Impact of Traffic Information Feedback Strategies on Signalized Two-Route Traffic Systems

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Abstract. The existing traffic information feedback strategies were originally proposed and evaluated for the two-route traffic systems without signal lights. However, traffic flow in urban traffic systems is rather complicated largely due to the presence of traffic signals. By introducing the signalized two-route traffic systems, this paper has investigated the eleven traffic information feedback strategies from system and user aspects for the first time, based on a set of two-route scenarios which simulate various combinations of traffic signal timing and location. The experimental results reveal the following findings. None of the test strategies can effectively improve road capacity for the scenarios where traffic lights are installed on both routes. The traffic information feedback strategies which use global information can reduce travel time to varying degrees, when dynamic vehicles become dominant on the roads. Furthermore, the eleven information feedback strategies have also been examined from the user equilibrium aspect and the corresponding results imply three congestion-based strategies can better approximate the user equilibrium as compared to the others. Finally, experiments demonstrate that the most inefficient strategy to achieve system optimality is the travel time feedback strategy.

Keywords: Intelligent transportation systems · Traffic information feedback strategy · Nagel-schreckenberg model · Signalized traffic systems

1 Introduction

To understand the traffic dynamics and solve the related congestion issue, researchers have proposed a number of theories [1][2] and realized that the informed travel can significantly increase the probability to avoid congestion [3]. Over the last decade, many researches have been dedicated to the traffic information feedback strategy for the situation where a driver can use the information provided at entrance to make a route choice. The work presenting the travel time feedback strategy (TTFS) by Wahle et al. [3], has triggered great interest of researchers to deliver more advanced information feedback strategies. In 2001, Lee et al. [4] developed a new information feedback strategy, named as mean velocity feedback strategy (MVFS). It has been proved that MVFS is more efficient than TTFS as MVFS diminishes the lag effect of TTFS [4][5].

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However, the information provided in MVFS can not reflect the real situation as MVFS incorporates the fragile velocity caused by the random mechanism of the Nagel-Schreckenberg (NS) model [6]. In 2005, Wang et al. [7] introduced a new traffic information feedback strategy, called the congestion coefficient feedback strategy (CCFS). It has been reported that CCFS outperforms TTFS and MVFS in terms of road capacity as CCFS provides congestion information [8]. However, CCFS is unable to reflect the influence of the distance of congestion to the vehicle newly entering the route. Aiming to enhance CCFS, a number of improved information strategies have been successively proposed in recent years. Dong et al. [8] developed a weighted congestion coefficient feedback strategy (WCCFS) by incorporating a linear weighting function to CCFS. Another notable improvement to CCFS is the exponential function feedback strategy (EFFS) which uses an exponential function to account for the distance effect of each congestion cluster to the vehicle newly arrived [9]. Dong et al. [10] proposed alternative way to add weight for each congestion cluster, yielding the corresponding angle feedback strategy (CAFS). CAFS calculates the angle between the two edges of each congestion cluster in reference to a site located vertically above the entrance instead of the cluster length as in CCFS, WCCFS, EFFS, in order to embed the cluster location information. To explicitly include the cluster length information, the improved congestion coefficient feedback strategy (ICCFS) incorporates CAFS into CCFS by using the corresponding angles as the weights for each congestion coefficient [11]. Nonetheless, CAFS and ICCFS have limited applications in that they are impossible to accurately calculate the angles of congestion clusters for the non-straight roads (e.g. the S-shape roads), as reported in Ref. [9]. In 2010, Dong et al. [12] developed a new information strategy, called vehicle number feedback strategy (VNFS), by examining the number of en-route vehicles. In 2012, Chen et al. [13] introduced the vacancy length feedback strategy (VLFS), by which drivers will be guided to the route with the larger number of empty sites from the entrance to the vehicle nearest to the entrance. In the same year, the authors from the same group (as in Ref. [13]) proposed two new information feedback strategies, namely the time flux feedback strategy (TFFS) and the space flux feedback strategy (SFFS), and found SFFS is the best one but TFFS generally performed same as that without information guidance based on the simulated two-route scenarios with two exits [14]. In 2013, Xiang and Xiong [15] proposed a weighted mean velocity feedback strategy (WMVFS) by applying a linear weighting function for each site in order to eliminate the influence of positioning errors (e.g., GPS error).

So far, all existing information feedback strategies are examined on either symmetrical or asymmetrical two-route systems with appropriate modifications [3]. However, travel delay in the urban road traffic system is largely caused by traffic signals, which is not considered in the previous researches. Therefore, this paper firstly introduces a signalized two-route traffic system and then evaluates eleven information feedback strategies based on a set of signalized two-route scenarios.

The rest of the paper is organized as follows. The next section is dedicated to an introduction of NS model and signalized two-route traffic system. The results obtained from a series of simulations are presented and discussed in Section 3, and this paper is concluded in Section 4.

2 NS Model and Signalized Two-Route Traffic System

2.1 NS Mechanism

The NS mechanism is a cellular automation model frequently adopted in analyzing traffic flow, as it is a simple model capable of mimicking the fundamental features of the real traffic follow, like stop-and-go wave, phantom jams, and the phase transition. This section provides a brief review on the NS mechanism for single lane traffic (and an excellent overview can be found in Ref. [1]).

In the NS model, the road is subdivided into a number of cells with equal length and each cell corresponding to 7.5m can be either empty or occupied by only one vehicle with a velocity ranging from 0 to $v_{\max}$ with integer interval ($v_{\max}$ is the maximum velocity permitted and set to be 3 cells/time step, corresponding to 81 km/h). The density ρ of a road of length L that carries N vehicles is defined as ρ = N/L. At each discrete time step (corresponding to 1 second), all en-route vehicles are subject to a motion update according to the following rules (parallel dynamics):

Rule 1. Acceleration: $v_i(t+1/3) \rightarrow \min\{v_i(t)+1, v_{max}\}$;
Rule 2. Deceleration: $v_i(t+2/3) \rightarrow \min\{v_i(t+1/3)+1, g_i(t)\}$;
Rule 3. Randomization: $v_i(t+1) \rightarrow \max\{v_i(t+2/3)-1, 0\}$ with probability p;
Rule 4. Movement: $x_i(t+1) \rightarrow x_i(t)+v_i(t+1)$.

Here, $x_i(t)$ and $v_i(t)$ are defined to be the location and the velocity of vehicle i at time t, respectively, and $g_i(t)$ is the number of empty cells in front of the vehicle i at time t.

2.2 A Signalized Two-Route Traffic System

It is assumed that a two-route traffic system includes traffic lights, which are operated in a fixed cycle manner. At each time step, a vehicle arrives at the entrance of the two-route system (i.e., the arrival rate r_a is 1) and will choose one route to enter if the first cell of the chosen route is empty. This means the vehicle will be deleted as the entrance of the desired route is occupied by the other vehicle arrived earlier. After entering the route, the vehicle moves through the route by following the NS rules as described in previous subsection. An en-route vehicle will check the gaps from its current position to the preceding vehicle and the stop-line of a signal intersection when the signal is red and stop at the stop-line if the gap from the stop-line is smaller. Note that the scenarios presented in this paper assume no vehicles at signal intersections will be diverted out and no vehicles will be added at any intersections (e.g., such intersections are often constructed for pedestrian crossing street in real world). When an en-route vehicle reaches the route end, it will be removed.

Furthermore, two different types of drivers are introduced in the system: static and dynamic drivers. The static driver will randomly choose a route to enter regardless of the information provided, while the dynamic driver will take advantage of the information to make a route choice. The rates of dynamic and static drivers are set to be S_d and 1-S_d, respectively.

The two-route system with one entrance and two exits is frequently adopted to evaluate the different information strategies due to its simplicity [7][12][14]. Such traffic system simulates the situations where the two facilities with the same functions are located on two routes (e.g., two banks on different locations).

2.3 The Related Definitions

The flux of the routes is frequently adopted to describe road capacity and is defined as follows:

$$F = V_{\text{mean}}\rho = V_{\text{mean}}\frac{N}{L} \tag{1}$$

where V_{mean} represents the mean velocity of N vehicles on the route of length L, ρ is the traffic density of the route.

Furthermore, the traffic system operating over T time period can be evaluated by calculating the so-called average flux as:

$$F_{\text{avg}} = \frac{\sum_{i=1}^{n}\sum_{t=1}^{T} f_{ij}}{T\times n} \tag{2}$$

Here, f_{ij} is the flux of the ith route of n routes at time t.

3 Simulation Results and Discussion

The eleven information feedback strategies (TTFS, MVFS, CCFS, WCCFS, EFFS, CAFS, ICCFS, VNFS, VLFS, SFFS, WMVFS) have been examined in terms of individual cost and system optimality by performing a series of simulations on the two-route traffic systems with two exits and one exit. The individual cost is measured by the time required by individual vehicle to traverse the chosen route, while the average flux for the two routes is used to indicate the system optimality. All simulation results presented here were performed over 25000 iterations.

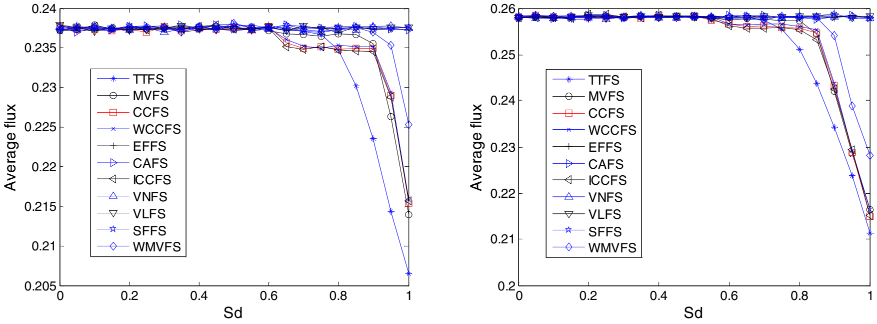
The eleven information feedback strategies can be classified into two categories: one is called global information strategy as they use the information reported by all vehicles and the other called local information strategy as only the information from a proportion of en-route vehicles is used. The strategies which apparently fall into the global information strategy are TTFS, MVFS, CCFS, WCCFS, CAFS, ICCFS, and WMVFS, while VNFS, VLFS, and SFFS belong to the second category. Although EFFS computes congestion coefficient using the information from all en-route vehicles, the exponential function employed considerably weights the vehicles near to the entrance, behaving similarly to the local information strategy. Consequently, EFFS is classified into the local information strategy in this paper. CCFS, WCCFS, EFFS, CAFS, and ICCFS compute congestion coefficients and therefore are called congestion-based strategies here. While TTFS is a time-based strategy, MVFS and WMVFS use the velocity information of en-route vehicles. VNFS provides the information on the number of a part of en-route vehicles. In contrast, only the distance from entrance to the vehicle closest to the entrance is provided by VLFS.

The evaluation on the eleven strategies were conducted based on 6 symmetric two-route scenarios, 2000 cells in length with one entrance and two exits, constructed by combining different signal timings and locations, as shown in Table 1.

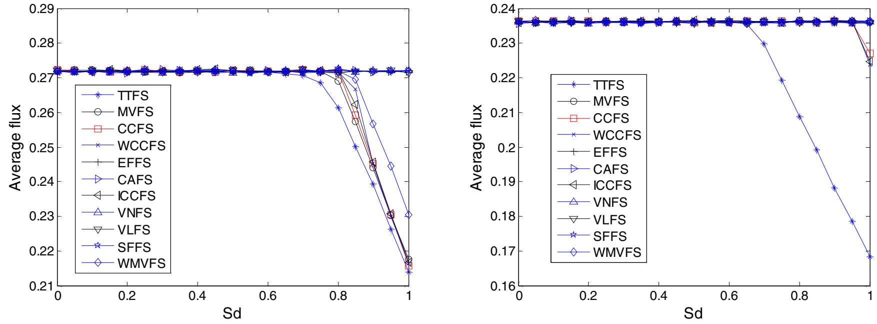
Table 1. Traffic signal configurations for the two-route scenarios

Scenario	Route	Red light on	Green light on	Signal light location
1	A	50	80	1000
	B	100	60	1000
2	A	100	80	1000
	B	40	70	1000
3	A	60	80	1000
	B	60	80	1000
4	A	50	50	200
	B	50	50	200
5	A	50	50	1800
	B	50	50	1800
6	A	50	50	200
	B	50	50	1800

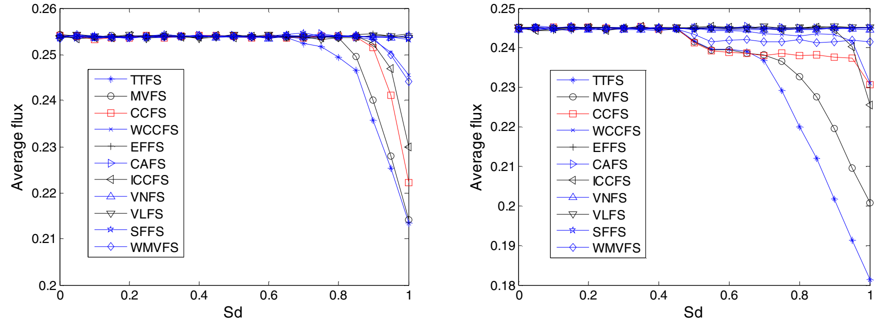
In reality, the rate of dynamic vehicles (S_d) may vary in a wide range and thus it is interesting to see the performance of different strategies in response to the changes in S_d. Fig. 1 shows the average fluxes obtained by taking the mean values over 10 independent runs. In general, TTFS has performed worst from the road capacity aspect, even though its performance is similar to the others when the proportion of dynamic vehicle is typically below 0.6 around. This finding is consistent to those previously reported for the symmetric two-route systems without signal lights due to the lag effect [13][15]. The road capacities realized by TTFS, MVFS, CCFS, WCCFS, ICCFS, and WMVFS are shrinking quickly while the others are apparently insensitive, as dynamic vehicles increasingly dominate on the roads for the scenarios except 4. The majority (i.e., EFFS, VNFS, VLFS, and SFFS) of the insensitive strategies belong to the category of local information strategy and consequently the lack of globe information can largely account for the insensitiveness. Furthermore, the results in Fig. 1 imply that all test strategies are unable to improve the system performance as the average fluxes have not been increased with information provision. This can be explained by the fact that all test strategies do not incorporate any information on the delay caused by traffic signals. Although scenarios 4 and 5 (in Fig. 1(d) and (e)) have same traffic signal configurations for the both routes, much less variations in average flux resulted from the strategies except TTFS can be observed for scenario 4. Notice that the locations of signal lights in scenario 4 are close to the entrance and therefore congestion near to the entrance is likely to be severe due to the traffic signal. Such important information can also be captured by the local information strategies which primarily focus on the local area near to the entrance. However, the local information strategies are unable to incorporate the congestion information when the traffic lights are located far from the entrance as the case in scenario 5. The first three scenarios have the signal lights located on the same sites but different timings and the different average fluxes presented in Fig. 1(a), (b), and (c) imply the signal timings have impact on road capacity. The average fluxes resulted from the last three scenarios suggest the averaged flux is influenced by the location of traffic light.



(a) scenario 1 (b) scenario 2



(c) scenario 3 (d) scenario 4



(e) scenario 5 (f) scenario 6

Fig. 1. Average flux by different strategies *vs.* S_d in the two-exit scenarios.

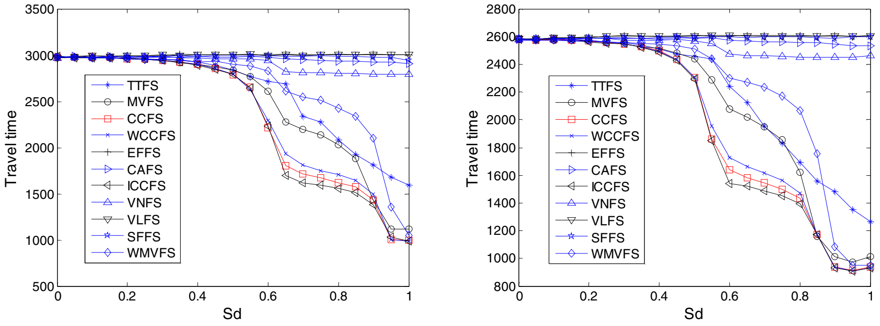
As road users always attempt to minimize their travel costs when choosing a route, the eleven strategies have been evaluated for the six scenarios in terms of travel cost measured by the time taken to pass through the chosen route. Fig. 2 shows the travel time averaged over 10 independent runs for the different proportions of dynamic vehicles ranging from 0 to 1 with the interval of 0.05. In general, TTFS, MVFS, CCFS, WCCFS, ICCFS, and WMVFS, which fall into the category of the global information strategy, can effectively reduce the average travel time when the dynamic vehicles are gradually becoming majority among all en-route vehicles. However, such reduction on travel cost is unlikely to be achieved at free of cost. It is evident from Fig. 3 that the number of vehicles passing through is lower than those achieved by EFFS, CAFS, VNFS, VLFS, and SFFS.

Therefore, it can be concluded that the improved travel time is obtained by satisficing traffic flow. Although CAFS uses global information, it generally fails to reduce travel time because it does not explicitly incorporate the information on the lengths of congestion which is likely formed when facing red light. Furthermore, the results from Fig. 2 imply the travel time is affected by the signal timing and location.

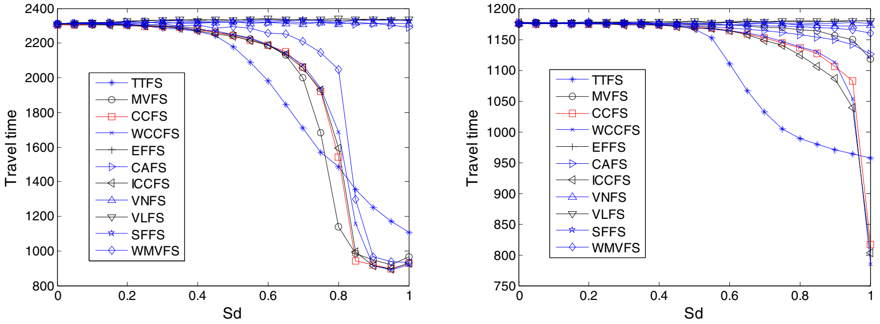
The differences in the results presented in Fig. 3(a), (b), and (c) imply that the number of vehicles passing through is influenced by the signal timing. However, the number of vehicle passing through is not sensitive to the signal location as the 5800 around vehicles over the test time span (i.e., 25000 time steps) can pass through for scenarios 4, 5, and 6, when the proportion of dynamic vehicles is lower than 0.6. Fig. 3 also demonstrates that the number of vehicles guided by TTFS through the routes is smallest for all test scenarios. It is noticed that Fig. 3(d) and Fig. 1(d) have the same pattern in the results obtained for the number of vehicles and average flux respectively, implying the average flux is only dependent to the number of vehicles passing through for scenario 4.

It is interesting to see whether the user equilibrium (UE) can be reached under information guidance, because UE is frequently used as a target in the traffic assignment. When the UE is reached, no driver can unilaterally reduce his/her travel costs (i.e., travel time) by shifting to an alternative route as the travel costs are equal on all used routes and less than on unused routes [16].

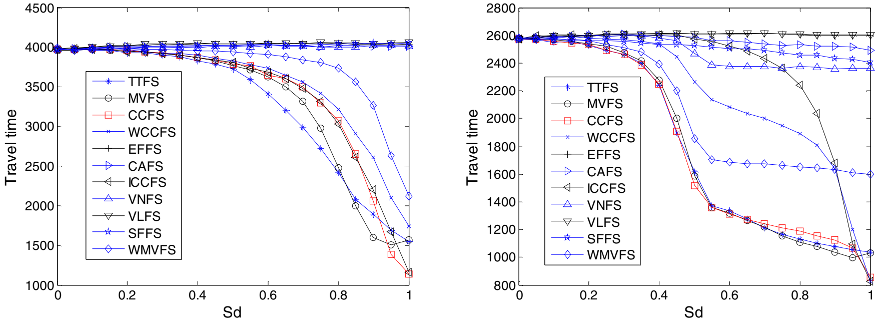
To evaluate the strategies in terms of the UE, all vehicles are assumed to be the dynamic type, i.e., all vehicles are subject to the guidance of information feedback strategy. Table 2 lists the absolute differences of travel times between route A and B, averaged over 10 independent runs for the six test scenarios, and their statistics (mean values and standard deviations). Additionally, the travel time differences for only static vehicles involved (i.e., $S_d = 0$) are also computed and the averaged results listed in the last row with bold and italic font. The maximum and minimum values for each test scenario are also distinguished from the others by italic and bold font, respectively. Furthermore, Table 2 also highlights the travel time differences which are larger than that when S_d is 0 for each scenario.



(a) scenario 1 (b) scenario 2

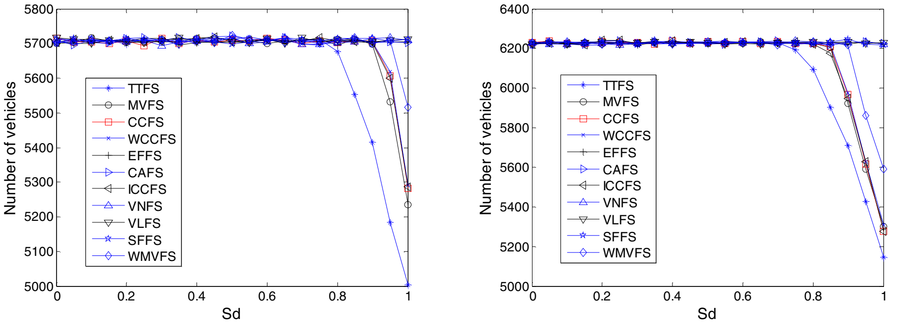


(c) scenario 3 (d) scenario 4

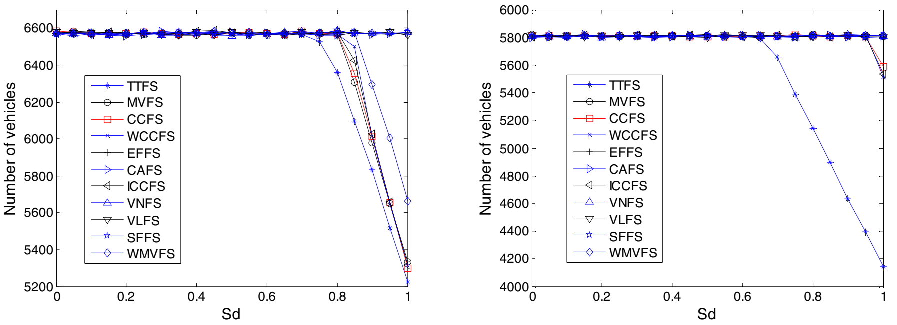


(e) scenario 5 (f) scenario 6

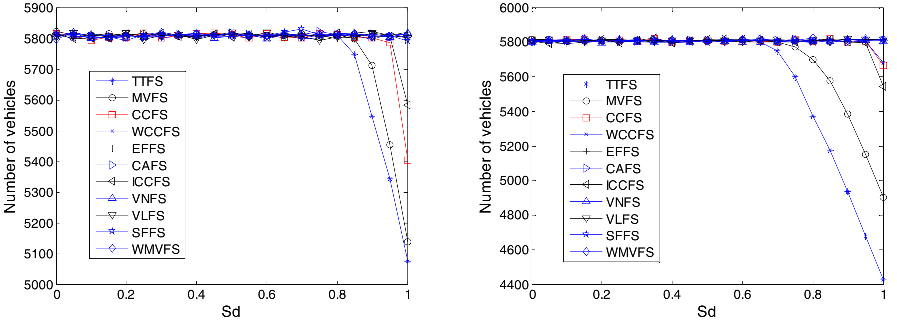
Fig. 2. Travel time by different strategies *vs*. S_d in the two-exit scenarios.



(a) scenario 1 (b) scenario 2



(c) scenario 3 (d) scenario 4



(e) scenario 5 (f) scenario 6

Fig. 3. Number of vehicles by different strategies *vs*. S_d in the two-exit scenarios.

Table 2. Travel time differences (×10^3) between route A and B by different strategies when S_d is 1 in the two-exit scenarios.

Scenario	1	2	3	4	5	6
TTFS	0.5188	0.2557	*0.0221*	*0.0097*	0.0277	0.0772
MVFS	0.2291	0.1406	0.0072	0.0009	0.0264	0.0445
CCFS	0.1317	0.0954	**0.0040**	0.0024	**0.0081**	**0.0035**
WCCFS	0.1313	0.0929	0.0043	**0.0006**	0.0141	0.0741
EFFS	1.8034	1.2234	0.0111	0.0048	0.0268	2.8431
CAFS	1.6597	1.1215	0.0064	0.0035	*0.0362*	*2.9302*
ICCFS	**0.1208**	**0.0883**	0.0043	0.0007	0.0187	0.0642
VNFS	1.4096	0.9443	0.0204	0.0033	0.0175	2.4388
VLFS	1.8137	1.2212	0.0139	0.0041	0.0167	2.8479
SFFS	*1.9206*	*1.2683*	0.0151	0.0053	0.0245	2.4583
WMVFS	0.2498	0.1105	0.0043	0.0025	0.0085	0.9390
Mean value	0.9080	0.5965	0.0103	0.0034	0.0205	1.3383
Standard deviation	0.7959	0.5435	0.0067	0.0026	0.0087	1.3405
$S_\mathrm{d} = 0$	***1.8126***	***1.2302***	***0.0172***	***0.0040***	***0.0387***	***2.8018***

It can be found that the travel times between the two routes can be mostly equalized by CCFS, WCCFS, and ICCFS which are all congestion-based strategies. This can be understood by the fact that these three strategies directly incorporate the congestion caused by the traffic signal. In contrast, the majority of the strategies which enlarges the gap of travel times between the two routes are local information strategies. The worst one in terms of the UE for scenario 1 and 2 is SFFS, while TTFS is the worst for scenario 3 and 4. For scenario 5, all strategies can reduce the gap of travel times between the two routes. As the same traffic signal configurations are arranged for the two routes in scenario 3, 4, and 5, the travel time differences between the two routes are small (which is reflected by the mean values in Table 2). The mean value and standard deviation for scenario 4 are smallest among all test scenarios. One possible explanation is that the traffic lights located near to the entrance in scenario 4 enable the local information strategies to incorporate the congestion resulted from the traffic signals.

4 Conclusions

In the urban traffic system, traffic signals contribute a large proportion of travel delay. This paper has investigated the eleven information feedback strategies have been examined from system and user aspects for the first time, based on the developed two-route traffic systems controlled by traffic signals.

A number of conclusions can be drawn from the experimental results obtained for a set of simulated scenarios. None of the test strategies is able to improve the road capacity achieved without guidance for the two-route systems with traffic lights installed on both roads. This inefficiency is likely rooted in the fact that none of them explicitly contains the information on the congestion caused by traffic signal. To improve the road capacity for the signalized roads, further work is required with a special focus on the incorporation of traffic signals. Secondly, the average flux and the number of vehicles obtained from all experiments indicate that TTFS is the worst one in terms of system optimality when the dynamic type of vehicles become majority among all en-route vehicles. Thirdly, TTFS, MVFS, CCFS, WCCFS, ICCFS, and WMVFS, which belong to the category of global information strategy, can effectively reduce the average travel time when the proportion of dynamic vehicles is large. Finally, the experimental results for travel time indicate that the congestion-based strategies of CCFS, WCCFS, and ICCFS can better approximate the UE, implying the congestion information is more important in the signalized traffic system. Nevertheless, the examination on the eleven strategies is limited to the traffic system with signalized interactions where the flow rates do not change.

Therefore, it would be interesting to further investigate the information strategies on more complex systems with traffic lights. Also, the further research will focus on a new information strategy which can accommodate the travel delay rooted from the traffic signal.

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