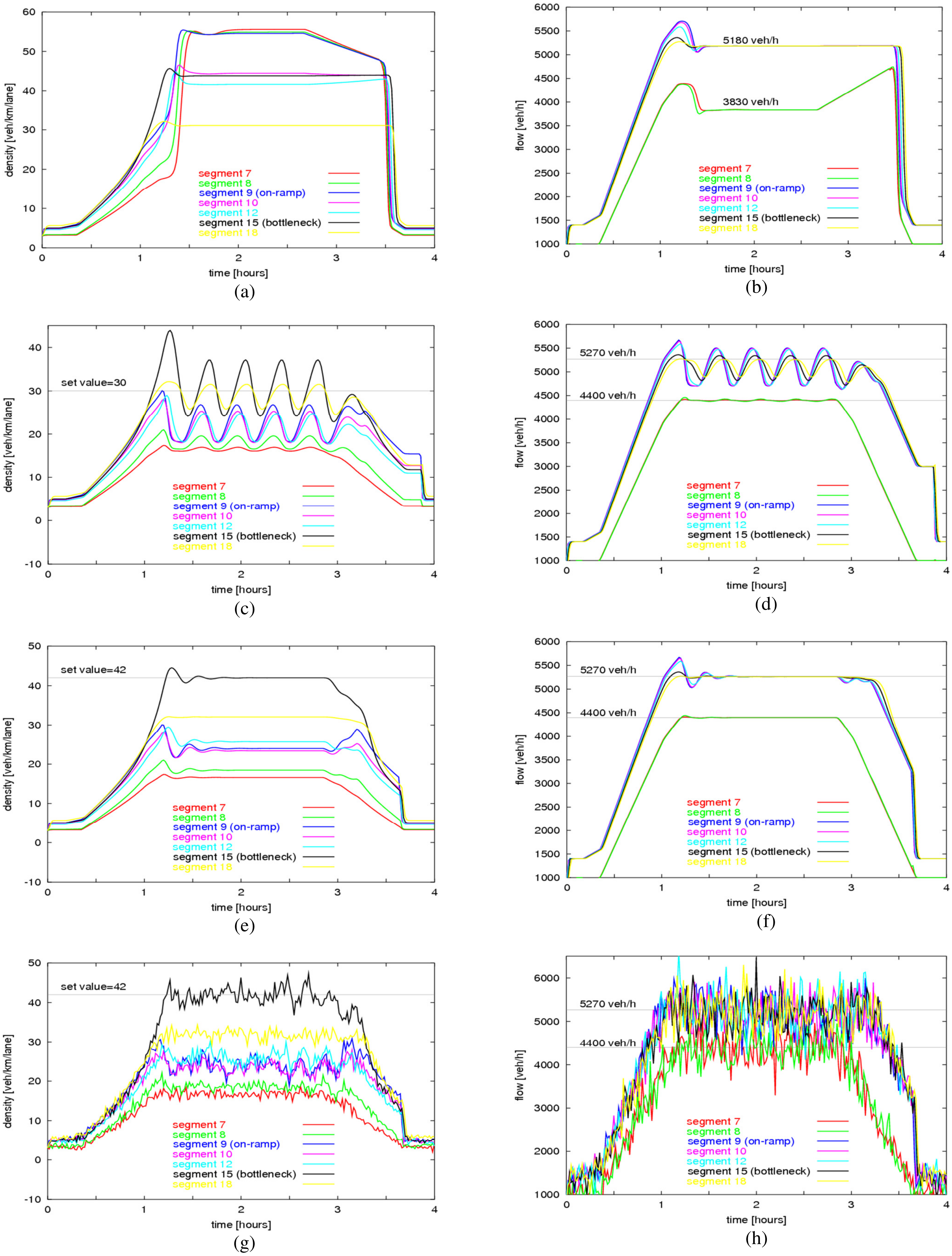

Fig. 6. Bottleneck case 1: (a) and (b) no-control; (c) and (d) ALINEA; (e) and (f) PI-ALINEA (deterministic); (g) and (h) PI-ALINEA (stochastic).

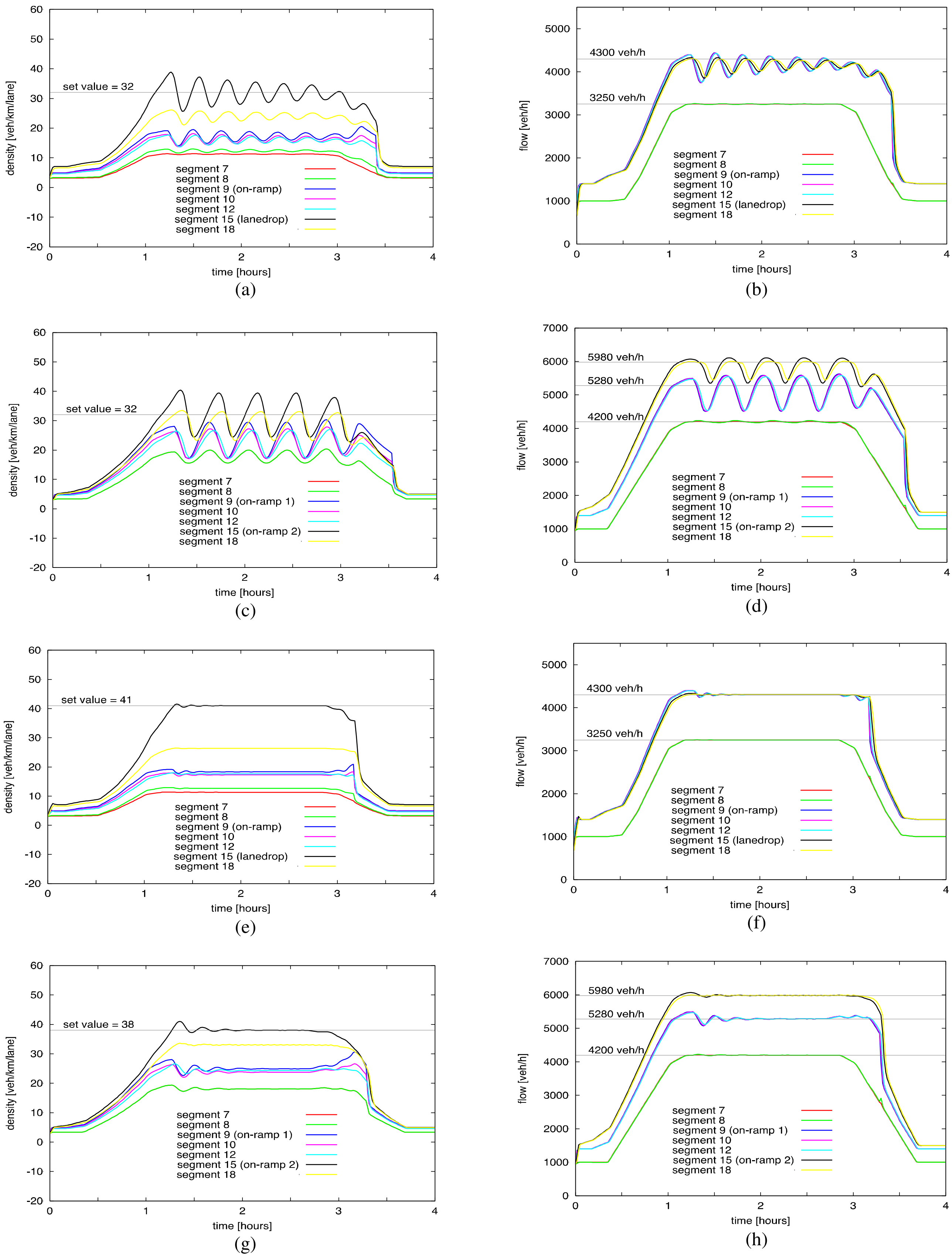

Fig. 7. ALINEA: (a) and (b) Bottleneck Case 2, (c) and (d) Bottleneck Case 3; PI-ALINEA: (e) and (f) Bottleneck Case 2, (g) and (h) Bottleneck Case 3.