Block-Moving Approach for Speed Adjustment on Following Vehicle in Car-Following Model

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Abstract. This paper utilizes the traffic flow model of car-following to study the movement of two consecutive vehicles travelling in the same lane of a freeway. The car-following models defined the speed and headway of a moving vehicle but have not analyzed their relation. In the proposed block-moving approach, the following vehicle is considered as a moving object obstructed by another one moving in the same direction. In that, the correlation between the speed and headway of the following vehicle, which are recorded discretely in real time by instruments installed on the following vehicle, is analyzed and processed to avoid collisions caused by the following vehicle. Additionally, the following vehicle must react accordingly to the behaviors of the leading vehicle by increasing or decreasing speed to a desired speed. This study proposed a methodology to effectively determine how much engine or brake force should be made to achieve the desired speed.

Keywords: Car-following · Traffic flow model · Two consecutive vehicles

1 Introduction

On a freeway, vehicles travel successively in lanes where the speed of each vehicle is determined by the speed of its leading vehicle. It is ideal if two vehicles in the same lane travel consecutively at the same speed and keep a constant distance from each other. However, in reality, the speed of a vehicle changes over time and this change affects the travel of the following vehicle. Consequently, the speed of the following vehicle needs to be adjusted accordingly to avoid collisions. Various car-following models have been proposed, some of them apply the data concerning each vehicle to depict the traffic flow as a group of vehicles travelling consecutively on freeway at macroscopic level, others apply the data of several consecutive vehicles to depict the movement of one vehicle at microscopic level.

For two vehicles moving consecutively, this paper considers the leading vehicle (leader) as an obstacle moving relatively with respect to the following vehicle (follower).

P. Cong Vinh et al. (Eds.): ICCASA 2017/ICTCC 2017, LNICST 217, pp. 100–109, 2018.
https://doi.org/10.1007/978-3-319-77818-1_10

To avoid collisions, the follower speed has to be adjusted accordingly over time by making engine force or brake force. We proposed a methodology to detect changes of leader speed based on the data collected from the follower and to determine how much engine or brake force should be made to achieve the desired speed.

This paper is structured as follows. The subsequent section mentions briefly the concepts of car-following models related in the study. The third section analyzes the relation between the acting forces and speed of a vehicle as well as the correlation between the headway and the speed of the follower in the travel of two consecutive vehicles. The fourth section proposes a methodology to effectively determine how much engine or brake force the follower should be affected by. The conclusion section summarizes the results of research.

2 Related Works

Car-following models are considered as half-microscopic, half macroscopic models because the data used in the models not only depict the movement of one vehicle but also the movement of a traffic flow of multiple vehicles [1–3]. Several authors approached car-following models to analyze traffic flow on freeway at the macroscopic level with data related to each vehicle. Others approached car-following models to analyze the data concerning two consecutive vehicles to suppress collisions caused by the follower.

As an earlier known car-following model, the General Motors' model is also known as the stimulus-response model because it depicts the relation between stimulus, which is the difference in speed of leader and follower, and the response of follower driver. The relation of stimulus-response is represented as kinetic equations for one particle [2, 4]. The model considers that the follower drivers are taken a time interval to react against some variation of the leader. As a researching result, the model provides the follower with acceleration at the time point when a reaction is carried out. The acceleration depends on the difference of speed between two consecutive vehicles at the moment of the change of leader speed. The follower acceleration at reacting moment is positive if at the moment of the leader changes speed, its speed is slower than leader speed, and vice versa. The model results in the correlation of speed and acceleration over time between two consecutive vehicles [5]. The General Motors' model demands experiments to obtain the parameters necessary for the calculation of sensitivity coefficient.

The basic optimal velocity model (OVM) as well as its updated models provide with the space headway of a vehicle and the difference on speed of two consecutive vehicles so that the follower driver can achieve the optimal speed. This model assumes that the follower driver can perceive the safe distance based on the speed difference of his vehicle from the leader as well as the safe speed based on its headway [2]. The model is applied for a flow of multiple vehicles travelling in a lane of freeway, where each vehicle demands to receive the data concerning other vehicles of the flow. The optimal velocity model is suitable for intelligent traffic systems (ITS) because drivers can get information concerning other vehicles from the system to determine their optimal speed. The model enables to stabilize traffic and suppress traffic jam because all drivers can find out their optimal speed [6].

The cellular automaton model separates a traffic flow into cells in space and time. It depicts space of flow as road segments of the same length, called space cells, where each space cell has only one state at a time point, occupied or not occupied by vehicles. It also divides time into equal intervals, called time cells, to update the state of space cells. The speed of each vehicle travelling on road is adjusted each time cell based on the information on the state of the space cells in front. The cellular automaton model can be applied suitably for intelligent traffic systems, where vehicles are provided the information on the state of space cells on road surface ahead. However, the model demands to install underground instruments to detect the state of space cells [2, 7].

The Newell model utilizes space-time trajectories on the $\boldsymbol{x}$-$\boldsymbol{t}$ coordinates of two consecutive vehicles to analyze their relative space-time positions, where the slope of a space-time trajectory changes when the speed of the corresponding vehicle changes. Two space-time locations of two trajectories on the $\boldsymbol{x}$-$\boldsymbol{t}$ coordinates at the time point they change speed constitute a rectangular defined by the necessary space headway and the time interval during which the follower driver reacts to the change of the leader. This rectangular represents the relation between the available space headway and the time interval during which the driver has to act on the follower to avoid a collision caused by the follower [7].

3 The Block-Moving Approach

The block-moving approach proposed in this paper is to adjust the speed of the follower in a sequence of two consecutive vehicles travelling in a straight line on an even road (i.e. gradient = 0) with good surface. At any moment, the safety of the two vehicles moving on road depends on their speed and the head distance between the front of follower to the rear of leader considered as a moving block ahead of the follower. As a result, the variation of the leader speed affects the head distance, which in turn affects the safety of the two vehicles. Consequently, the follower speed needs to be adjusted to ensure the head distance in a safety range avoiding collision.

3.1 The Clearance of a Moving Vehicle

The clearance of a moving vehicle is the clear distance necessary for vehicle moving ahead, it depends on the vehicle speed. In this study, a moving vehicle is considered as an object referring to time, i.e. time is the reference variable of vehicle attributes such as speed, headway, etc. [8]. Technically, the data of speed and headway are recorded and processed discretely at time points of regular interval Δt [9]. The interval Δt is so designedly small that during which, the speed of vehicles may be considered as linear.

Moving on road, a vehicle may have one of three speed states including unchanging, increasing, and decreasing. According to the second Newton's law on motion, the change of speed depends on the force acting on vehicle.

$$F(t) = m \cdot a(t) \tag{1}$$

Applying this law for a moving vehicle at the time point t_i:

$$F(t) = F_e(t_i) - F_r(t_i) - F_b(t_i) = m\frac{v(t_i) - v(t_{i-1})}{t_i - t_{i-1}} \tag{2}$$

or,

$$v(t_i) = v(t_{i-1}) + \frac{\Delta t}{m}\left[F_e(t_i) - F_r(t_i) - F_b(t_i)\right] \tag{3}$$

$$d(t_i) \approx \Delta t \cdot v(t_i) \tag{4}$$

$$d(t_i) \approx \Delta t \cdot v(t_i) = \Delta t \cdot v(t_{i-1}) + \frac{(\Delta t)^2}{m}\left[F_e(t_i) - F_r(t_i) - F_b(t_i)\right] \tag{5}$$

where

$F(t)$: the vector sum force of the forces acting on vehicle, including engine force, brake force, other resistance forces such as friction, air resistance, and so on.
m: the mass of vehicle, considered as constant.
$a(t)$: the instantaneous acceleration of the vehicle center at the time point t.
$v(t)$: the instantaneous speed of vehicle at the time point t.
$F_e(t)$: the engine force applied for vehicle at the time point t.
$F_r(t)$: the other resistance forces assumed as constant, $F_r(t) = F_r, \forall t$.
$F_b(t)$: the brake force controlled by controller.
$d(t_i)$: the distance in front of vehicle necessary for its movement during $[t_{i-1}, t_i] = \Delta t$, called the clearance at the time point t_i.

The engine or brake force acts on the movement of vehicle to constitute three speed states, unchanging, increasing, decreasing.

- *Unchanging speed:* At every time point, $F_e(t) = F_r$ and $F_b(t) = 0$, formula (3) becomes $v(t_i) = v(t_{i-1})$, i.e. the speed of vehicle does not change during $[t_k, t_l]$ for $\forall i | i \in [k + 1, l]$
- *Increasing speed:* It is assumed that from time point t_0, the vehicle is acted by a positive engine force F', i.e. $F_e(t_i) = F_r + F' | i = 0, 1, 2, \ldots$ while the brake force still keeps zero $F_b(t) = 0, \forall t \geq t_0$.

Applying to formula (3):

$$v(t_i) = v(t_{i-1}) + \Delta t \cdot \frac{F'}{m} = v(t_0) + i \cdot \Delta t \cdot \frac{F'}{m} \tag{6}$$

Associating formulas (4) and (6):

$$d(t_i) = \Delta t \cdot v(t_i) = \Delta t \cdot v(t_{i-1}) + (\Delta t)^2 \cdot \frac{F'}{m} = d(t_{i-1}) + (\Delta t)^2 \cdot \frac{F'}{m} \tag{7}$$

$$d\left(t_i\right) = d\left(t_0\right) + i \cdot (\Delta t)^2 \cdot \frac{F'}{m} \tag{8}$$

Acting an additional engine force F' on vehicle during the interval $\tau = n \cdot \Delta t$ from time point t_0, the vehicle needs a clearance D to travel ahead. From (8):

$$D(t_1) = d(t_1) = \Delta t \cdot v(t_0) + (\Delta t)^2 \cdot \frac{F'}{m}$$

Generally,

$$D(t_n) = d(t_1) + d(t_2) + .. + d(t_n) = \tau \cdot v(t_0) + \frac{n(1+n)}{2}(\Delta t)^2 \cdot \frac{F'}{m} \tag{9}$$

and

$$v(\tau) = v(n\Delta t) = v(t_0) + n \cdot \Delta t \cdot \frac{F'}{m} \tag{10}$$

The speed $v(t_i)$ in formula (6) is an arithmetic progression with positive common difference of $\Delta t \cdot \frac{F'}{m}$. Formula (7) provides the clearance necessary for the i^{th} period Δt (Fig. 1a). Formula (8) shows that the necessary clearance grows accordingly to a positive common difference of an arithmetic progression. If F' increases, the positive common difference increases, then the necessary clearance grows faster. Specially, formulas (6) and (8) provide the relation between speed and additional engine force as well as between clearance and additional engine force, respectively; they show that the increase of additional engine force results in the rapid increase of speed and clearance.

– *Decreasing speed:* From time point t_0, the vehicle is acted by a brake force F_b, while the engine force returns zero $F_e(t) = 0, \forall t \geq t_0$.

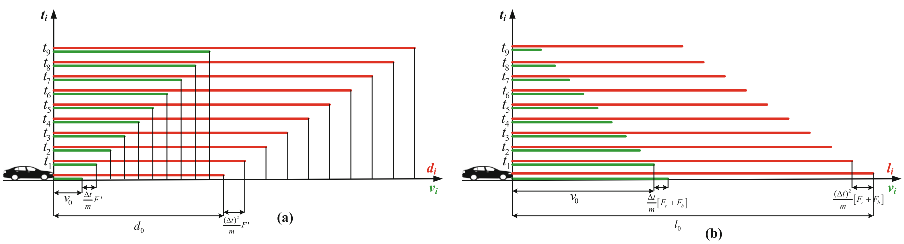

Fig. 1. The speed (green) of vehicle and the clearance (red) necessary for the movement of vehicle at the time points regular-spaced Δt: (a) increasing cumulatively over time according to arithmetic progressions as applying an additional engine force; (b) decrease cumulatively over time according to arithmetic progressions just cutting engine force and applying resistance and/or brake forces. (Color figure online)

Formula (3) becomes:

$$v(t_i) = v(t_{i-1}) - \Delta t \cdot \frac{F_r + F_b}{m} = v(t_0) - i \cdot \Delta t \cdot \frac{F_r + F_b}{m} \tag{11}$$

Formula (5) becomes:

$$d(t_i) = \Delta t \cdot v(t_i) = \Delta t \cdot v(t_{i-1}) - (\Delta t)^2 \cdot \frac{F_r + F_b}{m} \tag{12}$$

$$d(t_i) = d(t_{i-1}) - (\Delta t)^2 \cdot \frac{F_r + F_b}{m} = d(t_0) - i \cdot (\Delta t)^2 \cdot \frac{F_r + F_b}{m} \tag{13}$$

The speed $v(t_i)$ in formula (11) is an arithmetic progression with negative common difference of $\Delta t \cdot \frac{F_r + F_b}{m}$. Formula (12) provides the clearance necessary for the i^{th} period Δt (Fig. 1b). Formula (13) shows that the necessary clearance is reduced accordingly to the common difference of an arithmetic progression. If F_b increases, the negative common difference increases, then the necessary clearance is reduced faster. Specially, formulas (11) and (13) provide the relation between speed and brake force as well as between clearance and brake force, respectively. They show that the increase of brake force results in the rapid decrease of speed and clearance.

3.2 Moving-Block Approach to Adjusting Follower Speed

Studying the movement of two consecutive vehicles in the same lane of a freeway, the problem to be solved is how to adjust the follower speed in accordance with the behaviors of the leader. For solving this problem, the proposed moving-block approach considers the leader as a moving obstacle with respect to the follower to adjust the follower speed suitable for the leader behavior by using data collected from the follower, not requesting data from other sources. The controller of follower has to associate its headway with the clearance necessary for its travelling by increasing or decreasing speed to avoid a collision with the leader.

Technically, the follower can collect its instantaneous speed and the headway from instruments installed on vehicle. The control of the follower is created based on the relation between headway and speed. Based on the length of headway, the speed is controlled by acting an engine or brake force on the vehicle with the suitable intensity (Fig. 2).

$x_f(t)$: the location of the rear of the follower on the axis.
$x_l(t)$: the location of the rear of the leader on the axis.
$v_f(t)$: the instantaneous speed of follower.
$v_l(t)$: the instantaneous speed of leader.
S: the length of follower.

Δt: the sampling period, the time interval between the times recording the values of traffic variables.

$h_f(t)$: the distance from the front of follower to the bump rear of leader is called the space headway of follower, briefly called the headway of follower.

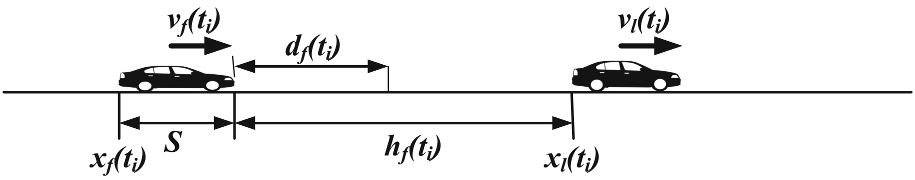

Fig. 2. The variables interacting between two vehicles moving consecutively in the same lane.

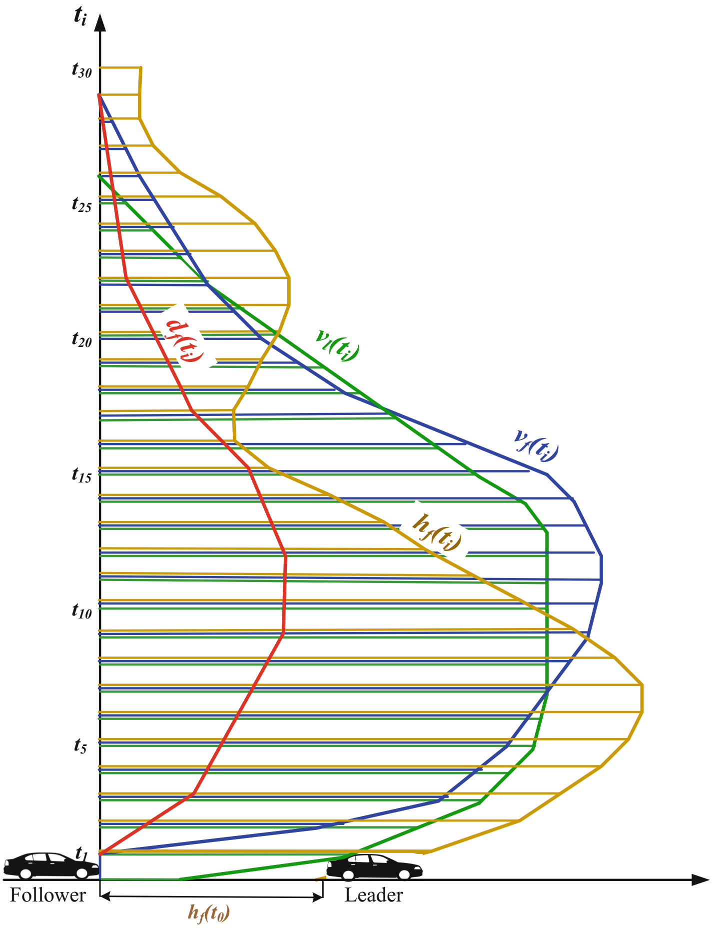

Fig. 3. Illustration of the relation among traffic variables of two consecutive vehicles moving in the same lane of freeway.

Basically, the distance passed by a moving object at regular speed is the product of the speed and the time interval during which the object takes for the distance. The traffic variables such as location, speed, and headway of moving vehicles change continuously over time, and are technically recorded discretely at regular-spaced time points [9]. During an enough small time interval $\Delta t = t_i - t_{i-1}, \forall i | i = 1, 2, ..$, the movement of a vehicle may be considered as regular and its speed $v(t)$ is calculated as follows.

$$v(t_i) = \frac{x(t_i) - x(t_{i-1})}{\Delta t} \tag{14}$$

Applying (14) for the follower and leader at t_i:

$$\begin{aligned}
&x_f(t_i) = v_f(t_i) \cdot \Delta t + x_f(t_{i-1}) \\
&x_l(t_i) = v_l(t_i) \cdot \Delta t + x_l(t_{i-1}) \\
&x_l(t_i) - x_f(t_i) = [v_l(t_i) - v_f(t_i)]\Delta t + [x_l(t_{i-1}) - x_f(t_{i-1})] \\
&[v_l(t_i) - v_f(t_i)]\Delta t = [x_l(t_i) - x_f(t_i)] - [x_l(t_{i-1}) - x_f(t_{i-1})] \\
&[v_l(t_i) - v_f(t_i)]\Delta t = [x_l(t_i) - x_f(t_i) - S] - [x_l(t_{i-1}) - x_f(t_{i-1}) - S] \\
&v_l(t_i) - v_f(t_i) = \frac{1}{\Delta t}[h_f(t_i) - h_f(t_{i-1})]
\end{aligned} \tag{15}$$

and

$$h_f(t_i) = h_f(t_{i-1}) + [v_l(t_i) - v_f(t_i)]\Delta t \tag{16}$$

(see Fig. 3).

4 Headway-Based Controlling Follower Speed

The condition of safe travel of two consecutive vehicles is indicated by the relation between the headway and speed of the follower as follows:

- $h_f(t_i) \approx \beta \cdot \Delta t \cdot v_f(t_i)$: two vehicles are moving in critical distance. Consequently, the follower speed should not be increased nor decreased;
- $h_f(t_i) < \beta \cdot \Delta t \cdot v_f(t_i)$: two vehicles are moving in hazard distance. Consequently, the follower speed must be reduced by decreasing the current engine force $F_e = F_r + F'$ or perform resistance and brake forces $F_r + F_b$;
- $h_f(t_i) > \beta \cdot \Delta t \cdot v_f(t_i)$: two vehicles are moving in safe distance. Consequently, the follower may increase its speed by changing the engine force F_e.

where β is the safe coefficient indicating the constraint distance for safety measured from the follower front to the leader rear, β is defined by the designer of the vehicle.

Formula (15) is developed as follows:

$$v_l(t_i) - v_f(t_i) = \frac{1}{\Delta t}[h_f(t_i) - h_f(t_{i-1})]$$

$$v_l(t_{i-1}) - v_f(t_{i-1}) = \frac{1}{\Delta t}[h_f(t_{i-1}) - h_f(t_{i-2})]$$

Transforming

$$[v_l(t_i) - v_l(t_{i-1})] - [v_f(t_i) - v_f(t_{i-1})] = \frac{1}{\Delta t}[h_f(t_i) - h_f(t_{i-1})] - \frac{1}{\Delta t}[h_f(t_{i-1}) - h_f(t_{i-2})]$$

It is assumed that,
$h_f(t_{i-1}) = h_f(t_{i-2}) > \beta \cdot d(t_{i-1})$ and $v_f(t_i) = v_f(t_{i-1})$ then
The change of leader speed results in the change of headway:

$$v_l(t_i) - v_l(t_{i-1}) > 0 \Rightarrow h_f(t_i) - h_f(t_{i-1}) > 0$$

$$v_l(t_i) - v_l(t_{i-1}) < 0 \Rightarrow h_f(t_i) - h_f(t_{i-1}) < 0$$

The data of follower speed and headway are recorded and analyzed by instruments installed on the follower. In this case, the follower speed may be adjusted to the desired speed $v_f^d(t_{i+1})$:

$$v_l(t_{i+1}) - v_f^d(t_{i+1}) = \frac{1}{\Delta t}[h_f(t_{i+1}) - h_f(t_i)]$$

$$v_f^d(t_{i+1}) = v_l(t_{i+1}) - \frac{1}{\Delta t}[h_f(t_{i+1}) - h_f(t_i)]$$

In the frame of safe coefficient β, $v_l(t_{i+1})$ may be assigned by $v_l(t_i)$:

$$v_f^d(t_{i+1}) = v_l(t_i) - \frac{1}{\Delta t}[h_f(t_{i+1}) - h_f(t_i)]$$

$$v_f^d(t_{i+1}) = v_f(t_i) + \frac{1}{\Delta t}[2h_f(t_i) - h_f(t_{i-1}) - h_f(t_{i+1})] \quad (17)$$

If $[2h_f(t_i) - h_f(t_{i+1}) - h_f(t_{i-1})] > 0$, then acting on the follower an additional engine force, obtained from (6):

$$F' = m \cdot \frac{[v_f^d(t_{i+1}) - v_f(t_i)]}{\Delta t} = \frac{m}{(\Delta t)^2}[2h_f(t_i) - h_f(t_{i-1}) - h_f(t_{i+1})] \quad (18)$$

If $[2h_f(t_i) - h_f(t_{i+1}) - h_f(t_{i-1})] < 0$, then acting on the follower the resistance and brake forces, obtained from (11):

$$F_r + F_b = m \cdot \frac{[v_f(t_i) - v_f^d(t_{i+1})]}{\Delta t} = \frac{m}{(\Delta t)^2}[h_f(t_{i+1}) + h_f(t_{i-1}) - 2h_f(t_i)] \quad (19)$$

5 Conclusion

The study proposes an approach to adjusting the speed of a vehicle following another based on the speed and headway data of the follower. Technically, these data are recorded discretely with very short time interval defined by the instruments installed on the follower. The proposed concept of moving block of a moving object referring time provides the necessary engine or brake force to increase or decrease speed for safe movement. The clearance resulted from the data of follower speed at each sampling time point is compared with the technically recorded headway to determine the desired speed. The difference between headway and clearance at the same moment provides with the value of engine or brake force performed by the follower. These results can be applied for various speed controlling procedures on vehicles. The diversity of the movement of two consecutive vehicles will be presented in next studies.

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