A weighted mean velocity feedback strategy in intelligent two-route traffic systems*

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Information feedback strategies can influence the traffic efficiency of intelligent traffic systems greatly. Based on the more practical symmetrical two-route scenario with one entrance and one exit, an improved weighted mean velocity feedback strategy (WMVFS) is proposed, which is not sensitive to the precision of global position system (GPS) devices. The applicability of WMVFS to different weight factors, aggressive probabilities, densities of dynamic vehicles, and different two-route scenarios (symmetrical scenario and asymmetrical scenario with a speed limit bottleneck) is analyzed. Results show that WMVFS achieves the best performance compared with three other information feedback strategies when considering the traffic flux and stability.

Keywords: traffic flow, cellular automaton model, weighted mean velocity feedback

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1. Introduction

Traffic flow consists of roads, vehicles, drivers, and the environment, which interact and form a complex system. To describe the complex behaviors of traffic flow, physicists have modeled traffic flow from different perspectives, such as macroscopic models,[1–4] mesoscopic models,[5–7] and microscopic models. Typical microscopic traffic flow models are car-following models[8–11] and cellular automaton (CA) models.[12–14] Based on these models, the evolvement process of traffic flow can be simulated in different scenarios, which can be used in traffic flow control and forecast in an intelligent transportation system (ITS) and can increase road capacity.

How to select a path with the lowest cost from the start point to the end point is a common problem for travelers. As an important part of an ITS, an advanced traveler information system (ATIS)[15] can provide travelers with real-time traffic information and help travelers to select paths. Due to the dynamic allocation of traffic flows in ATIS, the dynamic requirements of every traveler can be satisfied and the capacity of transportation infrastructure can be increased. Here, the core issue is which parameter can be used to describe the road situation.

Recently, some information feedback strategies were proposed based on the traffic information of roads and vehicles. In a symmetrical two-route scenario with one entrance and two exits,[16] there are two routes which have the same length from the entrance to the exit. Drivers can select one route according to the feedback information displayed on the information board at the entrance. There are some typical feedback strategies, such as the travel time feedback strategy (TTFS),[16] the mean velocity feedback strategy (MVFS),[17] and the congestion coefficient feedback strategy (CCFS).[18] When considering the above core issue, different parameters are used to describe the road situation, such as mean velocity in the MVFS. With the Nagel–Schreckenberg (NS) model, simulation results show that when considering the traffic flux and stability, the performance of the MVFS is better than that of the TTFS,[17] and the CCFS is better than the MVFS.[18] Based on the CCFS, some improved strategies were proposed. Dong *et al.* proposed the prediction feedback strategy (PFS),[19] the weighted congestion coefficient feedback strategy (WCCFS),[20] and the corresponding angle feedback strategy (CAFS).[21] The PFS uses the current road situation to predict the road situation in the future by computing a congestion coefficient. The predicted congestion coefficient is used as the feedback information at the current time step. The WCCFS and the CAFS give each congestion cluster a different weight according to the position information of each congestion cluster. For asymmetrical two-route scenarios, Sun *et al.* proposed the improved mean velocity feedback (IMVF) strategy and the improved congestion coefficient feedback (ICCF) strategy in Ref. [22].

Although the simulation results show that the CCFS achieves the best performance compared with the TTFS and the MVFS, the congestion coefficient of the CCFS is influenced by the precision of the global positioning system (GPS) devices heavily in practice. However, the precision of GPS devices has less influence on the MVFS. Detailed analysis is shown in Subsection 2.3. Based on this consideration, we proposed the weighted mean velocity feedback strategy (WMVFS) in Ref. [23]. The simulation results in the symmetrical two-route scenario with one entrance and two exits show that the performance of the WMVFS is better than that of the

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MVFS. In this paper, the adaptability of a weighted function is analyzed and a more practical symmetrical two-route scenario with one entrance and one exit[20] is used in simulation.

The rest of the paper is organized as follows. In Section 2, the NS model and the symmetrical two-route scenario are introduced, and the four information feedback strategies of TTFS, MVFS, CCFS, and WMVFS are all depicted in more detail. For the symmetrical two-route scenario with one entrance and one exit, the simulation results and performance analysis are shown in Section 3. To show the applicability to different scenarios, our strategy is used in an asymmetrical two-route scenario in Section 4. Finally, our work is concluded in Section 5.

2. The model and information feedback strategies

2.1. NS model

In the NS model,[12] the road is subdivided into cells and each cell with a length of 7.5 m can contain only one vehicle. Each cell has two states: occupied by one vehicle and empty. The velocity of each vehicle is an integer between zero and $v_{\max}$. The rules are listed below.

1) Acceleration: the velocity v of a vehicle will be advanced as $v_n \to v_n + 1$, if $v_n < v_{\max}$.

2) Slowing down: the vehicle will reduce its speed v_n to gap, if the vehicle sees the next vehicle ahead and gap $< v_n$, where gap is the distance between them.

3) Randomization: with probability p, the vehicle will reduce its speed as $v_n \to \max(v_n - 1, 0)$.

4) Car motion: each vehicle will advance its position as $x_n \to x_n + v_n$.

2.2. Information feedback strategies in a symmetrical two-route scenario

The symmetrical two-route scenario was proposed by Wahle *et al.*[16] to be used in TTFS simulation. Such a scenario gives a system with one entrance and two exits and the lengths of the two routes are the same. When a vehicle arrives at the entrance at each time step and selects one route, the rules in the NS model will be used. However, if the position of the selected route for the new arrived vehicle is occupied by another vehicle, the newly arrived vehicle will disappear. When a vehicle leaves the exit, it will also disappear. A snapshot of the scenario is shown in Fig. 1.[16]

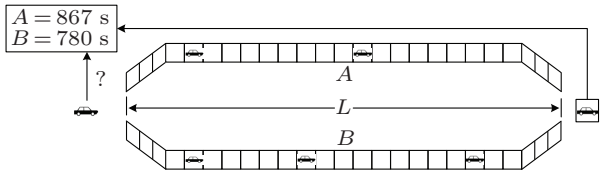


Fig. 1. A snapshot of the symmetrical two-route scenario.

There are two kinds of vehicles: static vehicles and dynamic vehicles. When selecting routes, static vehicles ignore feedback information and select one route randomly. However, dynamic vehicles will select one route according to feedback information. The density of dynamic vehicles is termed S_{dyn}.

Based on the symmetrical two-route scenario, there are three typical information feedback strategies: TTFS, MVFS, and CCFS, each introduced briefly here.

TTFS[16] means the travel time feedback strategy. With the TTFS, the latest travel time is computed and displayed on the board at the entrance and the newly arrived dynamic vehicle can select the route with shorter travel time. The travel time is computed as follows. When a vehicle enters one route and leaves the exit, the times of $t(n)_{\text{in}}$ and $t(n)_{\text{out}}$ are recorded, where n is the index of the vehicle. When a vehicle leaves the exit, the travel time is computed as $t(n)_{\text{out}} - t(n)_{\text{in}}$.

MVFS[17] means the mean velocity feedback strategy. With the MVFS, vehicles on the roads will upload their velocities to the control center at each time step. The control center will compute and display the mean velocity on the board. A newly arrived dynamic vehicle will select the route with larger mean velocity. The mean velocity is computed as

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i, \tag{1}$$

where n is the number of vehicles, and v_i is the velocity of the i-th vehicle.

CCFS[18] means the congestion coefficient feedback strategy. With the CCFS, the vehicles are clustered if they are close enough. At each time step, vehicles on the roads transmit the position information to the control center. The control center will compute the congestion coefficient of each route and display it on the board. A newly arrived dynamic vehicle will select the route with the lower congestion coefficient. The congestion coefficient is computed as

$$C = \sum_{i=1}^{m} n_i^2, \tag{2}$$

where m is the number of congestion clusters, and n_i is the number of vehicles in the i-th congestion cluster. Vehicles on road are divided into several congestion clusters according to adjoining vehicles.

As mentioned in Section 1, considering the precision problem of GPS devices, we proposed the weighted mean velocity feedback strategy (WMVFS). At each time step, vehicles on the roads transmit their position and velocity to the control center. The control center will compute the weighted mean velocity of each route and display it on the board at the entrance. A newly arrived dynamic vehicle will select the route with larger weighted mean velocity. Based on the

weighted function in Ref. [20], the weighted mean velocity of the WMVFS is defined as

$$\bar{V}_w = \frac{1}{L}\sum_{i=1}^{L}\left(k\times\frac{L-x_i}{L}+b\right)\times v_i, \tag{3}$$

where L is the length of each route, v_i is the current velocity of one vehicle at position x_i, k is the weight factor, and b is a constant. If a position is not occupied by one vehicle, the v_i is set to the maximum velocity $v_{\max}$. For the cell at the exit, $x_i = L$, thus the weight is b, which means the cell still has a weight. In this paper, b is set to 0.02. The weight factor k is larger than 0, and the influence of k on flux is analyzed in Subsection 3.2.

No matter which strategy is used, to ensure the traffic balance of two routes and increase road capacity, vehicles arriving at the entrance should select the route with lower congestion. In the MVFS, the mean velocity of vehicles on one route is used to reflect the congestion. Higher mean velocity means lower congestion, and *vice versa*. However, the position of vehicles is not considered in the MVFS. In the WMVFS, the weighted mean velocity of vehicles on one route is used to reflect the degree of congestion. The weight of each vehicle is related with its position. The vehicle has a higher weight if it is closer to the entrance, and a lower weight if closer to the exit. There are two reasons for such a consideration. First, vehicles have more difficulty in entering a route if the entrance is congested. Second, the traffic congestion close to the entrance will increase if a vehicle enters the route under the circumstances. Thus the traffic congestion has a higher influence on traffic flow if it is closer to the entrance.

In the WMVFS, we considered not only the position and velocity of vehicles, but also empty cells. The reason is that the congestion degree cannot be considered enough if only the velocities of vehicles are counted. Consider the scenario in Fig. 2.

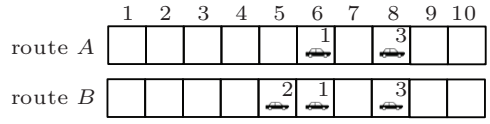


Fig. 2. An example for the computation of the weighted mean velocity.

In Fig. 2, the number on a vehicle is its velocity. If only the velocities of vehicles are counted, Eq. (3) gives the result as

$$\bar{V}_w = \frac{1}{n}\sum_{i=1}^{n}\left(k\times\frac{L-x_i}{L}+b\right)\times v_i, \tag{4}$$

where n is the number of vehicles. For simplification, suppose $L = 10$, $k = 1$, and $b = 0.02$. We can conclude that route B is more congested than route A in Fig. 2. However, according to Eq. (4), the weighted mean velocity of route A $\bar{V}_{wA}$ is 0.54, and $\bar{V}_{wB}$ is 0.71. Here, $\bar{V}_{wA} < \bar{V}_{wB}$, which is contrary to the above conclusion. If we compute the weighted mean velocity according to Eq. (3) with $v_{\max}$ set to 3, $\bar{V}_{wA}$ is 1.33, and $\bar{V}_{wB}$ is 1.27. Here, $\bar{V}_{wA} > \bar{V}_{wB}$, which is same as the above conclusion. Thus a cell without any vehicle cannot be ignored. If one cell does not contain any vehicle, the velocity of that cell is set to $v_{\max}$. The weighted mean velocity of each cell can reflect the congestion degree.

In the WMVFS, velocity and position are the required information. In practice, GPS devices can be used to collect the required velocity and position information in real time. Furthermore, GPRS (general packet radio service, a 2.5G technology) or 3G technologies can be used to upload the required information. When integrating the GPRS module or 3G module with GPS devices, the velocity and position information can be collected and uploaded in real time. These information collection and upload technologies are used in practice, such as the taxi scheduling and managing services in Shanghai. Thus, the WMVFS can be used in practice.

2.3. Influence of the precision of GPS devices

Simulation results show that when considering the traffic flux and stability, the performance of the CCFS is the best, compared with the TTFS and the MVFS. However, in practice, the congestion cluster of the CCFS is not indentified accurately because of the precision of GPS devices. The error of GPS devices is about 10 m due to the influence of weather and buildings along the roads. In the NS model, the length of each cell is 7.5 m. The position computed by a GPS device may differ by one cell from the real position. Under these circumstances, if imprecise positions are uploaded, the calculated congestion coefficient will be inaccurate. Consider the scenario in Fig. 3.

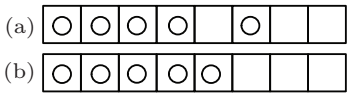


Fig. 3. An example for the influence of imprecise position on the congestion coefficient.

Figure 3(a) gives actual positions of vehicles on a road at one time step. According to the CCFS,[18] there are two congestion clusters and the congestion coefficient is $C_{\text{true}} = 4^2 + 1^2 = 17$. However, due to the precision of GPS devices, the position of the right vehicle is computed with a negative error of one cell in Fig. 3(b). The actual two congestion clusters become one congestion cluster and the congestion coefficient is $C_{\text{count}} = 5^2 = 25$. When computing the congestion coefficient of one route,[18] the congestion coefficient of each congestion cluster is the square of the number of vehicles in that cluster. Because of the amplification effect of squaring, a small error in identifying a congestion cluster will cause a large deviation of the congestion coefficient. And the deviation of congestion coefficient will influence the effect of the

CCFS, which means the CCFS is sensitive to the precision of GPS devices.

However, in the WMVFS, the weighted velocity of each cell is $[k \times (L - x_i)/L + b] \times v_i$. Suppose $L = 2000$, $k = 1$, $b = 0.02$. Considering a vehicle in the middle cell, which gives $x_i = 1000$, if $v_i = 2$, the weighted velocity of the vehicle is 1.04. However, due to the precision of GPS devices, the error of x_i is +1 or –1. Thus the value of x_i will be 1001 or 999, which makes the computed weighted velocity of the vehicle 1.039 or 1.041. The results show that the influence of positioning error on the weighted mean velocity is small, which means the WMVFS is not sensitive to the precision of GPS devices and is more practical than the CCFS. That is why we improved the algorithm based on the MVFS.

2.4. Rules in the scenario with one entrance and one exit

The one entrance and two exits system is used when simulating the typical strategies, such as TTFS, MVFS, and CCFS. However, a more practical symmetrical two-route scenario with one entrance and one exit is proposed in Ref. [20]. If two vehicles want to go out at one time step, they need to compete for the priority for going out. And the loser will move to the last cell of the route. The competing strategy in Ref. [20] is listed below.

(i) At the end of two routes, the car that is nearer to the exit goes first.

(ii) If the cars at the end of two routes have the same distance to the exit, the faster one drives and it goes out first.

(iii) If the cars at the end of two routes have the same speed and distance to the exit, the car in the route which contains more cars drives out first.

(iv) If the rules i), ii), and iii) are satisfied at the same time, then the cars go out randomly.

In our strategy, rule (iii) is excluded because the rule is idealistic. The drivers at the end of routes do not know or care about the number of vehicles on that route. The choice of the driver is influenced by two factors. The first is the competing vehicle on another route, which is objective. The second is the driving mode of the driver, which is subjective.

Laval and Leclercq[24] analyzed different driving modes of drivers based on a realistic dataset. Different drivers can behave aggressively or timidly and the same driver may behave differently at different times. In the scenario with one entrance and one exit, there is only one exit and only one vehicle can go out at one time step. Thus drivers will behave differently at the end of routes. In our strategy, based on the driving mode analysis, the velocity updating rules of vehicles at the exit are modified as listed below.

(I) With probability p_{agg}, $v_n \to \min(v_n + 1, v_{\max})$.

(II) With probability $1 - p_{\text{agg}}/2$, $v_n \to \max(v_n - 1, 0)$.

(III) With probability $1 - p_{\text{agg}}/2$, v_n is updated based on NS rules.

Here, p_{agg} is the aggressive probability of drivers at the exit. The influence of p_{agg} on traffic flow is analyzed in Subsection 3.4.

3. Performance analysis in a symmetrical two-route scenario

3.1. Configurations

The symmetrical two-route scenario with one entrance and one exit is used in this simulation. Here, the NS model is used. The length of one cell is 7.5 m and the length of the each route is 15 km. Thus we get $L = 2000$ cells. The other parameters are: $v_{\max} = 3$, $p = 0.25$. Both routes are empty at the beginning. Vehicles select their route randomly before the 100th time step. From the 101st time step, vehicles at the entrance select a route according to the information feedback strategy. The data are recorded after the 20000th time step. The performance metrics are flux F, mean velocity V_{mean}, and vehicle count N. The flux[18] is defined as

$$F = V_{\text{mean}} * N/L, \tag{5}$$

where V_{mean} denotes the mean velocity of all vehicles on each route, N means the number of vehicles on each route, and L is the length of each route. Flux F can reflect the road capacity.

3.2. Weight factor *k*

In Eq. (3), k is the weight factor. The influence of the weight factor on flux is shown in Fig. 4 and Fig. 5. In Fig. 5, we use the coefficient of variation of flux as the metric to measure oscillation. The coefficient of variation is the ratio of standard deviation to mean. The reason we use the coefficient of variation is shown below. Standard deviation can calculate the variation of the data about the mean value. However, when comparing oscillation, the mean values of two time series should be the same and the comparison of standard deviation is reasonable. We use the coefficient of variation to evaluate the oscillation of time series to avoid the requirement of the same mean when using standard deviation.

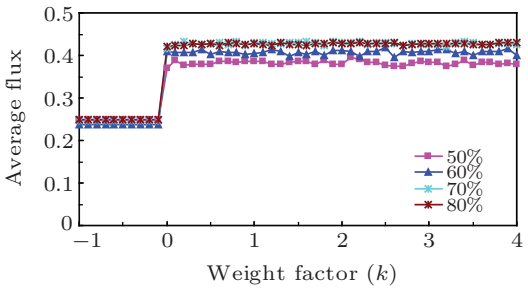


Fig. 4. (color online) Average flux for different weight factor and different p_{agg}. The parameters are $L = 2000$, $v_{\max} = 3$, $p = 0.25$, and $S_{\text{dyn}} = 0.5$. And p_{agg} is set to 50%, 60%, 70%, and 80% respectively.

In the WMVFS, the weight of each vehicle is related to its position. As analyzed in Subsection 2.2, because the traffic

congestion has higher influence on traffic flow if it is closer to the entrance, the vehicle has a higher weight if it is closer to the entrance, and a lower weight if closer to the exit. To ensure the condition, the weight factor k should larger than 0 in Eq. (3). Results in Fig. 4 validate the consideration. In Fig. 4, when $k < 0$, the results of average flux for different $p_{\rm agg}$ are all much less than that when $k > 0$. In fact, $k < 0$ means the vehicle has a lower weight if it is closer to the entrance, and a higher weight if closer to the exit, which is contrary to the idea of the WMVFS. However, if $k = 0$, the position parameter has no influence on the weighted mean velocity according to Eq. (3), which is not consistent with the idea of the WMVFS. Furthermore, when $k > 0$, for different weight factors, the average flux is rather stable for the same $p_{\rm agg}$.

Figure 5 shows that when $k = 0$, the coefficient of variation of flux is rather large, which means flux F has large oscillation. However, when $k > 0$, for different weight factors, the coefficient of variation of flux is rather stable for same $p_{\rm agg}$. In addition, when $k > 0$, for same k and different $p_{\rm agg}$, the values of coefficient of variation of flux do not differ much, which means when $k > 0$, the oscillation of flux F is not sensitive to the weight factor for different $p_{\rm agg}$ and our strategy is robust. Therefore, in all WMVFS simulations below, we set k to 1 with consideration of computation cost. In practice, $p_{\rm agg}$ can be influenced by many factors, such as the driving habits, weather, and road situation. The robustness means our information feedback strategy can be used in different environments.

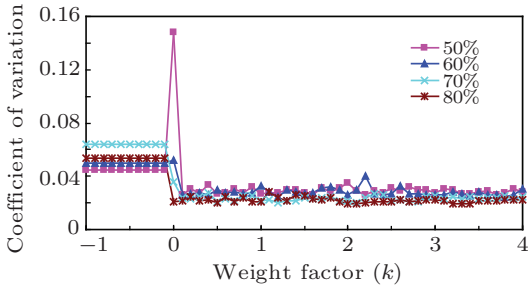


Fig. 5. (color online) Coefficient of variation of flux for different weight factor and different $p_{\rm agg}$. The parameters are set the same as those in Fig. 4.

3.3. Performance comparison

The simulation results of flux F, vehicle count N, and mean velocity $V_{\rm mean}$ of TTFS, MVFS, CCFS, and WMVFS are shown in Fig. 6, Fig. 7, and Fig. 8, respectively. For further analysis, the spatiotemporal diagrams of simulation results are shown in Fig. 9.

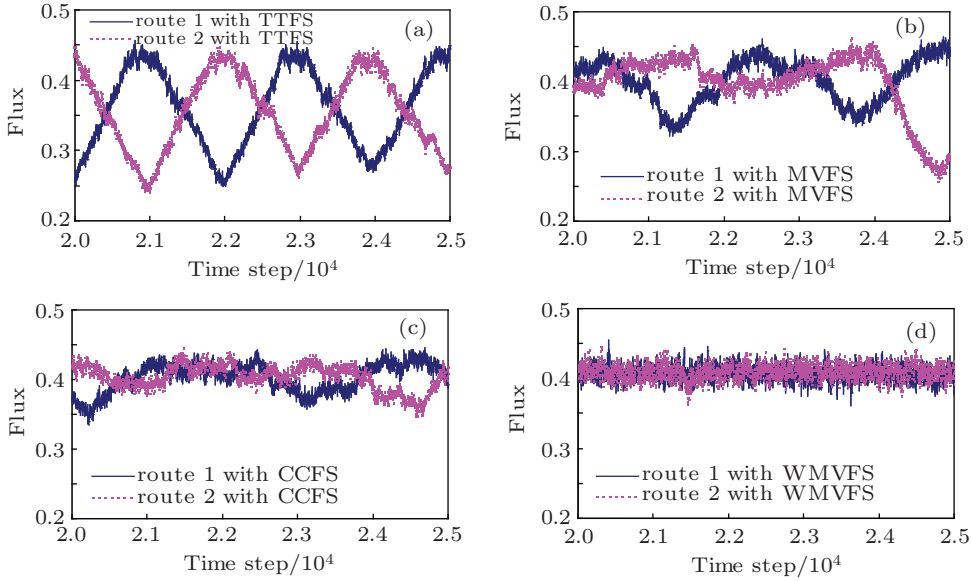


Fig. 6. (color online) Flux F of each route with different strategies. (a) Travel time feedback strategy. (b) Mean velocity feedback strategy. (c) Congestion coefficient feedback strategy. (d) Weighted mean velocity feedback strategy. The parameters are $L = 2000$, $v_{\rm max} = 3$, $p = 0.25$, $S_{\rm dyn} = 0.5$, $p_{\rm agg} = 0.6$, and $k = 1$.

In Fig. 6, the WMVFS achieves great improvement of performance compared with TTFS, MVFS, and CCFS. First, the WMVFS achieves the least oscillation of flux F. Secondly, the average flux with the WMVFS is the highest.

Figure 7 shows the vehicle count with different strategies. With the WMVFS, the road capacity is improved greatly. The vehicle count of each route is more than 650 with the WMVFS. However, the vehicle count of each route is less than 350 with the other three strategies. At the same time, the oscillation of the vehicle count is least with the WMVFS. The results show that the WMVFS achieves the largest accommodating capacity for roads.

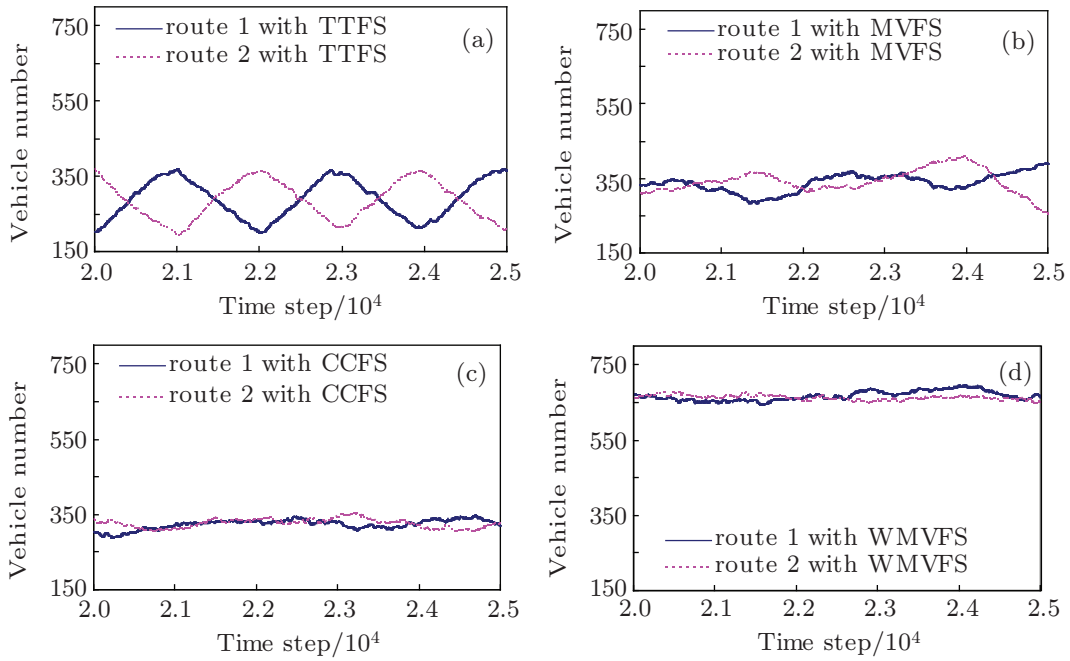


Fig. 7. (color online) Vehicle count N of each route with different strategies. (a) Travel time feedback strategy. (b) Mean velocity feedback strategy. (c) Congestion coefficient feedback strategy. (d) Weighted mean velocity feedback strategy. The parameters are set the same as those in Fig. 6.

Figure 8 shows the mean velocity V_{mean} with different strategies. With the WMVFS, the oscillation of the mean velocity is least. However, the mean value of V_{mean} is the least. That is reasonable. The road capacity can be reflected by flux F, which is proportional to the product of the mean velocity and vehicle count. The road capacity with the WMVFS is the best and the vehicle count is twice of that with other strategies. Thus the mean velocity with the WMVFS is least. Although the mean velocity decreases with the WMVFS, the accommodating capacity increases greatly, which means more vehicles can enter the route.

Figure 9 shows the spatiotemporal diagrams with different strategies. Compared with the other three strategies, the spatial distributions of vehicles with the WMVFS are more stable over time, which means that the flux of a whole road can remain stable over time under the control of the WMVFS. This conclusion corresponds to the results of flux analysis of Fig. 6. In addition, the WMVFS achieves the largest number of vehicles, which is consistent with the results in Fig. 7.

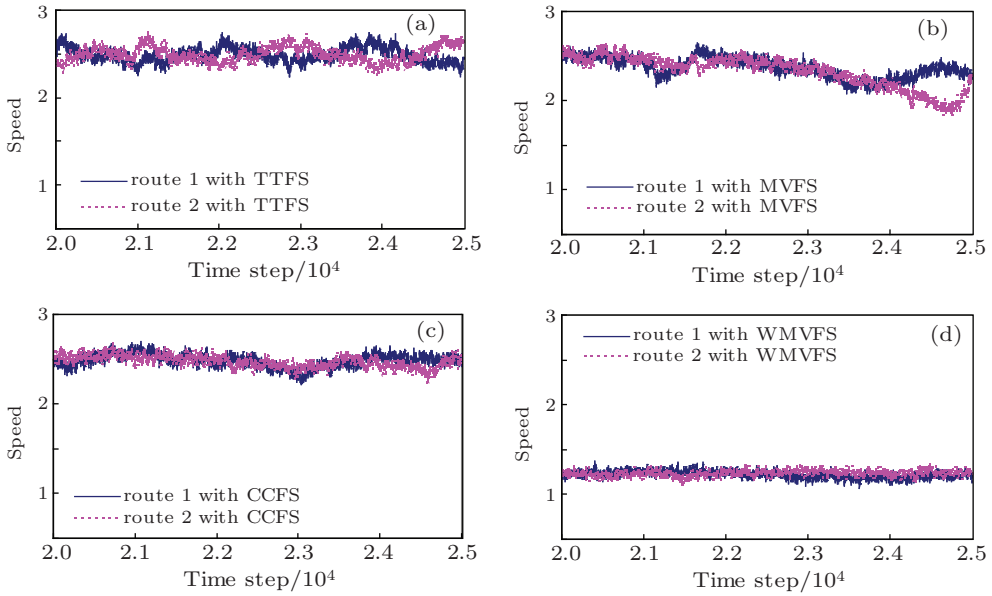


Fig. 8. (color online) Mean velocity V_{mean} of each route with different strategies. (a) Travel time feedback strategy. (b) Mean velocity feedback strategy. (c) Congestion coefficient feedback strategy. (d) Weighted mean velocity feedback strategy. The parameters are set the same as those in Fig. 6.

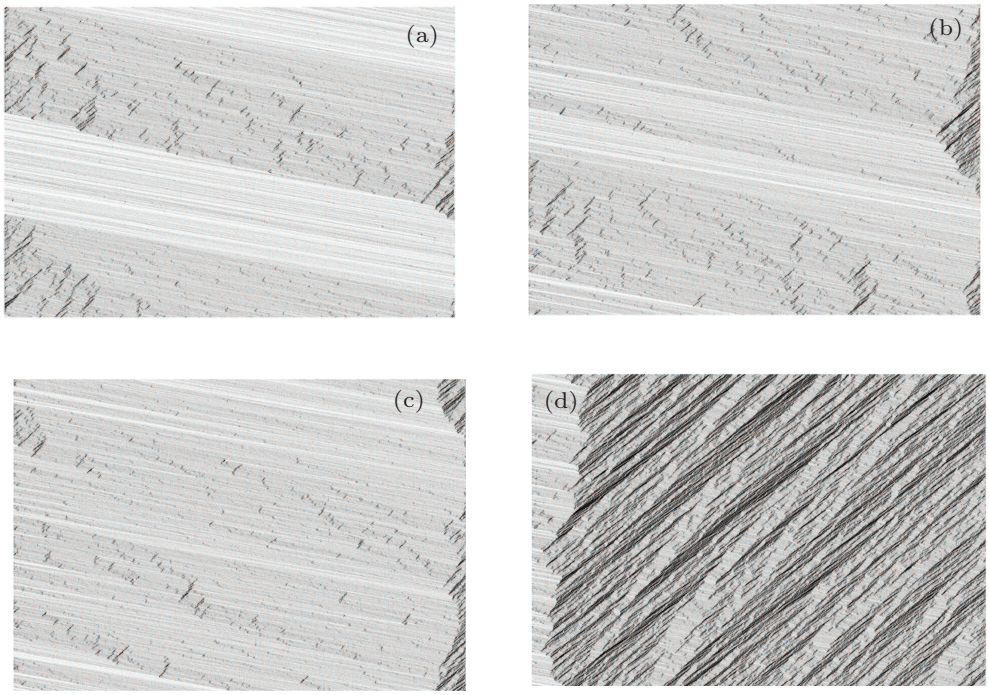


Fig. 9. Spatiotemporal diagrams with different strategies. (a) Travel time feedback strategy. (b) Mean velocity feedback strategy. (c) Congestion coefficient feedback strategy. (d) Weighted mean velocity feedback strategy. The vehicles are moving from left to right, and the vertical direction (down) is (increasing) time. The diagrams begin at the 20000th time step and end at the 23000th time step.

In general, performance with the WMVFS is the best. The reason lies in the better ability of the WMVFS to describe the nonuniform distribution of vehicles on roads, which can occur in two scenarios. The first is the congestion due to one exit. There is only one exit in the symmetrical two-route scenario and only one car can go out at one time step, which may cause congestion at the exit. The second nonuniform distribution reason is randomization, which may cause congestion randomly at an unfixed position on roads. Compared with the other three strategies, the WMVFS can use the weighted function to obtain the road situation and achieve the best performance.

3.4. Influence of aggressive probability p_{agg}

The performance of TTFS, MVFS, CCFS, and WMVFS is analyzed in the above sections with configuration of aggressive probability $p_{\mathrm{agg}} = 0.6$. However, as mentioned in Subsection 3.2, p_{agg} can be influenced by many factors. The results of flux F with different p_{agg} are shown in Table 1. With the WMVFS, for each p_{agg} configuration, the average flux is the largest, and the coefficient of variation is the smallest. Flux F represents the road capacity and the coefficient of variation means stability of flux F. The results in Table 1 show that the performance of the WMVFS is the best with different p_{agg}.

Table 1. Results of flux F with TTFS, MVFS, CCFS, and WMVFS for different p_{agg}.

p_{agg}	Average flux				Coefficient of variation of flux F			
	TTFS	MVFS	CCFS	WMVFS	TTFS	MVFS	CCFS	WMVFS
50%	0.3531	0.3641	0.3677	0.3855	0.1887	0.1727	0.1484	0.0264
60%	0.3568	0.3992	0.4028	0.4048	0.1537	0.0943	0.0476	0.0329
70%	0.3507	0.4193	0.4118	0.4303	0.1621	0.0295	0.0401	0.0214
80%	0.3523	0.4218	0.4229	0.4278	0.1683	0.0233	0.0237	0.0211

3.5. Influence of density of dynamic vehicles S_{dyn}

The performance of TTFS, MVFS, CCFS, and WMVFS is analyzed in the above sections, setting the parameter $S_{\mathrm{dyn}} = 0.5$. However, S_{dyn} may vary greatly in a real environment. The stability is very important when evaluating a strategy when the density of dynamic vehicles changes. The results are shown in Fig. 10 with different S_{dyn}. In Fig. 10, the oscillation range of flux F with WMVFS is the smallest as S_{dyn} increases, which means flux F is not sensitive to S_{dyn}. Meanwhile, most of the mean values of flux F with the WMVFS are larger than those with the other strategies. The results in Fig. 10 show the adaptability of the WMVFS when S_{dyn} varies, and the good road capacity.

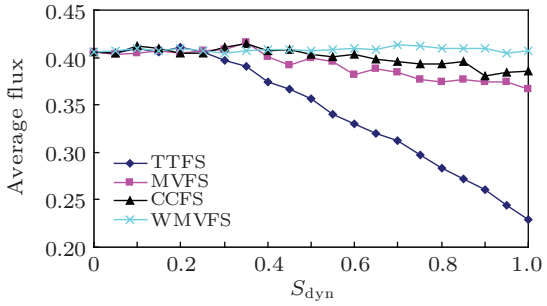


Fig. 10. (color online) Average flux with different strategies and S_{dyn}. p_{agg} is fixed at 0.6.

In addition, Dong *et al.* proposed the WCCFS and compared its performance with TTFS, MVFS, and CCFS in Ref. [20]. Their results show that the WCCFS performs better than the other three strategies. However, our strategy has two advantages compared with the WCCFS. First, the WCCFS is based on the CCFS. In Subsection 2.3, we show that the CCFS is sensitive to the precision of GPS devices, which means the WCCFS suffers from the same problem. Although the simulation results of the WCCFS and the WMVFS are similar, the WMVFS is more practical than the WCCFS because the WMVFS is not sensitive to the precision of GPS devices. Second, in Ref. [20], the optimal weight factor k for the best flux is set to -1.98 based on the simulation results. However, with the WMVFS, the flux F is not sensitive to the weight factor as mentioned in Subsection 3.2, which means the WMVFS is more robust.

4. Performance analysis in the asymmetrical two-route scenario

In the above simulations, the two routes are symmetrical. However, in a real environment, asymmetrical two-route scenarios also exist. Sun *et al.*[22] proposed an asymmetrical two-route system with a speed limit bottleneck, as shown in Fig. 11.

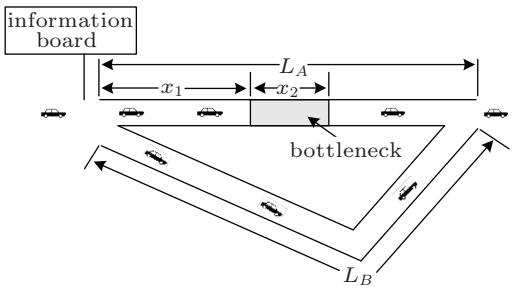


Fig. 11. Asymmetrical two-route system with a speed limit bottleneck in the middle of the route A. The parameters are $L_A = 15$ km, $L_B = 22.5$ km, $x_1 = 6.375$ km, and $x_2 = 2.25$ km.

Based on the scenario, Sun *et al.* proposed the improved mean velocity feedback (IMVF) strategy and the improved congestion coefficient feedback (ICCF) strategy in Ref. [22]. For IMVF, the feedback information is computed as $L/\langle v\rangle$, where L is the route length and $\langle v\rangle$ is the mean velocity of vehicles on the road. For ICCF, the feedback information is computed as C/L, where C is the congestion coefficient.

In the same scenario, for the WMVFS, the feedback information is $L/\bar{V}_w$. A newly arrived dynamic vehicle will select the route with less $L/\bar{V}_w$. In Ref. [22], the length of route A is 15 km and route B is 22.5 km, which means $L_A = 2000$ cells and $L_B = 3000$ cells. Other configurations are: $p = 0.25$, $S_{dyn} = 0.5$, $p_{agg} = 0.6$, $k = 1$, $x_1 = 850$ cells, $x_2 = 300$ cells. The maximum velocities in the unlimited region and in the limited region are 3 and 1, respectively. In our simulation, configurations are same as in Ref. [22]. The simulation results of flux F of IMVF, ICCF, and WMVFS are shown in Fig. 12.

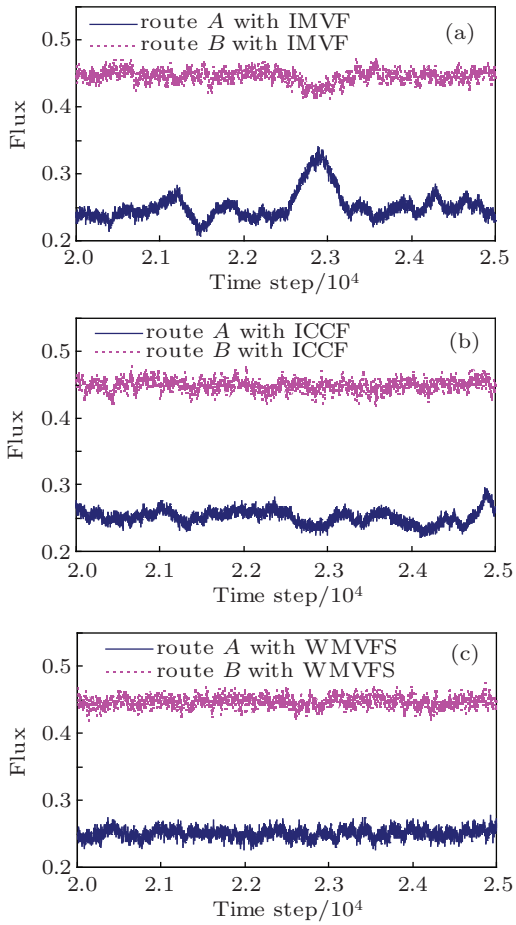


Fig. 12. (color online) Flux F of each route with different strategies in asymmetrical two-route scenario. (a) Improved mean velocity feedback strategy. (b) Improved congestion coefficient feedback strategy. (c) Weighted mean velocity feedback strategy.

In Fig. 12, results of the three strategies show similar average flux F and small oscillation of route B without bottleneck. However, the oscillation of route A with bottleneck is least with the WMVFS, which means it achieves the best performance compared with the other improved strategies pro-

posed in Ref. [22]. Regarding a nonuniform distribution of vehicles, in addition to the two scenarios mentioned in Subsection 3.3, the bottleneck on roads can also cause nonuniform distribution of vehicles on roads. Compared with IMVF and ICCF, the WMVFS possesses a better ability to describe the nonuniform distribution in such scenario and thus achieves the best performance.

In Subsection 3.2, the influence of the weight factor k on flux F is analyzed. The conclusion is also valid in the asymmetrical two-route scenario, as shown in Fig. 13 and Fig. 14. In Fig. 13, there is not much difference between the average flux when $k < 0$ and $k > 0$. However, in Fig. 14, when $k < 0$, the results of the coefficient of variation of flux are larger than those when $k > 0$, which means the flux F has large oscillation when $k < 0$. In addition, figures 13 and 14 show that when $k > 0$, the flux is still rather stable. That is the reason that the weight factor k is set to 1 in the above simulation with the asymmetrical two-route scenario.

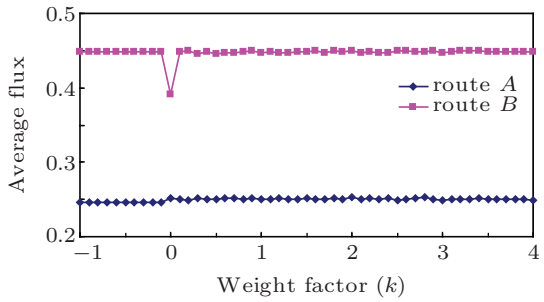


Fig. 13. (color online) Average flux for different weight factors. The route parameters are set the same as those in Fig. 11. $p = 0.25$, $S_{\rm dyn} = 0.5$, $p_{\rm agg} = 0.6$.

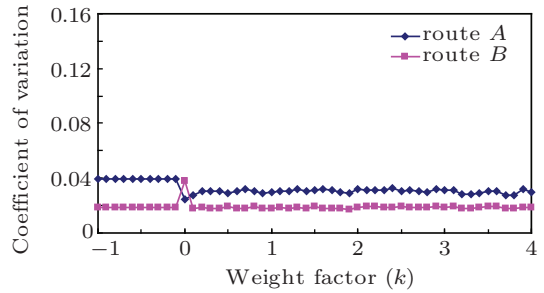


Fig. 14. (color online) Coefficient of variation of flux for different weight factors. The parameters are set the same as those in Fig. 13.

5. Conclusions

In this paper, the adaptability of weighted function is analyzed and a more practical symmetrical two-route scenario with one entrance and one exit is used in simulation. Simulation results show that the performance of the improved WMVFS is better than that of TTFS, MVFS, and CCFS when considering the traffic flux and stability. First, with the WMFVS, the flux F is not sensitive to the weight factor k for different $p_{\rm agg}$, which means our strategy is robust. Second, compared with the other three strategies, TTFS, MVFS, and CCFS, the results of performance metrics, flux F, mean velocity $V_{\rm mean}$, and vehicle count N show the best stability with the WMVFS. Meanwhile, the flux with the WMVFS is the highest and the vehicle count of each route increases greatly. Third, the WMVFS achieves the best performance with different configurations of aggressive probability $p_{\rm agg}$. With the WMVFS, the average flux is the largest, which means the highest road capacity, and the coefficient of variation is the smallest, which means the best stability. Last, with the WMVFS, the oscillation range of flux F is the smallest as $S_{\rm dyn}$ increases, which means the best stability. In addition, the applicability of the WMVFS to a different scenario (asymmetrical two-route scenario with a speed limit bottleneck) is presented and the simulation results also show the best performance of our strategy. The reason lies in that the WMVFS uses the weighted function considering the velocity and position of each vehicle and empty cells, thus can obtain the road situation adequately. The position information collected by GPS systems is not very precise, so it is important that our strategy is not sensitive to the precision of GPS devices.

The asymmetrical two-route scenario with a speed limit bottleneck is used in this paper to validate the applicability of WMVFS to different scenarios. However, in practice, the two routes may be asymmetrical due to other static or dynamic reasons. As to the static reasons, there are different route lengths and road conditions for two routes. As to the dynamic reasons, two routes will be asymmetrical due to unpredictable traffic accidents in a period of time. In addition, Dong *et al.* proposed that the route weight depends on the real route conditions with different exit scenarios and arrival rates, which means the weight of the route is dynamic.[25] For such complex scenarios, the adaptability of the WMVFS needs to be further investigated in the future.

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