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Multi-Directional Traffic Flow Fusion Analysis and Modelling for Urban Road Networks Serving Intelligent Transportation Systems

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Abstract. This paper investigates the fusion analysis of complex multi-directional traffic flows in urban areas based on macroscopic fundamental diagrams with the objective of serving urban traffic management subsystems in Intelligent Transportation Systems (ITS) at rush hour or under special circumstances. Therefore, travel efficiency and regional vehicle accumulation are used as basic parameters to model the macroscopic fundamental diagram based on city-regional road network and traffic flow data. According to the directional influx traffic flow, the city area division is defined, thus a multi-directional traffic flow fusion analysis model can be established. The multi-directional traffic flow fusion analysis model is used to accurately describe the changing characteristics of multi-directional traffic flow and the complex integration between them under the influence of directional incoming traffic in urban road network areas. The analytical model also reveals that in addition to the imposition of boundary control management to limit the influx of traffic, the internal flow in the peripheral area also has a non-negligible impact on the overall traffic system operation.

Keywords. Macroscopic Fundamental Diagram, Boundary Control Management, Multi-directional Traffic Flow Fusion Analysis, Urban Intelligent Traffic Management

1. Introduction

How to accurately analyze the complex multi-directional traffic flow is an important research topic in traffic theory, and it is also the key scientific problem of urban intelligent traffic management system, and its spatial and temporal development trend takes an indispensable position in regional traffic flow management, traffic planning and organization, etc. With the rapid growth of car ownership all around the world, the operation mechanism of urban regional traffic system, which originally showed sparse correlation, has become much stronger [1-4]. The traditional intersection traffic state analysis and traffic arterial control methods do not meet the analysis requirements of urban regional traffic system operation, and have limited capabilities the problem of

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regional traffic bottlenecks. Therefore, in order to maintain efficient traffic management, it is necessary to develop theoretical basis and methods for regional traffic analysis of urban road networks based on a macroscopic perspective.

Researches on the issue of macroscopic road network traffic management can be traced back to the 1950s and 1960s: a speed-flow relationship model considering the average width of roads and the average distance between intersections in the road network area was proposed by Wardrop; Herman et al. later divided the urban networks traffic flow into steady traffic flow and temporary stopping flow (traffic flow without any movement due to congestion or poor traffic management), thus proposing the two-flow theory and analyzing the correlation between the average speed and the stopping ratio coefficient in the urban road network. Godfrey also found a correlation between the average flow and the average density. Based on these theoretical studies, Daganzo and Geroliminis et al. first proposed a macroscopic model based on the macroscopic dynamic traffic flow equation that can describe the operation state of urban road networks – the macroscopic fundamental diagram [5-7].

The characteristics of real urban road networks macroscopic fundamental diagram have been extensively investigated with traffic data collected by traffic detectors scattered on the urban road network. Daganzo et al. analyzed the stability of urban road networks with inhomogeneous congestion loading patterns [8]. At that time, researchers were interested in analyzing the characteristics of road networks and assessing the level of traffic management by finding and simulating macroscopic fundamental diagrams with a complete representation of the shape of urban road networks [9-10]. Numerous examples prove that the macroscopic fundamental diagram also presents different characteristics under different road network structures, traffic demands and traffic management measures. Therefore, studies advocating the division for macroscopic fundamental diagram modeling analysis based on the respective traffic characteristics have been conducted extensively. By proposing boundary control management on each urban road network area that presents close correlation after division, not only can traffic management measures be individually tailored to the characteristics of each subarea, but also the efficient operation of the overall traffic area can be ensured [11-14].

However, most of the researches on the topic do not address the impact of complex multi-directional traffic flows in urban areas on the overall regional traffic system. Based on assimilated urban traffic big data, there is a lack of multi-directional traffic flow fusion analysis algorithms and refined modeling methods.

This paper considers the multi-directional traffic flow movement in urban areas theories, the regional traffic management measures that have been imposed, and uses the macroscopic basic graphical model for each area in order to implement multi-directional traffic flow fusion analysis and modeling, and perform calculations for the boundary control management that may be imposed between urban road network areas. These processes provide a sufficient theoretical support for the future refined urban regional traffic flow management in smart cities and lead to improvement of traffic flow operation efficiency.

2. Materials and Methods

During rush hour or under special circumstances, there is often a large targeted influx of traffic into an area via urban arterials. Without special traffic management strategies, this explicitly targeted traffic flow loading pattern not only leads to congestion in the flow area, but also causes traffic spillover due to the area's capacity limitation, which can also cause severe congestion over time. If this state is not interfered or worked on, it can lead to prolonged congestion in the overall urban regional traffic system.

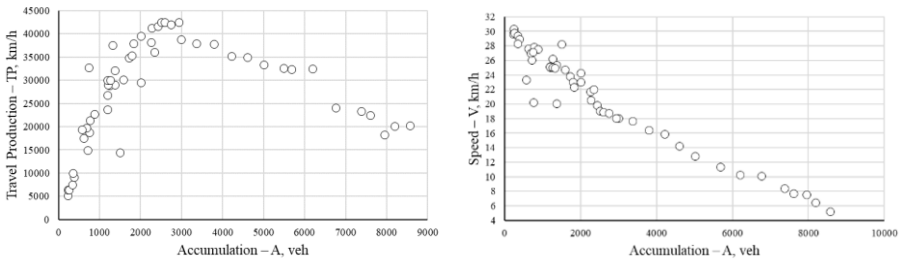
2.1. Macroscopic Fundamental Diagram and Multi-Directional Traffic Flow State Analysis

In order to give a better description of this common traffic scenario and further analyze the complex traffic flow trends, this paper uses the algorithm of regional road network based macroscopic fundamental diagram in addition to multi-directional traffic flow state analysis [15], while its analytical model is based on the data of Rostov-on-Don's 39 km long central city road network. Thus, the results of traffic flow trends are obtained.

In the process of constructing the road network macroscopic fundamental diagram, the traffic flow variable parameter "Travel Production (TP)" was introduced as one of the basic elements in the diagram. The equation of "Travel Production (TP)" is listed below [16-18].

$$P = Av_f \left\{ 1 - \exp\left[1 - \left(1 + \frac{v_j}{nv_f} \left(1 - \frac{A_j}{A} \right) \right)^n \right] \right\} \tag{1}$$

Where: P is the travel efficiency, A is the road network's vehicle accumulation, Aj is the road network's maximum vehicle accumulation, vj is the congestion speed, vf is the free-flow speed, and n is the correction parameter.



(a) (b)

Figure 1. The macroscopic fundamental diagram of Rostov-on-Don's central urban area road network: (a) Curve of the relationship between travel efficiency and vehicle accumulation; (b) Curve of the relationship between average speed and vehicle accumulation on the road network.

While keeping in mind the relationship between travel efficiency and cumulative vehicles in the network (shown in Figure 1(a)), it can be analyzed that the given network area achieves the maximum performance at the cumulative level of about 2500 vehicles and a maximum 10% deviation of parameters in the cumulative level range of 2000-3500. It also shows that the shape of "travel efficiency" as a basic element corresponds to a macroscopic fundamental diagram using the traditional classical parameter "total number of vehicles leaving the network". The relationship between the average network's speed and the accumulated vehicles in the network (shown in Figure 1(b)) can be roughly divided into four states of network operation: state A - steady state, average speed does not fall below 25 km/h; state B - network performance reaches its maximum, but the average speed drops to 17 km/h; state C - congested state, average speed drops to 7 km/h; State D - a "locked" network state, where the entire network is almost immobile due to intense congestion.

2.2. Development of Multi-Directional Traffic Flow Fusion Analysis Model

Therefore, in order to improve the efficiency of traffic flow management, such scenarios are usually divided into urban traffic control areas based on the main traffic flow direction, and the large amount of traffic flow area (the central area). The traffic generation area is set as the peripheral area, so that further traffic control measures can be taken to limit the influx of traffic into the central area.

After a large number of traffic surveys and data analysis, the obtained traffic flow trend can be roughly regarded as the main traffic shift from the "peripheral area" to the "central area", while the "central area" is also shown as the "protected area" which usually falls under the boundary traffic control. The transfer flow (main flow) is named q3, the internal flow of the "protected area" is q1 (origin and destination of the flow are located in this area), and the internal flow of the "peripheral area" is q2.

The basic idea of multi-directional traffic flow fusion analysis model is based on the respective macroscopic fundamental diagrams of "peripheral area" and "protected area", while transfer flow from "peripheral area" to "protected area" is considered to be the main variable parameter. The cumulative change of vehicles between the two areas is studied during the process of imposing different degrees of boundary control management in order to limit the transfer flow into the "protected area". Therefore, the traffic dynamics model is listed in the following equations:

$$\frac{dn_2(t)}{dt} = q_2 - \frac{n_2(t)}{n_2(t)+n_3(t)} \cdot P_2\left(n_2(t)\right) \tag{2}$$

$$\frac{dn_3(t)}{dt} = q_3 - \frac{n_3(t)}{n_2(t)+n_3(t)} \cdot P_2\left(n_2(t)\right) \cdot u(t) \tag{3}$$

$$\frac{dn_1(t)}{dt} = q_1 + \frac{n_3(t)}{n_2(t)+n_3(t)} \cdot P_2\left(n_2(t)\right) \cdot u(t) - P_1\left(n_1(t)\right) \tag{4}$$

Where: q1 is the internal flow in the "protected area"; q2 is the internal flow in the "peripheral area"; q3 is the transfer flow (veh/s).

n1 is the accumulation of vehicles in the "protection area"; n2 is the accumulation of vehicles in the "peripheral area"; n3 is the transfer flow’s accumulation of vehicles (veh).

P1, P2 are the travel efficiencies (km/h) for the "protected" and the "peripheral” areas, respectively;

u is the boundary control management imposed between the "protected area" and the "peripheral area", with a numerical value in the range 0-1 indicating the degree of control imposed (u=0 - no restrictions; u=1 - severe control is applied, i.e. no vehicle is allowed to enter the "protected area");

t - time.

The basic framework of the multi-directional traffic flow fusion analysis model is shown in the following Figure 2.

The multi-directional traffic flow fusion analysis model at time is set to maintain as much efficiency as possible, so that all vehicles can reach the final destination. It is understandable that there is a possibility to create a balance between the input and the output flows, i.e., the flow equilibrium state, because of the pre-existing respective traffic management strategies. The flows that can reach the equilibrium state in both areas are critical for the traffic management strategies development, because their original traffic management strategies are sufficient to cope with them.

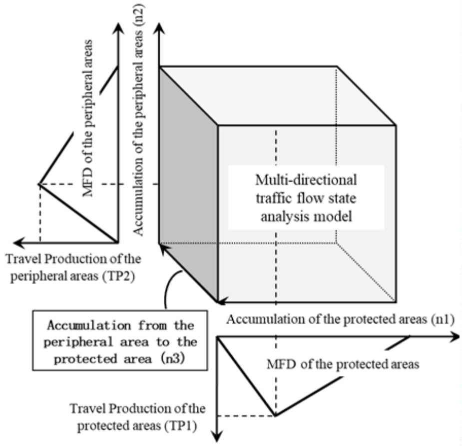


Figure 2. Complex multi-directional traffic flow analysis model.

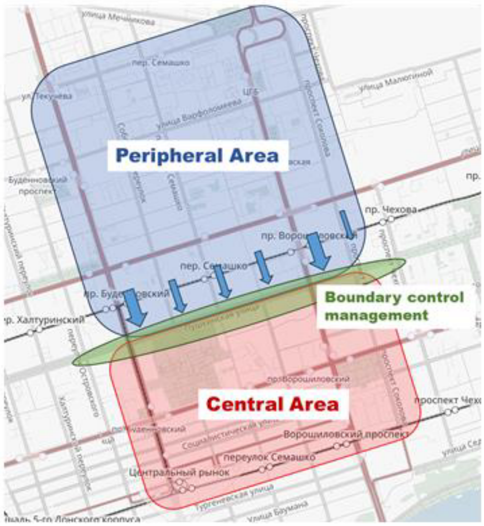


Figure 3. Regional calibration of the study road network (Rostov-on-Don, Russia)

For the practical simulation verification experimental road network in this paper, the central city of Rostov-on-Don (the length of the road network is about 15km) was chosen as the protected area, while the peripheral area was chosen as the area with high traffic generation (the length of the road network is about 25km), and the situation of the studied road network is illustrated in Figure 3.

In the following section, the results and discussion of the full time dimensional multi-directional traffic flow fusion analysis based on 39 km of actual traffic data in Rostov-on-Don, which includes the above-mentioned range of flows that tend to reach the equilibrium state, are given.

3. Results and Discussion of Multi-Directional Traffic Flow Fusion Analysis Based on Rostov-on-Don'S Traffic Data

The multi-directional traffic flow fusion analysis model is based on the traffic dynamics equations (2)(3)(4) enclosed by curves and lines as shown in Figure 4. Within these closed graphs, the kinetic curves representing the different traffic flow states that reach equilibrium over time; these closed graphs are defined as the attraction zone for both areas. In the area outside the attraction zone, the kinetic curves grow to infinity over time, eventually breaking the macroscopic fundamental graph's maximum cumulative vehicle capacity, leading to regional traffic closure.

However, this paper's regional road network showcases a complex correlation of multi-directional traffic flows to the overall attraction zone. When a large influx of steady traffic hits the protected area, the internal traffic in the peripheral area also greatly affects the overall traffic system operation.

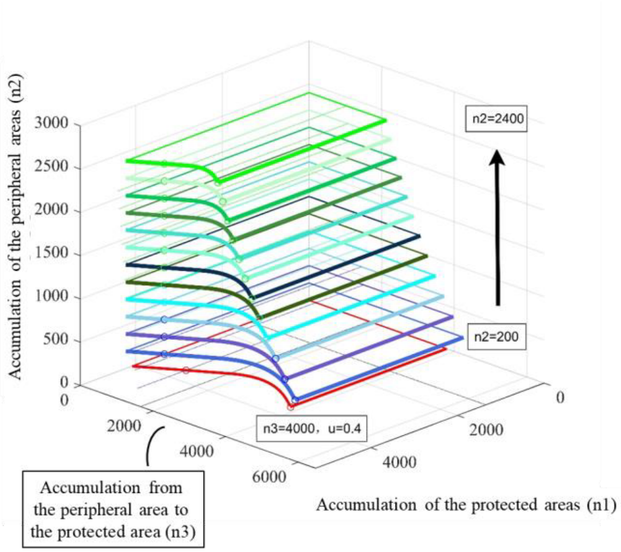


Figure 4. Changing patterns in the accumulation of the periphery of n2 (from 200 to 2400, interval 200) with boundary control u = 0.4, accumulation of movement n3 = 4000, endogenous flow q2 = 2/7 * total demand

First the protected area faces a steady influx of traffic (endogenous flow q2 = 2/7 * total demand), and there is a brief tendency for the attraction zone to expand as the internal flow n2 in the peripheral zone gradually increases from 200. This is due to the fact that the endogenous flow occupies a part of the total flow in the peripheral area, which briefly relieves the pressure of traffic on the protected area. However, as the internal flow n2 in the peripheral area continues to increase, it causes the peripheral area to face the traffic congestion pressure prior to the protected area. After the peripheral area reaches the traffic congestion state, the traffic spillover starts to occur, which results in the central protected area also reaching the traffic congestion state.

In order to verify the validity and accuracy of the multidirectional traffic flow fusion analysis model, using the same parametric experimental environment as in Fig. 4, the attraction zone formed by the upper and lower limits of the transfer flow (n2 = 200-2400 veh) is selected as a validation range and imported into the MFD data of the city of Rostov-on-Don for the simulation and validation of traffic flow trends. The results of the validation work are shown in Figure 5, the resulting traffic flow development curve towards uncontrollable congestion ("escape" curve - light blue curve) occurs outside the attraction zone; the corresponding traffic flow development curve towards a stable equilibrium point of controllable equilibrium ("attraction" curve - deep blue curve) occurs within the attraction zone, which is in line with the predictive analyses.

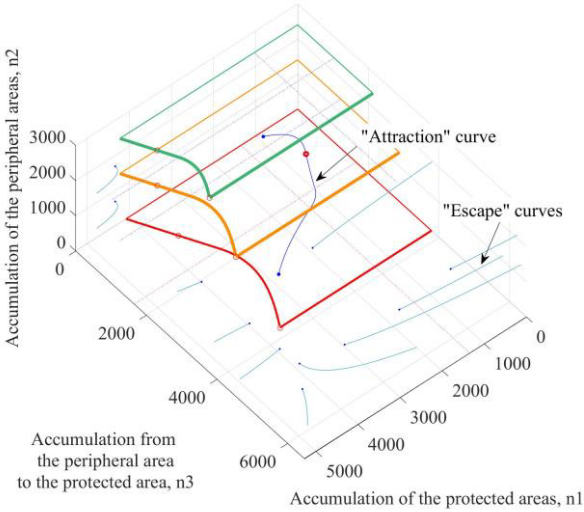


Figure 5. Simulated validation of the multidirectional traffic flow fusion analysis model under the above parameter conditions: Same conditions as in Fig. 4

4. Conclusions

This paper describes the problem of shifting directional traffic flows in urban traffic areas during rush hour or special circumstances, based on which a multi-directional traffic flow fusion analysis model serving the urban intelligent traffic management system is established. Several conclusions can be obtained from the model analysis as follows:

- Introduced travel efficiency as a basic parameter of the macroscopic fundamental diagram can replace the traffic flow efficiency for modeling representation;
- Multi-directional traffic flow fusion analysis model can accurately describe the characteristics of the individual traffic flow changes in the studied area and the complex correlation between them under the influence of urban road network area's incoming directional traffic flows;
- The work in this paper is limited by the availability of real-time traffic flow data on the overall urban road network, which should be monitored and analyzed for blocked urban traffic flow parameters.

In addition to imposing boundary control management to limit the influx of traffic flows into the protected area, corresponding traffic management should also be applied to its internal flows in the peripheral areas to avoid causing excessive congestion in the peripheral areas, thus causing traffic spillover and affecting the operation of the whole traffic system. Future work should focus on the integrated traffic flow management of the delineated study area and the extension of the results of this analytical modeling to a multi-area intelligent traffic flow management strategy for the city.

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