A Car Following Model for Motorway Traffic

Jiao Wang
Ronghui Liu
Frank Montgomery

Institute for Transport Studies
University of Leeds
Leeds LS2 9JT, UK
Email: r.liu@its.leeds.ac.uk
Phone: +44 113 343 5338
Fax: +44 113 343 5334

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Abstract
This paper presents a new car-following model which aims to capture some of the key motorway flow characteristics, namely traffic breakdown, hysteresis, shockwave propagation as well as close-following behaviour. The model proposes three different driving states: non-alert, alert and close-following. Under the different driving states, drivers apply different reaction time and acceleration. This paper presents the formulation and algorithmic implementation of the model. Theoretical analysis of the macroscopic flow-density relationships of the model is discussed. Simulation experiments are conducted and the results are examined at both the macroscopic level with regard to speed breakdown and traffic hysteresis, and the microscopic level with regard to gap distribution and shockwave propagation. The results show that the model is able to realistically capture the speed drop, traffic hysteresis and shockwave propagation as well as close-following behaviour. Further sensitivity studies of the key model parameters suggest that the drivers’ reaction times have a significant effect on the modelled capacity and occupancy, whilst the effect of the speed threshold which distinguishes a congested from a non-congested traffic flow is less significant.
INTRODUCTION

In recent years, the phenomena of flow breakdown, traffic hysteresis and close following of motorway traffic have received greater attention (e.g. (1), (2) and (3)). When a traffic flow breaks down, it generates a traffic jam together with what is termed a shockwave, by analogy with compression waves in fluids (4), (5). Considerably closer following is found when traffic is near capacity (but before the breakdown) and at high speed, that is, smaller gaps are accepted among passenger cars in non-congested than in congested flow conditions (6), (7). Traffic hysteresis is a phenomenon characterized by a loop structure seen on the empirical flow-occupancy diagrams, where the capacity of a traffic flow recovering from a flow breakdown does not reach the capacity before the breakdown (8), (9).

Car-following models are concerned with relationship between the driver-vehicle system to inter-vehicular dynamics in a single stream of traffic. They describe the movements of a following vehicle in response to the actions of the lead vehicle(s). There have been considerable interests in the development of car-following models to better understand the traffic flow concept in general (e.g. (10), (11)) and the observed phenomena in motorway traffic in particular (12).

Generally, the car-following models developed can be divided into three categories: stimulus-based models, safety distance models and action point models (13). The main idea of a stimulus-based model is that the acceleration of a following vehicle is determined by the driver’s reaction to the speed and position differences to the vehicle in front (11). The General Motors (GM) models are some of the well known stimulus-based models, which have been developed since the late 1950s with one of their latest modifications proposed by Ozaki (12). The safety distance models are based on the idea that the driver of a following vehicle would adopt such a speed and keep at such a distance that he would bring his vehicle to a safe stop should the vehicle in front breaks to a sudden stop. The Gipps car-following model (14) is one based on the safety-distance idea. The action point models are based on the idea that a driver’s driving behaviour would vary depends on the traffic state he is in: whether he is in free driving, approaching to the vehicle in front, following the vehicle in front or braking. The boundary conditions defining the different states are usually expressed as a combination of speed difference and relative distance to the vehicle ahead (e.g. (1), (15)).

However, most of the existing models (such as the GM models) are based on empirical investigations carried out on test tracks with driving speeds considerably lower than those on motorways, hence they may not reflect more general car-following behaviour (13). The Gipps model has the advantage that all its parameters have realistic physical meanings which makes it desirable without “resorting to elaborate calibration procedures” (14). Even so, the model is found to fail to reproduce the speed and capacity drops and close-following – the two prominent phenomena of motorway traffic flow (16), (17). Some models have attempted to rectify these problems for motorway traffic. For example, Brackstone et al. (18) calibrated the action points model for the close-following state based on the four thresholds proposed by Leutzbach and Wiedemann (15), but the model lacks the continuation with other normal following states, namely the free-flow following state.

Based on the Gipps’ model for normal following states and the action point model for the close-following situation, a new car-following model is developed which attempts to capture the full range of characteristics in motorway traffic, including free-flow following, traffic breakdown, traffic hysteresis, as well as close-following driving behaviour. This paper presents the formulation of the new model and discusses its macroscopic and microscopic properties. A generic validation procedure is developed and the model is validated against the observed travel behaviour on a busy UK motorway, the M25 orbital motorway around London.

THE DEVELOPMENT OF THE NEW MODEL

Reaction time which has been considered in many car-following models is the time lag between the detection of a stimulus and application of the response (19). Hereafter the term reaction time refers to a driver-vehicle unit. One of the common assumptions in car-following models is that drivers have the same reaction time and the same acceleration and deceleration throughout the different traffic states, i.e. whether they are in non-congested or congested traffic situations (e.g. (14)). It has been shown that models of this kind cannot represent the speed breakdown and traffic hysteresis as mentioned earlier.

Empirical experiments have shown that reaction times to expected and unexpected stimuli are different ((20), (21)). The experiments made by Johansson and Rumar (20) recorded the reaction times (the timings of vehicle brake lights after the klaxon in their experiments) of drivers who had forewarning that an incident was about to happen and compared to those without forewarning. They found a ratio of 1.35 between the mean braking reaction times of the expected stimuli to that of the unexpected stimuli. The idea of varying reaction time
in alert and non-alert states has recently been applied to car-following studies (e.g. (19), (22)) which have successfully reproduced the hysteresis loops in the modelled flow-occupancy diagrams. Similarly, Zhang and Kim (1) applied the idea for driving at different modes; they assumed a reaction time of 1.0 second when driving in cruising mode, 1.2 seconds for deceleration and 1.8 seconds for acceleration. They have shown the effectiveness of the model in representing traffic breakdown and hysteresis. A detailed examination of Zhang and Kim’s model suggests that the relative large changes in reaction times could result in discontinuities in the movements of vehicles and in unrealistically high acceleration and decelerations (16). None of the models which applied the varied reaction times have shown to reproduce the close-following phenomena of the motorway traffic.

The Gipps model has the advantage of representing realistically the individual vehicle’s speed control (i.e. with respect to their mechanical capabilities) and shockwave propagation (13), (17). As mentioned earlier, it is also desirable for model calibration. It is believed that the close-following situation is the cause of traffic instability (2). Brackstone et al. (18) calibrated the action point model and showed that it can reproduce small following gaps. The proposed new car-following model is developed based on a combination of the Gipps’ safety-distance model and the action point model, and is aimed to represent the full range of motorway flow characteristics.

We introduce the notations needed in the formulations:

- \( a_n(t) \) the instantaneous acceleration at time \( t \) of vehicle \( n \) (m/s\(^2\))
- \( b_n(t) \) the instantaneous deceleration at time \( t \) of vehicle \( n \), negative value (m/s\(^2\))
- \( v_n(t) \) the speed of vehicle \( n \) at time \( t \) (m/s)
- \( x_n(t) \) the current position of vehicle \( n \) at time \( t \) (m)
- \( L_n \) the effective size of vehicle \( n \), including the physical length plus a safe margin (m)
- \( S_n(t) \) the spacing between vehicles \( n \) and \( n+1 \) at time \( t \), equals to \( x_{n+1}(t) - x_n(t) - L_n \) (m)
- \( \tau \) the vehicle’s reaction time (s)
- \( a_{n\text{max}} \) the maximum acceleration that vehicle \( n \) wishes to undertake (m/s\(^2\))
- \( b_{n\text{max}} \) the maximum deceleration that vehicle \( n \) wishes to undertake, negative value (m/s\(^2\))
- \( b' \) the most severe braking that the driver of vehicle \( n-1 \) wishes to undertake estimated by driver \( n \), negative value (m/s\(^2\))
- \( V_n \) the speed at which the driver of vehicle \( n \) wishes to travel (m/s)
- \( D_c \) a deceleration threshold below which a vehicle’s deceleration will not be noticeable by its followers (i.e. braking lights are not lit) (m/s\(^2\))

The logic of the new car-following model is shown in Figure 1. The model is built on the concept that during the traffic build-up process (i.e. from non-congested to congested traffic), drivers shift from non-alert to alert state and this shift depends on the individual speeds (7). In low traffic speeds (under 50km/hr, congested traffic) drivers are considered to be alert (shorter reaction time and higher acceleration or deceleration). In higher traffic speeds (over 50 km/hr) drivers are considered to be either not alert or to be close-following subject to the satisfaction of close-following thresholds. The speed threshold \( v_C \) of 50 km/hr is obtained from the observation of speed breakdown during traffic build-up process in the real traffic (2), (7). During traffic recovery to free-flow states, however, the drivers are generally more relaxed and gradually increase their speeds (i.e. an overall acceleration of the traffic can be perceived). According to Zhang and Kim’s hypothesis, the reaction time for acceleration is longer than other phases (1). During traffic recovery when vehicles start to regain their desired speed, it is assumed that drivers are thus in non-alert situation. Different values of reaction time and maximum acceleration/deceleration are applied for alert and non-alert situations (see Table 1).

The Gipps car-following formulation is used to describe the alert situation and non-alert situations. The Gipps formulation is given as follows:

\[
v_n^s(t + \tau) = v_n(t) + 2.5 \times a_{n\text{max}} \times \tau \times [1 - \frac{v_n(t)}{V_n}] \sqrt{0.025 + \frac{v_n(t)}{V_n}} \tag{1}
\]

\[
v_n^d(t + \tau) = b_{n\text{max}} \times \tau + \sqrt{(b_{n\text{max}}^2 \tau^2 - b_{n\text{max}}^2)} \times \frac{2[x_n(t) - L_{n-1} - x_{n-1}(t)] - v_{n-1}(t) \tau - \frac{v_{n-1}^2(t)}{b'}}{2} \tag{2}
\]

\[
v_n(t + \tau) = \min\{ v_n^s(t + \tau), v_n^d(t + \tau) \} \tag{3}
\]

Close-following is defined in the model as the situation where none of the vehicles downstream in the platoon is braking apparently (i.e. the braking cannot be noticed by the following vehicles) and the following
vehicle will not brake very hard even when keeping a safe distance. In the model, the decelerations of only two front vehicles during the last reaction time interval in the platoon are checked. The action point model calibrated by Brackstone et al. (18) is used in the new model to represent vehicle following behaviour in the close-following situation. It gives the boundary conditions for close-following: $ABX$ (minimum desired following distance eq. (4)), $SDX$ (maximum desired following distance eq. (5)), $CLDV$ (closing relative speed, i.e. -2m/s), and $OPDV$ (opening relative speed threshold, i.e. 2m/s) specified in the action point model, which are used in the new model.

$$ABX = L_x + BX \sqrt{v_n(t)}$$  \hspace{1cm} (4)

$$SDX = L_x + BX \sqrt{EX \times v_n(t)}$$  \hspace{1cm} (5)

where: $BX$ and $EX$ are constants.

The different states of the new car-following model and the mathematical formulation of the car-following behaviour at each state are summarized in Table 1 with the following default values obtained from literature:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Distribution</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_n$ (m/s)</td>
<td>Normal distribution $N(20, 3.2^2)$</td>
<td>according to (14)</td>
<td></td>
</tr>
<tr>
<td>$L_n$ (m)</td>
<td>Normal distribution $N(6.5, 0.3^2)$</td>
<td>according to (14)</td>
<td></td>
</tr>
<tr>
<td>$A_1$ (m/s²)</td>
<td>Normal distribution $N(2.18,0.3^2)$</td>
<td>according to (22)</td>
<td></td>
</tr>
<tr>
<td>$A_2$ (m/s²)</td>
<td>Normal distribution $N(1.7,0.3^2)$</td>
<td>according to (14)</td>
<td></td>
</tr>
<tr>
<td>$A_3$ (m/s²)</td>
<td>the value of 0.6</td>
<td>according to (18)</td>
<td></td>
</tr>
<tr>
<td>$DC$ (m/s²)</td>
<td>the value of -1.48</td>
<td>according to (22)</td>
<td></td>
</tr>
<tr>
<td>$\tau_2$ (s)</td>
<td>the value of 0.8</td>
<td>according to the review by Toledo (19) for non-alert situation</td>
<td></td>
</tr>
<tr>
<td>$\tau_1$ and $\tau_3$ (s)</td>
<td>the value of 0.6 by applying the correction ratio of 1.35 between non-alert and alert situations according to (20)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To apply this model in simulation, the speed and position of a vehicle is simply updated according to the Newtonian equations of motion (eq. (6)-(8)).

$$v_n(t + \tau) = v_n(t) + a_n(t) \times \tau$$  \hspace{1cm} (6) \hspace{1cm} for acceleration

$$v_n(t + \tau) = v_n(t) + b_n(t) \times \tau$$  \hspace{1cm} (7) \hspace{1cm} for deceleration

The position of the vehicle, in all states, is then updated as:

$$x_n(t + \tau) = x_n(t) + \frac{1}{2} (v_n(t) + v_n(t + \tau)) \times \tau$$  \hspace{1cm} (8)

**THEORETICAL EXPLANATIONS**

The theoretical analysis of the proposed car-following model is performed through the uniform flow solutions (e.g. (17), (23), (24)) to derive the macroscopic flow-density functions. The assumptions of the proposed model suggest that during traffic build-up (i.e. the vehicle’s speed is more than the critical speed $v_C$), most drivers will be in the non-alert state (except a few who are close-following the leader, as described before, subject to the satisfaction to the close-following thresholds); when the traffic is congested (i.e. overall speed is less than the critical speed $v_C$), the driver will be in the alert state. During the process of traffic recovery, it is assumed the drivers are in the non-alert state with longer reaction times as discussed earlier. The relationships between flow ($q$) and density ($\rho$) of line AB, CJ and curve DE in Figure 2 can be represented in equations (9), (10) and (11). The detailed mathematic derivations of the model for the non-alert, alert and close-following states at macro-level are available from the authors.

**Line AB:**

$$q = \frac{2}{3 \tau_2} (1 - \frac{\rho}{\rho_C})$$  \hspace{1cm} (9)
where: \( \rho_j \) is the jam density.

Line CJ:
\[
q = \frac{2}{3\tau_1}(1 - \frac{\rho}{\rho_j})
\]  
(10)

Curve DE:
\[
q = \frac{4}{B\tau^2}(\frac{1}{\rho} - \frac{1}{2\rho_j} + \frac{\rho_j}{\rho})
\]  
(11)

Figure 2 shows the transition among different driving states. During the traffic build-up process, two different behaviours can be identified: some drivers may choose to drive in the close-following state subject to the satisfaction of the close-following thresholds, which may cause the traffic to shift from non-alert state (starts from point O to point A) to close-following state (point D) and stay in the close-following situation (the curve between D to E) till the speed drops to the level of \( v_C \). With the speed below \( v_C \), drivers start to shift from close-following state to alert state (point E to C); Some drivers who are not in the close-following state, may stay in the non-alert state (starts from point O to point A) and shift to alert state (from point B to C) when the speed drops to the level of \( v_C \). When the speed is below \( v_C \), all drivers are in the alert state till the traffic becomes jammed (point J). While during traffic recovery, in this model, it is assumed all drivers are relaxed thus staying in the non-alert state, i.e. traffic goes from J to B, A and finally O. In the field data, point D can be readily observed as the maximum overall traffic flow, point J the jam density, and point A the maximum flow during traffic recovery which can be identified from the speed- and/or flow-time profiles. Points B, C and E can not directly observed from the field data; however, the analysis presented in the next section shows that the boundary condition defined by these points do not play a significant effect on the modelled results.

**EXPERIMENTAL DESIGN AND SIMULATION DATA COLLECTION**

The simulation is conducted on a single lane, flat and one-way circular road (no consideration of curvature) similar to that proposed by Zhang and Kim (1). The simulation is updated every 0.2 second. Vehicles’ desired speed \((V_n)\) is normally distributed with \( v_f \) as the mean value and \( \sigma^2 \) as the variance:
\[
V_n \sim N(v_f, \sigma^2)
\]  
(12)

The simulation starts with an empty ring road which is then gradually filled with vehicles, representing the process of increased demand of traffic to the ring. Such ring roads are widely used in numerical experiments of car-following models (1), (17) and (25). It should be mentioned that the system performance can be different when open boundary conditions (such as a stretch of road) are applied, compared to the closed periodic boundary conditions (i.e. a ring road). However, they are believed to have wider applicability to real traffic situations such as traffic congestion and disturbance propagation through the importing of boundary conditions (17), (25). The length of the ring road is 1080m. The average vehicle length is assumed to be 6.5 metres (14); hence a total of 166 vehicles can cause total jam on the road. But only 85 vehicles in total are released on to the ring road according to the test designed by Zhang and Kim (1). This results in a maximum density of 78.7 vehicles/km over the ring road and an average spacing of 12.7 m including the vehicle lengths. Once the platoon has been generated, the front-most vehicle can be close enough to interact with the rear-most vehicle.

Once 85 vehicles are in the ring, there is a period of 200 seconds when no more vehicles are added to the ring and no vehicles leave the ring either. This is to allow the traffic properties under unstable congested (high density, low speed) situation to be examined. This period is termed constant demand in the simulation. At the end of the constant demand period, the vehicles begin to exit gradually. Vehicles enter and exit the ring road one by one every 20 seconds, representing the decreased demand process. An entering vehicle always joins the tail of the platoon, while a leaving vehicle can exit from any location when it finishes running for a period of 1900 seconds. This enables the test track to experience three different traffic flow stages: traffic build-up from free-flow to congestion, unstable congested traffic, traffic recovery from congestion to free-flow state.

An average speed collected by a 2-metre-long detector, located on the ring road, over a time interval \((\Delta T, \text{e.g. 30 seconds})\) is the average of all speeds of passing vehicles recorded by the detector, i.e.
\[ V(t, t + \Delta T) = \sum_{s=t}^{t+\Delta T} \sum_{i=1}^{M} \frac{v_i(s)}{M} \tag{13} \]

where: \(v_i(k)\) is the speed of vehicle \(i\) that passed the detector at time \(s\); \(M\) the total number of valid individual speeds being recorded during the interval \((t, t+\Delta T)\).

The data used to calculate the average flow is collected through point measurement as defined in TRB (26). The number of vehicles passing the start point of each detector over time period \(\Delta T\) is recorded. Then the average flow is calculated as:

\[ q(t, t + \Delta T) = \frac{N}{\Delta T} \tag{14} \]

Occupancy is the fraction of time that vehicles are over the detector. It is calculated as the sum of the time that vehicles are over the detector, divided by the interval \(\Delta T\). For each individual vehicle, the time spent over the detector is determined by the vehicle’s speed, \(v(t)\), and its length, \(L_i\), plus the length of the detector itself, \(d = 2\) metres.

\[ \text{Occ} (t, t + \Delta T) = \frac{\sum_{i=1}^{K} \left( L_i + d \right)}{\Delta T} \tag{15} \]

where: \(K\) is the number of vehicles over the detector during the interval \((t, t+\Delta T)\).

**MODEL VERIFICATION AND VALIDATION**

Model verification is concerned with determining whether the model outputs are reasonable and consistent through sensitivity analysis tests. Sensitivity studies of the key model parameters are carried out, and the results are examined against the fundamental diagram of flow-density distributions. The validation of new car-following model is executed later in the section with respect to its macroscopic properties (such as speed drop and traffic hysteresis) as well as its microscopic properties (such as shockwave propagation). The validation is to investigate the traffic properties between the simulation and the observations from UK motorways with respect to the similarity in pattern, magnitude of values and trend.

The theoretical analysis in the previous section showed that the reaction times affect the flow values during the traffic build-up and recovery process. The sensitivity tests are carried out on three model parameters reaction times \(\tau_1, \tau_2\) and speed criterion \(v_C\) (Figure 3). The application of different reaction times for the alert and non-alert states enables the model to capture traffic hysteresis (Figure 3 (a)-(f)). From the test results, we find that the model’s capacity during traffic build-up is most sensitive to the alert reaction time \(\tau_1\) with examples of the analysis shown in Figure 3 (a)-(f) and Table 2. The results show that the lower the value of \(\tau_1\), the higher the capacity and its corresponding occupancy. The results also show that the maximum flow during the traffic recovery process is sensitive to \(\tau_2\). In addition, it is found that when \(\tau_1 = \tau_2\), no traffic hysteresis can be reproduced. The effect of speed criterion \(v_C\), however, is less significant on the traffic capacity and its corresponding occupancy (Figure 3 (g)).

From the above analysis, it is found that traffic capacity is sensitive to the values of reaction times. Observations on the M25 motorway show that the real capacity of the nearside lane is at the level of 2000veh/hr, which is lower than simulated with a shorter alert reaction time (\(\tau_1 < 1.0s\)) (Table 2). The simulation results with relatively longer reaction times i.e. \(\tau_1 = 1s\) and \(\tau_2 = 1.2s\), are thus examined in model validation. The simulation is composed of three processes: the increased demand process, the constant demand process and decreased demand process is as mentioned earlier.

Figures 4(a) and (b) show the observations made from the M25 motorway in London. The M25 orbital motorway is a vital component in Britain's motorway network which encircles London with 31 junctions alongside (http://www.highways.gov.uk). The busiest, western section of M25 motorway regularly carries up to 200,000 vehicles per day. Most of the sections on M25 motorway are dual 4 lanes except those which are connected to the slip-roads with only 3 lanes constructed. The data source for observation analysis is the one-minute aggregated detector data of the nearside lane (slow lane) collected on 6th February 2002, located between Junction 11 and 12 on the western section of M25.

The simulated data are overlaid on the observed data in Figures 4(a) and (b). Although the simulated data from a ring road can not be directly compared with the observation made from an open stretch of motorway,
the aim here is to illustrate the scale of the modelled speed breakdown and traffic hysteresis compared to the scale of those observed. Two speed drops can be found during 7:00 to 7:30 am: one drop started at 7:00 (56 km/hr) and finished at 7:07 (25 km/hr); another sudden speed drop in the real traffic lasted for 4 minutes (started from 7:13, 68 km/hr to 7:17, 48 km/hr), when the speed dropped by 20 km/hr. From 7:30 to 9:40 am, the traffic was unstable with the speed oscillating around a low value less than 50 km/hr. During this period, the speeds from 7:30 to 7:45 only are illustrated in Figure 4(a) due to the size scale difference between the simulation and the real observation. The traffic started recovery from congestion at 9:40 to free-flow state at 9:50. Figure 4(a) shows that in the simulation the speed can drop suddenly during traffic build up: at time 870 s the speed is 66 km/hr and after one and a half minutes the speed is 45 km/hr, i.e. in 1.5 minutes speed dropped by 21 km/hr. Thus, the new model can reasonably represent speed breakdown.

Figure 4(b) shows that during traffic build-up, the simulated flow reaches its maximum at 2160 veh/hr. During traffic recovery, the maximum value is 1800 veh/hr. That is, the maximum traffic flow reached during the traffic build-up process cannot be achieved during traffic recovery. The real data (6:00 am to 7:20 am) shows that during traffic build-up the maximum flow was around 1900 veh/hr; after the traffic breakdown the maximum was around 1680 veh/hr. It is found that although the simulated data has slightly higher occupancy compared to the real data, it can reasonably capture the loop structure of the traffic hysteresis.

The simulated shockwave propagation is examined from the plot of individual vehicle trajectories. As shown in Figure 5(a), the traffic is examined during the simulation time 1050 - 1150 seconds when traffic starts getting congested and unstable as shown in Figure 4(a). Some shockwaves shown in Figure 5(a) can be easily identified with a reduction of traffic flow and velocity. These shockwaves are termed as backward propagated shockwaves according to Lighthill and Whitham (27) and May (11). The speed of shockwave \( v_{shock} \) can be approximately estimated from the flow and density difference collected from the detectors as:

\[
v_{shock} = \frac{\Delta q}{\Delta \rho} \tag{16}\]

where \( \Delta q \) the change in flow; \( \Delta \rho \) the change in density.

The simulated shockwave speeds range from -10 to -24 m/s (Table 3). Figure 5(b) shows a grey-scale map of the traffic speeds collected from the detectors between Junction 10 and 11 on the M25 motorway (courtesy of TRL, UK). The traffic speeds are mapped onto a space-time plane with the x-axis showing the time of the detector and y-axis the locations of the detectors. A number of low traffic speeds can be seen propagating backwards in space; the tangent of such propagation measures the shockwave speed. The measured shockwave speeds range from -8 to -18 m/s. Therefore the simulated shockwave speeds are comparable with the observed ones.

The modelled gap distribution is examined against those observed. Due to the apparent difficulty in directly calibrating the car-following model, the time gap distribution (18) is used here as an indicator of car-following model’s performance. The simulated gap is collected from the time gap among the individual vehicles; but those below 5 seconds were collected. The results are compared to the results simulated by Gipps’ model (14), Zhang and Kim’s model (1) (under the same experimental test design) and the real data by Brackstone et al. (18), which was collected by using an instrumented vehicle on M27 motorway, UK. As shown in Figure 6, it is found that generally, the distribution simulated by the new model is closer to the real data than those simulated by Gipps’ and Zhang and Kim’s model. It is possible that these models can improve their gap distribution performances if better calibrated. However, as neither of the models includes direct simulation of close-following situation, their capability of representing the smaller gaps distribution (e.g. less than 0.8 second) might be doubtful.

The sensitivity tests of the model parameters suggest that the model responds well at macro-level to the changes in the parameters of the alert reaction time and non-alert reaction time. The explanation of this may be that the smaller the alert reaction time, the smaller the acceptable spacings among drivers thus resulting in a higher capacity. The results indicate that the model can reproduce speed drop, traffic hysteresis and shockwave propagation as well as close-following behaviour.
SUMMARY

The phenomena of traffic breakdown, hysteresis, shockwave propagation and close-following are some of the key characteristics of motorway traffic flow. This paper presents a new car-following model which combines the idea of safe vehicle-following (14) and that the drivers may vary their driving behaviour in different traffic states (18). The model defines three driving states: non-alert, alert and close-following states, and applies to the driver different reaction times and acceleration and deceleration under the different states.

Simulation tests have shown that the model is able to realistically capture the speed drop, traffic hysteresis and shockwave propagation as well as close-following behaviour. Further sensitivity studies of the key model parameters suggest that the drivers’ reaction times have a significant effect on the modelled capacity and occupancy, whilst the effect of the speed threshold which distinguishes a congested from a non-congested traffic flow is less significant.

Further research will focus on applying the model to an open stretch of motorway. A simulation study of the proposed car-following model will be applied to a 1.1 km stretch of the M25 motorway road without any on-/off ramps in the vicinity of the site. There are three loop detectors placed along the stretch of the road. The upstream detector data will be used to generate the vehicles and their initial speeds into the simulation. Data from the detector located at the end of the section will be used to constrain the traffic movements downstream of the section. Calibration and validation will be carried out using data collected from the loop detector in the middle. The study will help answer questions of how to create shock waves in traffic simulation models.

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FIGURE 3 Sensitivity analysis of the effect of reaction times \(\tau_1\), \(\tau_2\) and speed criteria \(v_c\) on the macroscopic flow-occupancy relationships.

FIGURE 4 Speed-time (a) and flow-occupancy (b) diagrams simulated by the new model.

FIGURE 5 The simulated shockwaves from the plots of individual vehicle trajectories through model simulation (a) and the observed shockwaves illustrated from a grey-scale map of the traffic speeds collected from the detectors between Junction 10 and 11 on the M25 motorway (b) (courtesy of TRL, UK) - the traffic speeds are mapped onto a space-time plane with the x-axis showing the time of the day and y-axis the locations of the detectors with the detector identification marked. The lower traffic speeds are shown in lighter colours. Not all detectors are shown; between the detector 4727A and 4797A, only the alternative detectors are shown at a spacing of 1000m.

FIGURE 6 Gap distribution simulated by the new model compared to other models and real observation.
TABLE 1 The algorithms in the new car-following model.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Situation</th>
<th>Equation</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Build-up</td>
<td>Alert Situation</td>
<td>eq. (1), (2), (3) and (8)</td>
<td>$\tau = \tau_1$, $a_n^{\text{max}} = A_1$, $b_n^{\text{max}} = -2a_n^{\text{max}}$</td>
</tr>
<tr>
<td></td>
<td>Close-following Situation</td>
<td>eq. (6) or (7), and (8)</td>
<td>$\tau = \tau_3$, $a_n(t) = A_3$, $b_n(t) = -A_3$</td>
</tr>
<tr>
<td></td>
<td>Non-alert Situation</td>
<td>eq. (1), (2), (3) and (8)</td>
<td>$\tau = \tau_2$, $a_n^{\text{max}} = A_2$, $b_n^{\text{max}} = -2a_n^{\text{max}}$</td>
</tr>
</tbody>
</table>

Note: Due to the delay of drivers’ reaction, $b_{n-1}(t-\tau), b_{n-2}(t-\tau)$ instead of $b_{n-1}(t), b_{n-2}(t)$ are checked at time $t$ for the decision of close-following acceptance at the next moment ($t+\tau$).

TABLE 2 The capacity and corresponding occupancy under different $\tau_1$ and $\tau_2$.

<table>
<thead>
<tr>
<th>Reaction Time (s)</th>
<th>Traffic Build-up</th>
<th>Traffic Recovery</th>
<th>Hysteresis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\tau_1, \tau_2)$</td>
<td>Occ (%)</td>
<td>$Q_{\text{max}}$(veh/hr)</td>
<td>Occ (%)</td>
</tr>
<tr>
<td>(0.6, 1.0)</td>
<td>55</td>
<td>3560</td>
<td>31</td>
</tr>
<tr>
<td>(0.8, 1.0)</td>
<td>37</td>
<td>2640</td>
<td>29</td>
</tr>
<tr>
<td>(0.8, 0.8)</td>
<td>37</td>
<td>2640</td>
<td>-</td>
</tr>
<tr>
<td>(1.0, 1.0)</td>
<td>34</td>
<td>2160</td>
<td>-</td>
</tr>
<tr>
<td>(0.8, 1.2)</td>
<td>37</td>
<td>2520</td>
<td>23</td>
</tr>
<tr>
<td>(1.0, 1.2)</td>
<td>32</td>
<td>2160</td>
<td>25</td>
</tr>
</tbody>
</table>

TABLE 3 Backward propagated shockwave speeds of the new model shown in Figure 5(a).

<table>
<thead>
<tr>
<th>Shockwave</th>
<th>Time(s)</th>
<th>q (veh/s)</th>
<th>$\rho$ (veh/m)</th>
<th>$V_{\text{shock}}$(m/s)</th>
<th>Calculated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1060</td>
<td>0.80</td>
<td>$4.87 \times 10^{-2}$</td>
<td>-24.85</td>
<td>-22±2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1070</td>
<td>0.60</td>
<td>$5.76 \times 10^{-2}$</td>
<td>-22.52</td>
<td>-21±1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1090</td>
<td>0.80</td>
<td>$5.37 \times 10^{-2}$</td>
<td>-17.56</td>
<td>-14±3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1100</td>
<td>0.50</td>
<td>$6.70 \times 10^{-2}$</td>
<td>-10±2</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Note: Real observation from M25 motorway, UK shows that the shockwaves were backward propagated with a speed between -8 to -18 m/s.
Update the speed of vehicle

Traffic build-up process?

Y

Vehicle n alert?

N

Y

Two front vehicles braking apparently?

N

Y

Meet close-following thresholds?

N

Non-alert car-following

Y

Alert car-following

Close-following model

FIGURE 1 Flow chart of the new car-following model.

Flow (q)

Non-alert state during traffic build-up

Close-following state

Alert state

Transitions among different driving states

Non-alert state during traffic recovery

FIGURE 2 The transitions among different driving states.
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