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RESEARCH PAPER

Two-Vehicle Dynamics of the Car-Following Models on Realistic Driving Condition

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Abstract: The paper discusses the traffic dynamics in microscopic level and analyzes the dynamics characteristics of the traditional Gazis-Herman-Rothery model, the optimal velocity model with delay, and the intelligent driver model. An essential feature differentiating those models is that the traditional Gazis-Herman-Rothery model only governs the vehicle dynamics in the car-following state, but the other two models encompass larger interaction state including the free-flow state and the acceleration from the vehicle initial state. From this study, it can be concluded: (i) the optimal velocity model and intelligent driver model are more complete than the traditional model; (ii) the existing optimal velocity model may produce an unrealistic vehicle interaction; (iii) the optimal velocity model with a realistic delay can produce a stable interaction, and (iv) the intelligent driver model still needs further development particularly to take into account the driver delay which is an important aspect in the traffic dynamics on the microscopic level, and finally, (v) those three models may produce similar dynamics characteristics.

Key Words: intelligent transportation; optimal velocity model; intelligent driver model; micro-simulation; car-following model

1 Introduction

The continuous-in-time car-following models have been studied for almost 60 years since the early publication of Pipes[1]. This development is well-captured by Backstone and McDonald[2]. At some point, the development converged to the Gazis-Herman-Rothery (GHR) model or the General Motor nonlinear model[3–6]. Despite of this fact, we still find many new developments in this area to address limitations existed in the General Motor nonlinear model. For example, the model becomes more complex when we take into account realistic driving behaviors such as existence of a non-symmetric relationship between vehicle acceleration and its deceleration. To accommodate this fact, Aron[7] and Ozaki[8] suggested differentiating the model parameters for the vehicle acceleration from those for the deceleration. However, the approach increases complexity in implementing the governing equation in a micro-simulation framework because the status of each vehicle, accelerating or decelerating, must be checked on every time-step.

Beside the General Motor nonlinear model, the intelligent driver model (IDM)[6,9,10] and the optimal velocity (OV) model with delay[6,11–14] also receive major attention currently. These two developments seem to be able to address a number of drawbacks of the general motor nonlinear model with a reasonable expense. In the case of IDM, the model has increased its number of model parameters to eight. The general motor nonlinear model only has four parameters including a delay parameter. From those eight parameters, some are used to define the vehicle acceleration, and some for the vehicle deceleration. Unlike the general motor nonlinear model, the user does not require to evaluate the vehicle status because the vehicle acceleration will automatically be governed by relevant model parameters depending on the vehicle state. The model unifies the acceleration and deceleration terms into a single formula, and the acceleration term will dominate the deceleration term when the vehicle accelerates, and vice versa. The optimal velocity method is rather similar to the IDM model. However, the user should supply a complete velocity function, not only model parameters.

In this paper, we review those models mentioned above. Particularly, we look into their features, compare one to others, conclude similarities and differences, and demonstrate that

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those models can produce similar vehicle dynamics by properly tuning their parameters. In addition, we also raise an objection on the optimal velocity function proposed by Koshi et al.[15], which has been considered as realistic by some researchers. In addition, we also scrutinize the stability of the delayed optimal velocity model of Davis[16].

We limit our discussions to those three major models in the microsimulation. Both the GHR model and IDM model were developed on the basis of the stimulus-response model. The IDM is the most recent development in this group. Meanwhile, the OV model is mainly on the basis of the driver desired velocity. Another major model, not discussed in this paper, was developed on the basis of a safe braking distance or a collision-free driving[17–21]. In this group, no differential equation needs to be solved. Hence, the computation cost is quite low. Another group that receives attention these days is those on the basis of the cellular automata[6,22,23]. This particular approach is interesting because of its efficiency and fast performance.

2 Two-vehicle dynamic problem

On the microscopic level of the traffic simulation, a greater attention has been paid to the interaction of vehicles in a lane, particularly between a vehicle and its leader. The two-vehicle dynamic problem is the simplest model on the level that can be used to fully understand the nature of the interaction. Although the problem is extremely simple, but it reveals all necessary features of the car-following interaction and yet, the problem could accurately produce the characteristics of the traffic on the macroscopic level[9]. Therefore, we selected and utilized the two-vehicle problem for the purpose of the present study.

The two-vehicle problem essentially consists of a car approaching its leader. A rather large initial spacing is necessary to fully model the interaction spanning the acceleration state from a zero initial velocity, the free-flow state, and finally the car-following state. We need to note that the modern car-following models, such as the IDM and the OV model, govern those three states, unlike the traditional GHR model that only governs the vehicle dynamics in the car-following stage. This feature is a great advantage of the two models over the traditional model because it significantly simplifies the model implementation.

3 Theory

3.1 Traditional Gazis-Herman-Rothery model

This traditional model[3] has many names: Gazis-Herman-Rothery model, the General Motor nonlinear model, and the L&M model[24]. The first name is clearly after the authors of the seminal paper[3]; the second is after the authors company, and the last name is because the model has the constants m and l. The model can be written as:

$$a_n(t) = \alpha \frac{v_n^m(t) \cdot \Delta v_n(t - t_d)}{\Delta x_n^l(t - t_d)} \quad (1)$$

where $a_n(t)$ is the vehicle acceleration, $v_n(t)$ is the vehicle velocity, Δv_n and Δx, respectively, are the relative velocity and the relative position with respect to the leading vehicle. The model has three parameters α, m, and l, and has a delay of t_d.

Equation (1) was established on the basis of experimental data and an extensive use of the correlation analysis. Its historical development is well-documented by Brackstone and McDonald[2], and also by Gazis[24], which succinctly presented his personal account on the model development. Eq. (1) is nonlinear as Gazis *et al.*[3] so strongly believed; they wrote, “nevertheless it has again been ascertained that a nonlinear model is necessary to account for observed flow versus concentration data. However, it is not clear, on the basis of presently available data, that a somewhat more complicated nonlinear model has any distinct advantages over the simple nonlinear model.”

A large number of research activities have been performed to address the issue of the model parameters m and l. As a result, many values for the parameters existed, and some that regarded as reliable values are reproduced in Table 1. In the table, the values for those parameters are differentiated mostly between vehicle acceleration and deceleration. Even some differentiate them between breaking and no breaking. These treatments on the model parameters make the GHR model harder to be implemented because the vehicle state, accelerating or decelerating, and breaking or no breaking, has to be checked before a proper model parameter is assigned.

3.2 Optimal velocity model

The optimal velocity method proposed by Newell[29] can be expressed as[11,13]

$$a_n(t) = \frac{1}{\tau}(V(\Delta x_n(t) - v_n(t)) \quad (2)$$

with the velocity relaxation time τ, an optimal velocity function $V(\Delta x_n(t))$, and a distance to the leading vehicle Δx.

Furthermore, Bando *et al.*[12] revised Eq. (2) by adding a delay t_d due to the driver reaction time, which is a significant feature in the traffic dynamics. They proposed a delayed-differential equation formula in form:

$$\tau \cdot a_n(t) + v_n(t) = V(\Delta x_n(t - t_d)) \quad (3)$$

Table 1 Most reliable estimates of parameters of GHR model[2]

Source	m	l
Chandler *et al.*[25]	0	0
Herman and Potts[26]	0	1
Hoefs[27] (dcn no brk/dcn brk/acn)	1.5/0.2/0.6	0.9/0.9/3.2
Treiterer and Myers[28] (dcn/acn)	0.7/0.2	2.5/1.6
Ozaki[8] (dcn/acn)	0.9/-0.2	1.0/0.2

Note: dcn/acn: deceleration/acceleration; brk/no brk: deceleration with and without the use of brakes.