A Car-Following Model for Intelligent Transportation Systems Management

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Abstract: - Intelligent Transportation Systems (ITS) needs traffic flow models to provide real time traffic information and to analyze traffic properties. This study proposes a new microscopic traffic flow model to describe car-following process and to represent certain traffic flow phenomena. Driver individual maximum speed is considered to enable the model to reflect the external environment and driver characteristics. The proposed model can explain why speeds and spacing differ among drivers even when the driving conditions are identical. Illustrative simulations are presented. The simulation results indicate that the proposed model is explainable, and it can represent equilibrium and disequilibrium states of microscopic and macroscopic traffic, such as: stable traffic, unstable traffic, equilibrium speed-flow relationship, closing-in, shying-away, capacity drop, and traffic hysteresis.

Key-Words: - Individual maximum speed; Traffic phenomena; Car-following; Driver characteristic; Equilibrium state; Disequilibrium state; Microscopic traffic simulation.

1 Introduction

The increment of vehicle number and life quality request lead to develop Intelligent Transportation System (ITS) in the recent years. Advanced Transportation Management System (ATMS) and Advanced Traveler Information System (ATIS) are the two sub-systems of ITS. Information systems need traffic flow model to provide prediction, such as, travel time prediction. Traffic management systems need traffic flow models to analyze traffic flow so that they can provide better traffic control strategies.

According to the level of detail, traffic flow models can be divided into microscopic, mesoscopic, and macroscopic models [1]. Microscopic traffic flow includes car-following and lane-changing. This study focuses on car-following. Various carfollowing models are reviewed and discussed below.

Pipes [2] proposed a safe-distance model, and applied a very simple rule. The INTRAS [3] model is also a type of safe-distance model. This model assumes that the vehicle follows its leader by maintaining some spacing. It employed a sensitivity factor to describe different driver behaviors. The stimulus-response model [4]-[7] expresses the concept that a driver of a vehicle responds to a given stimulus based on the stimulus and its sensitivity. The psycho-physical spacing model [8]-[10] divides the car-following process into several behavior zones, each with its own behavioral rules. Benekohal proposed the CARSIM model [11], which computes various acceleration rates for different situations and chooses the most suitable one. Fuzzy models [12][13] comprise a set of fuzzy inference rules related to specific driving environments. The intelligent driver model [14] possesses only a few intuitive parameters with realistic values; the model reproduces a realistic collective dynamics, and leads to the plausible microscopic acceleration and deceleration behavior of single drivers. Newell [15] designed a very simple car-following rule for a homogeneous highway in which a vehicle follows the same trajectory as its lead vehicle except for a translation in space and time. However, it did not deal with the question of what determines speed. Zhang & Kim [16] developed a theory for explaining car-following behaviors in multiphase traffic flow. It specifies different functional forms of gap-time for different spacings, and it can reproduce both the so-called capacity drop and traffic hysteresis.

Some researchers reviewed some of the above models pointing out their merits and limitation. Aycin & Benekohal [17] noted that the INTRAS model has difficulty describing different traffic conditions when a single spacing equation is applied to different conditions, such as stop-and-go (congested) and noncongested traffic. The CARSIM model performs car-following by considering the emergency braking of the lead vehicle, but drivers are unable to determine the deceleration capability of their lead vehicle. Chakroborty & Kikuchi [18] observed that sometimes the following vehicle accelerates even though the speed of lead vehicle is slower than its speed (i.e. closing-in), and vice versa (i.e. shying-away). However, the stimulus-response model cannot describe the closing-in and shyingaway phenomena. The stimulus-response model implicitly assumes that the initial condition is an equilibrium condition, but the equilibrium spacing is only a function of the speed at which vehicles stabilize.

Limitations of both the psycho-physical spacing model and of fuzzy models seem less than safedistance models and the stimulus-response model. The psycho-physical spacing model and of fuzzy models can describe most traffic phenomena as behavioral rules vary according to traffic conditions.

According to the above review, simple models that have one or few functions, such as the safedistance and stimulus-response models, cannot describe certain traffic phenomena. On the other hand, simple models are more easily extended to macroscopic traffic flow. For instance, the stimulusresponse model can extend to macroscopic models, such as Greenshield, Greenberg, and Edie models [19]. Models with different rules for different conditions describe traffic flow better. However, involve more complex computations. thev Developing a macroscopic traffic flow model based on these models is extremely difficult.

Behavior varies among different drivers, with some drivers being aggressive and others less so. Drivers may keep different velocities or different spacings under the same conditions. Some traditional car-following models cannot reflect differences among drivers. Some models employ sensitivity or aggressiveness factor to describe differences among drivers, but these factors cannot be measured directly.

This study develops a microscopic traffic flow model that can represent certain traffic flow phenomena, and thus it has the potential for providing real time prediction, and being a tool to analyze traffic properties. The remainder of this paper is organized as follows: Section 2 proposes a car-following model which can reproduce certain traffic phenomena, and the model results are discussed in Section 3. Conclusions are finally drawn in Section 4, along with recommendations for future research.

2 Car-following Model

This study develops a simple car-following model capable of achieving the following. First, the model should describe certain traffic flow phenomena. Second, the model should reflect differences among individual drivers. Third, it should avoid certain deficiencies mentioned above, such as drivers having to determine the deceleration capability of their lead vehicle. Finally, the model should minimize the number of rules employed, and thus it has the capability to provide real time traffic information and be a tool to analyze traffic properties.

2.1 Model Assumptions

The car-following process is influenced by driver characteristics, external environment, and lead vehicle. If there is no lead vehicle, a vehicle will run at a specific speed (its individual maximum speed) influenced only by driver characteristics and external environment. Driving alone, different drivers may run at different speeds on the same road, implying that different drivers (i.e. different driver characteristics) have different individual maximum speeds. Driver individual maximum speed may vary with external environment, such as: freeway, urban street, and sunny versus rainy days. As driver characteristics and external environment are difficult to measure, the proposed model considers individual maximum speed to help reflecting the influence of driver characteristics and external environment. The individual maximum speed of a vehicle can be measured under certain situations. Where no lead vehicle is present, the vehicle speed is the individual maximum speed. Otherwise, if the speed of the following vehicle does not change with lead vehicle speed or spacing, its speed is considered to be its individual maximum speed.

If there is a lead vehicle, and as the spacing decreases, the following vehicle may slow down so that it cannot run at its individual maximum speed. According to the literature, following vehicle speed depends on the speed of the lead vehicle, the speed of itself, and the spacing between vehicles. Hence, the variables of the proposed model are individual maximum speed, the speed of the lead vehicle, the speed of itself, and the spacing between vehicles.

To model the aforementioned phenomena, the proposed model assumes that repulsion and thrust act on the following vehicle, which then sets an appropriate speed accordingly. Fig. 1 presents the proposed model. The model assumptions are listed below:

- 1) Aggressiveness: The model assumes that driver aggression increases with individual maximum speed. Drivers with high individual maximum speed maintain a higher speed or shorter spacing than do drivers with low individual maximum speed under identical conditions, and also have faster acceleration or deceleration.
- 2) Thrust: Each vehicle has its own individual maximum speed, which is regarded as the thrust. The individual maximum speed thus becomes the force driving the following vehicle forward. If there is no lead vehicle, the vehicle will run at its individual maximum speed. Individual maximum speed depends on external environment and driver characteristics, which are not determined car-following process. Individual by maximum speed thus is an exogenous variable.
- Repulsion: Because the lead vehicle can 3) prevent the following vehicle from running at its individual maximum speed, the lead vehicle is considered to be repelling the follower. The repulsion is related to the speed of the lead vehicle, the speed of the follower, and the spacing. Given faster lead vehicle speed or longer spacing, the repulsion should be reduced because drivers will maintain higher velocity under this condition. On the other hand, drivers may slow down if their speed is too fast, and vice versa, leading repulsion to increase with increasing follower speed. As an aggressive driver may perceive the obstacle created by the lead vehicle as being of greater significance, it is also assumed that a driver with a higher individual maximum speed will perceive higher repulsion under the same traffic conditions.
- 4) *Velocity decision:* The following vehicle decides its appropriate velocity based on existing thrust and repulsion, with the appropriate velocity equaling thrust minus repulsion.
- 5) *Safety:* Since some drivers exhibit unsafe behaviors, the proposed model assumes that drivers do not consider safe distance. Drivers only consider the standstill spacing.

Thrust (Individual Maximum Speed)

Fig. 1. Illustration of the car-following concept.

2.2 Modeling

The proposed model is expressed in Eqs. (1) to (5). To describe closing-in and shying-away, the relative speed form is not chosen because it cannot decide whether the acceleration of the following vehicle is positive or negative. If both the lead and following vehicles are running, the follower will choose an appropriate speed, which equals thrust minus repulsion (as shown in (1)). Sometimes the same condition will result in different speeds for different drivers, the type of difference which is indicated by (1).

If the speed of the lead vehicle is zero (as shown in (2)), the following vehicle decelerates its speed so that it can stop before a collision occurs. The distance that the following vehicle can move before collision equals the spacing minus the safe standstill spacing. If the lead vehicle is moving and the following vehicle is stopped, the follower will not start to move immediately. The follower usually remains stopped, and only moves once the spacing is greater than a specific spacing (i.e. the start spacing). The follower then moves at the next time step, with its acceleration equaling its desired start acceleration (as shown in (3)). Finally, if the following vehicle stops and the spacing is less than the start spacing, the follower remains stopped at the next time step (as shown in (4)).

$$\widetilde{V}_{n,t+1} = \nu_{n,d} \left(1 - \exp\left(-\lambda \frac{(V_{n-1,t})^{\alpha}}{(V_{n,t})^{\beta}} \left(\frac{H_{n,t} - S_n}{L}\right)^{\gamma}\right) \right),$$

for $V_{n-1,t} \neq 0 \& V_{n,t} \neq 0$ (1)

$$\widetilde{V}_{n,t+1} = V_{n,t} - \frac{(V_{n,t})^2}{2(H_{n,t} - S_n)}T,$$

for $V_{n-1,t} = 0 \& V_{n,t} \neq 0$

$$V_{n,t+1} = a_{n,d}T,$$

for $V_{n-1,t} \neq 0 \& V_{n,t} = 0 \& H_{n,t} \ge Z_n$
(3)
 $\tilde{V}_{n,t+1} = 0,$ for $V_{n,t} = 0 \& H_{n,t} < Z_n$
(4)

where $\tilde{V}_{n,t+1}$ is the speed of the following vehicle at time step t+1, $V_{n,d}$ is the individual maximum speed of the following vehicle, $V_{n,t}$ is the speed of the following vehicle at time step t, $V_{n-1,t}$ is the speed of the lead vehicle at time step t, $H_{n,t}$ is the position of the following vehicle at time step t, S_n is the safe standstill distance headway of the following vehicle, $\lambda, \alpha, \beta, \gamma, L$ are nonnegative parameters, *T* is the length of a time interval which equals to reaction time of drivers, $a_{n,d}$ is the desired start acceleration of the following vehicle, and Z_n is the minimum start spacing.

Aside from the repulsion and thrust, the speed of the following vehicle also depends on its capability. Vehicle acceleration should be between the maximum and minimum acceleration of that vehicle. Therefore, the proposed model should be modified as shown in (5), where $a_{n,max}$ denotes the maximum acceleration of the follower, $a_{n,min}$ represents the minimum acceleration (i.e. maximum deceleration) of the follower, and *T* is the length of the time interval.

$$V_{n,t+1} = \tilde{V}_{n,t+1}, \quad for \quad a_{n,\min} \le a_{n,t+1} \le a_{n,\max}$$

$$V_{n,t+1} = V_{n,t} + a_{n,\max}T, \quad for \quad a_{n,t+1} > a_{n,\max} \quad (5)$$

$$V_{n,t+1} = V_{n,t} + a_{n,\min}T, \quad for \quad a_{n,t+1} < a_{n,\min}$$

3 Results and Discussion

A car-following model should be calibrated before application. However, calibration of a microscopic traffic flow model is costly. Daganzo [20] mentioned that assumptions of microscopic simulation are difficult to validate because human behavior in real traffic is difficult to observe and measure. Hence, it is better to check that the model can reflect some traffic patterns before calibration. If a model can reproduce real traffic patterns then its calibration is worthwhile. This section presents some single lane car-following simulations. First, microscopic traffic flow phenomena are discussed in Section 3.1. Equilibrium state is represented in Section 3.1.1. Unstable traffic, closing-in, and shying-away are discussed in Section 3.1.2. Macroscopic traffic flow data, such as: flow, density, and space-mean speed, can be measured from the aggregation of individual data. Section 3.2 discusses macroscopic traffic flow phenomena. Macroscopic equilibrium state, capacity drop and traffic hysteresis are discussed in Section 3.2.1 and Section 3.2.2, respectively.

The model parameters for these simulations are: $\lambda = 1$, $\alpha = 1$, $\beta = 1.1$, $\gamma = 1$ L = 20 (they have not been calibrated), $S_n = 5$ m , T = 0.5 sec , $a_{n,\text{max}} = 5\frac{m}{\text{sec}^2}$, $a_{n,\text{min}} = -5\frac{m}{\text{sec}^2}$. Simulations show that the proposed model can describe certain traffic phenomena under identical model parameters.

3.1 Microscopic Traffic Flow Phenomena 3.1.1 Microscopic Equilibrium State

This section discusses the equilibrium state that the spacing between the lead and following vehicles reaches a particular value as time tends to infinity. An earlier paper by Cho and Wu [21] discussed the traffic stability properties of the proposed model. If the lead vehicle is in equilibrium state (i.e., its speed and spacing never change as time passes), and its equilibrium speed is $V_{n-1,e}$. The equilibrium spacing

 $H_{n,e}$ of its follower is as shown in Eq. (6)

$$H_{n,e} = L_r \sqrt{-\lambda^{-1} (V_{n-1,e})^{\beta - \alpha} \ln \left(1 - \frac{V_{n-1,e}}{V_{n,d}}\right) + S_n}.$$
 (6)

The necessary condition for linearized stability of equilibrium state is

$$(1 - D_{n})^{\left(1 - \frac{1}{D_{n}}\right)} \leq \exp\left(\frac{1}{\beta}\right) \cap$$

$$T \leq \left(1 - \left(\beta\left(\frac{1}{D_{n}}\right)\left[\ln(1 - D_{n})\right]\left(1 - D_{n}\right)\right]^{-1}\right), \quad (7)$$

$$\cdot \left(\frac{2\beta(H_{n,e} - S_{n})}{\gamma V_{n-1,e}}\right)$$

and the sufficient condition is

$$(1 - D_n)^{\left(1 - \frac{1}{D_n}\right)} < \exp\left(\frac{1}{\beta}\right) \cap$$

$$T < \left(1 - \left(\beta\left(\frac{1}{D_n}\right) \left[\ln(1 - D_n)\right] (1 - D_n)\right]^{-1}\right), \quad (8)$$

$$\cdot \left(\frac{2\beta(H_{n,e} - S_n)}{\gamma V_{n-1,e}}\right)$$
where $D_n = V_{n-1}/V_n$

where $D_n = V_{n-1,e} / V_{n,d}$.

This section provides numerical examples. An example involving the movements of four vehicles is illustrated below. The individual maximum speeds of the first, second, third and fourth vehicles are 30, 50, 60, and 70 km/hr, respectively. Moreover, the initial speeds of these vehicles are their individual maximum speeds, and the initial spacings are 100 meters.

Fig. 2 shows the car-following trajectories of these four vehicles. As there is no vehicle in front of the first vehicle, the first vehicle runs at its individual maximum speed (i.e. 30 km/hr). According to Eqs. (7)-(8), following vehicles satisfy the necessary and sufficient conditions for linearized stability, therefore, they finally run at equilibrium state. The movement of platoon then stabilizes.

Fig. 3 shows the spacing between these vehicles. All spacings eventually settle at a specific value (i.e. equilibrium spacing). As mentioned in Section 2, Fig. 3 also reflects the model assumption that drivers with higher individual maximum speed maintain a higher speed or a shorter spacing under identical condition.

The equilibrium spacing only depends on the final speed and not on anything else [18]. The following example shows that ultimate spacing depends on the lead vehicle and following vehicle rather than the initial conditions. The individual maximum speeds of the lead and following vehicles are 50 and 60 km/hr, respectively. The initial conditions include the initial spacing and the initial speed of the following vehicle. Six initial condition examples are listed below.





Fig. 2. Car-following trajectories.





Figs. 4 and 5 are the simulation results. Fig. 4 indicates that follower equilibrium speed is determined by the lead and following vehicles. Moreover, Fig. 5 reveals that spacing reaches a single value regardless of initial conditions. Finally, Fig. 4 and 5 indicate that equilibrium spacing depends only on the final speed and not on initial condition.



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Fig. 4. Following vehicle speeds under different initial conditions.



Fig. 5. Spacings under different initial conditions.

3.1.2 Microscopic Disequilibrium State

This section discusses microscopic disequilibrium state. Traffic flow does not always lead to equilibrium state as time tends to infinity, and this is the so-called unstable traffic (If traffic flow leads to equilibrium state as time tends to infinity, traffic is stable). Unstable traffic example is illustrated first. When traffic is not in equilibrium state, vehicles are accelerating or decelerating. The speed of a vehicle increases or decreases depends not only on the relative speed but also on other conditions, such as spacing. Thus, closing-in and shying-away occur, and they are discussed later.

Sometimes unstable traffic occurs. Speed and spacing may change repeatedly over time. For example, when traffic conditions are heavy, vehicles sometimes fall into a stop-and-go situation. An example is shown to illustrate that the proposed model cannot only describe stable traffic, but can also describe unstable traffic. In the following example, the individual maximum speed of the first vehicle is assumed to be 5 km/hr so that it will run at 5 km/hr to simulate the heavy traffic condition. Meanwhile, the individual maximum speeds of the following vehicles are 80 km/hr. Additionally, the initial spacings between lead and following vehicles are 150 meters. Since following vehicles cannot satisfy Eqs. (7)-(8), all following vehicles cannot reach the equilibrium state. Fig. 6 shows the velocity profile for the 7th vehicle in the platoon. It shows the stop-and-go traffic condition in which vehicles sometimes stop and sometimes move.

Sometimes the following vehicle accelerates despite the lead vehicle traveling slower than it is (i.e. closing-in) and vice versa (i.e. shying-away) [18]. The following examples indicate that the proposed model can describe the closing-in and shying-away phenomena.

It assumes the individual maximum speed of the first vehicle (lead vehicle) is 5 km/hr, that of the following one is 90 km/hr, and the initial spacing is 50 meters. Fig. 7 shows the simulation results from the 5th to the 13th time steps (Relative Speed $=V_{n-1,t} - V_{n,t}$). At T=2.5, the lead vehicle is slower than the following vehicle, but the following vehicle accelerates at next time step. The same situation occurs at T=3.5, T=4.5, and T=5.5, and the phenomenon is closing-in.



Fig. 6. Velocity profile under unstable traffic.



Fig. 7. Acceleration and relative velocity (closing-in phenomenon).

Fig. 8 shows an example of shying-away. The individual maximum speed of the lead and following vehicles are 50km/hr and 70km/hr, respectively, and the initial spacing is 20 meters. The lead vehicle is traveling faster than the following one at T=1, but the follower still

decelerates at the next time step. At T=2, T=3, and T=4 the same situations occur. This is the so-called shying-away phenomenon.



Fig. 8. Acceleration and relative velocity (shying-away phenomenon).

3.2 Macroscopic Traffic Flow Phenomena

Macroscopic traffic flow models discuss flow, density, and speed. The relationship between these variables is q = ku, where q denotes flow, kdenotes density, and u denotes speed. Macroscopic equilibrium state is often observed under low density, and is hardly observed under high density. As it is difficult to observed equilibrium state in congested traffic, the flow-density or speed-density data points distribute over a broad region. This section discusses the equilibrium and disequilibrium states of macroscopic traffic flow.

3.2.1 Macroscopic Equilibrium State

If every driver has identical driver behavior (i.e., identical individual maximum speed), the macroscopic equilibrium state can be obtained from the microscopic equilibrium state (i.e., Eq. (6)). The reciprocal of spacing is density, thus flow equals speed divides spacing. When every driver has identical individual maximum speed v_d , the free-flow speed equals v_d . Thus the flow rate of equilibrium speed V_a is

$$V_e \left(L_v \sqrt{-\lambda^{-1} \left(V_e \right)^{\beta - \alpha} \ln \left(1 - \frac{V_e}{v_d} \right)} + S \right)^{-1}, \qquad (9)$$

where S is the averaged safe standstill distance headway. Fig. 10 is the equilibrium speed-flow relationship as estimated by Eq. (9). It is assumed that driver characteristics are homogenous. It shows different free-flow speed result in different speedflow curve.



Fig. 9. Speed-flow relationships [22] (reproduced)





Fig. 9 is the speed-flow relationship of the undersaturated traffic flow for basic freeway segments. The undersaturated flow is regarded as stable traffic, i.e., traffic flow reaches the equilibrium state. Fig. 9 indicates that average speed under identical flow rate and capacity increases with free-flow speed. The speed is insensitive to flow in the low range. Fig. 10 shows that the relationship between free-flow speed and average speed or capacity is similar to that shown in Fig. 9. The estimated speed is also insensitive to flow in the low range. The difference between Fig. 9 and Fig. 10 is the turning point. Fig. 10 shows that if the free-flow speed is higher, drivers can keep his speed as freeflow speed under higher flow rate. On the other hand, drivers with lower free-flow speed must reduce their speed to below free-flow speed under lower flow rate. This is because the proposed model assumes driver aggression increases with individual maximum speed. Compare with Fig.9, Fig. 10 indicates that the proposed model can reflect the equilibrium state of undersaturated traffic flow except the turning point.

3.2.2 Macroscopic Disequilibrium State

Section 3.2.1 discusses macroscopic equilibrium state, and it only discusses undersaturated traffic

flow. If the oversaturated traffic flow is considered, flow-density curve jumps at a particular density. The maximum flow rate of low density is higher than the maximum flow rate of high density. This is the so-called capacity drop which is an important feature of multiphase traffic flow. Koshi et al [23] found that flow-density diagram is similar to a reversed λ . Furthermore, Kerner [24][25] analyzed German data to find that synchronized flow covers a broad region along a line (wide moving jam) under high density.

Static macroscopic traffic flow models describe the relationship between speed and density. It is a one-to-one relationship, and only valid at equilibrium. These relationship models frequently serve as a state equation in dynamic macroscopic traffic flow models. In fact, when traffic flow is not at an equilibrium (i.e. acceleration or deceleration), the speed-density relationship is not one-to-one. The acceleration curve differs from the deceleration curve, known as the traffic hysteresis phenomenon. Maes [26] observed that the deceleration curve lies above the acceleration curve under both light and heavy density. Treiterer and Meyers [26] found that the curves form two hysteresis loops, and the acceleration curve lies above the deceleration curve in situations of low density whereas the deceleration curve lies above the acceleration curve under high density.

This section presents a microscopic traffic flow simulation example and aggregates individual data to reproduce capacity drop and traffic hysteresis. Leutzbach [10] developed a generalized method to measured macroscopic traffic flow data from microscopic traffic flow data. The flow is measured as

$$q = \frac{\sum x_i}{\tau \cdot X},\tag{10}$$

where τ denotes the time length of observation, X represents road length of observation, and x_i is the travel distance of vehicle i. The density is measured as

$$k = \frac{\sum t_i}{\tau \cdot X},\tag{11}$$

where t_i denotes the travel time of vehicle i. Since $q = k \cdot u$, the space-mean speed is

$$u = \frac{\sum x_i}{\sum t_i},\tag{12}$$

The vehicle arrival rate is 700 veh/hr of the simulation, and it is a Poisson distribution. The simulation duration is 10800 seconds, and the length of a single lane road is 4000 meters. The individual

maximum speed of all drivers is a truncated normal distribution. The mean value is 90 km/hr, the standard deviation is 10.8 km/hr, and the upper and lower limits are 122.4 km/hr and 57.6 km/hr, respectively. An incident occurs at 3000m and blocks the exit from $t = 1200 \sec$ to $t = 3600 \sec$, lasting for 2400 seconds.

The flow-density data of the road section between 1000m and 3000m is as shown in Fig. 11, and they are measured every 30 seconds. Fig. 11 illustrates that capacity drop occurs when free flow transits to oversaturated flow. Since $q = k \cdot u$, the secant line of the flow-density diagram is the speed. The dashed line illustrates the free-flow speed, and Fig. 11 indicates that speed is close to free-flow speed under low density. When an incident occurs and blocks the exit, the first vehicle of the platoon is stopped at 3000m, and following vehicles start to decelerate their speed. The density increases as the speed decreases. As the incident lasts for 2400 seconds, all vehicles between 1000m and 3000m are stopped, and the density becomes jam density finally. Since the standstill distance is 5 meters, the jam density is 200 veh/km. After the incident disappears, vehicles start to move, and the density decreases as the speed increases. When the density reaches a particular value, the flow rate reaches the maximum value, i.e., capacity.

The flow-density data of deceleration traffic shows a broad and complex spreading of measurement points. From the viewpoint of microscopic traffic flow, the equilibrium speed of a platoon is the speed of the first vehicle. Since incident occurs, the speed of the first vehicle is zero. As mentioned in Eq. (7) and (8), unstable traffic is likely to occur if the difference between the equilibrium speed and the individual maximum speed is large. Hence, the deceleration traffic is unstable, and the data points spreads widely. After the incident disappears, the equilibrium speed of the first vehicle and the platoon is the individual maximum speed of the first vehicle. The difference between the equilibrium speed and the individual maximum speed is small. Thus, the data points do not spread widely.

Fig. 12 is the trajectory for the speed-density, and the solid and dashed lines are guidance lines illustrating the acceleration and deceleration trends. The solid and dashed lines form a hysteresis loop, and the acceleration line lies above deceleration line. It indicates that speed-density relationships of acceleration and deceleration traffic are different.



Fig. 11. Disequilibrium flow-density relationship.



Fig. 12. Disequilibrium speed-density relationship.

4 Conclusion

This study computationally investigated traffic flow phenomena. The model formulation is mainly based on an estimation of speed with consideration given to repulsion and thrust. The model applies individual maximum speed as a model variable, and thus reflects the difference between different drivers under the same condition. Unlike the application of aggression or sensitivity factor in other carfollowing models, individual maximum speed is not a parameter that should be calibrated, and it can be measured directly. Numerical results confirm that the proposed model can describe the car-following process. The model successfully reflected certain microscopic traffic flow phenomena, such as: stable traffic, unstable traffic, closing-in, and shying-away. This study also examined macroscopic traffic flow phenomena, such as: equilibrium speed-flow relationship, capacity drop and traffic hysteresis. This approach provides an alternative means of simulating and analyzing modern traffic flow for ITS. The model is currently being calibrated with the field data.

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