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Comparative Evaluation of Microscopic Car-Following Behavior

Sakda Panwai and Hussein Dia

Abstract—Microscopic traffic-simulation tools are increasingly being applied to evaluate the impacts of a wide variety of intelligent transport systems (ITS) applications and other dynamic problems that are difficult to solve using traditional analytical models. The accuracy of a traffic-simulation system depends highly on the quality of the traffic-flow model at its core, with the two main critical components being the car-following and lane-changing models. This paper presents findings from a comparative evaluation of car-following behavior in a number of traffic simulators [advanced interactive microscopic simulator for urban and nonurban networks (AIMSUN), parallel microscopic simulation (PARAMICS), and Verkehr in Städten—simulation (VISSIM)]. The car-following algorithms used in these simulators have been developed from a variety of theoretical backgrounds and are reported to have been calibrated on a number of different data sets. Very few independent studies have attempted to evaluate the performance of the underlying algorithms based on the same data set. The results reported in this study are based on a car-following experiment that used instrumented vehicles to record the speed and relative distance between follower and leader vehicles on a one-lane road. The experiment was replicated in each tool and the simulated car-following behavior was compared to the field data using a number of error tests. The results showed lower error values for the Gipps-based models implemented in AIMSUN and similar error values for the psychophysical spacing models used in VISSIM and PARAMICS. A qualitative “drift and goal-seeking behavior” test, which essentially shows how the distance headway between leader and follower vehicles should oscillate around a stable distance, also confirmed the findings.

Index Terms—Car-following models, microscopic traffic simulation.

I. INTRODUCTION

MICROSCOPIC traffic-simulation tools are increasingly being applied by traffic engineers and transport professionals to deal with dynamic and operational traffic problems and to evaluate a range of new intelligent transport systems (ITS) applications. There are many problems such as adaptive traffic management, traveller information, and incident management systems that are difficult to evaluate using traditional analytical tools due to the complex nature of the underlying system dynamics in these applications. Microscopic traffic-

simulation tools provide an environment where different scenarios can be introduced and evaluated in a controlled setting without disrupting traffic conditions on the road. These traffic-simulation tools are based on different theories of microscopic traffic behavior such as car following and lane changing. Car-following behavior, in particular, has a significant impact on the accuracy of the simulation model in replicating traffic behavior on the road.

This paper outlines the microscopic traffic-behavior characteristics of a number of traffic-simulation tools. The paper first describes the car-following models in three of the most commonly used traffic-simulation tools: advanced interactive microscopic simulator for urban and nonurban networks (AIMSUN), Verkehr in Städten—simulation (VISSIM), and parallel microscopic simulation (PARAMICS). A methodology for assessing the microscopic traffic behavior is then described and the results from a comparative evaluation of the performance of the three models in replicating field car-following behavior are presented.

II. BRIEF REVIEW OF CAR-FOLLOWING MODELS

Car-following behavior, which describes how a pair of vehicles interact with each other, is an important consideration in traffic-simulation models. Understanding driving behavior is a key issue in evaluating model performance. A number of factors have been found to influence car-following behavior. These factors can be classified into two categories [1]. The first category is individual differences consisting of age, gender, risk-taking behavior, driving skill, vehicle size, and vehicle performance characteristics. The second category is situational factors involving both the environment and the individual. These include factors such as time of day, day of week, and weather and road conditions. Individual factors include situations of distraction, impairment due to alcohol, drugs, stress and fatigue, trip purpose, and length of driving. Headways have been found to increase with driver age and males are reported to choose shorter headways than females [2]. In addition, drivers aged 59 or more preferred a headway 1.83 s, about 23% more than the normal driver (age range from 23 to 37) [3].

A study by Brackstone and McDonald [4] classified car-following models into five groups as follows: Gazis–Herman–Rothery (GHR) model, collision-avoidance model (CA), linear model, psychophysical or action-point model (AP), and fuzzy-logic-based model. These models (and the desired-spacing model not covered in their review) are briefly described next.

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A. The GHR Model

The first formulation of this model was proposed in 1958 at the General Motors research laboratory in Detroit [5]. The model is based on (1), which relates acceleration to the speed of the leader vehicle, relative speed and spacing between follower and leader vehicles, and driver reaction time.

$$a_n(t) = cv_n^m(t) \frac{\Delta v(t-T)}{\Delta x^l(t-T)} \quad (1)$$

where

- $a_n(t)$ is the acceleration of vehicle n implemented at time t ;
- v_n is the speed of n th vehicle;
- Δx is the relative distance between vehicle n and $(n-1)$;
- Δv is the relative speed between vehicle n and $(n-1)$;
- T is the driver reaction time; and
- l, m , and c are constants.

The application of this model requires that the parameters l and m to be calibrated for a particular network. This has been reported to limit the application of the model. In addition, a large number of contradictory findings of the correct values of m and l have also been reported [4].

B. CA Model

This model was firstly presented by [6]. A number of variants of the model are also reported in the literature [6]–[8]. The model is based on (2), which describes the safe following distance (required to avoid collision with the vehicle ahead) as a function of the speeds of the follower and leader vehicles and the driver's reaction time.

$$\Delta x(t-T) = av_{n-1}^2(t-T) + \beta_1 v_n^2(t) + \beta v_n(t) + b_0 \quad (2)$$

where

- v_n is the speed of n th vehicle;
- v_{n-1} is the speed of $(n-1)$ th vehicle;
- Δx is the relative distance between vehicle n and $(n-1)$;
- T is the driver reaction time;
- α, β, β_1 , and b_0 are calibration constants.

The Gipps model [9], which is widely used in microscopic traffic simulation, is based on the CA model. One of the factors for the popularity of the model is the realistic behavior reported for situations involving either a pair of vehicles or platoons. In addition, the model can be calibrated using basic [9] assumptions about driver behavior and can be readily verified from field observations.

C. Linear Model

The basic form of this model (3) relates the acceleration of the follower vehicle to desired following distance, speed of the follower vehicle, relative distance and speed between follower and leader vehicles, and driver's reaction time. This model had

its origins in the GHR model described previously and was further improved by Helly [10], who introduced the desired following distance factor. The model was found to present a good fit to observed data. The main difficulty is with the calibration of constant parameters for a particular study.

$$\begin{aligned} a_n(t) &= C_1 \Delta v(t-T) + C_2 \{\Delta x(t-T) - D_n(t)\} \\ D_n(t) &= \alpha + \beta v(t-T) + \gamma a_n(t-T) \end{aligned} \quad (3)$$

where

- $a_n(t)$ is the acceleration of vehicle n implemented at time t ;
- $D_n(t)$ is a desired following distance at time t ;
- v is the speed of n th vehicle;
- Δx is the relative distance between vehicle n and $n-1$;
- Δv is the relative speed between vehicle n and $n-1$;
- T is the driver reaction time; and
- $\alpha, \beta, \gamma, C_1$, and C_2 are calibration constants.

D. Psychophysical or AP Model

This model is based on the assumption that a driver will perform an action when a threshold, expressed as a function of speed difference and distance, is reached. Three different types of threshold are implemented [11]. For example, when the value d/dt ($\sim \Delta v/\Delta x^2$) is exceeded, drivers would decelerate until the relative speed between follower and leader vehicles becomes zero. The second type of threshold is a spacing-based threshold (Δx), which is particularly relevant at close headways. Thus, for any change to be noticeable, Δx must vary by a "just noticeable distance" (JND). The third threshold is obtained from a series of perception-based experiments that require passengers in test vehicles to observe a target vehicle and make a decision whether the car-following gaps are widening or shortening. Clearly, the ability to perceive speed differences and estimate distances varies widely among drivers and hence, the difficulty in estimating and calibrating the individual thresholds associated with this model.

E. Fuzzy-Logic-Based Model

This model is based on fuzzy-set theory, which describes how adequately a variable fits the description of a term. The application of fuzzy-logic principles to the GHR model was reported in [12]. The model divides the selected inputs into a number of fuzzy sets and logical operators are then used to produce fuzzy output sets or rule-based car-following behavior. For example, two principal inputs to the decision-making process can be relative speed and the separation divergence (or the ratio of vehicle separation to the driver's desired following distance). A typical fuzzy rule for the car-following model would then have the form: If Distance Divergence is "Too Far" and relative speed is "closing," then the driver's response is "No Action." The main difficulty in the application of this model is

the determination of membership functions, which are crucial to the operation of the model.

F. Desired-Spacing Models

The desired-spacing models [13], [14] are based on a desired-spacing criterion, which is assumed as a linear function of the speed. The models are based on the premise that desired spacing is an individual-driver characteristic and that drivers have different desired-spacing criteria in acceleration and deceleration. These models eliminate the problems associated with reaction times used in other models because they describe car following based on desired spacing between vehicles without attempting to explain the behavioral aspects of car following. A more detailed discussion of these models can be found in [14] and [15].

III. CAR-FOLLOWING MODELS IN COMMONLY USED TOOLS

The car-following models of three commonly used traffic-simulation tools is evaluated in this study. A brief description of the car-following behavior implemented in each tool is presented next.

A. AIMSUN

AIMSUN is a microscopic traffic simulator developed at the Laboratorio de Investigación Operativa y Simulación, a research group in the Department of Statistics and Operations Research of the Universitat Politècnica de Catalunya [16].

The car-following models implemented in AIMSUN are based on the Gipps model [9], [17], [18]. Vehicles accelerate to achieve the desired speed and decelerate when drivers have to avoid a collision while trying to maintain the desired speed. The maximum speed depends on acceleration as expressed in (4).

$$V_a(n, t + T) = V(n, t) + 2.5a(n)T \times \left(1 - \frac{V(n, t)}{V^*(n)}\right) \sqrt{0.025 + \frac{V(n, t)}{V^*(n)}} \quad (4)$$

where

- $V(n, t)$ is the speed of vehicle n at time t ;
- $V^*(n)$ is the desired speed of vehicle n for the current section;
- $a(n)$ is the maximum acceleration for vehicle n ;
- T is the reaction time (this is equal to simulation step).

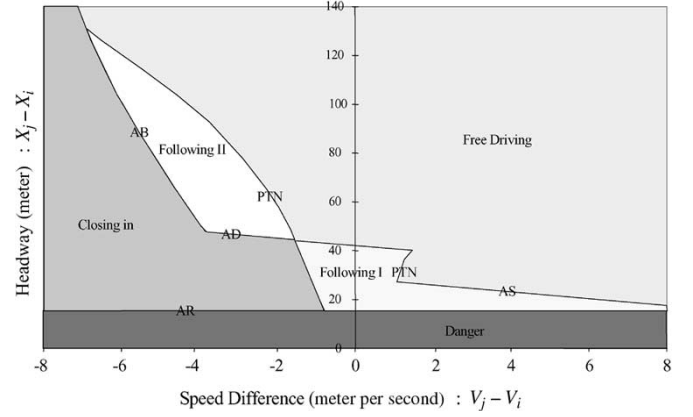


Fig. 1. Car-following phase-space diagram ($v_j = 20$ m/s, $b_m = 0.2$ m/s²) [19].

The speed is also influenced by vehicle characteristics and the limitation imposed by the leader vehicle, as shown in (5) at the bottom of the page

where

- $d(n)$ is the maximum deceleration desired by vehicle n ;
- $x(n, t)$ is the position of vehicle n at time t ;
- $x(n - 1, t)$ is the position of preceding vehicle ($n - 1$) at time t ;
- $s(n - 1)$ is the effective length of vehicle ($n - 1$);
- $d'(n - 1)$ is an estimate of the desired deceleration of vehicle ($n - 1$).

The maximum desired speed during simulation is the lower value returned by (4) and (5). Further details about the model can be found in [17].

B. PARAMICS

The car-following model in PARAMICS is based on the psychophysical model reported in [19]. The basic concept is that the car-following plane is divided into five phases (or regions) representing different modes of car following as shown in Fig. 1. This figure depicts a two-vehicle car-following case where the lead vehicle is traveling at 20 m/s. The five phases are denoted as: Following I, Following II, Danger, Closing In, and Driving Freely. These phases are determined using the following thresholds.

- 1) Perception-Threshold Negative (PTN) is defined as the negative relative speed of a pair of vehicles ($\Delta v = v_{j\text{-leader}} - v_{i\text{-follower}}$).

$$V_b(n, t + T) = d(n)T + \sqrt{d(n)^2 T^2 - d(n) \left(2 \{x(n - 1, t) - s(n - 1) - x(n, t)\} - V(n, t)T - \frac{V(n - 1, t)^2}{d'(n - 1)} \right)} \quad (5)$$

TABLE I
REGIONS OF THE CAR-FOLLOWING PHASE SPACE

Phase	Response From Follower Vehicle (<i>i</i>)
Danger	$\Delta x \leq AR$ Action: Deceleration necessary
Closing In	$AR < \Delta x \leq AR$, and $\Delta x \leq \Delta v_{PTN}$ Action: Deceleration necessary
Following II	$\Delta v \leq \Delta v_{PTN}$, and $AD < \Delta x$ Action: None
Free Driving	$[\Delta v > \Delta v_{PTN}$, and $AD < \Delta x]$ or $[\Delta v > \Delta v_{PTP}$, and $AS < \Delta x]$ Action: Uninfluenced by leader vehicle
Following I	$[\Delta v_{PTN} < \Delta v < \Delta v_{PTP}$, and $AR < \Delta x < AD]$ or $[\Delta v \geq \Delta v_{PTP}$, and $\Delta x < AS]$ Action: None

- 2) Perception-Threshold Positive (PTP) is defined as the positive relative speed of a pair vehicles.
- 3) Desired-Distance (AD) threshold represents a comfortable distance headway of the vehicles, which is related to speed of the follower vehicle.
- 4) Risky-Distance (AR) threshold represents conditions when the distance headway is too close for comfortable driving.
- 5) Safe-Distance (AS) threshold represents conditions when a driver cannot decelerate quickly enough to avoid a risky situation, as defined by the risky distance threshold (AR).
- 6) Braking-Distance (AB) threshold is an additional threshold used to avoid collisions that may occur because of higher speeds or late deceleration.

Table I summarizes the conditions that govern the determination of the five regions of the car-following model.

A variant of this model is used in the PARAMICS simulation software. However, the differences or similarities between the published version of the Fritzsche model and the version used in PARAMICS are unknown [20].

C. VISSIM

The car-following model in VISSIM is based on the psychophysical models reported in [21] and [22]. The basic assumption in these models is that a driver can be in one of four driving modes.

- 1) Free-driving mode, where no influence is exerted from leading vehicles. In this mode, the driver attempts to reach and maintain a desired speed.
- 2) Approaching mode, when the driver of the follower vehicle consciously observes that she is approaching a slower vehicle in front.
- 3) Following mode, where the headway for a pair of vehicles is between the maximum following headway and the safe headway. In this mode, the follower vehicle is able to accelerate or decelerate in accordance with the vehicle in front.
- 4) Braking mode, when the headway between vehicles drops below a desired safety distance.

The VISSIM traffic model comprises a psychophysical car-following model for longitudinal vehicle movement and a rule-based algorithm for lateral movements (lane changing). The car-following behavior switches from one mode to another

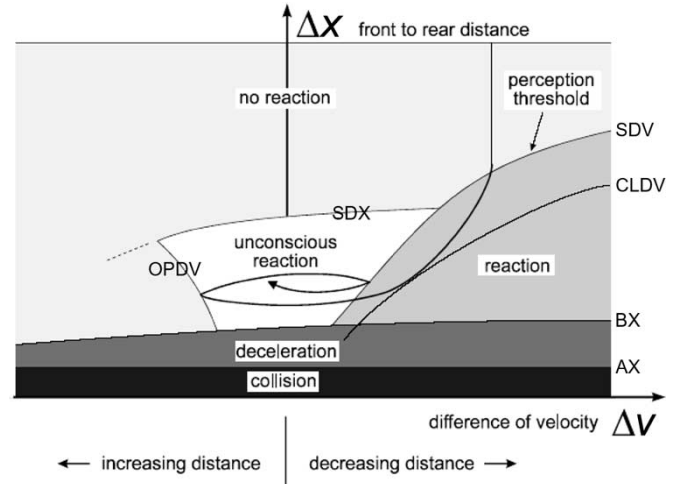


Fig. 2. Car-following model by Wiedemann [21].

according to predetermined perceptual threshold levels that form the basis of the psychophysical models. These thresholds are defined as a combination of speed and headway differences [21], [22]. In VISSIM, each driver-vehicle unit is described as a driver-vehicle element (DVE). Fig. 2 shows the interaction between two vehicles where DVE_j is moving faster than and approaching a slower vehicle DVE_i. Driver *j* begins to decelerate until an individual threshold, which is a function of acceptable speed difference and spacing, is reached. Driver *j* then maintains a speed at or below the current speed of DVE_i, until other thresholds are reached and the driver then accelerates again [23].

One of the challenges of a psychophysical model rests with the distributions of thresholds. Continuous measurements of different traffic conditions are required to calibrate the model in a realistic manner. The thresholds in Fig. 2 are defined below [24]. Driver-specific perception abilities and individual risk behavior is modeled by adding random values to each of the parameters.

- AX Desired distance between the front sides of two successive vehicles in a standing queue.
- ABX Desired minimum following distance, which is a function of AX, a safety distance, and speed.
- SDV Action point when a driver consciously observes approaching a slower vehicle. SDV increases with increasing speed differences. In the original work of Wiedemann [21], an additional threshold is applied to model additional deceleration by usage of brakes.
- OPDV Action point when drivers of follower vehicles notice that they are traveling slower than the leading vehicles and start to accelerate again.
- SDX Perception threshold to model the maximum following distance, which is about 1.5–2.5 times ABX.

A driver reacts to the leading vehicle when the distance between the two vehicles approaches 150 m. The minimum acceleration and deceleration rate is set to be 0.2 m/s². Maximum rates of acceleration depend on vehicles' technical features. The model also includes a rule for exceeding the maximum deceleration rate in case of emergency.

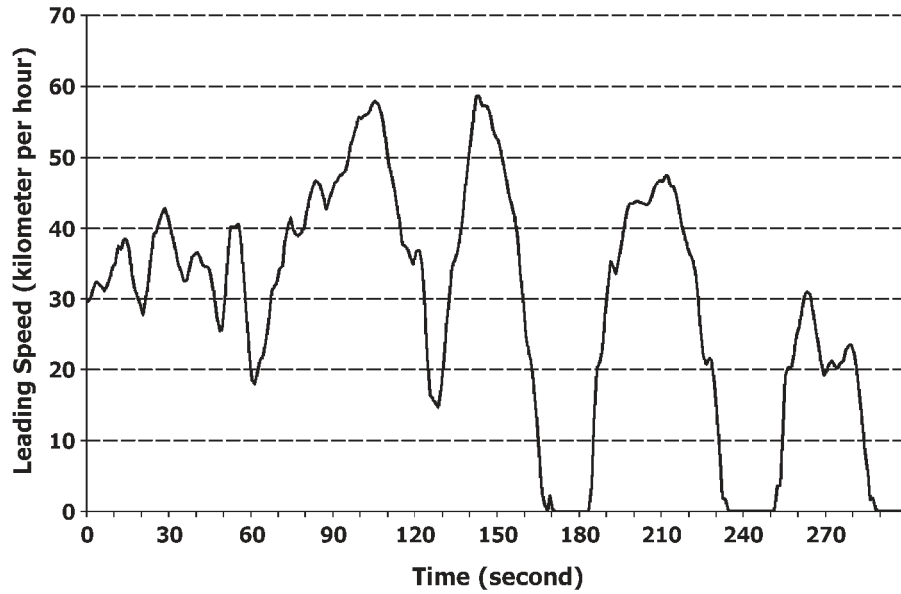


Fig. 3. (a) Speed profile of leader vehicle.

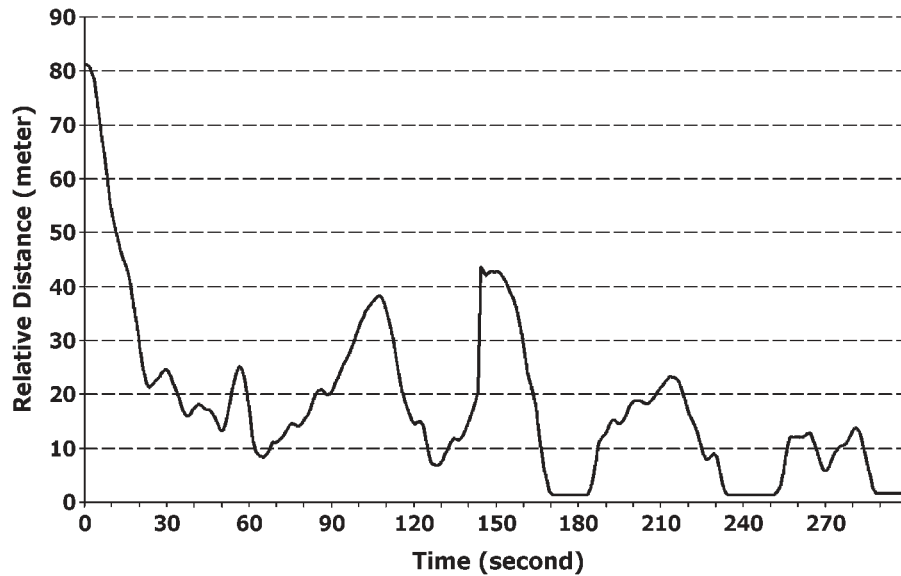


Fig. 3. (b) Profile of headway to leader vehicle.

IV. RADAR SPEED DATA FOR EVALUATION STUDIES

A number of studies on evaluating car-following models are reported in the literature. The Robert Bosch GmbH Research Group [25] collected speed data under stop-and-go traffic conditions on a single lane in Stuttgart, Germany during an afternoon peak. These data were used to evaluate a number of car-following models [16], [25], [26]. The results reported in this paper are also based on the same data and will be used to evaluate the most recent versions of car-following models in a number of traffic-simulation tools. A description of the data is presented next.

A. Characteristics of the Radar Speed Data

The Robert Bosch GmbH Research Group [25] used an instrumented vehicle to record the difference in speed and

headway between the instrumented vehicle and the vehicle immediately in front. The response of the follower vehicle (the instrumented vehicle), in terms of acceleration or deceleration, was also recorded. These data were recorded in 100-ms intervals for a total duration of 300 s for a single run on a single-lane road in Stuttgart, Germany.

Fig. 3(a)–(d) depict the driving behavior between the follower and leader vehicles. Fig. 3(a) shows the speed profile of the leader vehicle. The speed range during the experiment was between 0 and 60 km/h. The vehicle came to a complete stop on three occasions during the experiment [as shown in Fig. 3(a)]. The relative distance to the leader vehicle (headway), is presented in Fig. 3(b). The plot shows that the initial distance to the leader vehicle was 81.1 m. The follower vehicle was then able to drive at a free-flow speed until approximately 25 s into the experiment when the headway started to decrease.

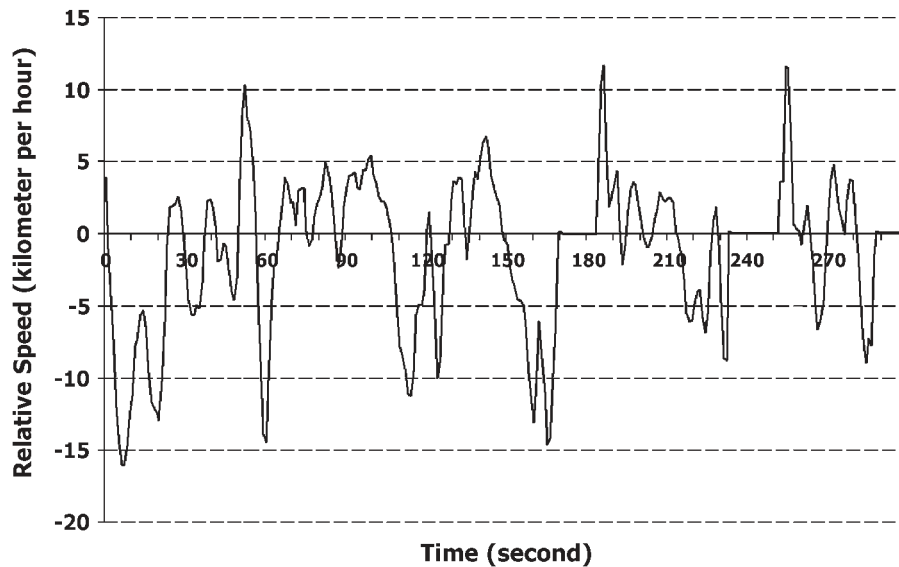


Fig. 3. (Continued.) (c) Profile of relative speed between vehicles.

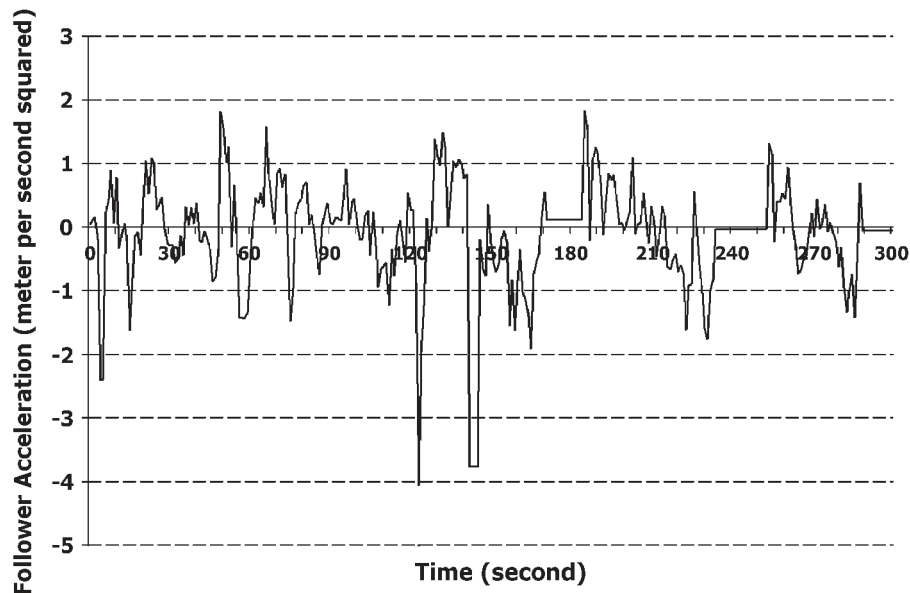


Fig. 3. (Continued.) (d) Acceleration of instrumented vehicle.

Fig. 3(c) shows the relative speed between the follower and leader vehicles. The absolute values of relative speed ranged between 12 and 15 km/h. The response of the instrumented vehicle when the leader vehicle accelerated or decelerated is shown in Fig. 3(d). The plot shows that the response of the instrumented vehicle ranged between -4.0 m/s (deceleration) to around $+2.0$ m/s (acceleration).

B. Summary of Results Obtained in Previous Studies

The time-series data collected by the Robert Bosch GmbH Research Group were applied to six car-following models [25].

- 1) MITSIM model. This model was developed by the traffic simulation laboratory (SIMLAB) at Massachusetts Institute of Technology (MIT) for evaluation of dynamic traffic-management systems. The MITSIM model is based on Herman's car-following model [27].
- 2) Wied/Pel model. This model is based on the Wiedemann model developed at the Technical University of Aachen [28].
- 3) Wied/Vis model. This model, which is also based on the Wiedemann model, is implemented in the commercial tool VISSIM (v2.4) [23].
- 4) Nagel/Schreckenberg model (NSM). This model is based on a cellular-automata approach describing single-lane traffic flow on a ring road [29].
- 5) Optimal velocity model (OVM). This is a dynamic model of traffic congestion based on equations of motion for each vehicle. The model assumes that drivers adapt their acceleration/deceleration response according to the difference between an optimal speed and current speed and as a function of distance headway [30].
- 6) T^3 Model. This model, which is similar to the OVM model, is based on regression analysis of measurement

TABLE II
EM RESULTS FOR SELECTED MODELS

Model	MITSIM*	Wied/Pel*	Weid/Vis*	NSM*	OVN*	T ³ M*	AIMSUN*
EM	3.75	14.01	10.67	24.51	9.37	2.4	3.47

* Results as reported in [25]

* Result as reported in [16] and [26]

data. A detailed discussion of this model appeared in a more recent publication by Fellendorf and Vortisch [31]. The function determining a driver's acceleration is chosen by using a polynomial function [32]. Speeds of the follower and leader vehicles and distance headway are used as input values to produce an output value, the acceleration rate.

The study used an error metric (EM) on distance as a key performance measure. The distance to the leader vehicle observed in the field (d_f) was compared to the values obtained from each traffic simulator (d_s). To avoid overrating on discrepancies for large distance, the EM was weighted by logarithm and squared, as shown below [25]:

$$EM = \sqrt{\sum \left[\log \frac{d_s}{d_f} \right]^2}. \quad (6)$$

In a separate study [16], [26], the same methodology was applied to evaluate the car-following behavior in the commercial tool AIMSUN. Table II summarizes the EM results obtained by these studies.

V. EVALUATION OF CAR-FOLLOWING BEHAVIOR

The results reported in this paper are based on an independent evaluation of recent versions of the commonly used traffic-simulation tools: AIMSUN (v4.15), VISSIM (v3.70), and PARAMICS (v4.1). It should be noted that the evaluation studies reported before were based on earlier versions of AIMSUN and VISSIM. These models are continually being developed and it is unknown if the underlying algorithms have changed or not. Furthermore, this study also includes an evaluation of PARAMICS, which was not included in previous studies.

A. Evaluation Approach

Each simulator was used to model the car-following experiment from which the radar speed data were collected. To set up the experiment, firstly, the initial distance and speed of the leader vehicle was set in accordance with the speed data. The leader vehicle was first placed at a distance of 85.6 m from the start of the section. The leader speed of 29.6 km/h was also set out according to the observed data. To replicate the behavior of the leader vehicle, two parameters (time and speed) were controlled every time step. Secondly, the follower vehicle was programmed to enter at the start of the section and control was passed over to the car-following model in each simulator for the remainder of the simulation period. Finally, each simulator's output (speed, time, and distance headway of both vehicles) was captured and compared to the field measurements.

To achieve the above task, it was necessary to replicate the behavior of the leader vehicle in each simulator. This task was implemented in AIMSUN using the Generic Environment for Traffic Analysis and Modelling (GETRAM) extension module, which provides facilities to interface external applications to the simulator. In every time step, the extensions module communicates with the AIMSUN simulator using a dynamic link library (DLL) file, which overrides the speed behavior of the leader vehicle according to values stored in an external database. Further details about the GETRAM extension module can be found in [17]. VISSIM executes this task using an external vehicle-course file, which also controls the driving behavior of the leader vehicle in every time step during the simulation period. Further details about this facility can be found in [33]. For PARAMICS, the speed of the leader vehicle is controlled using PARAMICS Programmer, which provides an application programming interface (API) to facilitate communication between the simulator and external applications. Further details about Programmer can be found in [34].

It should be emphasized here that the leader vehicle's arrival into the network and its speed profile were controlled by an external module and were not allowed to vary in order to replicate the exact behavior of the leader vehicle in the field. Similarly, the follower vehicle's arrival into the network was also controlled by an external module to replicate the positioning of the follower vehicle at the start of experiment in the field.

Fig. 4 illustrates the concept of overriding the driving behavior in the simulation tools using external controllers. The field experiment data gathered from the German study are stored in the database. Each simulation step, the external controller obtains the leader speed from the database, and implements it in the traffic simulator. The behavior of the follower vehicle is implemented by the car-following model in each simulator.

B. Scope and Assumption

The Bosch data show the car-following behavior of only one driver. However, it is generally accepted that car-following behavior is an individual characteristic and it is therefore not expected that the default model parameters would correspond to that particular individual's characteristics. The models would need to be calibrated (including acceleration/deceleration parameters) to that individual driver to produce better results. Due to the variable requirements of each model, sensitivity analyses of such impacts were not investigated for any of the tools considered in this study. It is also noted that the car-following behavior in this study was tested on a single-lane urban road. Car-following behavior for critical driving situations, e.g., on multiple-lane facilities, near on and off ramps on freeways, and near entrances to roundabouts, should be further investigated. This paper presents some basic findings of macroscopic behavior (in terms of how each simulator replicates relative speeds between follower and leader vehicles) but there is scope in future studies to investigate a more comprehensive macroscopic verification of microscopic behavior as described in [16] and [25]. Finally, this study only considered car-following behavior. There is also scope in future studies to consider other important factors such as lane-changing behavior.

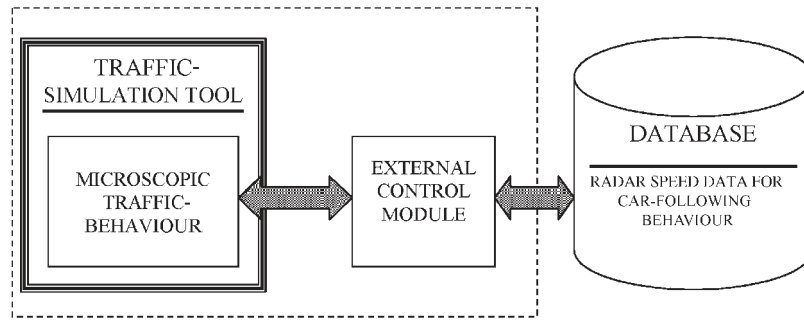


Fig. 4. Overriding driving behavior using external controllers.

TABLE III
SELECTED SIMULATION PARAMETERS

Simulator	AIMSUN2				VISSIM	PARAMICS	
<div>Vehicle Features</div>	Standard						
	Mean	Deviation	Minimum	Maximum			
	Length (meter)	4.5	0.0	4.5	4.5	4.11-4.76 [#]	4.5
	Width (meter)	2.0	0.0	2.0	2.0	2.0	2.0
	Maximum Desired Speed (kilometer per hour)	100.0	20.0	80.0	160.0	250 ^{##}	160.0
	Maximum Acceleration (meter per second squared)	2.5	0.0	2.5	2.5	3.5 ^{##}	2.5
	Normal Deceleration (meter per second squared)	4.5	0.0	4.5	4.5	(-2.8,-2.8) ^{##}	4.5
	Maximum Deceleration (meter per second squared)	8.0	0.0	8.0	8.0	(-7.5,-5.1) ^{##}	-
	Road Geometric						
Road Type	Urban				urban	urban	
Maximum Speed (kilometer per hour)	60.0				60.0	60.0	
Lane Width (meter)	2.75				2.75	2.75	
Global Simulation Settings							
Simulation Steps Per Second	1.0				1.0	2.0 [*]	
Reaction Time (second)	1.0				**	1.0	

* The validated value of simulation time step is between 2-5 [34]

Selected randomly between 4.11 and 4.76

Default values from speed – acceleration curve as specified in VISSIM.

** N/A. See Section 3.2 for details.

C. Controlled Parameters

The performance of each simulator will depend to a large extent on the proper selection of a large number of parameters. Some of the relevant parameters used in each traffic-simulation tool are shown in Table III. It should be noted that each simulator had been validated for a range of values as reported in the respective manuals and publications. These values were adopted to represent best case scenarios of performance. The specification and investigation of ranges of values for which the simulators have not been validated during their development was not explored in this study.

The maximum acceleration and deceleration values are relevant parameters to all three models while other parameters such as vehicle and lane widths are only relevant to the VISSIM simulator (considered in conjunction with car-following and overtaking behavior). It should also be emphasized here that

the simulation time step, reaction time, and other parameters for each car-following model can have a significant impact on the performance of the model. No sensitivity analysis was performed in this study to evaluate such impacts although there is scope in future studies to examine calibration methodologies such as those reported in, e.g., [35] and [36]. The simulation time steps used in this study were based on default or recommended values in the relevant simulators' manuals or publications.

D. Error Tests

A number of performance measures and error indicators are used to assess the fitness of simulation output to the field data [25], [37]. The criteria implemented in this study are described below.

TABLE IV
PERFORMANCE OF THE CAR-FOLLOWING MODEL
IN THE SELECTED TRAFFIC SIMULATORS

Simulator	AIMSUN (v4.15)	VISSIM (v3.70)		PARAMICS (v4.1)
		Wiedemann 74	Wiedemann 99	
Error Metric (EM)	2.55	4.78	4.50	4.68
RMS Error	4.99	5.72	5.05	10.43

1) *The Root Mean Square (RMS) Error:* This well-known error test measures the divergence of the simulated result from the observed value. The RMS error formulation used in this study is

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{n=1}^N (d_s - d_f)^2} \quad (7)$$

where

- d_s is the simulated car-following distance to the leader vehicle at simulation time t ;
- d_f is the field car-following distance to the leader vehicle at time t ;
- N is the number of observations.

2) *The EM on Distance:* This error was weighted by the logarithm and squared to avoid overrating discrepancies for large distance [25]. The EM formulation used in this study is

$$\text{EM} = \sqrt{\sum \left(\log \frac{d_s}{d_f} \right)^2} \quad (8)$$

where

- d_s is the simulated car-following distance to the leader vehicle at simulation time t ;
- d_f is the field car-following distance to the leader vehicle at time t .

VI. EVALUATION RESULTS

Car following is essentially a control process that a driver of a following vehicle uses to maintain a safe distance to the vehicle ahead by using either acceleration or deceleration, according to the actions of the leader vehicle. To verify whether a traffic-simulation tool reasonably replicates that behavior, a quantitative statistical test on the car-following distance as recommended in [25] and a qualitative drift and goal-seeking behavior, as recommended by Chakroborty and Kikuchi [38], are presented next.

A. Quantitative Statistical Results

The EM and RMS error, which were described in Section V-D, are used as the key performance measures in the quantitative analysis. The results for the three models are shown in Table IV. The EM indicates similar values for the psychophysical spacing models used in VISSIM and PARAMICS with better values reported for the Gipps-based models implemented in AIMSUN. These results are also depicted in Fig. 5,

which shows the distance to the leader vehicle (in meters) as replicated by each of the simulation tools. As can be seen in Table IV and Fig. 5, the three models replicated field car-following behavior with varying degrees of accuracy.

This study also explored a basic macroscopic characteristic of the simulators, namely, how each simulator replicates the relative speed between the leader and follower vehicles, as shown in Fig. 6 below. The figure shows a substantially different speed behavior for PARAMICS than the other two simulators. As was mentioned before, there is scope in future studies to investigate a comprehensive macroscopic verification of microscopic behavior such as speed-flow, flow-density, or any similar fundamental relationship.

B. Qualitative Drift and Goal-Seeking Behavior

The drift and goal-seeking behavior of a pair of vehicles is essentially related to how the distance headway between leader and follower vehicles oscillates (drifts) around what might be termed as a stable distance headway [38]. This behavior happens because the driver of the follower vehicle cannot judge the leader vehicle's speed accurately or cannot maintain their own speed precisely.

Drift behavior can be illustrated by plotting relative distance against relative speed, as shown in Fig. 7. The x -axis shows the relative speed of the vehicles while the y -axis represents the distance to the vehicle ahead. The data points appearing in the negative regions correspond to the follower vehicle traveling at speeds greater than the leader vehicle. Fig. 6 depicts how the car-following model for each simulator reproduces the real-world interaction between the follower and leader vehicles.

These figures only provide a qualitative measure of the degree to which each simulator replicates the measured drift behavior. The figures, however, clearly show that both AIMSUN and VISSIM produced a very similar curve to the measurements when compared to the PARAMICS curve, which reproduced the relative speed between vehicles with much larger oscillations. These differences in drift behavior are clearly a reflection of the various driving modes implemented in each car-following algorithm implemented in each simulator.

VII. FINDINGS AND CONCLUSION

The accuracy of a traffic-simulation system depends highly on the quality of the traffic-flow model at its core. The two main components at the heart of the traffic-flow model are the car-following and lane-changing models. This study aimed to evaluate only the car-following models in a number of traffic simulators.

Speed data obtained from instrumented vehicles traveling on an urban road in Germany were provided by the Robert Bosch GmbH Research Group. A methodology to investigate the car-following models in the traffic simulators was described. The car-following behavior for each simulator was compared to the field data using a number of error tests. The EM on distance was used as the key performance indicator. The results showed similar EM values for the psychophysical spacing models used in VISSIM and PARAMICS with better values reported for the Gipps-based models implemented in AIMSUN. The RMS error

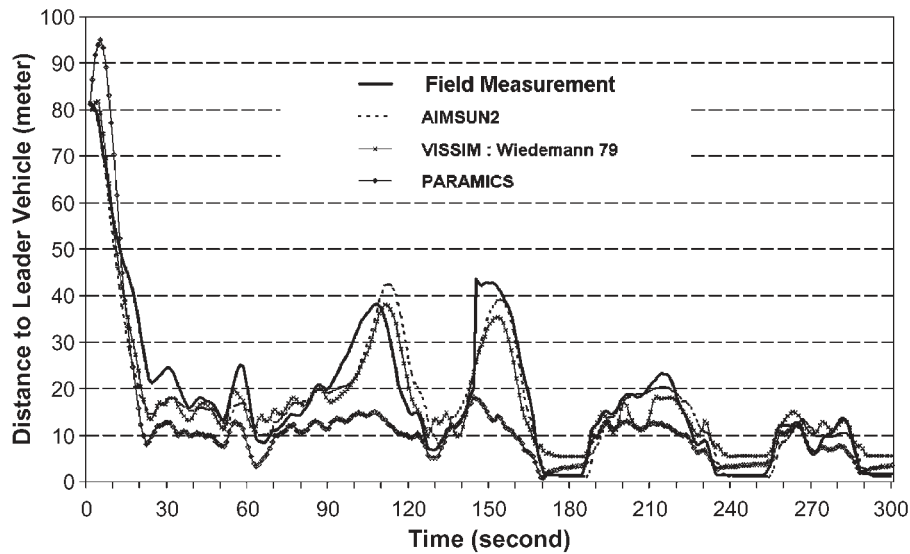


Fig. 5. Distance to leader vehicle as replicated by each simulator.

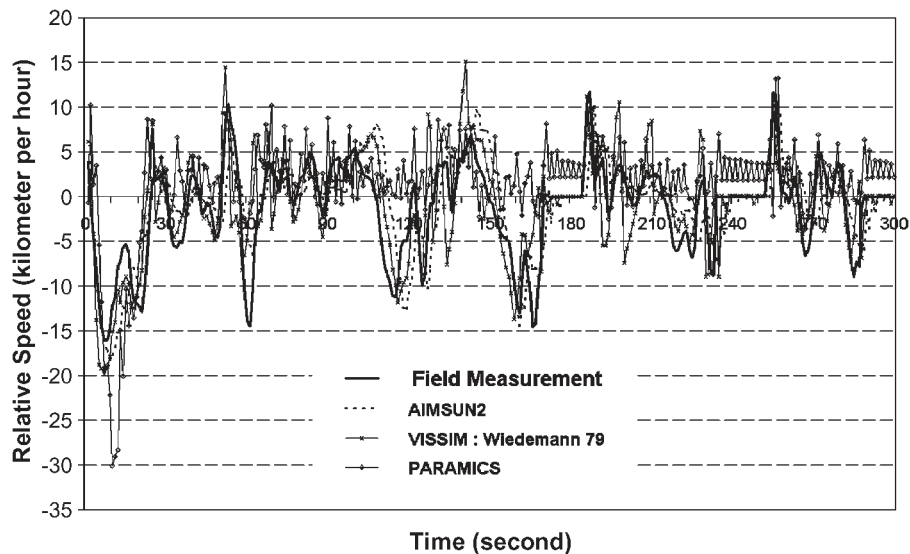


Fig. 6. Relative speed between leader and follower vehicles as replicated by simulators.

and the qualitative drift and goal-seeking analyses also showed a substantially different car-following behavior for PARAMICS than the other two models.

There is scope in future studies to extend this evaluation framework to include car-following behavior for critical driving situations (e.g., near on and off ramps on freeways) and to conduct sensitivity analyses to evaluate the impacts of some of the critical parameters in each model, such as the simulation time step and reaction time. Furthermore, this study only considered car-following behavior. The adoption of any traffic-simulation tool for research and development purposes, however, will need to take into consideration other important factors such as lane-changing behavior and the ease of interfacing the traffic-simulation system to external applications (e.g., driving simulators, adaptive traffic-management systems, optimization, and artificial-intelligence software tools). This requirement is becoming increasingly important for conducting research into modeling the impacts of ITS and

evaluating applications of advanced technologies to surface transportation.

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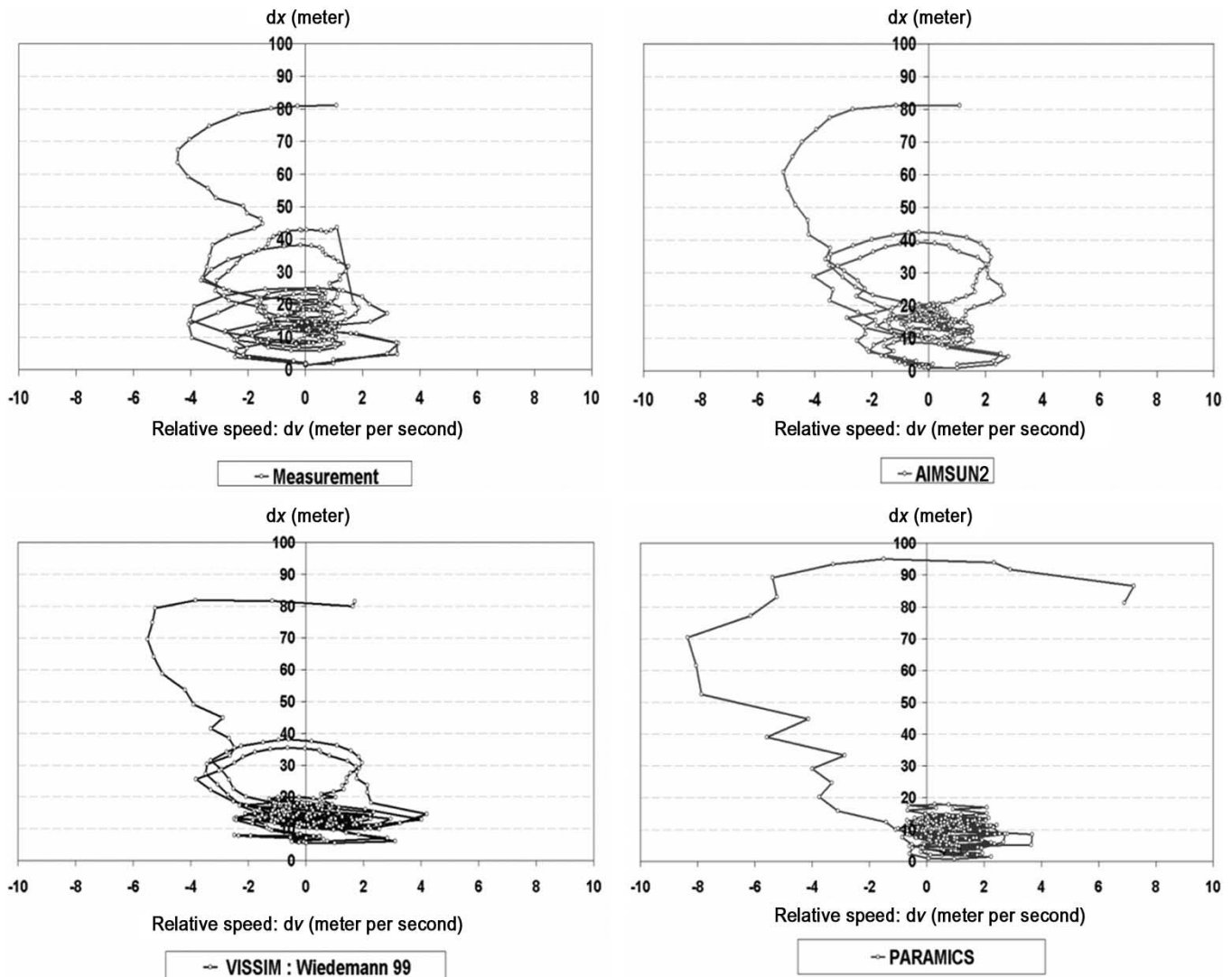


Fig. 7. Drift and goal-seeking behavior in car following.

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