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论文题目：交通流复杂动态特性的微观和宏观模式研究

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中 文 摘 要

当前，社会经济的迅速发展与交通建设的相对滞后，已经构成非常突出的世界性的矛盾。交通拥挤带来的经济损失和环境污染愈演愈烈。基于此，如何充分有效的利用有限的交通资源，以科学的理论来指导交通规划、设计、控制和管理，以缓解失衡的交通供求关系，成为亟待解决的问题。现代交通流理论的研究随之应运而生。

另一方面，作为一种典型的自驱远离平衡态系统，交通流理论研究可以加深人们对人类社会生活中一类伴有复杂相互作用的多体系统远离平衡态时的演化规律的认识，促进流体力学、统计物理、非线性动力学、应用数学、交通工程学等多学科的交叉和发展。因此开展交通流研究，不仅具有重要的工程应用价值，还有其深远的科学意义。

交通流理论研究的目标是要建立能描述实际交通一般特性的交通流模型，以揭示控制交通流动的基本规律。根据研究方法的不同，可以将各种交通流模型分为微观模型，宏观连续模型和中观气体动理论模型。根据交通流理论研究中，对待不同理论模型，应相互包容，共同发展的原则，本文站在交叉学科基点上，综合分析现有不同类型的交通流模型存在的问题，提出了一系列更为符合实际的新模型，并通过理论分析和数值模拟，研究了交通流中的各种非线性现象，探讨了不同类型模型之间的相互联系。本文主要工作如下。

宏观模型方面：

宏观连续模型又称为流体力学模型，它将交通流视作由大量车辆组成的可压缩连续流体介质，关注车流的平均性质如车流平均速度以及平均密度等。它的发展始于 Lighthill-Whitham-Richards(LWR)模型。LWR 模型使用连续方程，辅以平衡速度密度关系，来描述道路上的车辆数目守恒。该模型可以描述一些基本的交通现象如交通激波的形成，交通堵塞的疏散等。但由于该模型假定车流始终处于平衡态，所以不能描述各种非平衡交通现象如时走时停交通等。为了解决 LWR 模型的问题，Payne 提出了一个高阶流体力学模型，他以关于速度的动力学方程取代平衡速度密度关系。Payne 模型可以描述非平衡交通现象，因此高阶流体力学模型在 20 世纪八九十年代得到迅速发展。1995 年，著名学者 Daganzo 指出，已有高阶连续模型中均存在一个大于车流宏观速度的特征速度，这意味着车辆运动将受后方车辆影响，违背了车流各向异性的特性。他指出，这将会导致某些情况下，车辆出现倒退现象。Daganzo 的批判使得迅速发展的高阶连续模型方法进入停滞阶段。

为了解决这一问题，我们提出了一种新的速度梯度(SG)高阶连续模型。在 SG 模型中，我们从双曲型偏微分方程组的特征理论出发，经过推演，得到以速度梯度项取代密度梯度项的动

力学方程。这一取代使得 SG 模型中不存在大于车流宏观速度的特征速度，从而解决了现有模型中存在的不合理特征速度问题，可以更好的描述实际交通。分析指出，在 SG 模型中，不会出现车辆倒退现象。模拟显示，SG 模型可以描述时走时停交通以及局部集簇效应。SG 模型的提出解决了 Daganzo 提出的有关高阶连续模型研究交通流的质疑，为高阶连续模型的进一步发展创造了条件。

我们对 SG 模型做了相关的理论分析，探讨了此模型的线性稳定性，波系结构以及松弛极限下模型解的结构特性。分析指出, 在 SG 模型中存在 1-激波, 1-膨胀波和接触间断, 而无不符合物理意义的 2-激波和 2-膨胀波。

我们使用 SG 模型研究了两个不同密度的车队的汇合情况，包括减速交通和加速交通。研究发现不同密度车队汇合时的各种交通模式可分为稳定模式和不稳定模式两种情况，我们分析了不稳定模式向稳定模式过渡的原因。

我们还用 SG 模型模拟了有加速道的一类匝道交通情况。与微观模型模拟相比，连续模型模拟这类问题显得十分方便。结果表明主道越宽，主道和匝道之间的相互作用就越不明显，这与我们的日常经验是一致的。

微观模型方面：

微观模型研究单个车辆在相互作用下的个体行为。它包括车辆跟驰模型和元胞自动机模型。车辆跟驰理论将交通中的车辆看成是分散的粒子，在假设没有超车的情况下，通过研究个体车辆一辆跟随一辆的方式，来了解交通流的特性。从力学观点来看，它实际上是一种质点系动力学系统。

根据实际交通中，前车对后车的作用不仅与两车之间的距离有关，还与前、后车速度有关这一客观事实，我们提出了一种新的全速度差(FVD)跟驰模型。该模型中，不会产生过大的加速度，启动波速也符合实测结果，亦不会出现撞车现象，从而一定程度上解决了现有模型存在的问题。不仅如此，FVD 模型还是我们直观推导 SG 模型的基础。

模拟显示，FVD 模型可以描述交通失稳、堵塞演化、走走停停交通。我们使用 FVD 模型探讨了限速瓶颈处的车流情况。分析指出，从自由流到同步流的相变与瓶颈性质有关，在长限速瓶颈处是连续相变而在短限速瓶颈处则为一阶相变。我们还用 FVD 模型研究了行人横穿道路问题。模拟发现，行人横穿道路对交通所造成的影响和行人选择的安全系数以及行人之间的相互影响有关。

我们使用车辆跟驰方法研究了 SG 模型中的小扰动传播速度(PSSD)的性质。研究发现，PSSD 与平衡速密关系有关，另一方面，PSSD 还受敏感系数的影响。线性稳定性比较验证了这一模拟的合理性。我们的工作不仅为研究和辨识小扰动传播速度这一很难实测获得的参量提供了一条可行之路，还在一定程度上揭示了微观模型和宏观模型之间的联系。

元胞自动机模型是在上世纪 80 年代提出，90 年代得到迅猛发展的一种新的交通流模型。人们将元胞自动机理论应用于交通流的研究，采用离散的时空和状态变量，规定车辆运动的演化规则，通过大量的样本平均，来揭示交通流规律。

我们使用 Nagel-Schreckenberg(NS)元胞自动机模型模拟了匝道系统交通情况。与以往工作不同，我们不但考虑到了匝道对主道的作用，亦考虑到主道对匝道的作用。模拟指出，匝道车流和主道车流是相互影响的，随着主道流量和匝道流量的不同，共有四种情况：匝道主道均为自由流，主道对匝道形成瓶颈效应，匝道对主道形成瓶颈效应，主道匝道互为瓶颈。

我们还讨论了基于 NS 模型的交通事故发生情况，改进了已有工作中的概率发生条件。模拟显示，当最大速度 vmax=1 时（对应实际速度为 25 公里/小时），事故发生概率为零；当 vmax>1 时，在确定性条件下，事故概率呈二维散布，在非确定条件下，事故概率则仅仅依赖于密度。

提出了两种新的元胞自动机模型：根据实际交通中，前车对后车的作用不仅与两车之间的距离有关，还与前、后车速度有关这一客观事实，提出了一种考虑到前车速度效应的元胞自动机模型。在非确定性条件下，其模拟所得最大流量大于 NS 模型下的最大流量，更接近于实测情况。在确定性条件下，则可以模拟出滞后现象。通过改进刹车灯规则及慢化规则，我们还提出了一种新的模拟同步交通流的元胞自动机模型。 使用这一模型，在宏观上可以模拟出轻同步流和平均速度大于 24km/h 的重同步流，平均速度小于 24km/h 的同步流是不稳定的，它很快演化为堵塞、自由流与轻同步流的共存态，这与实验观测是一致的。

上述理论研究结果，已分别整理成多篇文章，在国际交通流及其交叉学科研究领域最主要的学术刊物“Transportation Research B”、 “ Physical Review E”、 “ Journal of Physics A”、 “Physica A”、 “Chinese Science Bulletin” 等上发表(详见附件)。这些工作也为我们进一步开展交通流理论和应用的深入研究奠定了坚实的基础。

关键词： 交通流； 跟驰模型； 元胞自动机； 连续模型； 自由流； 同步流； 堵塞

Study on the Complex Dynamic Properties of Traffic Flow from the Micro and Macro Modeling

Jiang Rui

ABSTRACT

Currently, the rapid development of the society economy and the relative lag of the transportation have been a prominent problem all over the world. The economic expenses and the environment pollutions caused by the traffic congestion become more and more serious. Thus, how to utilize the limited traffic resources adequately and effectively, how to guide the traffic planning, designing, controlling and management with scientific theory, how to alleviate the unbalanced traffic supply and demand, all of these become urgent problems. Under such situation, the study of traffic flow theory emerges as the times require.

On the other hand, the traffic system is a typical self driven system that is far from equilibrium. Therefore, the study of traffic flow theory may help to better understand the evolution laws of many body systems that are far from equilibrium, promote the cross and development of such subjects as fluid mechanics, statistical physics, nonlinear dynamics, applied mathematics, traffic engineering and so on. Therefore, the traffic flow study is not only important for engineering application but also scientifically significant.

The aim of theory study on traffic flow is to establish the traffic flow models that can describe the general properties of the real traffic and to disclose the basic laws of traffic flow. According to the different study methods, the various kinds of models can be classified into microscopic ones, macroscopic continuum ones and mesoscopic gas-kinetic-based ones. According to the principle that different models should co-develop with each other, this paper presents a series of more realistic new models based on the point of view of cross-discipline as well as the synthetical analysis of the existing different ones. The various nonlinear phenomena in traffic flow are investigated through theoretical analysis and numerical simulations, the relationships between different kinds of models are discussed. The contents of the paper are as follows.

Macroscopic models:

Macroscopic continuum model is also named fluid dynamic model, it regards the traffic flow as the compressible continuum fluid medium composed of many vehicles and focuses on the average properties of traffic flow such as average speed and average density etc. It began from the Lighthill-Whitham-Richards (LWR) model. The LWR model employs the continuum equation, supplied by the equilibrium speed density relationship, to describe the conservation of vehicle number on the road. The model can describe some basic traffic phenomena such as the formation of traffic shock, the evacuation of jams, and so on. However, since it is assumed in the model that the traffic flow is always in equilibrium, the model cannot describe such nonequilibrium phenomena as stop-and-go traffic. To solve the problem in LWR model, Payne

proposed a high-order fluid dynamic model. He replaced the equilibrium speed density relationship by a dynamic equation about average speed. Payne model can describe the nonequilibrium traffic phenomena, therefore, the high-order fluid dynamic models developed very quickly in the 1980s' and 1990s'. In 1995, the well-known scholar Daganzo pointed out that in existing high-order continuum models, there exists a characteristic speed greater than the macroscopic traffic speed. This means that the motion of vehicle is affected by those vehicles behind, which does not obey the anisotropic property of trafficflow. He also pointed out that this will lead to wrong way travel phenomenon under certain situations. The critique of Daganzo makes the quick development of high-order continuum models stop.

To solve the problem, we present a new speed gradient (SG) high-order continuum model. In SG model, we start from the characteristic theory of hyperbolic partial differential equations, and derive out the dynamic equation in which the speed gradient term replaces the density gradient term. The replacement enables the SG model to exhibit no characteristic speed greater than the macroscopic speed, thus it overcomes the unrealistic characteristic speed problem in the existing models and can describe the traffic flow better than the previous ones. It is shown that there is no wrong way travel problem in SG model. The simulations indicate that the model can simulate stop-and-go traffic as well as local cluster effect. The presentation of SG model solves the doubt on the high-order continuum models proposed by Daganzo, and enables the further development of high-order continuum models.

The linear stability, the wave hierarchy and the structural properties of the solutions in the relaxation limit have been discussed. It is found that there exist 1-shock, 1-rarefaction wave and contact discontinuity without the nonphysical 2-shock and 2-rarefation wave.

We have applied the SG model to study the merging of two moving platoons with different densities, including both accelerating traffic and decelerating traffic. It is found that the traffic patterns of merging are classified into stable ones and unstable ones. We have analyzed the reason of the transition from unstable patterns to stable ones.

We have also used the SG model to simulate the on-ramp system with acceleration lane. It is shown that the wider the main lane is, the weaker the interaction between the main road and the on-ramp is. This is consistent with our daily experience.

Microscopic model:

Microscopic model studies the individual behavior of interacting vehicles. It can be further classified into car-following model and cellular automata model. Car-following theory regards the vehicle as particle, it studies the properties of traffic flow by investigating the following behavior of the vehicles under the assumption that there is no overtaking. From the point of view of mechanics, it is a dynamic system of particles.

Based on the fact that the effect of the leading car on the following car depends not only on the distance between the two cars but also on the speeds of the two cars, a new Full Velocity

Difference (FVD) car-following model is presented. The model not only predicts correct start wave speed but also does not lead to unrealistically high acceleration and car accident, thus to some extent, it solves the problems in the existing models. Moreover, the FVD model is also base of derivation of SG model.

The simulations show that FVD model can describe traffic instability, evolution of jams as well as stop-and-go traffic. Applying the model, we have discussed the traffic situation under the speed limit condition. It is shown that the type of the phase transition from free flow to synchronized flow depends on the type of the inhomogeneity. It is second order continuous phase transition if the speed limit region is long and first order if the speed limit region is short. We also use the FVD model to study the effect on the traffic flow caused by the traverse of the pedestrians. It is found that the effect depends on the safe coefficiency chosen by the pedestrians and the interactions between pedestrians.

The propagation speed of small disturbance (PSSD) has been studied using the car-following method. The investigations pointed out that on the one hand, the PSSD depends on the equilibrium speed density relationship, on the other hand, it is affected by the sensitivity parameters. The linear stability comparison verifies the feasibility of the simulation. Our work not only provides us a realistic way to study and to calibrate PSSD, which is difficult to measure from field, but also to some extent discloses the relationship between microscopic and macroscopic models.

Cellular automata traffic flow model was firstly proposed in 1980s' and it quickly developed in 1990s'. The theory of cellular automata is applied into traffic flow study: the discretized space and time and state variables are used, the evolution rules of movement of vehicles are designed. By averaging from simulations, the traffic discipline is disclosed.

We have applied the Nagel-Schreckenberg (NS) cellular automata model to simulate the on-ramp system. Different from previous works, not only the influence of the on-ramp on the main road but also the opposite effect are considered. It is shown that the traffic flows on main road and on on-ramp are affected by each other. With different flow rates on main road and on on-ramp, four cases are classified: the flow on both main road and on-ramp are free; the main road is bottleneck to on-ramp; the on-ramp is bottleneck to main road; both main road and on-ramp are bottleneck to each other.

We have discussed the car accident probability due to careless driving within the framework of NS model. The conditions that the car accident may happen are modified. It is found that when the maximum speed vmax=1 (corresponding to real speed 25 km/h), there is no accident; for vmax>1, the probability covers a two-dimensional region in the deterministic case whereas it only depends on the density in the non-deterministic case.

Two new cellular automata models are presented. Based on the fact that the effect of the leading car on the following car depends not only on the distance between the two cars but also on the speeds of the two cars, we present a cellular automata model that considers the velocity effect of the preceding car. The simulations show that under non-deterministic situation the maximum flow of the new model is much closer to the real measurement than that of the NS model; under deterministic situation the hysteresis can be reproduced. By modifying the braking light rule and the slow-to-start rule, we present a new model that can simulate synchronized flow. Using the model, the light synchronized flow and heavy synchronized flow with average speed greater than 24 km/h can be reproduced. For the heavy synchronized flow with average speed less than 24 km/h, it is unstable and will quickly evolves into coexistence of free flow, light synchronized flow and jam, which is consistent with experimental observations.

The above mentioned theory study results have evolved into a series of papers and those papers were published in such main international journals in the field of traffic flow research as "Transportation Research B", "Physical Review E", "Journal of Physics A", "Physica A", "Chinese Science Bulletin" and so on (for details, see attachment). These works are concrete base for further traffic flow theory and application study.

Key board: traffic flow; car-following model; cellular automata; continuum model; free flow; synchronized flow; jam