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Transportation Research Part C 13 (2005) 37–62

TRANSPORTATION RESEARCH PART C

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Modelling vehicle interactions in microscopic simulation of merging and weaving

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Received 25 June 2002; received in revised form 5 February 2004

Abstract

This paper presents data, collected from video-recording, on the microscopic details of merging and weaving manoeuvres under congested traffic conditions. Based on these observations, a classification of the manoeuvres into free, forced and cooperative lane changes is proposed. A new lane change model is developed, incorporating explicit modelling of vehicle interactions using intelligent agent concepts. The model was implemented in the ARTEMiS traffic simulator, and several hypothetical test studies were conducted to demonstrate the capabilities of the new model. The results show that the model is able to reproduce the observed behaviour of individual vehicles in terms of speed, gap acceptance and conflict-resolution in all three types of lane change manoeuvres, and hence, it is able to simulate highly congested flow conditions in a realistic manner. The macroscopic results in terms of speed-flow relationship are close to the typical expected results. The model can simulate both freeways and signalised urban arterial networks.

Keywords: Micro-simulation; Lane changing; Merging; Agents

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0968-090X/$ - see front matter
doi:10.1016/j.trc.2004.12.003

1. Introduction

Microscopic simulation of road traffic has received increasing attention in the last decade. There are many problems, such as congestion and incident management, signal control optimisation, public transport priority, etc. that cannot be solved by traditional tools based on analytical methods due to the complexity of the urban road transport system. Microscopic simulators allow transport operators to model the whole system in its complexity and to evaluate various traffic management alternatives in order to determine the optimum solution for any traffic scenario. Several traffic simulation tools have been developed recently, such as MITSIM (Yang and Koutsopoulos, 1996), PARAMICS (Duncan, 1995), AIMSUN-2 (Barceló et al., 1996). A recent survey of such systems, however, reports several major problems including computational performance, the accuracy of models in representing the traffic flow, and the difficulty of integration with advanced traffic management and traffic information systems (Skabardonis and May, 1998).

ARTEMiS (Analysis of Road Traffic and Evaluation by Micro-Simulation, previously called SITRAS) is another microscopic time-interval update simulation model being developed by the author at the University of New South Wales since 1995. The main aim of the model is to provide a general evaluation tool for advanced traffic management applications such as congestion and incident management, public transport priority and dynamic route guidance. The model concepts and specifications and the first application of the model in the area of incident modelling in urban arterial networks were described in previous papers (Hidas and Behabahanizadeh, 1995, 1997, 1998; Behbahanizadeh and Hidas, 1996, 1998).

The aim of this research is to investigate the application of intelligent agent based techniques in a microscopic traffic simulation model in order to improve the overall efficiency and reliability of the simulation in complex traffic scenarios. In the multiagent simulation approach, each vehicle, together with its driver, is modelled as an intelligent agent: reactive, autonomous, internally-motivated entity that inhabits a dynamic, not fully predictable traffic environment (Weiss, 1999). The agent architecture used in the ARTEMiS model was described in Hidas (2002). Driver-vehicle agents (DVAs) have individual goals, i.e. reaching their individual destinations, and while doing so, agents have to interact and cooperate with other agents to solve many conflicting goals throughout their journey. Note that the terms "vehicle", "driver" and "DVA" are used interchangeably in this paper.

This paper presents the details of the lane changing and merging models developed using agent-based concepts. Lane changing is a vital component of any traffic simulation model, that involves a high level of interaction between the vehicles, where the behaviour of each vehicle is influenced by the behaviour of the other, thus they need to react and to make decisions based on their knowledge of the assumed intentions of the other vehicle and of the surrounding traffic environment. These interactions require complex behavioural decision-making processes which can best be modelled by intelligent agent techniques.

The difficulties of modelling congested conditions in merging and weaving areas with existing simulation models are well known. Prevedouros and Wang (1999) reported such problems with INTEGRATION, FRESIM and WATsim. Some models, e.g. AIMSUN, use a user-defined maximum waiting time while a vehicle is attempting to change lane, after which it gives up and continues in the wrong direction, becoming a 'lost vehicle' (TSS, 2002). This is an obvious failure of the modelling procedure, and the number of 'lost vehicles' is an indication of simulation success.

Few studies in the literature dealt with vehicle interactions in detail. Kita (1998) and Kita and Fukuyama (1999) modelled vehicle interactions in a merging situation at expressway on-ramps, based on game theory. They modelled the interaction between the merging vehicle and a 'through car' (a vehicle in the through lane upstream of the merging vehicle) as a two-player non-zero-sum non-cooperative game, in which the merging vehicle must select one of two strategies: (merge or stay in the merge lane) and the through car selects one of two strategies: (give way i.e. switch to the inner lane, or do not give way i.e. stay in the first through lane). They describe the various equilibrium situations corresponding to the relative spacing and speed of the vehicles involved, and determine when and where the merging occurs in each situation. This concept is based on a simple assumption that the driver will select the action with the lower level of risk, where risk is expressed as the time to collision (TTC). While this is a logical assumption, it is severely simplified and unrealistic because it does not consider a number of other factors, such as the effect of a leader vehicle present in the through lane which may make it impossible or unsafe to merge immediately. Kita et al. (2002) presented a further improvement of the model, which takes into account the presence of leader vehicles, but there are still a number of simplification in the model, such as

- it does not consider the minimum safe gap between vehicles: the selection of the preferred strategy is only based on the comparison of the TTC between the two vehicles and the time to reach the end of the lane;
- it does not consider the fact that the merging vehicle must slow down and stop before the end of the lane if it cannot merge safely into the through lane; in reality, merging becomes increasingly difficult as the speed difference between the merging and through vehicles increases, thus, from the moment the merging vehicle starts to slow down while approaching the end of the merging lane, its chances of making a safe merge before coming to a complete stop almost disappear.
- it assumes that all vehicles travel at constant speed and it does not consider the actions of the merging driver to actively change its behaviour (i.e. speed) in order to reach a better position for merging, neither the option for the through vehicle to slow down when staying in the through lane.

Due to these limitations, this model would not be able to simulate the complexity of all merging situations occurring in real traffic situations, especially when the flow becomes congested. A lane change model based on autonomous agent concepts was developed and implemented in SITRAS (Hidas and Behbahanizadeh, 1999; Hidas, 2002), incorporating procedures for 'forced' and 'co-operative' lane changing which are essential for lane changing under congested—and incident-affected—traffic conditions. The models described in this paper eliminate the shortcomings of the previous models, and implement new concepts based on data collected from video recorded lane change observations.

The basic notation used to describe the interactions during a lane change manoeuvre are shown in Fig. 1. The subject vehicle intends to move from its current lane (the subject lane) to the target lane, into the gap between two vehicles travelling in the target lane: these will become the leader and follower of the subject vehicle when the manoeuvre is finished.

The paper is structured as follows. After the introduction, first the data collection and analysis is presented. The next section introduces the concepts of the lane change model. This is followed

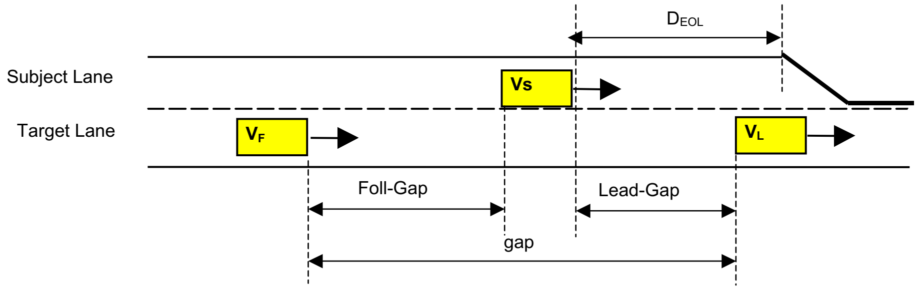

Fig. 1. Basic notation for a lane change manoeuvre.

by a description of the case studies and results used to test the performance of the new model. Finally, some conclusions and recommendations for further work are presented.

1.1. Relationship between the car following and lane changing models

Because of the close relationships between the lane changing and car following models, it is necessary to summarise briefly the car-following model implemented in ARTEMiS. A car-following model was developed specifically for the microscopic simulation of congested urban traffic flow conditions. The model is based on a desired spacing criterion. The desired spacing (D_i) is assumed to be a linear function of the speed:

$$D_i = \alpha v_i + \beta \tag{1}$$

where v_i is the speed of vehicle i, and α and β are constants. The model has been validated for urban interrupted flow conditions. A full description of the car following model was published in Hidas (1998).

While the model performed well in most situations, problems were found when a lane changing (or merging) occurs. In such situations, the vehicle moving in from another lane causes a distinct reduction of the spacing between its leader and follower vehicles. If the spacing before the lane change was close to the desired spacing at the given speed, it will be significantly less than the desired spacing, and as a result the car following model will calculate an emergency deceleration, which in turn, will generate a shock-wave slowing down all the vehicles upstream in the lane. However, in real traffic, many lane changes occur at very short spacing without causing an emergency braking in the following vehicle. It seems that while drivers do have a given desired spacing (which is a function of the speed), they are also willing to tolerate much shorter spacing under some circumstances: when they can clearly see the situation and can *anticipate* the actions of the other drivers. In the lane changing situation, instead of emergency braking, usually only a moderate/minimal deceleration is used to ensure that the spacing gradually increases to the desired spacing. According to observations this process takes about 5–10 s. This process creates an important link between the lane changing and car following models. One of the roles of the lane changing model is to determine under what conditions a vehicle is allowed to move into the target lane, and in this process it takes into account the spacing and speed of its potential leader and follower vehicles in the target lane. Thus, while the decision whether or not a lane change is "feasible" is based on the *prevailing* conditions in the target lane, at the same time it will have a great impact on the conditions *after* the lane change has taken place. This effect is now handled in ATREMiS by the improved car following model and the new lane changing model presented in this paper.

2. Data collection and analysis

In order to study the conditions during lane changing under congested conditions, the Transport Management Centre of the NSW Roads and Traffic Authority (RTA) provided video recording of four selected sites in the Sydney CBD from its traffic surveillance CCTV cameras. A total of about 20 h of recording was collected from reasonably high vantage points allowing a view of about 80–100 m section of road where a large number of lane changing or merging manoeuvres were expected. However, only about 4 h of data were analysed in detail so far, due to funding limits. The tapes were first viewed and a number of lane changing manoeuvres were identified. Then, each manoeuvre was analysed in detail, and the position and speed of each vehicle involved in the manoeuvre were identified at 0.2 s intervals using frame-by-frame analysis. The results obtained for one lane change manoeuvre are illustrated in Figs. 2 and 3.

Fig. 2 shows the positions of the leader and follower vehicles relative to the subject vehicle (i.e. the one performing the lane change), and Fig. 3 shows the calculated speed of the three vehicles during the manoeuvre. In Fig. 2, the thin lines represent the raw position data as estimated from the video frames. Due to the nature of this kind of data analysis, these position data can only be estimated from the video frames to a ±1.0 m accuracy. In the next step, this data is then smoothed using a third-degree polynomial curve, and these are taken as the calculated vehicle positions, represented by the thick lines. The calculated relative position of the subject vehicle is therefore represented by the X-axis. The distance between the thick lines and the X-axis shows the space gap between the leader and subject, and the subject and follower vehicles during the lane changing manoeuvre (excluding the length of the Subject vehicle). The position of the Y-axis represents

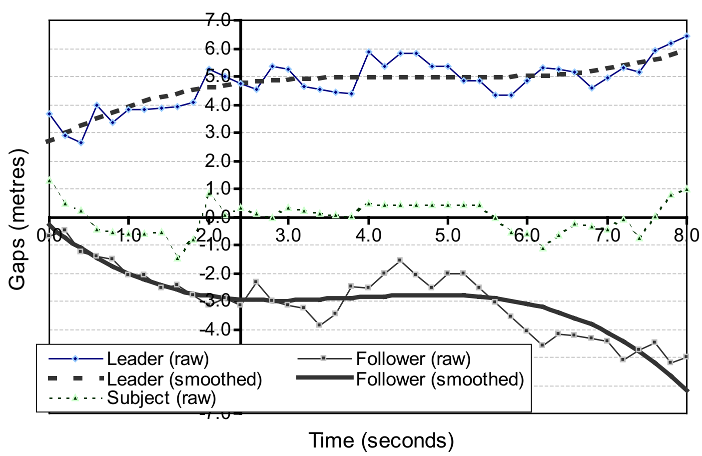

Fig. 2. Relative vehicle positions during lane change.

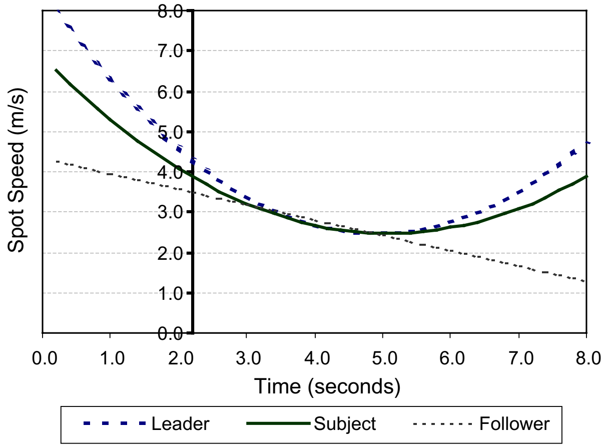

Fig. 3. Vehicle speeds during lane change.

the point in time when the subject vehicle started to move into the target lane, based on the subjective judgement of the observer. This representation allows the inspection of the interactions between the vehicles involved in the manoeuvre in a microscopic scale. It can be seen that there are important changes occurring over several seconds before and after the moment of change.

A total of 73 lane change manoeuvres were analysed in detail. The analysis has confirmed the field observations that under congested conditions lane changes occur at very short space gaps, and that the accepted gaps are more closely related to the *relative speed* between the leader–follower vehicles than to the absolute speed of the follower vehicle, as is the case in a "normal" car following situation. Fig. 4 shows the observed space gaps as a function of the follower vehicle. It can be seen that there is virtually no relationship between the observed *minimum* gaps and the

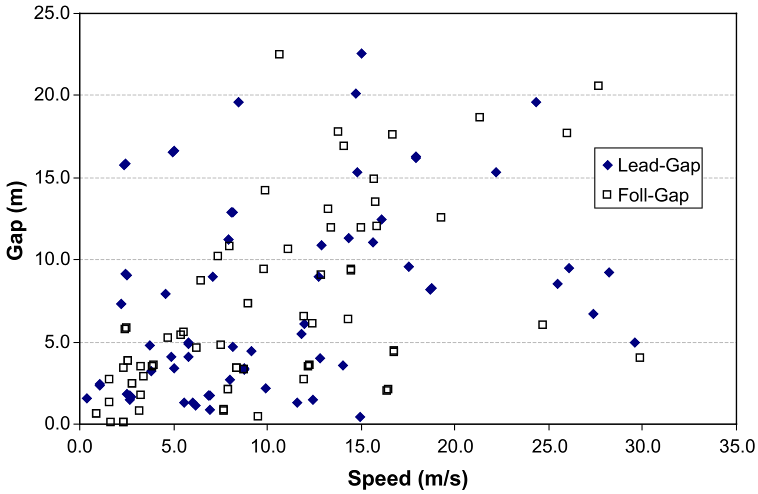

Fig. 4. Observed gaps as a function of speed.

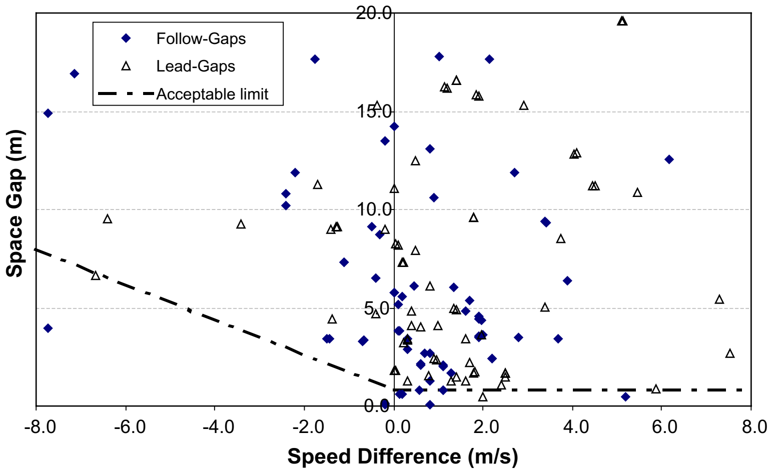

Fig. 5. Observed gaps as a function of speed difference.

speed. Fig. 5 shows the same gaps as a function of the speed difference between the leader and follower vehicle. It shows that as long as the leader vehicle is faster than the follower, the minimum accepted gap remains constant, and its value is about 1.0 m. However, when the leader is slower than the follower, the minimum accepted gap increases with the speed difference in a quasi-linear fashion. Fig. 5 also shows that there is no observable difference between the accepted lead-gaps and follow-gaps. This relationship can be used to define the minimum acceptance gap criteria in the lane changing models.

The detailed analysis of the space gaps during the lane change process (before and after the time of entry to the target lane) allows also a classification of different lane change manoeuvres. Based on the relative gaps between the leader and follower, lane changes can be classified into three distinct types:

1. Free lane change—in this case, there is no noticeable change in the relative gap between the leader and follower during the whole process, indicating that there was no interference between the subject and the follower vehicle (Fig. 6).
2. Forced lane change—this type of lane change is indicated by a distinct change in the gaps before and after the entry point: the gap between leader and follower was either constant or narrowing before the entry point, and it starts to widen after the subject vehicle enters, indicating that the subject vehicle has "forced" the follower to slow down (Fig. 7).
3. Cooperative lane change—this type is characterised by an opposite change in the gaps before and after the entry point: the gap between the leader and follower is increasing before the entry point, and it starts to decrease afterwards, indicating that the follower slowed down to allow the subject vehicle to enter (Fig. 8).

The main difference between the above three cases is in the nature of interaction between the subject and follower vehicles (the leader vehicle is usually a passive player in the lane change process, representing a constraint for the subject and follower vehicles). In a free lane change

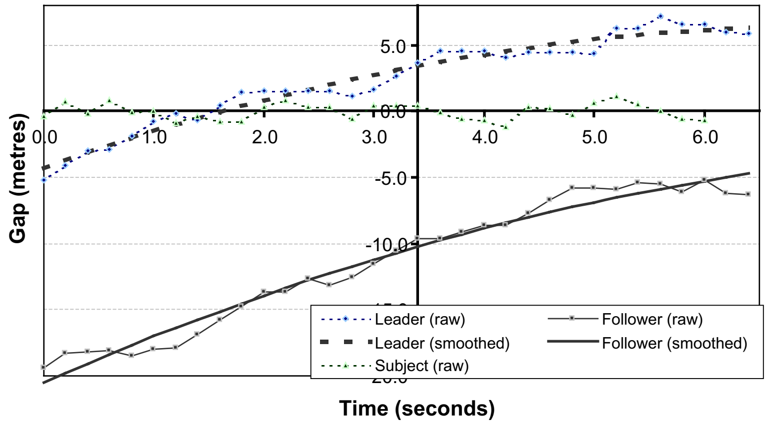

Fig. 6. Free lane change (observed).

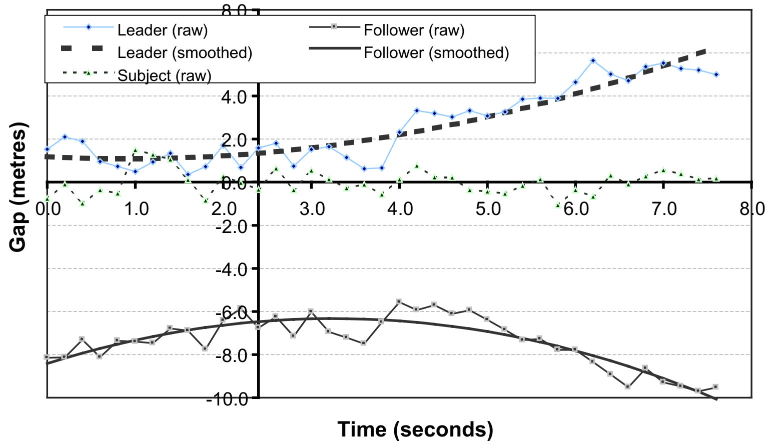

Fig. 7. Forced lane change (observed).

manoeuvre there is no interaction at all. In a forced lane change, the interaction is such that the subject vehicle plays the active role by initiating the interaction and the follower reacts by slowing down. While in a cooperative lane change the interaction has three components:

(a) first, the subject vehicle indicates that it wants to move into the target lane,
(b) then, the follower vehicle recognises this situation, decides to cooperate and slows down, creating a longer space gap in front,
(c) finally, the subject vehicle realises that the follower vehicle gave way and when the gap is long enough for a safe lane change, it executes the manoeuvre.

This process may take several seconds during which the vehicles must be able to communicate and coordinate their actions. Simulation tests show that cooperative lane changing has a significant effect on the macroscopic flow results (see Figs. 20, 21 and 23).

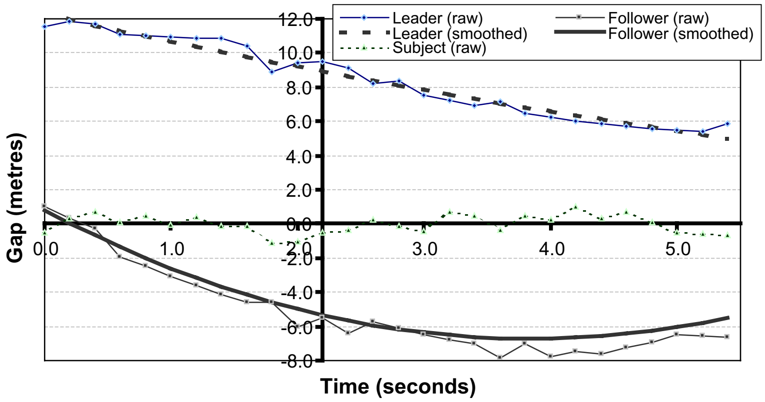

Fig. 8. Cooperative lane change (observed).

Note that the distinction between forced and cooperative lane changing may be ambiguous. In a real traffic situation it may happen that the subject vehicle starts moving closer to the target lane when the follower vehicle is too close for a safe manoeuvre, and it starts to slow down to avoid a collision before the subject vehicle is actually entering the target lane. This case, in terms of a logical chain of actions–reactions, should be characterised as a forced lane changing. In theory, the distinction between a forced and cooperative lane change would depend on the order of decisions made by the two drivers.

However, in the simulation model where the lateral position of vehicles within the lane is not represented, this will be equivalent to a cooperative lane change, because the follower vehicle starts to slow down before the subject vehicle is moving into the target lane.

3. Lane change model concepts

This section presents the concepts implemented in the lane change model.

3.1. Feasibility criteria

The basic concept of the lane change model is illustrated in the time–distance diagram shown in Fig. 9. The *subject vehicle* wishes to move into the *target lane*, in between the *follower* and *leader vehicles*. The conditions in which this manoeuvre is safe can be defined as follows.

The subject vehicle can merge into the target lane if, at the end of the merging manoeuvre, the space gaps in front (g_l) and behind the vehicle (g_f) are not less than some given minimum acceptable space gaps:

$$g_l \geqslant g_{l,\min} \quad \text{and} \quad g_f \geqslant g_{f,\min} \tag{2}$$

The space gaps at the end of the manoeuvre can be calculated based on the assumed speed conditions during time Dt. If all speeds are constant, then

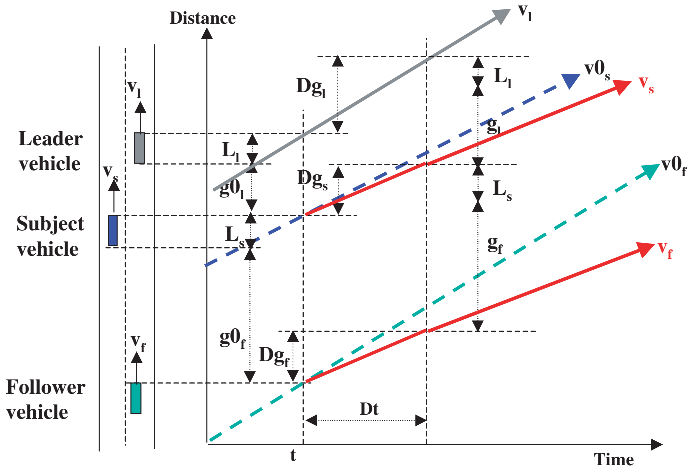

Fig. 9. Time–distance diagram for a lane changing situation.

$$
\begin{aligned}
g_l &= g_{0l} - v_s \mathrm{D}t + v_l \mathrm{D}t \\
g_f &= g_{0f} - v_f \mathrm{D}t + v_s \mathrm{D}t
\end{aligned} \tag{3}
$$

If the subject vehicle uses b_s deceleration (or acceleration) during the manoeuvre, and it assumes that the follower vehicle is willing to break by b_f deceleration ($b_f \ll b_{\max}$), then

$$
\begin{aligned}
g_l &= g_{0l} - (v_s \mathrm{D}t - b_s/2\mathrm{D}t^2) + v_l \mathrm{D}t \\
g_f &= g_{0f} - (v_f \mathrm{D}t - b_f/2\mathrm{D}t^2) + (v_s \mathrm{D}t - b_s/2\mathrm{D}t^2)
\end{aligned} \tag{4}
$$

In the simulation model, lane changing is simulated as an instantaneous action, therefore Dt can be taken as equal to the simulation update period of 1 s. In this case

$$
\begin{aligned}
g_l &= g_{0l} - (v_s - b_s/2) + v_l \\
g_f &= g_{0f} - (v_f - b_f/2) + (v_s - b_s/2)
\end{aligned} \tag{5}
$$

The minimum acceptable space gaps depend on the assumed driver behaviour, and the following three cases can be considered.

3.1.1. No interaction: free lane change

For this case it is required that at the end of the manoeuvre the space gaps are at least equal to the desired space gaps according to the given speeds:

$$g_{l,\min} = g_l(v_l) \quad \text{and} \quad g_{f,\min} = g_f(v_s) \tag{6}$$

These criteria are suitable for free-flow conditions, when vehicles have many opportunities to change lane, and the lane change is not urgent, therefore they may be able to wait until such favourable conditions occur.

3.1.2. "Cooperative" lane changing

The conditions of a safe lane change for the subject vehicle are the same as in the forced lane changing case. However, the conditions leading to the decision of the follower vehicle to slow down need to be established. This decision-making by the follower vehicle has two distinct parts: (a) evaluation of the DVA's *willingness* to slow down, and (b) evaluation of the *feasibility* of slowing down.

3.1.2.1. Evaluation of the DVA's willingness to slow down. If the follower driver voluntarily decides to slow down to let the subject vehicle move in front of it, under any circumstances this action has a negative effect on its travel time. Thus, this action is always in contradiction to the main goal of the DVA: to reach its destination as soon as possible. If this behaviour exists, as proven by field observations, the only logical explanation can be to assume that the follower driver understands the difficulties of the lane changing manoeuvre because s/he has been in the same situation before, s/he is willing to assist, hoping that others will do the same when s/he is in difficulty again. The willingness may depend on the following factors:

- the driving experience of the follower driver;
- the "aggressivity" parameter of the follower driver;
- the mental state of the driver (whether s/he is in a hurry, or disconcerted by some other events, etc.);
- the "necessity" and "urgency" of the lane changing manoeuvre, as assessed by the follower vehicle;
- the downstream traffic conditions: for example, field observations show that drivers are willing to slow down when they would have to stop soon after due to a red signal.

Not all these factors are easy to consider in a simulation model. A suitable modelling concept is to assume that the follower vehicle has a certain maximum speed decrease, Dv, that it is willing to give up in this situation. The value of Dv may be selected as a function of the DVA's aggressivity parameter. It is also reasonable to take into account the urgency of the lane changing manoeuvre, expressed as the "time-to-end-of-lane", TEOL and assume that the value of Dv increases as the TEOL decreases.

3.1.2.2. Evaluation of the feasibility to slow down. The time of the deceleration period Dt can be calculated from the acceptable deceleration rate and speed decrease:

$$\mathrm{D}t = \mathrm{D}v/b_f \tag{7}$$

Note that this time may be more than 1 s (the simulation update interval). The follower vehicle may assume that the subject vehicle will travel at a constant speed during this period. Then, the space gap between the subject vehicle and the follower vehicle at time t + Dt is

$$g_f = g_{0f} - (v_f\,\mathrm{D}t - b_f/2\,\mathrm{D}t^2) + v_s\,\mathrm{D}t \tag{8}$$

It is feasible to slow down if the space gap at the end of the deceleration period is at least equal to the minimum acceptable space gap:

$$g_{f,\min} = g_{\min} + \begin{cases} c_f(v_f - v_s) & \text{if } v_f > v_s \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

where $g_{\min}$ is a minimum safe constant gap that is independent of the speed difference between vehicles (this may be taken as equal to the *jam* gap), and c_f is constant. Note that this condition is used by the follower vehicle to decide whether or not to slow down and allow the subject vehicle to move in. At the same time, the subject vehicle must also evaluate the feasibility of the manoeuvre. In this case, according to field observations the minimum acceptable space gaps may be shorter than the space gaps for the desired gaps corresponding to the given speeds. The minimum acceptable space gaps can be calculated as follows:

$$g_{l,\min} = g_{\min} + \begin{cases} c_l(v_s - v_l) & \text{if } v_s > v_l \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad g_{f,\min} = g_{\min} + \begin{cases} c_f(v_f - v_s) & \text{if } v_f > v_s \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

where c_l is a similar constant to c_f, all other notations are as above.

This situation means that at the end of the lane change, the vehicles are closer to each other than based on the simple car following relationship they should be, and the follower vehicle is forced to slow down during the next few seconds to restore its desired spacing in line with the speed. According to field observations, this slowing down occurs at a low deceleration rate, even if the actual spacing is much shorter than the desired spacing. This indicates that the drivers involved in the manoeuvre are willing to take a higher than normal risk, assuming that no emergency braking will occur during that period. This interaction must be controlled by the car following model.

3.1.3. Forced lane change

The criteria and the calculation process of a forced lane change are identical to the cooperative lane change, with the only difference that in this case, it is the *subject vehicle* that makes assumptions about the maximum speed decrease, Dv, and the maximum deceleration, b_f, that the follower vehicle is willing to use in the given situation. If the manoeuvre is feasible with these assumed values, the subject vehicle will "force" these values on to the follower and it will carry on the lane change.

3.2. Calculation of the merge-acceleration

Besides checking the feasibility of a lane change, the subject vehicle often have to modify its own behaviour in order to reach the required position where it can move into the Target lane. This is more important at congested flow conditions when the gaps in the target lane are shorter, but it may be necessary even at low flow levels. Consider the situation illustrated in Fig. 10. The subject vehicle (V_S) is located at the side of a vehicle in the target lane (V_L). If the two vehicles are travelling at approximately the same speed, it would never be able to merge into the target lane. The subject vehicle must make a decision whether to merge in front of the other vehicle or behind it, then modify its speed to reach the point within the selected gap where the conditions for the

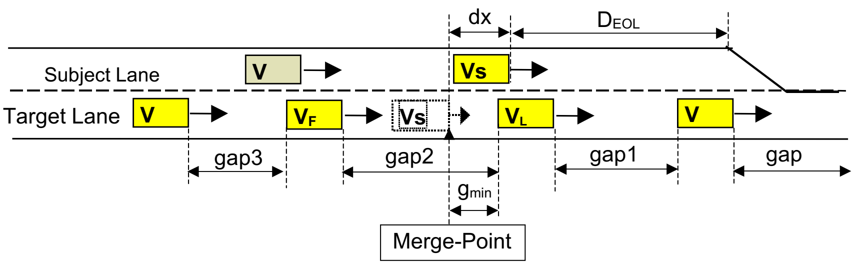

Fig. 10. Location of the Merge-Point for the subject vehicle.

manoeuvre are feasible. This point is called the Merge-Point, and the acceleration to reach the Merge-Point is called the Merge-Acceleration.

The procedure developed in the new model for calculating the Merge-Acceleration is presented in Fig. 11, and the steps are briefly described below.

Select first gap: The process starts by checking the gap immediately beside the subject vehicle.

Check the gap length: If the gap between the leader and follower is shorter than the minim lead plus follow gaps plus the length of the subject vehicle, then the process continues from step 5 below.

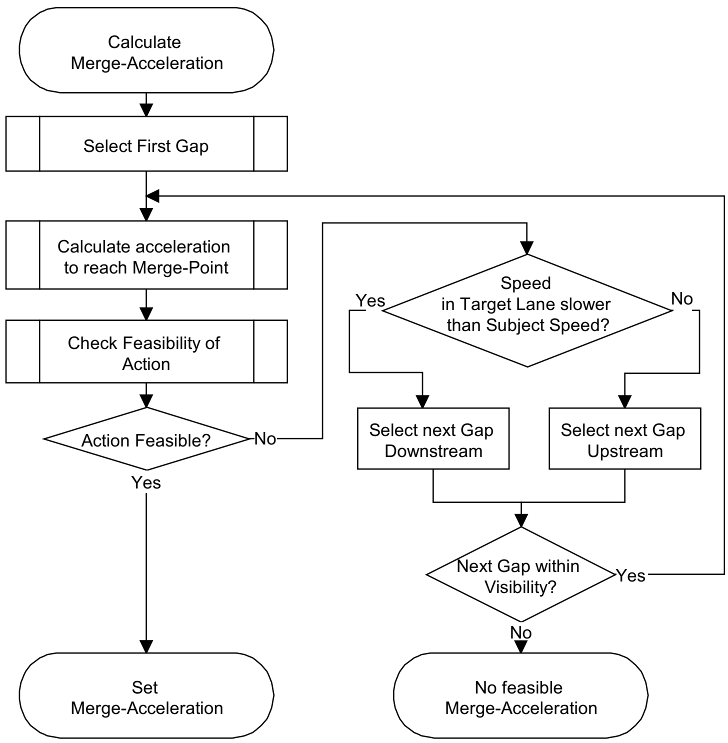

Fig. 11. Flow-chart of the Merge-Acceleration process.

Calculate acceleration to reach Merge-Point: The distance to the Merge-Point (dx) is calculated as either:

- the minimum gap distance behind the tail of the leader, or
- the minimum gap distance plus the subject vehicle length in front of the follower, or
- zero, if the gap between the leader and follower is longer and the subject vehicle is located within the above limits.

Then, from the current location, speed and acceleration data of the three vehicles involved, the Merge-Acceleration (A_M), required by the subject vehicle to reach the Merge-Point in the next simulation interval of 1 s, can be calculated as

$$A_\mathrm{M} = (\mathrm{d}x + v_\mathrm{MP} + a_\mathrm{MP}/2 - v_s)^{*}2 \tag{11}$$

where dx is the distance to the Merge-Point, v_MP and a_MP are the speed and acceleration of the Merge-Point respectively (assumed to be the same as either the leader or follower vehicle, depending on whether the gap is behind or ahead of the subject vehicle), and v_s is the speed of the subject vehicle. If this Merge-Acceleration is within acceptable limits (i.e. within the feasible minimum–maximum range), this value is set by the subject vehicle, otherwise the minimum (or maximum) acceleration is used, and the process must be repeated in the next interval.

Check feasibility of action: This step involves predicting whether the subject vehicle can reach a situation where the lane change is feasible *before* overshooting the End-Of-Lane. The positions are calculated from the current location and speed of the three vehicles, assuming the accelerations remain constant. If the action is feasible, the Merge-Acceleration calculated in step (2) is set, otherwise the process continues by checking the next gap.

Select next gap: The next gap is selected downstream if the speed of the vehicles in the target lane is slower than that of the subject vehicle, otherwise the next gap upstream is selected. The process is terminated if either a feasible gap is found or the visibility distance (set at 80 m) is reached. If the process is unsuccessful, the direction may be reversed in the next time interval.

3.3. Forced lane change

The decision whether to force the follower to give way is made by the subject vehicle during the calculation of the Merge-Acceleration. It involves two subsequent decisions:

1. First, the subject vehicle decides whether it *wants* to force the lane change. This is done once at the beginning of the Merge-Acceleration calculation, based on the urgency of the manoeuvre: if the estimated time before reaching the End-Of-Lane is less than 10 seconds, the vehicle will try to force its way into the target lane.
2. If this condition is true, then, for each gap tested in step (3) of the above process, it checks the potential follower to decide whether it is *necessary and possible* to force it to give way. Forcing is considered as an option in the algorithm if
   (a) the Foll-Gap is positive (i.e. the follower is behind the subject vehicle), and
   (b) Foll-Gap is less than critical gap required for a lane change.

If the subject vehicle decides to force the lane change, it uses the selected maximum speed decrease, Dv, and the maximum deceleration, b_f, for the Follower to calculate the feasibility of the action in step (3) of the above process, and if the action is feasible, these values will be passed on to the follower. The selection depends on the aggressivity parameter of the subject vehicle: a more aggressive driver will assume a higher speed decrease for the Follower than a less aggressive one.

3.4. Cooperative lane change

If a vehicle is involved in a lane change as a follower, an acceleration is calculated due to cooperative lane change. This is a similar process to the calculation of Merge-Acceleration, including the following steps:

1. Check if the subject vehicle needs cooperation. Cooperation is needed if
   - the Foll-Gap is positive (i.e. the follower is behind the subject vehicle), and
   - Foll-Gap is less than critical gap required for a lane change.
2. If cooperation is needed, the follower selects the maximum speed decrease, Dv, and the maximum deceleration, b_f, that it is willing to use. The selection depends on the aggressivity parameter of the follower: a more aggressive driver will select less speed decrease—or none at all—than a less aggressive one.
3. Using the selected values, the follower then checks the feasibility of the action: by predicting, using the speed and acceleration selected in step (2), whether the subject vehicle can reach a situation where the lane change is feasible *before* overshooting the End-Of-Lane. If the action is feasible, the cooperative-acceleration selected in step (2) is set, otherwise the cooperation is deemed to be unfeasible and the process is terminated.

Note that the cooperation may last several seconds. In this case only step (3) is repeated after the first interval, using the speed and acceleration selected during the first interval in step (2).

3.5. Lane-change plan

It is clear from the modelling procedures described above that the three vehicles involved in a lane change manoeuvre must be able to "see" and to communicate with each other throughout the process, which may take several seconds, in order to make decisions, to resolve conflicts and to collaborate with each other. In ARTEMiS these requirements were integrated into the existing model framework through the creation of a Lane-Change Plan. When developing the new concept, the computational efficiency of the whole simulation model must be kept in mind. In any realistic traffic simulation scenario there may be several thousands of DVAs present simultaneously in the model. Therefore, the size of the DVAs (i.e. the number of individual parameters stored) must be kept to the minimum. It is clear that simple driving tasks require less information—and hence, less individual parameters—than more complex tasks. It is also likely that at any one time during a simulation run, the large majority of the DVAs would carry out simple tasks, and only a small proportion would be involved in more complex tasks. Therefore, when extending the capabilities of the DVAs, the agent model should be able to adapt flexibly to the dynamically changing information needs during the simulation.

The solution proposed in ARTEMiS is the creation of a Lane-Change Plan as a separate vehicle-control entity. A Lane-Change Plan is created when a vehicle determined that a lane change is essential, but it is not immediately feasible. The Lane-Change Plan is "owned" by the DVA that must change lane. One DVA can only "own" one Lane-Change Plan at a time, but a DVA may be

Fig. 12. Flow-chart of the Vehicle Update process (note: the shaded components are new/modified).

involved in several Lane-Change Plans as a Leader or Follower. The Lane-Change Plan provides that common place where the vehicles involved in the manoeuvre can communicate and resolve potential conflicts and make coordinated decisions based on cooperation. The vehicle update process (including the new model components) is presented in Fig. 12 and the details of the acceleration calculation are shown in Fig. 13.

The Lane-Change Plan is continuously updated during the process to reflect any change in the traffic environment (i.e. if a Leader or Follower moved out of the target lane) and is destroyed

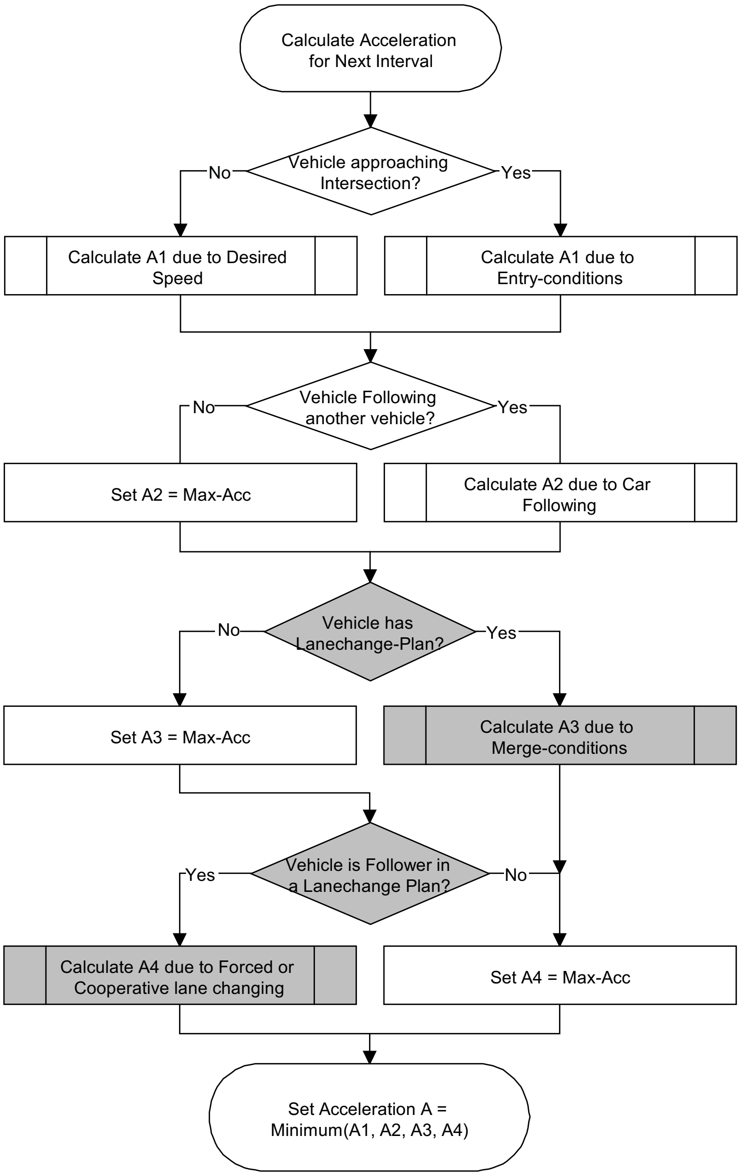

Fig. 13. Flow-chart of the Acceleration Update process (the shaded components are new/modified).

when the lane change has taken place. The procedures for the calculation of the Merge- and Cooperative-Accelerations are implemented as methods of the Plan, accessible by both the subject and the follower vehicles.

This solution ensures fast and direct communication between the vehicles involved, with a minimum increase of DVA-size and allows the most efficient computation possible.

4. Model testing and results

The lane change model was implemented in ARTEMiS and tested on several simple hypothetical road network scenarios. This section presents the test scenarios and simulation results, to demonstrate the capabilities of the new model.

4.1. Ramp terminal scenario

The first scenario used to test the lane change model is a freeway on-ramp situation, shown in Fig. 14. The freeway section has two lanes and the legal speed limit is 110 km/h. The one-lane ramp speed limit is 80 km/h, and the acceleration lane (the ramp terminal) is 150 m long. The model parameters used in the feasibility criteria of the new lane change model are as follows:

- Average maximum speed decrease, $Dv = 2.7$ m/s ($\sim$10 km/h).
- Average minimum safe constant gap $g_{\min} = 2.0$ m.
- Acceptable gap parameter $c_f = c_l = 0.9$.

These parameters were estimated from the collected video data, and modified for individual vehicles according to their aggressivity parameter. Other model parameters, such as acceleration–deceleration and car following parameters, were used unchanged in the previously calibrated model.

Several simulation runs were made with gradually increasing input flow rates (including 2% heavy vehicles), to test the lane change model under a wide range of congested flow conditions.

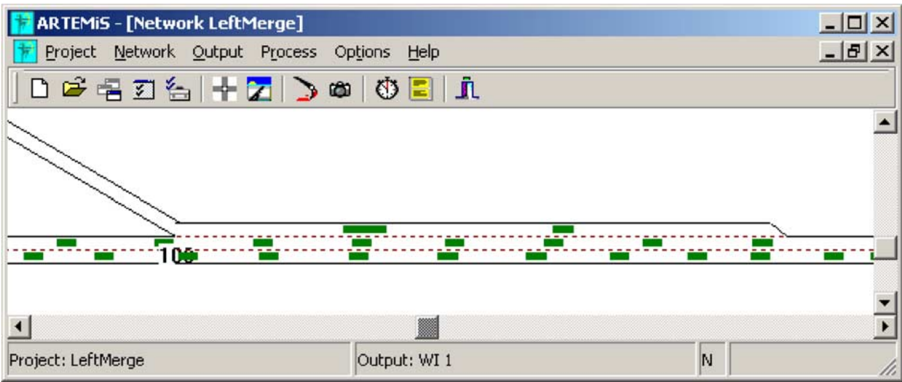

Fig. 14. ARTEMiS animation showing the merge test example.

The simulation outputs were analysed to illustrate the effects of the lance change model both on individual vehicles and on overall flow parameters such as the relationship between average speed and flow rate.

5. Microscopic results

The following figures illustrate the working of the proposed lane change model on individual vehicles in a forced and cooperative lane change situation (free lane change is excluded due to space limitations as it does not require the functionality provided by the new model). Fig. 15 shows the time–distance diagram of a *forced lane change* situation. As in the figures of the observed situations, the time = 0 axis indicates the point in time when the actual lane change occurred, and the figure shows how the location of the three vehicles involved changed a few seconds before and after the lane change. It can be seen on the left from the y-axis that the subject vehicle modified its behaviour by moving back behind the leader, and on the right from the y-axis the follower modified its behaviour due to the forced merge by the subject vehicle.

Fig. 16 shows the speed and gap diagram for the same situation as Fig. 15. In this case, as on the figures of the observed situations, the x-axis represents the position of the subject vehicle throughout the manoeuvre, and the lead- and Foll-gaps are measured from the front and tail of the subject vehicle respectively. This figure shows more clearly the details of a typical forced lane change manoeuvre: the follower travels at the same constant speed until the subject vehicle enters the target lane, and at that moment the follower reacts by slowing down to maintain a safe follow-gap behind the subject vehicle. Fig. 16 also shows that the subject vehicle slows down (from the same constant speed as the other two vehicles) at the beginning of the process to reach the Merge-Point within the selected gap. The lane change occurs as soon as the minimum lead-gap is reached, and the subject vehicle continues to adjust its speed to increase the lead-gap until the desired spacing for the prevailing speed is achieved.

Figs. 17 and 18 show similar details for a typical *cooperative lane change* situation. It can be seen that in this case, the follower starts to slow down a few seconds before the actual lane change occurs, then its speed starts to increase again after the lane change. In this case, the lane change occurs when the Foll-gap satisfies the condition specified in Eq. (10).

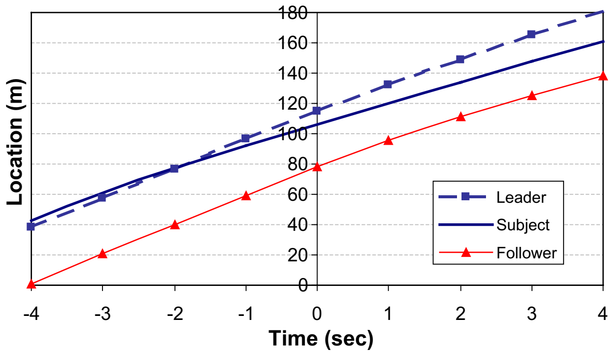

Fig. 15. Time–distance diagram of forced lane change (simulated).

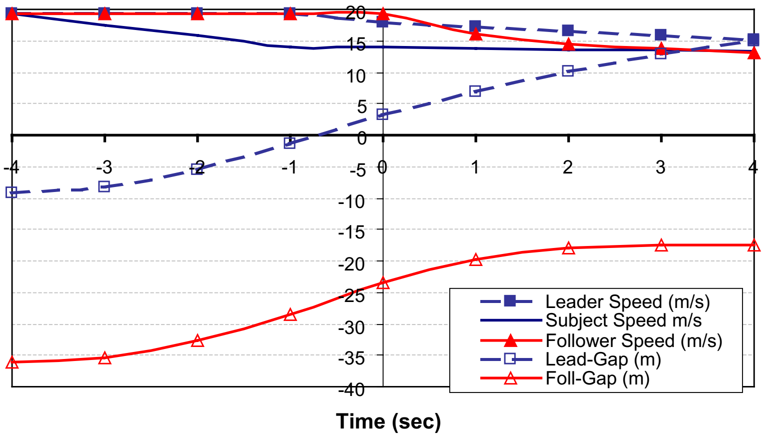

Fig. 16. Speed and gap diagram of forced lane change (simulated).

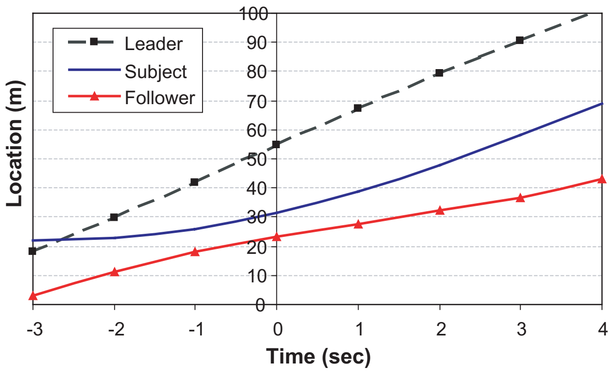

Fig. 17. Time–distance diagram of cooperative lane change (simulated).

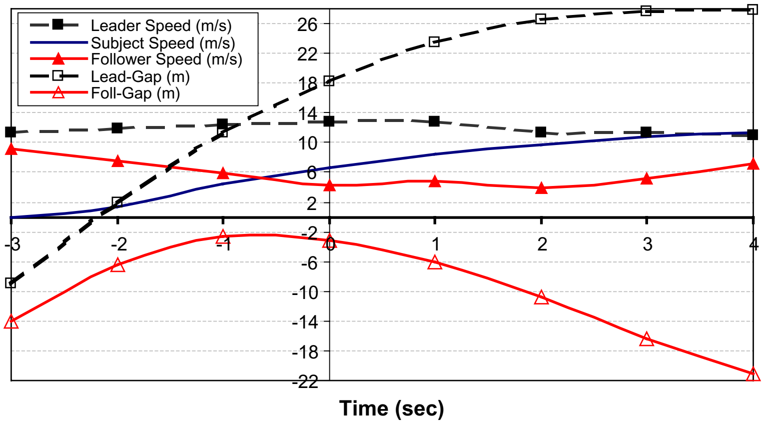

Fig. 18. Speed and gap diagram of cooperative lane change (simulated).

6. Macroscopic results

Fig. 19 shows the modelled results of the minimum accepted lane change gaps, both for lead- and follow-gaps, compared with the critical conditions specified in Eq. (10), represented by the dash-dot lines. It can be seen that the model complies with the implemented gap acceptance criteria.

In order to demonstrate the macro-effects of the new lane change model, several simulation runs were made in three configurations:

- with the new model enabled;
- with the new model enabled but the cooperative acceleration function disabled;
- with the new model disabled.

Fig. 20 shows the speed–flow relationship measured on the freeway along the ramp terminal section for the three model configurations. For comparison, the figure also shows the typical speed–flow curve calculated for the same traffic situation using the Highway Capacity Manual (TRB, 1994) method. It can be seen that up to about 2000 veh/h flow rate the modelled results are very close to the HCM-curve, but under fully saturated conditions the modelled speeds are lower than what is expected from the HCM-curve. At this flow rate, above 2000 veh/h, there is a significant difference among the three model configurations: while the average speed under fully saturated conditions is around 60 km/h with the new model enabled, it drops to about 50 km/h without cooperation and to below 40 km/h when the model is disabled.

The same difference among the three model configurations can be seen in Fig. 21 in terms of the stop rates: as long as the flow is uncongested, the three configurations produce very similar results, but under fully saturated conditions the average stop rate per vehicle increases steeply when the lane change model is disabled.

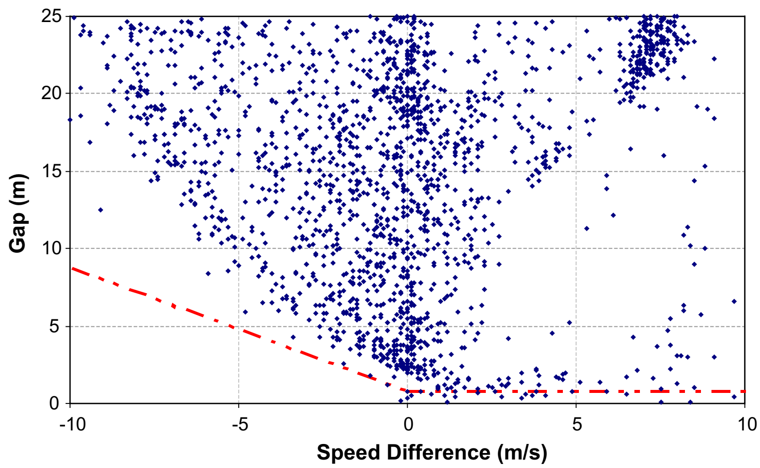

Fig. 19. Speed difference vs gap (simulated).

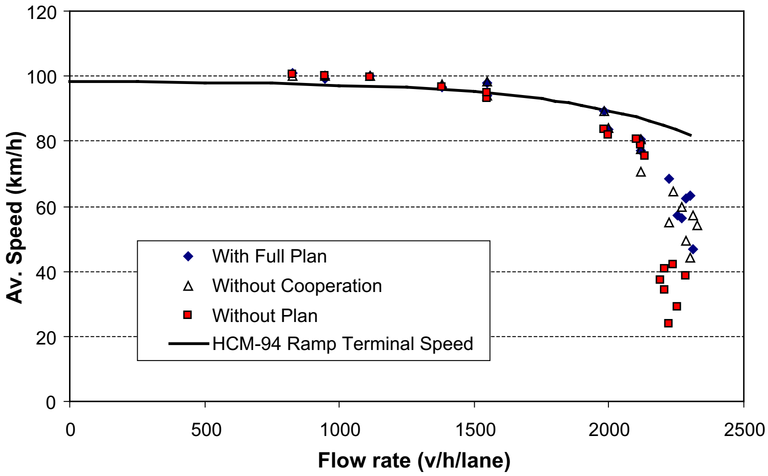

Fig. 20. Speed–flow relationship of the Merge scenario (simulated).

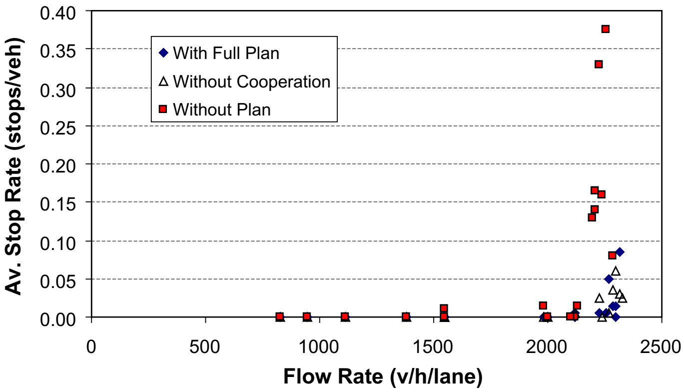

Fig. 21. Stop rate as a function of flow rate (simulated).

6.1. Weaving section scenario

The ramp terminal scenario presented above is a relatively simple situation in that it is only the vehicles entering from the ramp that must merge into the target lane. There are many traffic situations where at the same time the vehicles in the target lane may also need to change into the subject lane, and this may lead to further conflicts that the lane change model must be able to resolve. These problems are frequent in freeway weaving sections and in urban arterial networks where vehicles must move into a lane that allows their intended turning movement at signalised intersections.

Consider the weaving situation shown in Fig. 22. There are two origins at the left side and two destinations at the right. From both origins, 70% of the vehicles travels to the destination on the same side, and 30% must merge to the other lane in the weaving section to reach its destination.

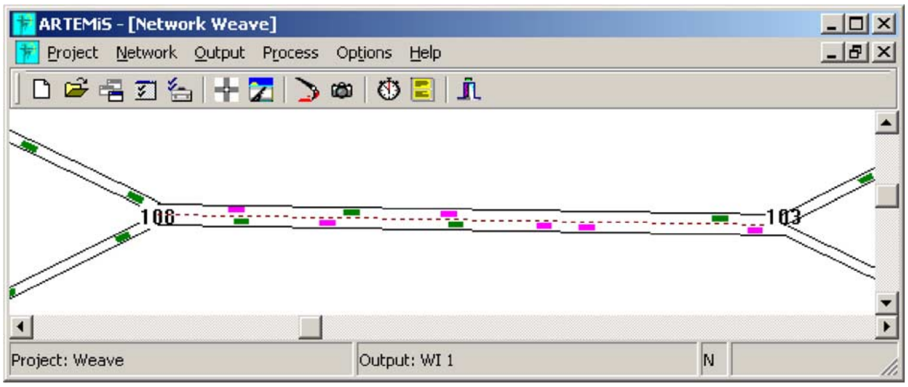

Fig. 22. ARTEMiS animation showing the weave test example.

In this case, it often happens that two vehicles travelling side by side wish to swap places. As in the simulation model vehicles are updated in sequence, link-by-link, lane-by-lane within a link, starting at the first vehicle in the lane, the vehicle located in the first lane will create its Lane-Change Plan, and it will decide whether to move behind or ahead of the vehicle on its side, and it will set the other vehicle as its Leader or Follower accordingly. When the second vehicle is updated, it will go through the same process, but in setting its Leader and Follower, it is crucial to avoid a situation where the two vehicles would mutually decide to move ahead or behind each other.

In the model proposed here, this is ensured by the Test-Cooperation function, a method of the Lane-Change Plan, which is used each time when a new Lane-Change Plan is created and/or validated. When a new Leader/Follower is selected in a Plan, this function is called to check and resolve potential conflicts with other existing Lane-Change Plans:

- first, it checks if the other vehicle is involved in another Plan, and if yes,
- it checks if the other vehicle intends to move into the subject lane, and if yes,
- it checks if the intended action of the two vehicles are in conflict (i.e. they both intend to move ahead or behind the other), and if yes,
- it checks, which vehicle is in a better position to move ahead of the other by calculating the position of both vehicles in 2-s time (thus, both the current position and speed of the vehicles are considered in the decision; if they are in equal position, the more aggressive is selected), and
- it eliminates the conflict between the two Plans by changing the decision of one of the Plans, so that one vehicle will intend to move ahead of the other, and the other will follow suite.

This process attempts to model what logically happens in real-life situations: two drivers in adjacent lanes may initially compete to move in front of each other, but when they realise the intention of the other, one will change its aim and it is usually the one in the worse position that will give way. The outcome of the process is that the two Plans will cooperate to achieve a common goal, i.e. the lane change of the vehicle in the better position, which, in turn, will facilitate the lane change of the second vehicle as well. Note that this is a cooperation between two

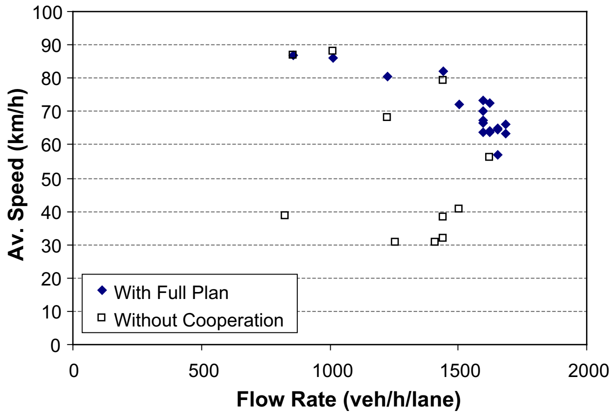

Fig. 23. Speed–flow relationship for the weaving section (simulated).

Lane-Change Plans, a higher level and more complex interaction than the cooperation between the subject and follower vehicles in one plan.

The effects of the model in a weaving traffic scenario are presented in Fig. 23, which shows the speed flow relationship on the weaving section, for several simulation runs with the full lane change model enabled and with the cooperative acceleration function disabled. It can be seen that the full plan ensures a speed–flow curve consistent with the expected shape, while the model without cooperation leads to highly congested situations at much lower flow rates. Further, what is not visible in Fig. 23, the simulation without cooperation could not be terminated normally: after about 2.5 h of simulation time at the end of the weaving section two vehicles were unable to swap lanes thereby creating a full blockage of the road. It is for this same reason why results with the new lane change model disabled are not presented in Fig. 23, as in this case a full blockage occurs very soon after the start of the simulation. This example demonstrates the crucial importance of modelling conflict resolution and cooperative behaviour in traffic simulation, especially when modelling congested conditions. With the implementation of the new lane change model, ARTEMiS can model congested weaving scenarios without 'lost vehicles'.

7. Summary and conclusions

This paper first presented data, collected from video-recording, on the microscopic details of lane change manoeuvres under congested traffic conditions. Based on these observations, a classification of the manoeuvres into free, forced and cooperative lane changes is proposed. Then, a new lane change model is developed, incorporating explicit modelling of vehicle interactions using intelligent agent concepts. The model was implemented in the ARTEMiS traffic simulator, and several hypothetical test studies were conducted to demonstrate the capabilities of the new model. The results show that the model is able to reproduce the observed behaviour of individual vehicles in terms of speed-, gap acceptance and conflict-resolution in all three types of lane change manoeuvres, and hence, it is able to simulate highly congested flow conditions in a realistic manner. The macroscopic results in terms of speed–flow relationship are close to the expected average results, although further tests are necessary to fine-tune the numerical parameters of the model according to any realistic traffic scenario. The explicit modelling of forced and cooperative lane change can eliminate the weaving and merging problems experienced in most simulation models under congested flow conditions. The model can simulate both freeways and signalised urban arterial networks.

The lane change model presented in this paper is the first outcome of this research project aimed at investigating the application of intelligent agent based techniques in a microscopic traffic simulation model in order to improve the overall efficiency and reliability of the simulation in complex traffic scenarios. Another important component of the simulation model is lane selection. Drivers' decision about lane selection is based on a combination of, often conflicting, factors. The most important factors, including end of lane, intended turning movement, lane blockage, speed and queue advantage, are included in the current ARTEMiS model. However, there are several other factors, such as downstream short lanes, shared straight-turning lanes, the presence of a heavy vehicle ahead and the intended turning movement at a downstream intersection, that also need to be included in the model to make it more realistic. As many of these factors involve vehicle interactions, conflict-resolution and interdependent decision-making, agent-based techniques will be used to develop new models for lane selection in the next phase of this research project.

Acknowledgments

This research was funded by the University Research Support Program (URSP) received from the University of New South Wales. The author wishes to express his gratitude to UNSW for the financial support of this research. Thanks also to the anonymous referees for their thoughtful comments.

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