

Research Article

Feedback Gating Control for Network Based on Macroscopic Fundamental Diagram

YangBeibei Ji,¹ Chao Mo,¹ Wanjing Ma,² and Dabin Liao³

¹School of Management, Shanghai University, 99 Shangda Road, Baoshan, Shanghai 200444, China

²The Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, 4800 Cao'an Road, Shanghai 201804, China

³Wuhan Planning and Design Institute, Wuhan 430010, China

Correspondence should be addressed to Wanjing Ma; mawanjing@tongji.edu.cn

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Empirical data from Yokohama, Japan, showed that a macroscopic fundamental diagram (MFD) of urban traffic provides for different network regions a unimodal low-scatter relationship between network vehicle density and network space-mean flow. This provides new tools for network congestion control. Based on MFD, this paper proposed a feedback gating control policy which can be used to mitigate network congestion by adjusting signal timings of gating intersections. The objective of the feedback gating control model is to maximize the outflow and distribute the allowed inflows properly according to external demand and capacity of each gating intersection. An example network is used to test the performance of proposed feedback gating control model. Two types of background signalization types for the intersections within the test network, fixed-time and actuated control, are considered. The results of extensive simulation validate that the proposed feedback gating control model can get a Pareto improvement since the performance of both gating intersections and the whole network can be improved significantly especially under heavy demand situations. The inflows and outflows can be improved to a higher level, and the delay and queue length at all gating intersections are decreased dramatically.

1. Introduction

Traffic congestion in urban road networks is still a problem of modern society although it has been studied in a variety of ways during the past decades. Due to the high unpredictability of choices of travelers, realistic modeling and efficient control of urban road networks remain a big challenge. By increasing road capacity or reducing traffic demand, we can change the situation of the congested networks, while the provision of new infrastructure is usually not a feasible solution, and we should make full use of the existing infrastructure. There is a vast literature of congestion dynamics, control, and spreading in urban road networks traffic systems with different traffic modes and the gating control is an import practical tool to realize the network control strategy.

Gating control is frequently employed against oversaturation of significant or sensitive links, arterials, or urban

network parts [1]. The idea is to protect links from oversaturation, whereby the level or duration of gating may depend on real-time measurements from the protected links. Gal-Tzur proposed a strategy which employs the concept of metering for small congested networks with one critical intersection [2]. However, gating is usually employed in an ad hoc way (based on engineering judgment) regarding the specific gating policy and quantitative details, which may lead to insufficient or unnecessarily strong gating actions. Moreover, the optimal condition of network is very important for gating control, and how to define the optimal condition remains the biggest obstacle to making use of gating control in reality.

Recently, Daganzo proposed a new concept of macroscopic relationship between average network flow and density, which is called the Macroscopic Fundamental Diagram (MFD) [3]. MFDs describe the relationship between inflows, outflows, and number of vehicles in the network in a very

clear and simple way, which provide an efficient tool for control and mitigate network congestion based on detected data. This characterization of the traffic state makes it possible to diagnose the emergence of congestion and choose measures to mitigate traffic problems by redirecting flows to areas with spare capacity [4].

Since then, the basic property and influence factors of MFD have been done. Leclercq et al. [5] showed that the MFDs are an envelope of possible traffic states. Christine and Ladier [6] use all the data available for a medium-size French city to explore the impact of heterogeneity on the existence of a MFD. They studied the impact of differences between the surface and highway network, distance between loop detectors and traffic signals within the surface network, and differences between penetrating and ring roads within the highway network [6]. Geroliminis and Sun show that different freeway subnetworks do not have a well-defined MFD with low scatter because the aggregated patterns do not just exhibit some high degree of random scatter [7]. Gayah and Daganzo studied the effect of turning volume on MFD with the help of simulation [8]. Ji and Geroliminis also explore the spatial and temporal characteristic of congestion in urban networks [9]. Zhang et al. explore MFD of a network under three different adaptive traffic control modes (SCATS-L, SCATS-F, and SOTL) [10]. Mühlich et al. [11] found from simulation that when traffic density becomes higher, gridlock may occur: queues remain on the intersections after the end of a green phase, blocking the traffic flow for a following signal phase. If this happens, the average flow diminishes with growing traffic densities. Haddad and Geroliminis analyzed the stability of traffic control for two-region urban cities [12] and designed a robust perimeter controller for an urban region [13]. Gayah et al. [14] examined the impact of locally adaptive traffic signals on network stability and the MFD by a family of signal control strategies.

The application of MFD to control a network is also a very important branch. Geroliminis and Daganzo proposed a control rule based on the MFD concept that maximizes the network outflow; however, the proposed method cannot be directly employed for practical use in urban networks [15]. Li et al. introduced a fixed-time signal timing perimeter control by exploiting the MFD, albeit without adaptation to the prevailing real-time traffic conditions [16]. Aboudolas and Geroliminis developed a PI regulator for multiple regions. However, MPC calls for sufficiently accurate model and external disturbance predictions, which may be a serious impediment for practicable control [17]. Keyvan-Ekbatani et al. proposed a generic real-time feedback-based gating concept, which exploits the urban MFD for smooth and efficient traffic control operations, with an application to the network of Chania and Greece [18], which is different from Aboudolas and Geroliminis [17] that researched the gating control for only one urban network, while Aboudolas and Geroliminis [17] separated the whole network, and investigating the boundary control occurs at the intertransfers between neighborhood reservoirs.

Keyvan-Ekbatani et al. demonstrated that efficient feedback-based gating is actually possible with much less real-time measurements, that is, at lower implementation

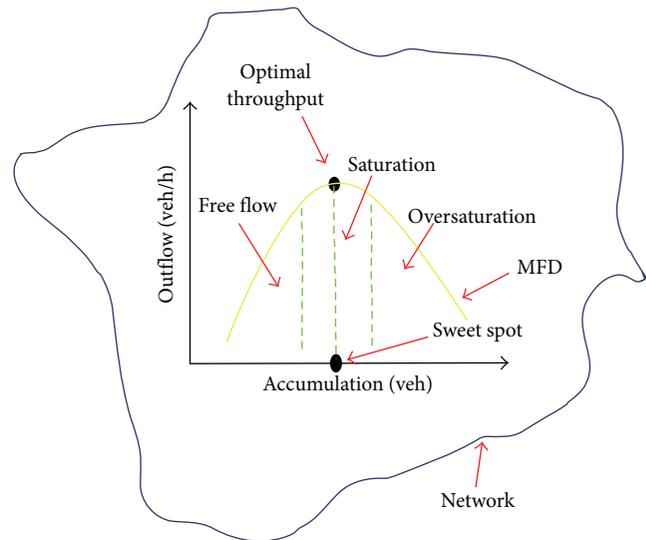


FIGURE 1: MFD of network.

cost [19]. Keyvan-Ekbatani et al. further proposed a multiple concentric-boundary gating strategy, which implements the aforementioned feedback-based gating strategy, along with considering the heterogeneity of a large-scale urban network like San Francisco, USA [20]. Aboudolas and Geroliminis extended the basic feedback approach for application to multiple subnetworks with separate individual MFD in a heterogeneous urban network [17]. Yildirimoglu et al. [21] explored the effect of route choice behavior on MFD modeling in case of heterogeneous urban networks by extending two MFD-based traffic models with different granularity of vehicle accumulation state and route choice behavior aggregation.

Despite the informative results offered by previous studies, many issues on network gating control have not been sufficiently addressed. The network related data such as dynamic origin-destination (OD) needed by classical gating control model, especially, is not easy to be obtained [3]. The optimization of signal timings has not been explicitly addressed in very limited research on MFD-based network control. How to balance between the performance of gating intersections and target network is also a remaining problem. In response to the above needs, this paper proposed a new feedback gating control strategy with a model to distribute allowed inflows among gating intersections based on MFD.

The paper is organized as follows. The gating control model based on MFD is developed in Section 2. Section 3 presents evaluation and analysis results of the proposed gating control model based on simulation. Conclusions and future research needs are summarized in the last section.

2. Gating Control Model

2.1. The Control Strategy. MFD reflects the relation between the vehicle accumulation in network and outflow of network. It approximates a parabola going downward. Figure 1 show the MFD of a network, the horizontal axis is the total vehicle

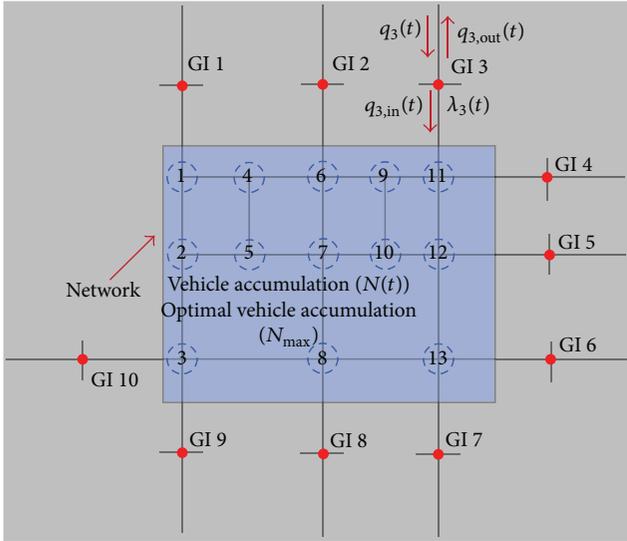


FIGURE 2: Control parameter of model.

in the network and the vertical axis is the total vehicles that leave the network or arrive at the destination in the network. When the vehicle accumulation in network is less than the sweet spot, the outflow of network increases with the increase of the accumulation and then arrives at the optimal throughput. If the vehicle accumulation in network is more than the sweet spot the outflow of network decreases with the increase of the accumulation. Hence, we should take some actions to control the number of vehicles entering the network to prevent network congestion (e.g., maintain the accumulation around the sweet spot to maximize the outflow).

MFD of network can be divided into three parts: the free flow condition, the saturation condition, and the oversaturation condition. During the free flow condition, more vehicles can get in network, while in the saturation condition we should control the number of vehicles getting in network to keep the accumulation around the sweet spot and then the outflow around the maximum throughput; if the condition of network is in the oversaturation condition we must control the vehicle strictly to reduce the accumulation to prevent network from getting blocked.

In order to control input vehicle, a feedback gating control model is proposed. The blue circle in Figure 2 represents the boundary of the network and the red dots represent the gating intersections (GI); all vehicles get in/out of network through gating intersections and intersections on the boundary (i.e., signalized intersection on the boundary of the network); $q_{i,out}(t)$ represent the outflow of signalized intersection i at time t represented by the red solid line in Figure 2; $q_i(t)$ represents the demand of signalized intersection i at time t , $C_i(t)$ represents the total capacity of all lane groups heading to the network at intersection i , and $q_{i,in}(t)$ represents the permitted number of vehicles that gets in network through signalized intersection i at time t just like the blue dash line; $\lambda_i(t)$ represent the controls parameter of signalized intersection i at time t just like the yellow solid line; $N(t)$

TABLE 1: Time parameters for 60-second cycle for 13 intersections.

Intersections	1	2	3	4	5	6	7	8	9	10	11	12	13
West-east	36	38	25	18	13	30	33	25	19	19	42	32	32
North-south	20	18	30	37	42	25	22	31	37	37	13	23	23

TABLE 2: Time parameters for 80-second cycle for 13 intersections.

Intersections	1	2	3	4	5	6	7	8	9	10	11	12	13
West-east	48	51	33	24	17	40	44	33	25	25	56	43	43
North-south	27	24	40	49	56	33	29	41	49	49	17	31	31

TABLE 3: Time parameters for 100-second cycle for 13 intersections.

Intersections	1	2	3	4	5	6	7	8	9	10	11	12	13
West-east	60	63	42	30	22	50	55	42	32	32	70	53	53
North-south	33	30	50	62	70	42	37	52	62	62	22	38	38

TABLE 4: Time parameters for 120-second cycle for 13 intersections.

Intersections	1	2	3	4	5	6	7	8	9	10	11	12	13
West-east	72	76	50	36	26	60	66	50	38	38	84	64	64
North-south	40	36	60	74	84	50	44	62	74	74	26	46	46

TABLE 5: Time parameters for 140-second cycle for 13 intersections.

Intersections	1	2	3	4	5	6	7	8	9	10	11	12	13
West-east	84	89	58	42	30	70	77	58	44	44	98	75	75
North-south	47	42	70	86	98	58	51	72	86	86	30	54	54

represent the accumulation of vehicles in network at time t and N_{max} represent the sweet spot of network.

2.2. The Control Model

2.2.1. The Control Objective. In order to prevent network from getting blocked and serve more vehicles, a suitable control objective is to maximize the total vehicles that leave the network (we do not consider the vehicle arriving at the destination in the network). With this objective, the optimal policy is to allow as many vehicles to enter the network as possible without allowing the accumulation to reach oversaturation condition. Hence if we keep the accumulation around sweet spot, then the outflow is around the optimal throughput, and more vehicles will leave the network which means that more vehicles can get in the network. The control objective as follows:

$$\max Z = \sum_i \sum_t q_{i,out}(t) = \int_{t_0}^t G(N(t)) dt, \quad (1)$$

where $G(x)$ is the expression of MFD.

The signal control time table is calculated using Synchro and the signal time parameters are shown in Tables 1–5.

2.2.2. The Feedback Gating Control Model. Equation (1) is not easy to be implemented in practice. Hence, we transfer this problem to a feedback control scheme. When we get the MFD

of a network we know the sweet spot of the network; namely, we know the optimal number of vehicles in the network. The number of vehicles entering, leaving, and remaining in the network timely can be calculated based on detectors located on the boundary intersections. Then we can calculate the number of vehicles which can be allowed to get in the network.

Note that $q_{oi}(t)$ includes both internal (off-street parking for taxis and pockets for private vehicles) and external noncontrolled inflows. The conservation equation for the network is

$$\frac{d(N(t))}{d(t)} = Q(t) + q_{oi}(t) - q_{out}(t), \quad (2)$$

$$q_{out}(t) = G(N(t)). \quad (3)$$

Combine (2) and (3); we get

$$\frac{d(N(t))}{d(t)} = Q(t) + q_{oi}(t) - G(N(t)). \quad (4)$$

The linearization yields may be linearized around an optimal steady state by Taylor expansion. Combining with the research target, the best condition of network is the optimal steady state. When the network is in the best condition, the number of vehicles in the network will reach the best condition, the number of vehicles outflowing the network will be the maximum, the number of vehicles outflowing the network from signal intersections will be the maximum, and the number of vehicles outflowing the network from uncontrolled intersections will be the maximum and satisfy the following conditions:

$$\begin{aligned} \bar{Q} + \bar{q}_{oi} &= \bar{q}_{out}, \\ \Delta Q(t) &= Q(t) - \bar{Q}, \\ \Delta q_{oi}(t) &= q_{oi}(t) - \bar{q}_{oi}, \\ \Delta N(t) &= N(t) - \bar{N}, \\ \Delta q_{out}(t) &= q_{out}(t) - \bar{q}_{out} = G(N(t)) - G(\bar{N}). \end{aligned} \quad (5)$$

The results of linearization are

$$\begin{aligned} \frac{d(\Delta N(t))}{d(t)} &= A\Delta Q(t) + B\Delta q_{oi}(t) - C\Delta N(t), \\ A &= \left. \frac{\partial F}{\partial Q} \right|_{Q(t)=\bar{Q}, q_{oi}(t)=\bar{q}_{oi}, N(t)=\bar{N}}, \\ B &= \left. \frac{\partial F}{\partial q} \right|_{Q(t)=\bar{Q}, q_{oi}(t)=\bar{q}_{oi}, N(t)=\bar{N}}, \\ C &= \left. \frac{\partial F}{\partial N} \right|_{Q(t)=\bar{Q}, q_{oi}(t)=\bar{q}_{oi}, N(t)=\bar{N}}. \end{aligned} \quad (6)$$

From (2) to (6), we get

$$\frac{d(\Delta N(t))}{d(t)} = \Delta Q(t) + \Delta q_{oi}(t) - \Delta N(t)G'(\bar{N}). \quad (7)$$

Formula (7) can be denoted by

$$\frac{d(\Delta N(t))}{d(t)} = D(\Delta Q(t) + \Delta q_{oi}(t)) + E\Delta N(t). \quad (8)$$

Formula (8) is temporal continuity, which can be discretized by Euler formula:

$$\begin{aligned} \Delta N(t+1) &= Y\Delta N(t) + Z(\Delta Q(t) + \Delta q_{oi}(t)), \\ Y &= e^{ET} = e^{-G(\bar{N})T}, \\ Z &= \frac{Y-1}{D}E = (Y-1)E \\ &= (1 - e^{-G(\bar{N})T})G(\bar{N}). \end{aligned} \quad (9)$$

Based on feedback control logic, the optimal inflow of network at t is given by

$$\begin{aligned} Q(t) &= Q(t-1) - K_p[N(t) - N(t-1)] \\ &\quad + K_I(\bar{N} - N(t)). \end{aligned} \quad (10)$$

Meanwhile, the external demand of each boundary intersection should also be taken into account. The total actual inflow at time t can be calculated by the following equation:

$$q_{i,in}(t) = \min \begin{cases} Q(t) \times \alpha_i \\ q_i(t). \end{cases} \quad (11)$$

2.2.3. The Inflow Distribution. In order to determine the inflows at each boundary intersection evenly and minimize the impacts of gating control on the performance of gating intersections, both the demand and capacity of each boundary intersection are taken into account. A parameter α_i is used to represent the ratio of inflows assigned to the intersection i ; it can be calculated by the following equation:

$$\alpha_i = \frac{q_i(t)^2 [S_i - S_i(t)]}{\sum_i q_i(t)^2 [S_i - S_i(t)]}. \quad (12)$$

When we get the $q_{i,in}(t)$ of each intersection, we can adjust the green time of each intersection according to the data of detector.

Then the green time of the lane group heading to network at boundary intersection i can be calculated as

$$t_i(t) = q_{i,in}(t) \times \frac{T}{S_i}. \quad (13)$$

We also take the constraint condition of maximum and minimum green time into consideration, as follows:

$$t_{g,\min} \leq t_i(t) \leq t_{g,\max}. \quad (14)$$

3. Simulation and Analysis

3.1. Network Description and Simulation Setup. In order to test the feedback gating control model, we build a microsimulation network by VISSIM. The network includes 13 intersections and 8 main roads; traffic signals are all multiphase fixed-time operating on a common cycle length of 120 s, shown in Figure 2 by the blue dotted line circle. The red point represents the gating intersections at the border of the protected network, which could be the intersections upstream of the controlled network.

We consider vehicles entering the network if they pass the gating intersections from outside and getting out of the network if they pass the gating intersections to the destination. The loop detectors have been installed at gating intersections to collect the number of vehicles getting in/out of the network.

Nine-hour simulation with time-dependent demand is carried out to test the performance of the proposed feedback control logic. The traffic demand on each entry lane of the boundary intersections is evenly varied from 0 to 900 vehicles in one cycle of 30 minutes. The traffic demand on each internal entrance is evenly varied from 0 to 450 vehicles in one cycle of 30 minutes. The inflow, outflow, and number of vehicles in the network are collected every 120 s.

3.2. Macroscopic Fundamental Diagrams. Through the timely data from detectors, we can get the MFD of the test area which reflects the relation of the outflow and vehicle accumulation in the network. The MFD's y -axis represents the number of vehicles leaving the test area per control cycle (outflow), while the x -axis represents the number of vehicles in the test area (accumulation). The outflow and the vehicle accumulation in the network are obtained from the (emulated) loop measurements via the following equations:

$$\begin{aligned} \text{Outflow}(t) &= \sum_i q_{i,\text{out}}(t), \\ \text{accumulation} &= \sum_i \sum_t (q_{i,\text{in}}(t) - q_{i,\text{out}}(t)), \end{aligned} \tag{15}$$

where $q_{i,\text{out}}(t)$ is the number of vehicles leaving the network from intersection i at time t ; $q_{i,\text{in}}(t)$ is the number of vehicles getting in the network from intersection i at time t . Then we get the MFD of the test network as shown in Figure 3.

In Figure 3, at the beginning of simulation, the outflow per control cycle increases with the increase of the number of vehicles in the test area (accumulation); when the accumulation is around 800 (veh) and outflow around 225 (veh/cycle), the outflow does not increase with the increase of the accumulation; it is in a relatively steady state, while the outflow will decrease with the increase of the accumulation steadily until the outflow is 0 (veh/cycle) and the accumulation is 2500 (veh). Although there is a fluctuation when the accumulation is around 1200 (veh), it is not unstable. Hence the test area will operate at optimal status when the accumulation is around 800 (veh) and the outflow around 225 (veh/cycle), and this is our optimal state

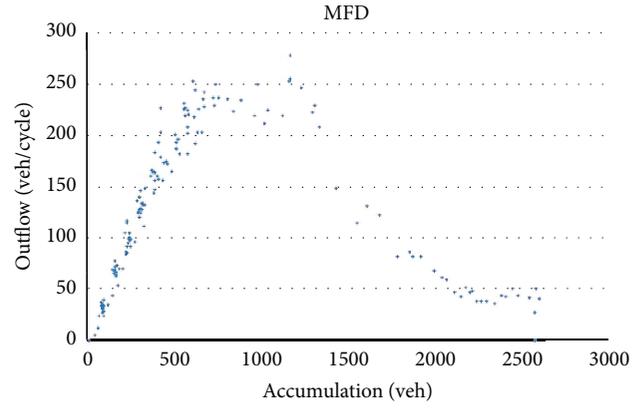


FIGURE 3: The MFD of the test area.

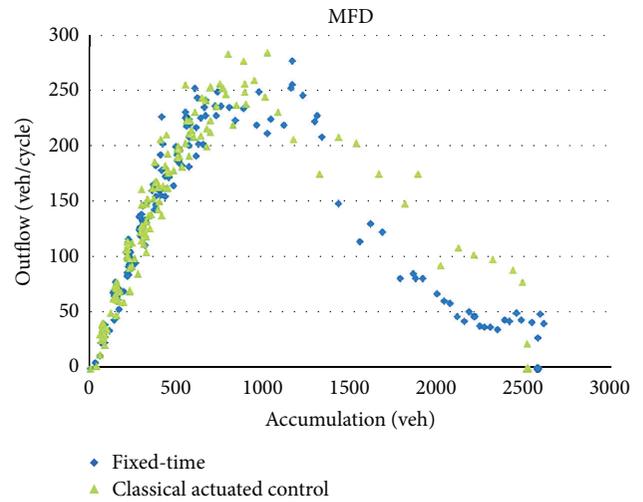


FIGURE 4: Influence factors of MFD.

which ought to be reached by the proposed feedback control method.

3.3. Experiment Design. In order to test the feedback gating control and explore the influence of different control strategy of intersection in the test area, the following two cases are considered.

Case 1 (fixed-time control). The control plans are optimized by Synchro.

Case 2 (classical actuated control). The classical control plans illustrated in text book [22] are used.

As shown in Figure 4, different control strategies have different influence on MFD. Generally speaking, comparing with the MFD of fixed-time, actuated control improves the maximum outflow slightly. The maximum outflow changes from 250 (veh/cycle) to 280 (veh/cycle) while the accumulation in network remains the same.

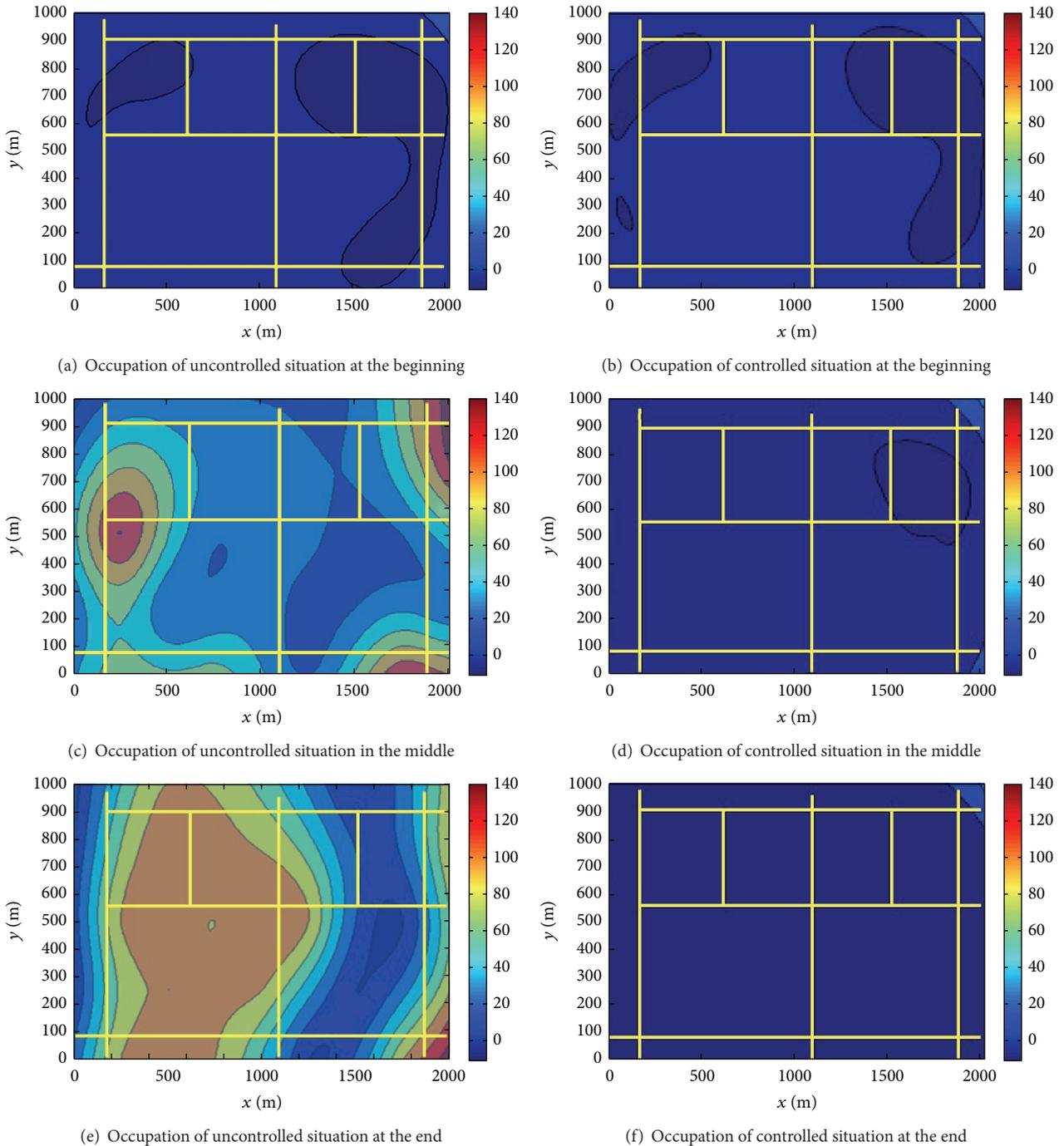


FIGURE 5: The occupation of uncontrolled/controlled during the simulation.

4. Simulation Results

4.1. Network and Gating Intersection Performance Analysis. In order to reveal the evolution process of the testing network without and with feedback gating control under fixed-time and classical actuated control cases, the occupation of the network is extracted as shown in Figure 5, and the total number of inflows, the queue length, and delay at gating intersection are shown in Figures 6(a)–6(f).

In Figure 5, we choose three periods of simulation to analyze the occupancy of network: the beginning of simulation, the middle of simulation, and the end of simulation time. The yellow line represents the roads in testing network.

As shown in Figures 5(a), 5(c), 5(e), 5(b), 5(d), and 5(f), the occupation of the network without control increases as time goes by while occupation of the network under control does not change significantly. Comparing Figures

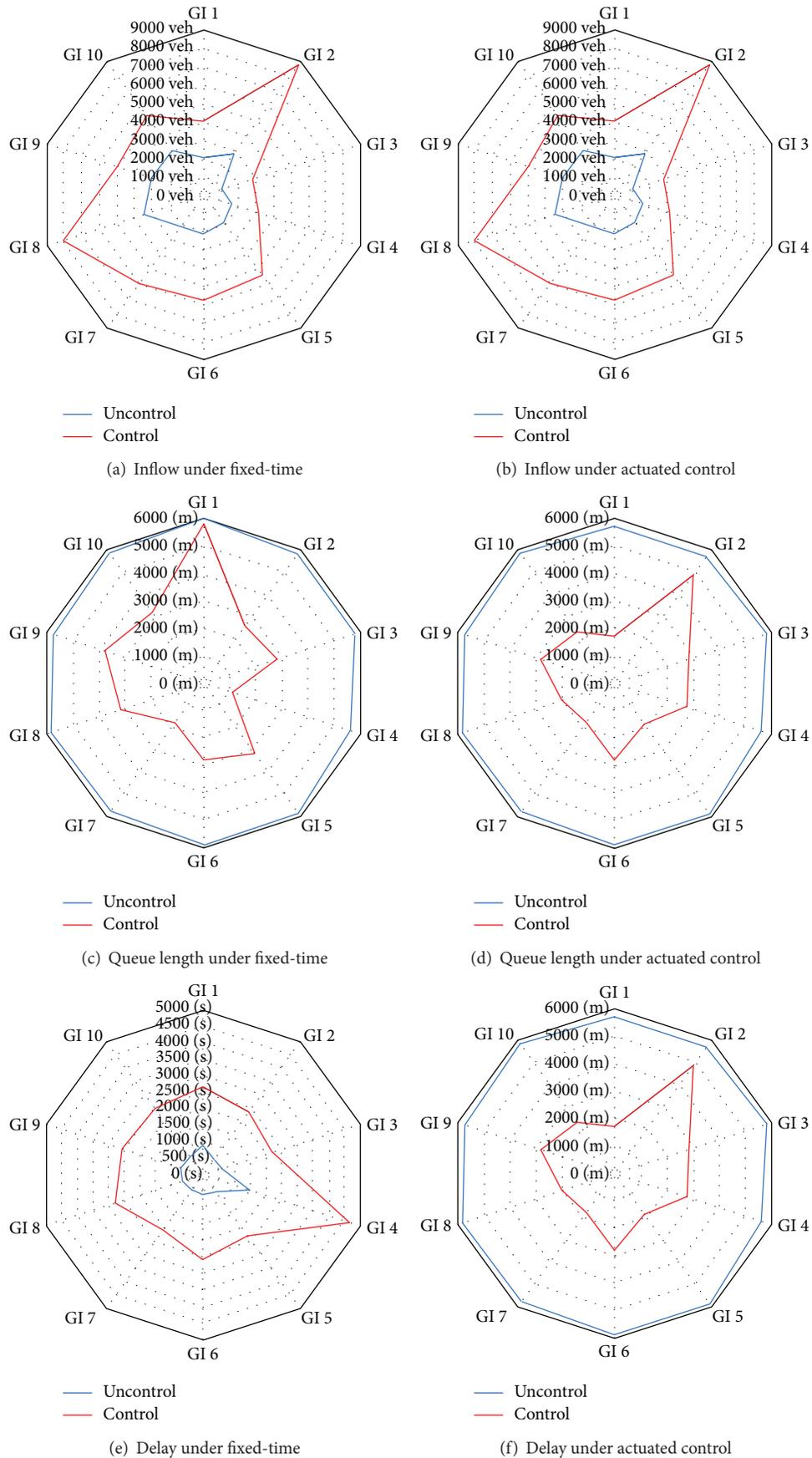


FIGURE 6: The total number of inflows, queue length, and delay of each approach.

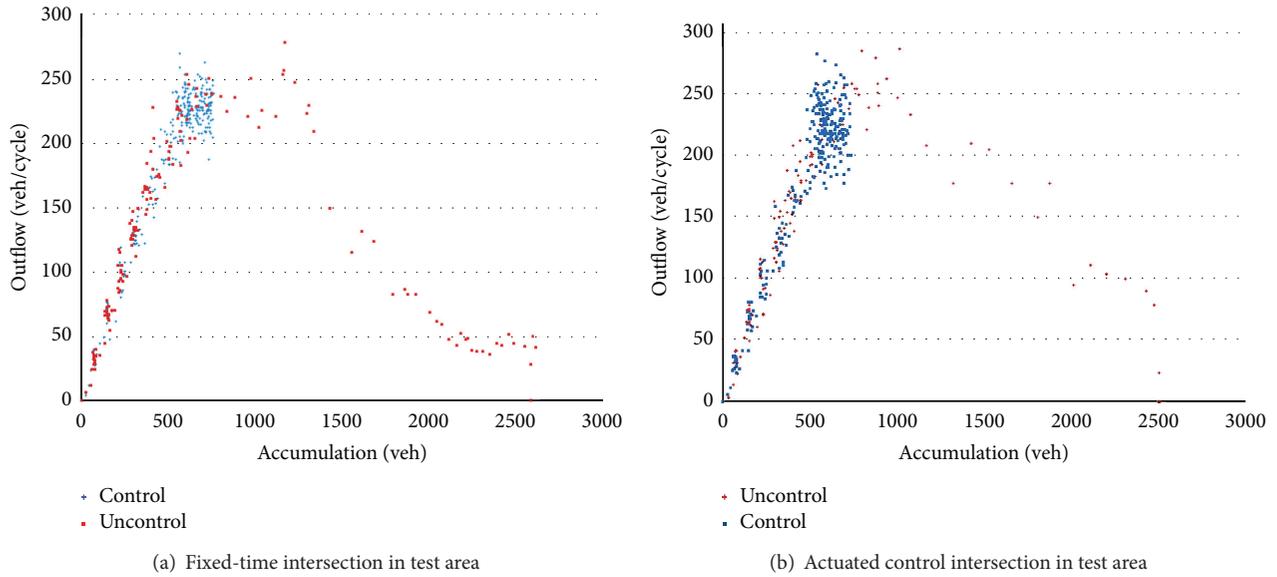


FIGURE 7: The MFD of two situations.

TABLE 6: The index of the test area under two situations.

Index	Fixed-time intersection in test area			Actuated control intersection in test area		
	Control	Without Control	Optimized proportion	Control	Without control	Optimized proportion
Average delay time per vehicle (s)	923	3704	75%	928	3767	75%
Total delay time (h)	13756	26966	49%	13698	26881	49%
Number of vehicles that have left the network	50211	20318	147%	49711	19874	150%
Total travel time (h)	18985	29167	35%	18873	29038	35%

5(a) and 5(b), the occupation is the same for both situations which means that at the beginning of simulation the network does not have difference under controlled and uncontrolled condition. The obvious differences shown in Figures 5(c) and 5(d) reflect that the test network without control becomes congested in some parts while this phenomenon does not appear in controlled condition since its occupation is still low. As time goes by, congestion in the test network without control keeps spreading and almost covers most of the network. However, congestion does not appear in the test network under control condition from the very beginning to the end.

Figures 6(a) and 6(b) show that the total amount of inflows from each gating intersection under the feedback control is far more than that under the situation of without control. Figures 6(c), 6(e), 6(d), and 6(f) reflect the same tendency of queue length and delay. Hence, the results of Figure 6 validate that the inflows are properly allocated to all gating intersections, and the proposed gating control policy reaches a Pareto improvement since the performance of all gating intersections is improved in terms of inflow rate, delay, and queue length.

In order to reveal the average improvements reached by the proposed feedback gating control policy, four performance measures including average delay, total delay, outflow, and total travel time are used to further evaluate the impacts of the proposed feedback control method. As shown in Table 6, all the performance indexes of network with control are fully superior to the situation without control. Moreover, there is no significant difference between fixed-time control and the actuated control, which demonstrates that the influence of the control policy implemented in the intersections within the network on MFD is negligible.

4.2. The Comparing of MFD. The MFDs of the test network with and without feedback control are presented in Figure 7. It can be seen that before accumulation arrives at the sweep spot, the two MFDs under the conditions of control and uncontrol are the same. With the increasing of accumulation, the network under the feedback gating control only displays the left half of the total MFD and reaches a stable state around the optimal state. In contrast, the network without gating control has a complete MFD and the outflow approaches 0 as the accumulation exceeds the sweet point of the network.

4.3. *The Comparing of Inflow/Outflow/Accumulation.* The impacts of feedback control on inflow rate, outflow rate, and accumulation of vehicles in the network are presented in Figure 8. It can be seen from Figures 8(a) and 8(b) that, at the beginning of simulation, the inflow, outflow, and accumulation increase as the increase of demand outside of gating intersection, and there is no difference between feedback control and no control situations. However, before the network reaches sweet point, the state of network with and without feedback control exhibits different features. The maximum inflow rate under feedback control is around 250 (veh/cycle) while that under no control condition is a little bit higher, around 300 (veh/cycle). After 13000 s, the inflow under control is remaining at 200–250 (veh/cycle) while that under no control situation gradually decreases to 0 (veh/cycle), and the network finally gets blocked. The outflow of the network shows similar features as shown in Figures 8(c) and 8(d).

As shown in Figure 8(c), the vehicles accumulation rate of the network is the same for both control and uncontrol situations. After around 15000 s, the differences of vehicle accumulation rate under two situations becomes significant. The vehicle accumulation rate gradually turns to be stabilized at around 800 (veh). In contrast, the vehicle accumulation rate under no control situation increased rapidly and finally stabilized at around 2500 (veh), and the network gets blocked at that time. Moreover, both actuated control and fixed-time control exhibit similar features. The analysis results validate that the proposed feedback control performs well in terms of increasing inflow and outflow of networks and preventing network congestion.

5. Conclusion

Based on the recently proposed concept of an operational urban MFD, this paper proposed a feedback gating control policy which can be used to mitigate network congestion by adjusting signal timings of gating intersections. The objective of the feedback gating control model is to maximize the outflow and distribute the allowed inflows according to external demand and capacity of each gating intersection. An example network is used to test the performance of proposed feedback gating control model. Two types of background signalization types for the intersections within the test network, fixed-time and actuated control, are considered. Through extensive simulation based analysis, this study has reached the following tentative conclusions:

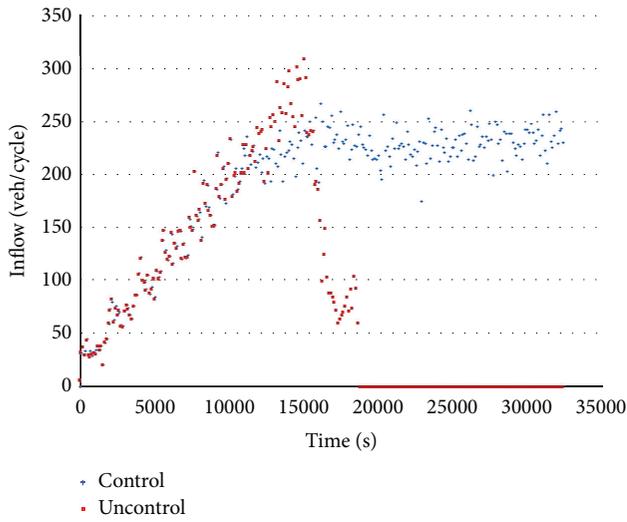
- (1) The proposed feedback gating control model can reach a Pareto improvement since the performance of both gating intersections and the whole network are improved.
- (2) Under the feedback gating control, the inflows and outflows can be stabilized at a very high level instead of decreasing all the way to 0 as the increase of external demand.
- (3) Compared with no control case, especially under heavy demand situations, the delay and queue length

at all gating intersections are decreased dramatically. Moreover, the total inflows are distributed among all gating intersections properly. In this sense, the proposed approach reaches another Pareto improvement in terms of balancing performance of gating intersections.

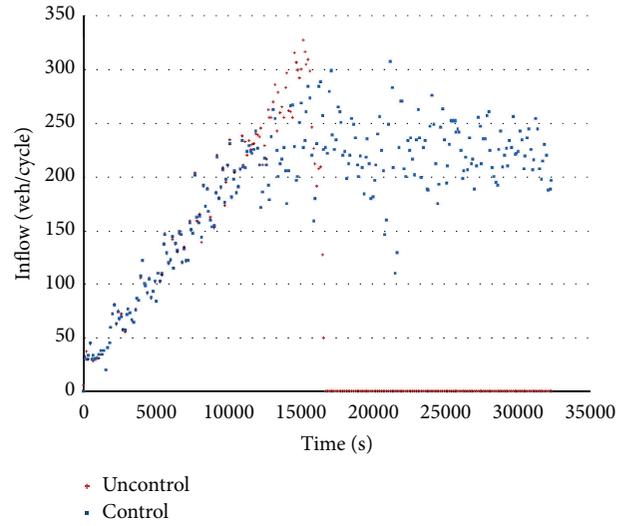
Note that this paper has presented preliminary evaluation results for the proposed model and only one small network is used for testing. More extensive numerical experiments or simulation tests will be conducted to assess the effectiveness of the proposed model under various traffic demand patterns and network geometry configurations. Another possible extension to this study is to study a more comprehensive control policy for a network with multiple subnetworks.

The Variables and Their Definitions

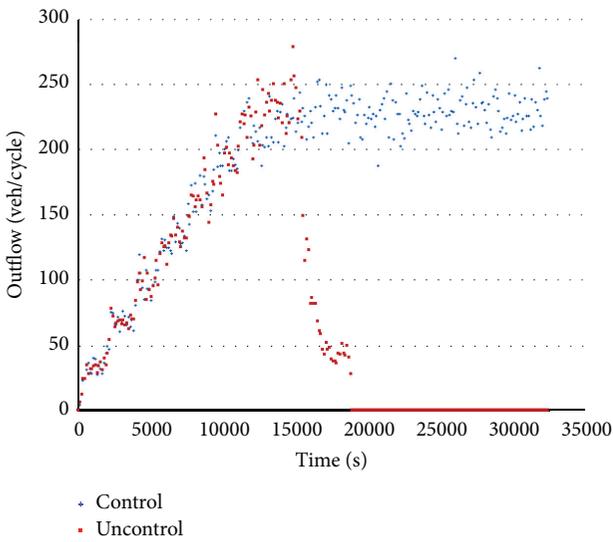
$N(t)$:	The number of vehicles in the network at time t (veh)
$Q(t)$:	The number of vehicles inflowing the network from controlled intersection at time t (veh)
$q_{oi}(t)$:	The number of vehicles inflowing the network from uncontrolled intersection at time t (veh)
$q_{out}(t)$:	The number of vehicles outflowing the network at time t (veh)
$G(N(t))$:	The calculating formulae of optimum curve regression model of MFD
\bar{N} :	The optimal number of vehicles in the network (veh)
\bar{q}_{out} :	The maximum number of vehicles outflowing the network (veh)
\bar{Q} :	The maximum number of vehicles inflowing the network from controlled intersection (veh)
\bar{q}_{oi} :	The maximum number of vehicles outflowing the network from controlled intersection (veh)
$\Delta Q(t)$:	The increment number of vehicles inflowing the network from controlled intersection at time t (veh)
$\Delta q_{oi}(t)$:	The increment number of vehicles inflowing the network from uncontrolled intersection at time t (veh)
$\Delta q_{out}(t)$:	The increment number of vehicles outflowing the network at time t (veh)
$\Delta N(t)$:	The increment number of vehicles in the network at time t (veh)
T :	The cycle of controlled intersection (s)
K_I :	Integral gains of the feedback control
α_i :	The distribution ratio of the number of vehicles inflowing the network from controlled intersection at time t
$q_i(t)$:	The demand of controlled intersection i at time t (veh)



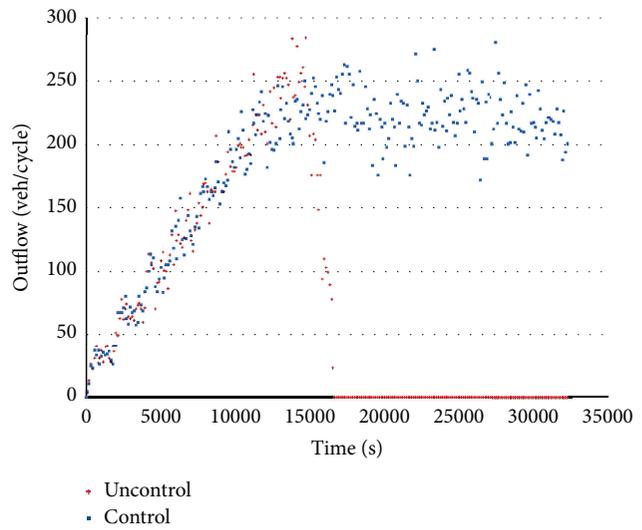
(a) Inflow rate in fixed-time



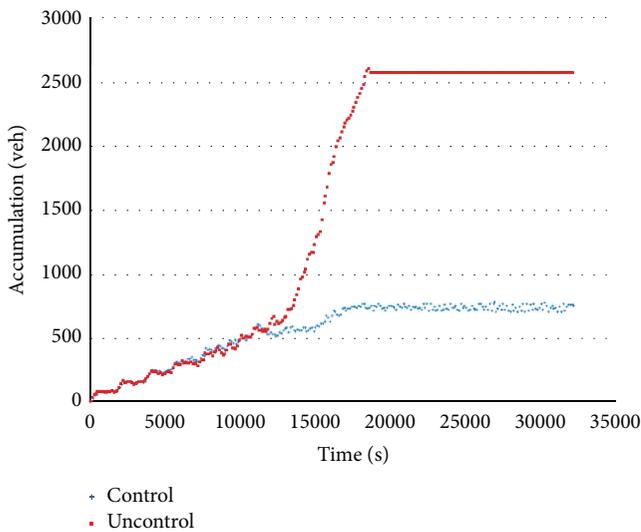
(b) Inflow rate in actuated control



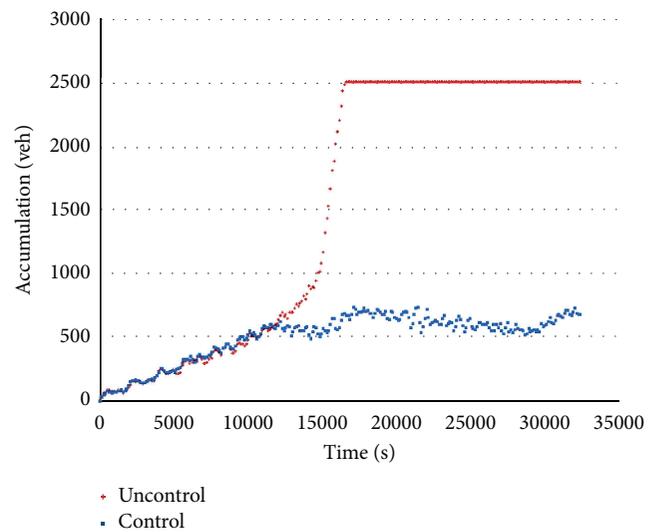
(c) Outflow rate in fixed-time



(d) Outflow rate in actuated control



(e) Accumulation in fixed-time



(f) Accumulation in actuated control

FIGURE 8: The comparing of under control and without control situations.

- $q_{i,\text{in}}(t)$: The number of vehicles allowed to inflow to the network from controlled intersection i at time t (veh)
- $q_{i,\text{out}}(t)$: The number of vehicles allowed to outflow to the network from intersection i at time t (veh)
- S_i : The capacity of intersection i under the maximum green time (veh/cycle)
- $S_i(t)$: The capacity of intersection i at time t (veh/cycle)
- $t_i(t)$: The green time of intersection i at time t (s)
- $t_{g,\text{max}}$: The maximum green time (s)
- $t_{g,\text{min}}$: The minimum green time (s)
- K_P : Proportional gains of the feedback control.

Competing Interests

The authors declare that they have no competing interests.

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