Route Guidance Strategy for Heterogeneous Traffic Flow in an Asymmetric Two-Route Scenario

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ABSTRACT

During serious emergencies or congestion, it is very important to alleviate road traffic congestion and improve the road capacity to reduce casualties. Most of the advanced route guidance strategies have been developed for homogeneous traffic flows, to reduce traffic congestion and enhance the road capacity in a symmetric multi-route scenario. Information guidance strategies have rarely been considered for heterogeneous traffic flows, including different types of vehicles with variable velocities and sizes in an asymmetric multi-route traffic system. In this study, we propose a weighted road occupancy feedback strategy (WROFS) for heterogeneous traffic flows including large vehicles and small vehicles, which considers the characteristics of different types of vehicles, such as maximum speed, sizes and position, using real-time information feedback technology to guide traffic flow. Based on comparisons with the two previously proposed advanced strategies, the simulation results obtained in an asymmetric two-route traffic scenarios demonstrate that the proposed strategy improves the road capacity, balances traffic states on two routes, achieves better spatial distribution of traffic flow and enhances the stability of traffic flow about flux, average speed and the number of vehicles.

INTRODUCTION

With the dramatic increase in traffic or the occurrence of some emergency, urban traffic congestion occurs frequently. Traffic congestion need to be handled effectively either by law enforcement personnel at intersections or using effective intelligence route guidance strategies. Maximizing the throughput of traffic in a minimum time and making full use of road resources are traffic optimization issue that continues to be a major challenge for traffic managers.

Recently, due to the rapid development of intelligent transport systems, various information guidance strategies have been developed to efficiently manage traffic and improve road conditions. Many road guidance strategies have been investigated using cellular automata traffic flow models in simple two-route traffic systems with one exit. Wahle et al.[1] first proposed the travel time feedback strategy (TTFS) in a symmetrical two-route scenario. Then, Lee et al.[2] proposed the mean velocity feedback strategy (MVFS). Wang et al.[3] proposed congestion coefficient feedback strategy (CCFS). TTFS, MVFS and CCFS were three typical information feedback strategies. Subsequently, many improved strategies were proposed based on the above three kinds
of feedback strategies, for example, prediction feedback strategy[4], corresponding angle feedback strategy[5], weighted vehicle density feedback strategy (WVDFS)[6], mean velocity difference feedback strategy and congestion coefficient difference feedback strategy[7], vacancy length feedback strategy[8], flux feedback strategy including time flux feedback and space flux feedback[9], and exponential function feedback strategy[10], tour-time feedback strategy[11]. In addition, Zhao et al.[12] introduced a bounded rational threshold into existing feedback strategies to improve their efficiency in terms of their capacity, oscillation, and deviations from the equilibrium. However, despite the increasing number of studies and improvements to the capacity of traffic networks in previous studies, these strategies have mainly been applied to homogeneous traffic flows and in symmetric two-route traffic scenarios. He et al.[13] also found that only MVFS is able to equalize travel time though conducting eight prevalent strategies on an asymmetric two-route traffic network. Although the efficiency of the WVDFS and the weighted mean velocity feedback strategy (WMVFS)[14] is independent of the length and the number of the routes, and they perform better than others in terms of improving the road capacity, but there have been no previous considerations of heterogeneous traffic flows with different maximum velocities and sizes, which are very common on urban roads in developing countries. Moreover, some researchers proposed some new strategies to integrate signal control and route guidance for dynamic pure traffic flow management ([15],[16]), and analysed real world traffic data to predict travel time and maximum journey speed ([17],[18]). To develop a better heterogeneous traffic guidance strategy for traffic management, we introduce a new weighted road occupancy feedback strategy.

SIMULATION SCENARIO AND ROAD GUIDANCE STRATEGY

Simulation Scenario

Here, we investigate a heterogeneous traffic flow and a simple asymmetric two-route traffic scenario for emergency evacuation scenario, which has the “one entrance and two different exits” structure and one-way traffic flow from entrance to exit, as shown in Figure 1. The two roads are asymmetric and the two routes L1 and L2 are set to 500 cells, where each cell corresponds to 7.0 m. The width of each road is 5/7 cell (5.0 m), with two lanes. The entrance indicates the source of the disaster and the exits are the evacuation destinations. During the travel process, all vehicles at the entrance zone begin to evacuate simultaneously. At each time step, there is an evacuee who arrives at the origin and chooses to drive on one road (\(V_p = 1\)). \(V_p\) means the percentage of vehicles (evacuees) arriving at the entrance of traffic system at each time step. The route selection process is described in the following. After selecting a route, the vehicle will move through the system according to the dynamics of the Nagel–Schreckenberg (NaSch) model[19], to simulate heterogeneous traffic flow behavior on routes.

Here, two different types of vehicles are considered when selecting a route: dynamic vehicles and static vehicles. The dynamic vehicles choose the route with the best conditions according to the road guidance information provided on a variable message board (VMB), whereas the static vehicles choose a route randomly, ignoring any advice. Here, the parameter \(S_{dyn}\) denotes the ratio of dynamic vehicles.
Road Guidance Strategy

In general, the traffic conditions on a road can be characterized by the road capacity, e.g., flux and velocity.

The flux is defined as follows:

\[ F_m = V_m \rho = V_m \frac{N_m}{L} \]  

(1)

The average flux is defined as follows:

\[ F_{avg} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{T} F_{ij}}{T \times n} \]  

(2)

where \( V_m \) represents the mean velocity of all the vehicles on a route, \( \rho \) denotes the traffic density on the route, \( N_m \) is the number of vehicles on the route, \( L \) is the length of the route, \( F_m \) is the flux defined by the number of vehicles passing a specific location within a specific time interval, \( F_{ij} \) is the flux on route \( i \) at time \( j \), \( T \) denotes the total time steps, and \( n \) is the number of routes.

Previous studies have employed the vehicle density, velocity, or other features of the route’s conditions to guide the behavior of vehicles, e.g., WVDFS and WMVFS, which are defined as follows.

WVDFS: WVDFS is based on the vehicular density feedback strategy (VDFS), where VDFS computes the vehicle density without a weighted coefficient as the feedback information; however, in WVDFS, the vehicle density on each route is computed using a reasonable weighted function, which is defined as follows.

\[ \rho_w = \sum_{i=1}^{N} \frac{F(n_i)}{L} = \sum_{i=1}^{N} \left( \frac{k \times n_i + b}{L} \right) \]  

(3)

where \( n_i \) denotes the position of vehicle \( i \), \( N \) is the total number of vehicles on a route during a time step, \( L \) is the length of the route, \( k \) is a weighted factor which denotes the weight of distance between the vehicle and the entrance, and \( b \) is a constant that denotes the weight of the cell at the exit.

WMVFS: The vehicle’s position is detected at every time step and the mean velocity is computed for each route with a reasonable weighted function, before it is displayed on a board. The velocities include the velocities of vehicles and empty cells on the roads. The velocity of an empty cell is equivalent to the maximum speed of
vehicles. At the entrance, road users choose the road with a higher mean velocity, which is defined as:

$$\bar{v}_w = \frac{1}{L} \sum_{i=1}^{L} \left( k \times \frac{L - n_i}{L} + b \right) \times v_i$$

(4)

where \(v_i\) denotes the velocity of vehicle \(i\), \(k\) is a constant that denotes the weight of distance between the vehicle position and the exit. The definitions of other parameters are the same as that of formula (3).

Based on the common objectives of the evacuation, we need consider the minimum evacuation time, the minimum system congestion, and the maximum flux as measures. For heterogeneous traffic flow with different sizes and maximum speeds, the traffic congestion state on each route can be represented by the road occupancy. In order to improve road capacity, that is, as far as possible to balance traffic crowded conditions and improve total traffic flux on two routes at each time step, the paper makes the flux, vehicle number and velocity as criteria to reflect road capacity. Less congestion or jams and larger average flux are conducive to speed up to evacuation of vehicles.

For a heterogeneous traffic flow in an asymmetric two-route traffic system, in order to correctly and effectively to guide the behavior of vehicles during the evacuation process, we propose a new road guidance strategy called the weighted road occupancy strategy (WROFS), which is based on the ideas of WVDFS and WMVFS.

**WROFS:** The position data and type data for each vehicle are received by the traffic control center. The control center computes the road occupancy for each road using a reasonable weighted function and records their values. The road users at the entrance select a road with smaller weighted road occupancy.

The weighted road occupancy is defined as:

$$O = \frac{1}{S} \sum_{i=1}^{N} \left( k \times \frac{L - n_i}{L} + b \right) \times S_i$$

(5)

Where \(n_i\) denotes the position of vehicle \(i\) that is the distance from the entrance to the vehicle’s head, \(N\) is the total number of vehicles on a route during a time step, \(S_i\) is the size of vehicle \(i\) that is equal to the vehicle’s length times width, \(L\) is the length of the route, \(S\) represents the area of the route. Each type of vehicle is evaluated a weight \(w\) which indicates an index of relative vehicle size, here \(w=1.5\) is the most appropriate value, which has maximum average flux (see figure 2). \(k\) and \(b\) are constants that denote the weight of distance between the vehicle position and the exit and the weight of the cell at the exit, respectively.

In order to improve road capacity, we define the weighted road occupancy as the index to indicate the extent of road traffic conditions and to maximize the control flux. If the occupancy is greater, the road congestion is higher, and vice versa. The road users at the entrance select a road with smaller weighted road occupancy to reduce traffic congestion and achieve system load balance as far as possible. According to Eq. (5), the occupancy value is related to the size, type, position of vehicles, which have not been considered simultaneously in previous studies. In this equation, we consider the following two aspects of the positions of vehicles. First, if the vehicle is closer to the entrance, the weighted position value \(k \times \frac{L - n_i}{L}\) should be greater, whereas the weighted position value should be smaller closer to the exit. This is because the entrance becomes
more crowded, and thus it is more difficult for vehicles to enter. The entrance congestion will also increase further if the vehicle enters at this time. Second, the traffic has the property of wave propagation. Thus, a traffic jam will spread upstream (the opposite direction from that in which the vehicles are traveling) with time. Therefore, the traffic jam becomes closer to the entrance, which has a greater effect on the traffic flow. Moreover, if the vehicle is larger in size, its road occupancy will be greater. Thus, the maximum number of large vehicles that can be accommodated on the same road is less than that of small vehicles. The value of the type weight $w$ is a constant, which actually reflects the impact of the size and velocity of different types of vehicles on road occupancy.

![Figure 2. Average flux versus weight factor ($w$) under WROFS.](image)

**SIMULATION RESULTS**

**Condition of Experiment**

In order to verify the practicability and adaptability of the proposed WROFS, simulations are carried out in a scenario shown in Figure 1. The lengths of the small and large vehicles are one cell and two cells, respectively. The widths of the small and large vehicles are $2.5/7$ cell (2.5 m). The maximum velocities of the small and large vehicles can’t exceed $v_{1\text{max}} = 3$ cells/time step and $v_{2\text{max}} = 2$ cells/time step, respectively. The proportion of the small vehicles and large vehicles is 75% and 25%, respectively. The ratio of dynamic drivers is set to $S_{dyn} = 0.5$ and the random brake probability is $p = 0.25$. The total number of time steps in the simulation is 15000. During the initial 100 time steps in the simulation, vehicles enter the routes randomly. The feedback starting at the 101st second is based on the 100th second route state which is shown on boards. The road users at the entrance select a route based on a feedback indication of the traffic status displayed on boards. In every analysis of the weight factor, vehicle number, vehicle velocity, and average flux, the initial 10000 iterations are ignored. In general, the traffic capacity of two roads’ exits can’t be exactly same. Here, the evacuation capacities of exit 1 and exit 2 are set to 0.4 vehicle/time step and 0.5 vehicle/time step, respectively.

**Analysis and Discussion of Results**

Figure 3 shows the dependence of the average flux on the weight factor ($k$) using WROFS, two arrival rates $p_V$, and different values for the parameter $b$. Here, the physical sense of average flux is the average number of vehicles passing the exits of the
traffic system at each time step. Figure 3 is based on the average of 11 simulations. When the average flux $F_{avg}$ is higher, the route-processing capacity of the traffic system is better. In the simulations, the capacity of the entrance is set to one vehicle per time step higher than that of the two exits, and 0.6 vehicles per time step lower than that of the two exits in the two exits traffic system, respectively. If the vehicle is farther from the exit, the road is more prone to congestion and the weighted road occupancy of WROFS is greater, and vice versa. According to the slopes of the curves, it is reasonable for the average flux on the two routes in the range of $k > 0$ to be larger than that of the routes in the range of $k < 0$. In addition, when $b = 0.02$, the maximum average flux is the same as that for $b = 2$, which indicates that the value of $b$ plays little contribution to the route saturation state. But the average flux is more stable than that when $b = 2$ with the change of $k$. Figure 3(a) indicates that when $k > 0$ or $k \leq 0$ and $b = 0.02$, the value of the weight factor $b$ has very little effect on the average flux in the two exits system. The positions of the maximum average flux values are in the range of $k > 0$. The same, when $b = 2$, there is no obvious peak position and the average flux on two routes in the range of $k \geq 2$ is higher than that in the range of $k < 2$ under two different arrival rates (refer to Figure 2 (b)). Therefore, we set $k = 1$ and $b = 0.02$ when we use WROFS, with $V_p = 1.0$ and $V_p = 0.6$. As emergency evacuations scenario, we mainly investigate the guidance strategies when the arrival rate at the entrance is $V_p = 1.0$.

![Figure 3](image)

Figure 3. Average flux versus weight factor ($k$) with arrival rate ($V_p$) under WROFS. The parameters are $L_1 = 500$, $L_2 = 600$, $p = 0.25$, and $S_{dyn} = 1.0$. (a) $b = 0.02$, (b) $b = 2.0$.

Figure 4 shows the relationship between the average flux and the ratio of dynamic drivers under various guidance strategies. Under WVDFS and WMVFS, the average flux decreases as $S_{dyn}$ increased. The average flux is the highest with WROFS and the average flux increased as $S_{dyn}$ increased. This is because the performance of WROFS is related to the vehicle position, velocity, and size, which can influence the route capacity. The presence of heterogeneous traffic reduces the capacity under WVDFS and WMVFS with $S_{dyn}$. The practical suitability of a road guidance strategy depends on whether the capacity of the route improves as $S_{dyn}$ increases. Thus, we find that WROFS delivers the best performance among the three feedback strategies. In reality, it is impossible for all vehicles to select a route according to the instructions given by a guidance strategy at each time step, because of some internal and external factors of drivers, such as, different destinations, the herd phenomenon, the reverse psychology of
drivers, information delay by traffic control central, et al. Thus, we test the results obtained when $S_{\text{dyn}} = 0.5$ in the present study.

Figure 4. Average flux versus ratio of the dynamic drivers ($S_{\text{dyn}}$).

Figure 5 and 6 show the variations in the number of vehicles and the flux at each time point on the routes under WVDFS, WMVFS, and WROFS. Figure 5 shows that the number of vehicles on each route is higher under WROFS than that of under WVDFS, but the vehicle number fluctuated little. The number of vehicles on route 2 is higher with WMVFS than that of WROFS (Figure 5 (b)). Although due to different lengths of routes, the difference in the number of vehicles on routes is reasonable, the difference between the numbers of vehicles on two routes is very high. The vehicle drivers mainly select route 2 and route 2 is more prone to traffic jams. These results demonstrate that WROFS can make full use of road resource, reduce fluctuations in the vehicle numbers, and ensure that two roads are utilized more equally. Figure 6 shows the average flux on each road under WVDFS, WMVFS, WROFS and total flux on two routes under the three strategies. Compared with the other strategies, the flux is relatively stable under WROFS, with no obvious fluctuations or periodic oscillation state, and the average flux is almost the same on different routes. However, the flux curves have larger fluctuations under WVDFS and WMVFS than those with WROFS, thereby maintaining better spatial distribution of traffic flow under WROFS. Meanwhile, compared with WVDFS and WMVFS, the average total flux on two routes under WROFS is the highest.
Figure 5. Vehicle number of each route with time step: (a) WVDFS, (b) WMVFS, (c) WROFS.

Figure 6. Average flux of each route with time step: (a) WVDFS, (b) WMVFS, (c) WROFS, (d) total flux on two routes.

Figure 7. Velocity of each route with time step: (a) WVDFS, (b) WMVFS, (c) WROFS.
Figure 7 illustrates the changes in the vehicle velocity on each route versus time using the three different strategies. Figure 7(a) and 7(c) show that the velocity of most of the vehicles is between 1.4 cells/s and 2 cells/s on the two roads when WVDFS and WROFS are used, respectively. However, the velocity of most of the vehicles on route 2 is less than 1.4 cells/s which is smaller than that of on route 1 when using WMVFS, as shown in Figure 7(b). Thus the system more readily goes to the zero state under WMVFS. The zero state means the average speed of vehicles on one road is always less than that of the other road. The result demonstrates that the traffic flow is not distributed reasonably on the two routes, where there is congestion traffic on route 2 but smooth traffic on route 1 all of the time. The exits are fixed, so the choice of routes by drivers at the entrance is the main factor that affects the capacity for traffic evacuation. Thus, the weight on the entrance is very important.

According to the analysis described above, WROFS delivers the best overall performance compared with WVDFS and WMVFS.

CONCLUSIONS

To help travelers’ select appropriate route choices to improve the overall capacity of the roads, the efficiency of many of the strategies developed in most of the previous studies was only investigated with homogeneous traffic flows and in symmetric multi-route traffic systems. By contrast, in our simulation scenario, we considered an asymmetric multi-route scene and heterogeneous traffic flow on the roads. We proposed a new strategy called WROFS. Using the NaSch model as the update mechanism for vehicles, we compared the performance of WROFS with two previously proposed strategies (WVDFS and WMVFS) in two asymmetric two-route scenarios, and we obtained simulation results after changing the heterogeneous vehicle number, speed, and flux at each time step, as well as the average flux according to the ratio of dynamic vehicles. The results of these simulations demonstrated that WROFS obtained better overall capacity of the roads than WVDFS and WMVFS. The traffic flux was improved. The oscillations in the flux and velocity were reduced, as well as the extent of congestion.

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