Platoon based macroscopic intelligent traffic model

Dong Ngoduy,

Institute for Transport Studies, University of Leeds, UK

Phone: +44 113 343 5345/ e-mail: d.ngoduy@leeds.ac.uk

Information and communication technologies (ICT) are now in the early stages of transforming transportation systems by integrating sensors (remote sensing and positioning), control units (traffic signals, message signs) and automatic technologies with microchips to enable them to communicate with each other through wireless technologies. It is expected that in the coming 5 to 10 years ICT will considerably progress worldwide so that intelligent vehicles, in which the driving tasks are shifted from the driver to the vehicle through autonomous vehicle-to-vehicle and vehicle-to-infrastructure communication, will make up a significant share of the traffic flow. Therefore, it is essential to evaluate the effects of intelligent vehicles on traffic flow dynamics well in advance before they are widely implemented and designed so that the negative effects can be minimised. To date, there have been impressive advances in modelling the dynamics of intelligent traffic systems in the US (Bose and Ioannou, 2003), in Europe (van Arem et al., 2007, Kesting et al., 2008) and in Asia (Kikuki et al., 2003), most existing work relies on a microscopic modelling approach which describes traffic flow at a high level of detail such as the movement of individual vehicles. In this paper, we focus on a macroscopic modelling approach depicting traffic flow at a low level of detail via aggregate traffic variables such as flow, mean speed and density. In contrast to microscopic models, macroscopic models are preferred for real-time prediction and control applications due to their fast computational demand and less calibration effort.

In general, either microscopic or macroscopic models show that intelligent vehicles will stabilize traffic flow with respect to both small and large perturbation such as sudden deceleration or lane changes and lead to significantly increased capacity and reduced travel time. However, in intelligent traffic flow systems, the important functionality of ICT is to arrange vehicles in closely spaced groups, which are called platoons. In such traffic systems, the intra-platoon spacing (that is the vehicle spacing within a platoon) is kept smaller and the inter-platoon spacing (that is the spacing between platoons) is kept larger than in manual traffic systems. Consequently, the current macroscopic traffic models are still insufficient as they do not adequately capture the platoon based operation in intelligent traffic systems. In principle, the platoon based operation will model traffic flow to contain many platoons moving together (instead of many individual vehicles moving together as in manual traffic flow). The behavior of vehicles inside the platoon (hereafter the platooning) is determined by that of the platoon leader (hereafter the platooner) whereas the behavior of the (following) platooner is determined by the leading platoon. To contribute to the state of the art in traffic flow theory, this paper will propose a new platoon based model to describe more realistically the dynamics of intelligent traffic flow.

Platoon based generalized force model

We have chosen the generalized force model of Helbing and Tilch (1998) because it is well suited for the gas-kinetic model as the deceleration (or braking) time is explicitly taken into account and we can derive a macroscopic model which is well tractable and is consistent with the general form of other macroscopic models. According to Helbing and Tilch (1998), the amount and direction of a behavioral change such as the acceleration/deceleration is given by a sum of generalized forces reflecting the different motivations which a driver feels at the same time. Since these forces do not fulfill Newtons laws: *action* = *reaction*, they are called generalized forces. Helbing and Tilch (1998) argued that the success of this approach in describing traffic dynamics is based on the fact that driver reactions to typical traffic situations are more or less automatic and determined by the optimal behavioral strategy. Now let us consider the operations of intelligent vehicles, which are basically moving in a form of many platoons. The dynamics of intelligent traffic flow are described by the interactions between platooners while the platooning will be controlled by their own platooner. If we consider each platoon an entity moving together and the interaction between each platoon also be described by the car-following rule, the dynamics of a platooner *p* with velocity $v_p(t)$ at place $x_p\,(t)$ and time instant *t* is given by the equation of motion:

$$\frac{dv_p}{dt} = \underbrace{\frac{v_0 - v_p}{\tau_p}}_{\text{acceleration}} + \underbrace{f_{p,p-1}\left(v_p, x_p, v_{p-1}, x_{p-1}\right)}_{\text{repulsive interaction}} \tag{1}$$

In equation (1), τ_p and v_0 denote the acceleration time and the desired speed, respectively, of platooner *p*. The *acceleration* term presents the motivation of vehicle *n* to reach its desired speed v_0 while the *repulsive interaction* term describes the motivation of that vehicle to keep a safe distance from the leading platooner $p-1$. The repulsive interaction function $f_{p,p-1}$ is determined as:

$$f_{p,p-1}\left(v_p, x_p, v_{p-1}, x_{p-1}\right) = \frac{V_e\left(s_p\right) - v_0}{\tau_p} - \frac{v_p - v_{p-1}}{\tilde{\tau}_p} H\left(v_p - v_{p-1}\right) e^{-\left(s_p - s_p^0\right)/R} \tag{2}$$

Here:

- s_0^p denotes the speed dependent safe-distance between platoons, defined as $s_0^p = d_p + T_p v_p$. Here, T_p is the time headway between platooners and d_p is the safe distance when the platoons stop completely.
- $s_p = x_p - x_{p-1}$ is the distance headway between platooner *p* and its leading platooner $p-1$
- v_{p-1} is the speed of the leading platooner.
- $H(.)$ denotes a Heaviside function, a dimensionless quantity.
- *R* is the distance measured by a range of the braking interaction (m).
- $V_e(s_p)$ is the headway-dependent equilibrium speed.
- $\tilde{\tau}_p$ is the braking (deceleration) time. Typically, $\tilde{\tau}_p < \tau_p$ since deceleration capabilities of vehicles are greater than acceleration capabilities.

Note that if we neglect the contribution of the finite deceleration time $\tilde{\tau}_p$, the model of Bando et al. (1995) or OV-type model is obtained. There are some important properties of the *repulsive interaction* term as described in literature (Helbing & Tilch, 1998). First, it will guarantee early enough and sufficient braking in cases of large relative speed (v_p-v_{p-1}). Second, this force increases with growing relative speed (v_p-v_{p-1}), but will only be effective, if the speed of the follower is larger than that of the leader (i.e. $H(v_p$-$v_{p-1}) = 1$). Third, it will increase with decreasing distance headway s_p, but vanish for large one (i.e. $s_p \to \infty$).

Let *m* denote the number of vehicles within a platoon. In principle, *m* is dependent on traffic situations. In contrast to the platooners, platooning are moving much closer together are assumed uniformly distributed due to the intelligent device, so we can model the dynamic length of the platoon as:

$$L_p = (m-1)\left(d_0 + T_0 v_p\right) \tag{3}$$

Where L_p is the length of the platoon *p*, T_0 and d_0 denote the time headway and safe distance at complete stops of the platooning. Practically, $T_0 < T_p$ since the platooning drive very close to each other.

The distance (or space) headway between platoons in space (*x*) and time (*t*) now defined as $s_p(x,t) = s(x+L_p, t)$ where *s* is the distance headway between the considered platooner and its direct leading vehicle (i.e. the last vehicle of the leading platoon).

Platoon based gas-kinetic equation

In this section, we apply the gas-kinetic equation to vehicular traffic. This equation will serve as the basis for the subsequent derivation of the platoon based macroscopic model in the full paper. As we will show in the next section, the derivation method uses some exact integration calculations to end up with the macroscopic variables. Let $\rho_p\left(x, v_p, t\right)$ denotes the phase and space density (PSD) distribution of platooner *p* driving with speed v_p ($v_p \in \left[v_p, v_p + dv_p\right]$) at location x ($x \in [x, x+dx]$) and time instant t, where dv_p and dx are small deviation of speed and location of the platooner p, respectively. It is also worth mentioning that, in a traffic problem, a phase-space quantity represents all possible states of traffic flow in time and location. For a homogeneous freeway (e.g. without on-and off-ramps), the platoon based gas-kinetic model reads:

$$\frac{\partial \rho_p}{\partial t} + \underbrace{\frac{\partial\left(\rho_p v_p\right)}{\partial x}}_{\text{convection}} + \underbrace{\frac{\partial}{\partial v}\left(\rho_p \frac{dv_p}{dt}\right)}_{\text{interaction}} = 0 \tag{4}$$

In equation (4), the *convection* term describes the changes of the PSD due to the movement of vehicle platoons along the road while the *interaction* term depicts the changes of the PSD due to the acceleration to the desired speed as well as the deceleration of the platooner.

Let us substitute equations (1)-(2) into the gas-kinetic equation (4) to obtain:

$$\frac{\partial \rho_p}{\partial t} + \underbrace{\frac{\partial\left(\rho_p v_p\right)}{\partial x}}_{\text{convection}} = -\underbrace{\frac{\partial}{\partial v}\left(\rho_p \frac{v_0 - v_p}{\tau_p}\right)}_{\text{acceleration}} - \underbrace{\frac{\partial}{\partial v}\left(\rho_p \frac{V_e\left(s_p\right) - v_0}{\tau_p} - \rho_p \frac{v_p - v_{p-1}}{\tilde{\tau}_p} H\left(v_p - v_{p-1}\right) e^{-\left(s_p - s_p^0\right)/R}\right)}_{\text{deceleration}} \tag{5}$$

In equation (5) the deceleration is determined by the interaction between the following platooner and the leading platoon, speed of which is defined by the leading platooner. From equation (5), we will generate a macroscopic model in which the platoon based driving behaviour has been incorporated. This is the subject of the full paper.

References

Bando, M., K. Hasebe, A. Nakayama, A. Shibata, and Y. Sugiyama (1995). Dynamical Model of Traffic Congestion and Numerical Simulation. *Physical Review E, 51*, 1035-1042.

Bose, A. and P. Ioannou (2003). Analysis of traffic flow with mixed manual and semi- automated vehicles. *IEEE Transactions on Intelligent Transportation Systems*, 4, 173-188.

Helbing, D., and B. Tilch (1998). Generalized Force Model of Traffic Dynamics. *Physical Review E, 58*, 133-138.

Kesting, A., M. Treiber, M. Schonhof and D. Helbing (2008). Adaptive Cruise Control Design for Active Congestion Avoidance. *Transportation Research Part C, 16*, 668-683.

Kikuchi, S., N. Uno and M. Tanaka (2003). Impacts of Shorter Perception-Reaction Time of Adapted Cruise Controlled Vehicles on Traffic Flow and Safety. *Journal of Transportation Engineering, 129*, 146-154.

van Arem, B., H. Driever, P. Feenstra, J. Ploeg, G. Klunder, I. Wilmink, A. Zoutendijk, Z. Papp, B. Netten (2007). Design and evaluation of an integrated full-range speed assistant, *Technical Report No. DR0280/B*, TNO, the Netherlands.