Modeling of Motorway Operations

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Over the last 5 to 10 years rising levels of traffic flow on motorways have lead to the development of increasingly advanced intelligent vehicle-highway systems dedicated to improving capacity, stability, and safety. Many of these advances are to be achieved by modifying behavior or introducing a degree of vehicle control. To fully understand the effects of these mechanisms, however, it is necessary to develop and use appropriate microscopic simulation models. Accurate modeling of microscopic driver behavior presents several difficulties, ranging from the requirement for high-quality (dynamic) data on real driving behavior through the methodology used for cross-checking between simulated and observed behavior to the philosophical basis of modeling itself. These issues are discussed, the degree of shortfall present in current simulation and analysis techniques is examined, and potential guidelines for increasing the validity of microscopic simulation models are suggested.

With the rapid growth in motorway traffic driver behavior is perceived as becoming of increasing importance to safety and capacity. Measures designed to address these problems, formulated as part of the PROMETHEUS and DRIVE initiatives in Europe and VERTIS in Japan, face an increasingly difficult task because of the costliness of potential field trials, both financially and in possible increases in risk exposure to the driving public. Therefore, the use of simulation models as a cost-effective way of investigating intelligent vehicle-highway system (IVHS) solutions at a fundamental level has become an increasingly attractive alternative, allowing complex investigations to be conducted in a repeatable and controllable manner.

Although forming a highly diverse group, such models can broadly be divided by two criteria:

1. The scale of the traffic system modeled:
   –Urban regions, where vehicle interactions are primarily related to nodal points in a network (such as signalized intersections) and link behavior is relatively unimportant [e.g., CONTRAM, SATURN, NETSIM (*1–3*)], and
   –Interurban regions, where interactions typically occur through grade-separated junctions and link behavior becomes increasingly relevant because of the high proportion of travel time spent between the nodes, for example, SIMAUT (*4*).
2. The basis on which traffic dynamics are simulated:
   –Macroscopic formulation, in which variables such as average traffic density and speed over specific sections are used to define traffic behavior, for example, by expressing disturbances in traffic density as shock waves in a continuous medium through the use of continuity equations [e.g., META (*5*)], and
   –Microscopic formulation, in which the interactions of individual vehicles with each other is taken explicitly into account and calibrated or validated by using parameters such as speed, which can be observed as distributions at key points and reproduced through Monte Carlo-based simulations [e.g., Autobahn Simulator AS (*6*)].

As interest in the control of motorway networks has grown over the last 5 to 10 years, macroscopic interurban models have become comparatively commonplace and have been applied with some success. For example, motorway control algorithms have been tested through the simulation of motorway orbital routes surrounding major cities (*5*); these algorithms consist of a series of 10 to 20 junctions with spacings of about 1 km. However, as the complexity of IVHS technology rapidly increases, the degree of detail used in these models and available in their output is becoming more and more unsuitable. This is because consideration of the effect that advanced (individual) vehicle control systems (e.g., advanced intelligent cruise control) may have on the operation of the motorway as a whole is increasingly needed. This effect can be represented accurately only at a microscopic level.

Microscopic models are predominantly based on two fundamental behavioral mechanisms that are considered to describe the basic decision-making processes undertaken during motorway driving:

1. Car following, which describes the longitudinal speed–distance relationships adopted by a driver when following another vehicle. A range of such theories is in use. These are typically based on either the acceleration stimulus provided by the followed vehicle [according to relative speed and separation (*7*)] or maintenance of a set deceleration and an attempt to follow at a set stopping distance (*8*). For a more comprehensive review of these models see Brackstone and McDonald (*9*).
2. Lane changing, which governs the circumstances in which a vehicle moves into an adjacent lane. This may be considered in terms of a number of perception thresholds, the crossing of which activates the next stage in a maneuver or process. For example, the speed advantage that would be obtained if a vehicle were to change lanes to pass a slower vehicle in front may be required to exceed a set amount for the maneuver to be considered worthwhile (*10,11*).

These mechanisms are frequently enhanced by researchers as more scenarios are needed and more empirical evidence is accumulated. Typical modules attached to most models at a later stage of their development may include the following:

- Entry or exit behavior to cope with the short-headway lane change decision that is common near or at motorway merges and diverges, when drivers are forced to accept gaps that are substantially smaller than that which they would usually prefer to accept. This allows the simulation of technologies such as ramp metering or off-ramp control by vehicle type (*12*).
- Lane preference factors to allow the testing of alternate lane usage strategies, for example, goods vehicle lanes and speed banding. This typically involves continual refinement of the lane change

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algorithm to incorporate a wider range of factors contributing to lane choice, such as the effects of goods vehicles slowing on an incline (*13*).

- Intelligent vehicle applications, incorporating automatic speed or headway control algorithms. Modifications may also be required to model how driving behavior may change in the presence of such devices, that is, changes to the desired deceleration rates used by the driving population.

A brief list of the capabilities of the main models in use in European national and international research programs known to the authors is given in Table 1.

As this process of enhancement inevitably continues, the research community is forced to confront a growing need for data with which to validate these models. This is a far from straightforward task, however, with a range of almost philosophical traps awaiting the unwary:

- The use of inappropriate data.
- The use of inappropriate validation or calibration procedures caused by a lack of understanding of model sensitivity.
- An increase in discontinuities within the modeling.

These issues will be discussed in this paper, and ways in which microscopic modeling may need to develop in the remainder of this decade are suggested.

DEFINITIONS

In many references the distinction between calibration and validation is unclear, and the following definitions are given for clarification: *Validation* is undertaken at a macroscopic scale to ensure that the overall behavior of a model matches that readily observable. *Calibration* is undertaken at a microscopic level with regard to individual vehicle-to-vehicle interactions; it is the tuning of the many behavioral parameters comprising the decision-making processes.

USE OF INAPPROPRIATE DATA

By using the definitions given in the preceding section, two types of data are needed to check if a simulation model is correctly formulated. Validation data, which can be obtained in a comparatively straightforward manner and which typically consists of minute-by-minute records of flows, average speeds or headways, and traffic stream composition, can be easily extracted from loop data or video recordings of the road taken from a suitable viewpoint. Calibration data can also be obtained, but it is far more difficult to obtain these data because of the number and diversity of the parameters involved and because the parameters are often not directly related to easily observable quantities.

Typical records that would be required to examine the behavior or response of any one vehicle during the calibration process may include the following:

- Type, speed, relative speed, and distance to the vehicle being followed. In more critical situations this could be extended to the next but one vehicle to the front and even the vehicle to the rear.
- Types and speeds of adjacent vehicles in neighboring lanes. Data from these vehicles can be used to calculate the sizes and relative speeds of gaps into which the vehicle could move.
- Local flow or density and relative proportions of vehicle types, an approximate measure of how busy the driver believes the road to be.
- Geometry, that is, vertical and horizontal curvature of the road. This may affect visibility, desired speeds, and braking thresholds.

The majority of these parameters describe dynamic quantities, such as the relationship between the acceleration of a vehicle and changes in the relative speeds of and distances to surrounding vehicles. Thus, to fully understand such a process one must attempt to sample data at a rate similar to that at which changes may take place. This is an exceptionally difficult problem, however, because most of the variables are required relative to the probe vehicle, which is moving along the road and hence cannot be sampled sufficiently frequently by any method that relies on making observations at a set point.

TABLE 1 European Microscopic Interurban Simulation Models

	Details			
Model (Country of Origin, Reference)	Developer	Primary Current Research Use	Calibration Notes	Additional Modules
AS (D, 6)	Benz AG	PROMETHEUS		AVCS[a]
MISSION (D, 11)	IfV. Univ. Karlsruhe	National	Uses data from basic instrumented vehicle	AVCS[a]
SISTM (UK, 12, 13)	Wootton-Jeffreys-Atkins Ltd.	National (TRL/DoT)		EE[b], ML[c]
SPEACS (I, 14)	CSST	PROMETHEUS	Uses SCAN driving simulator, for direct input to data base	AVCS[a], EE[b]?
PELOPS (D)	IfK. RWTH, Univ. Aachen	PROMETHEUS		AVCS[a]
MONET3 (D)	RWTH, Univ. Aachen	PROMETHEUS		RC[d]

[a]Advanced Vehicle Control System modules
[b]Entry-Exit behaviour
[c]Enhanced for multi-lane vehicle distribution
[d]Roadside IVHS Communication protocols

A method frequently cited as being a solution to this problem is the monitoring of the behavior of a vehicle as it passes along a stretch of road by the use of a series of video cameras. This was attempted in the United Kingdom in 1993 (*13*), in which a series of video cameras was set up on a high embankment overlooking the M27 motorway. Each camera was set up to observe a 50-m longitudinal section of the road, and from the synthesis of data collected from the group of cameras over a total of 500 m, it was possible to track vehicles and measure their speeds and separations (Figure 1).

Analysis focused on attempting to find relationships between the relative speed between a lane-changing vehicle and up to four neighboring vehicles and the associated headway time (allowing an examination of questions such as, Do vehicles pull out earlier to lane change if they are moving faster?). Despite the presence of apparent trends in plots of these variables (Figure 2), regression analysis of the data did not enable any underlying relationships to be identified. A wide scatter was present in the data, and typical R^2 values (describing the degree to which the empirical data can be explained by the optimum linear relationship possible) were of the order of ~2 percent (i.e., only 2 percent of the variation observed could be explained by assuming the presence of a linear relationship).

Although the multicamera approach provided useful and previously unavailable data on lane-changing rates, the method did not allow the development of any significant findings on the individual processes under investigation, that is, gap acceptance on lane changing. This was considered to be primarily through the inaccuracy of the video-based measurement technique (5 to 7 percent in speed) and the inability to monitor vehicles over a sufficiently long stretch.

The main data collection alternative to this method is to place a single driver and his or her vehicle in a controlled environment where its response can be regularly and consistently measured. The obvious candidate here is to use vehicle simulators. However, at present these are generally restricted to simple scenarios, and by their nature they are an artificial environment in which errors in perception are not a potential matter of life and death. A more realistic option is to use an instrumented vehicle in which a vehicle driven in the traffic stream is used as a platform from which to observe the behaviors of adjacent drivers. Past applications of this technique have been very limited, but recent work (*15,16*) with laser and radar sensors seem to have decreased the measurement inaccuracy caused by so hostile an environment and may well yield high-quality behavioral data in the next few years as increased exploitation is made of sensor technology made available through advanced vehicle control system programs.

CALIBRATION AND VALIDATION PROCEDURE

Simulation models are validated to a large extent according to the particular phenomena of traffic flow that they are designed to investigate. Thus, microscopic models are validated according to the model's ability to produce flow breakdown and speed–flow relationships, whereas network-based models such as CONTRAM are assessed according to average flows observed on key links or nodes or queue lengths at particular junctions. This type of approach produces a validation or calibration that is necessarily restricted to a

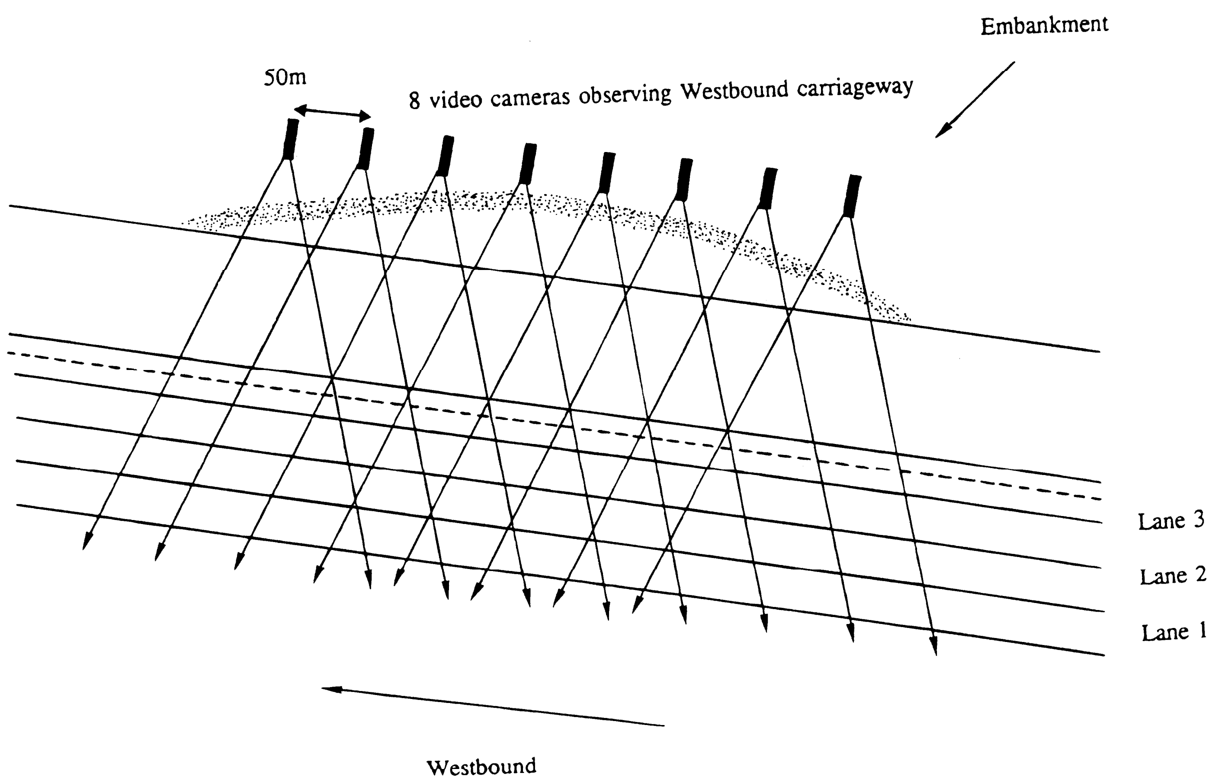

FIGURE 1 Schematic of video-based vehicle tracking method showing separation against closing speed between vehicle changing to a faster lane and an obstructing vehicle.

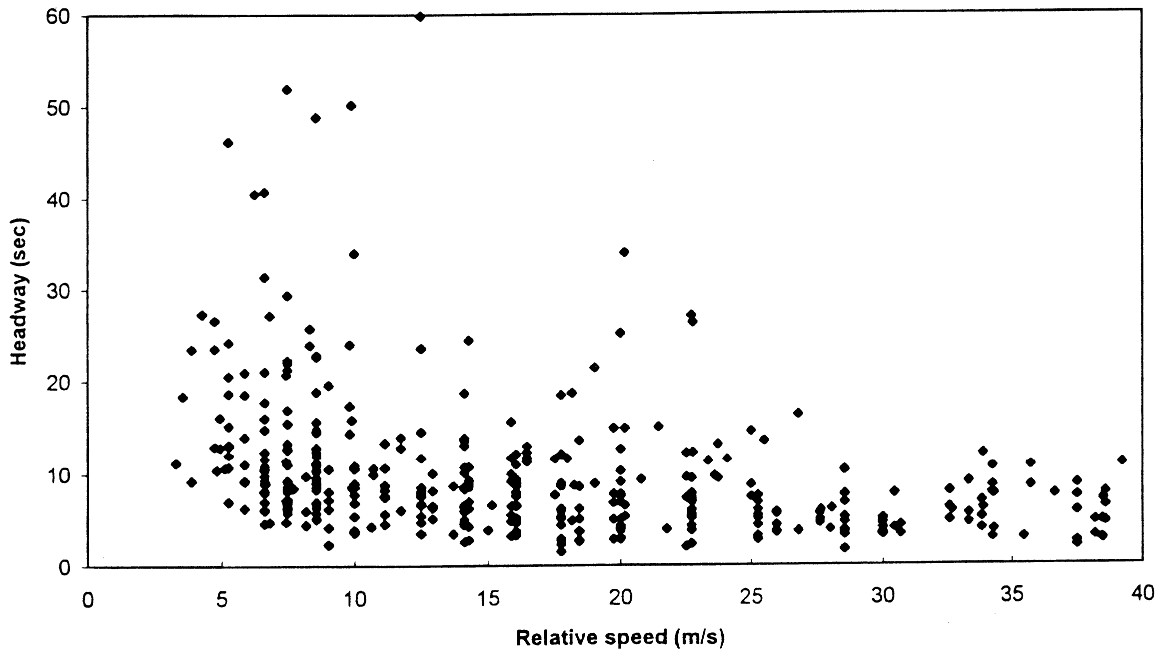

FIGURE 2 Example of data collected from video-based tracking experiment.

small number of readily observable phenomena that can be adequately replicated in most models, but that does not necessarily ensure that the model is an accurate descriptor over a wide variety of circumstances or in sufficient detail.

On attempting to validate a simulation model, the user is faced with the prospect of the variation of many parameters, all of which could potentially affect the particular measure under investigation. Although it may be possible to identify parameters that would have an easily detectable macroscopic impact through a common sense approach (e.g., increasing tolerance of speed differences would reduce lane-changing rates), this process is often hampered by an absence of information on model sensitivities. Although this may not initially seem to be a problem of any great significance, it poses potentially the most dangerous trap into which simulation-based traffic research can currently fall. However, with the current quality of the available data, no true microscopic calibration can be performed, and this has resulted in the use of a mesoscopic calibration in which an attempt is made to validate a number of more fundamental parameters that are not explicitly present in the model's formulation or that are not easily observable.

As an illustration of this point consider the calibration of a quantity such as the distribution of gap sizes accepted when moving into an offside lane. This quantity is not microscopic, because it is a by-product of many other factors contributing to the lane change decision, such as speeds and relative speeds of the vehicles involved. Nor is it macroscopic, however, because it cannot easily be measured without the use of specialized methods and does not itself comprise one of the fundamental measures of traffic flow.

Because of the use of this hybrid validation–calibration method, it is possible to arrive at a set of calibrated model parameters that produce a reasonable macroscopic fit and that may intuitively seem to be correct but that may nonetheless be an incorrect combination, producing inappropriate behavior in a measure not examined. For example, reproducing speed–flow relationships or lane splits to a high degree of accuracy does not guarantee that the simulated lane change rate (a potential measure of risk exposure) will be as accurate (*13*). The more detailed the behavior that one attempts to simulate, the greater the potential for a mismatch between the true microscopic calibration required and the mesoscopic calibration achieved.

Even if large amounts of new data were to become available, an improvement on this standard approach would still be required and would entail the testing of the decision-making processes in isolation from the simulation run as a whole. This would additionally involve the simulation of many individual events, varying the distributions of the behavioral parameters involved. Because many hundreds of runs of each scenario would thus be required, this would entail a program of investigation that would be of a magnitude similar to that of the data collection task itself.

MODELING DISCONTINUITIES

As this paper has progressed it has posed a series of questions and definitions as to what may constitute an accurate calibration. From the earlier sections it can be seen that such an answer requires a large amount of data to be matched under a wide range of circumstances by an equally large quantity of model output. Every time that a new question arises or a new set of behaviors is required, the model must be updated and revalidated.

By using traditional modeling philosophy an accurate calibration for universal application cannot be achieved, because the modeled behavior will be posed in terms of a growing set of if–then–do rules, which can easily become contradictory and discontinuous. The modeling task would therefore seem to require a forever-increasing amount of effort to produce each successive stage of detail or validity. The true driving process is obviously different, moving smoothly from one task to another, and is represented more accurately by the presence of a degree of error within each decision-making process. Until recently, such an approach to behavioral or control science would have been deemed conceptually impossible; however, with the introduction of so-called fuzzy reasoning such a treatment could now be undertaken. By this method a degree of confidence could be attached to each observable in a decision-making process, which itself would use linguistically defined variables by categorizing relative distance, for example, as close, very close, or dangerously close.

Although the use of fuzzy logic in traffic simulation is still in its infancy (*17*), it is clear that such an approach could provide a powerful tool in the simulation of driver error and overreaction and may enable investigators to bypass the ever-growing set of rules and parameters that characterizes microscopic models.

SUMMARY

A number of problems surrounding the use of microscopic motorway simulation models have been examined, and an attempt has been made to identify the steps required to produce a major upgrade in their validity and transferability. Two key points have been identified:

1. A more critical degree of calibration is necessary if models are to truly fulfill their description as microscopic, with individual driving processes being examined in isolation and receiving dedicated attention from specific data collection exercises, which themselves reflect the dynamic nature of the process.
2. A degree of uncertainty must be introduced into the microscopic decision-making processes. This may seem like a contradiction, but it is likely to produce a far more realistic description of real behavior, because drivers do not have perfect reactions, identical perceptions, or access to exact data from which to calculate their course of action.

In conclusion, for the validity of microscopic simulation models to advance for use as assessment tools in the development of IVHS, road design, and even driver education or legislation, it will probably prove to be necessary to shift emphasis away from traditional concepts, such as the quantity of data used in validation and calibration, to increasing the suitability of data and the relevance of the calibration processes and replicating the true nature of the behavior that is being modeled.

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