Simulation and Evaluation of Freeway Traffic using Interchangeable Behavioral Models

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Abstract
Microscopic simulation of traffic flow has spawned many different behavioral models, some of them commercially distributed, some developed at academic institutions for scientific purposes. These models are either kept secret (for commercial products) or substantially lacking in terms of usability and visualization. In this paper, we introduce the simulation environment BABSIM that allows for different driving behaviors to be integrated into one common simulation package. An overview of microscopic simulation is given, and several existing models and their implementations are being discussed. The fundamental structure of the BABSIM package, its user interface and the calibration of the model parameters are presented.

Introduction
The number of motorized vehicles on this planet is steadily increasing, and there is no indication that this trend is going to abate in coming years. The German federal highway network alone consists of about 12100 kilometers of road, with a planned growth of 15\% in the next couple of years (BMVBW, 2004), not counting the inevitable maintenance efforts. To cope with these complex planning tasks, traffic engineers are increasingly using traffic simulation as a means for effectively evaluating the capacity of new road designs.

Numerous established microscopic simulation packages exist for emulating the flow of individual vehicles on a more or less complex road network. Some of these programs are being commercially developed and distributed. As the targeted market segment is relatively small, the competition is rather fierce, and the underlying simulation models are often not disclosed. Such a black-box concept discourages the use of traffic simulation for public road planning projects, as no certified model exists and the validity of simulation results cannot be verified.

The project BABSIM, carried out in joint research between the ICE and the Institute for Traffic Engineering at the Ruhr-University, addresses this problem by integrating several well-documented and established car-following and lane-change behaviors into one common simulation environment. Furthermore, the user is enabled to introduce new behavioral strategies to address his specific planning requisites. BABSIM specializes in simulating the traffic on multi-lane freeways, including the complex weaving behaviors in proximity of freeway junctions.
Microscopic traffic simulation
Traffic simulation models are often distinguished into four classes, according to their level of simulations detail. Most common, are macroscopic models where traffic flow is emulated as a stream of particles subjected to the laws of fluid dynamics. Also often used are microscopic models that focus on individual vehicles and their driving behavior. While macroscopic models use less computational resources and, therefore, allow the simulation of large road networks, the results are often less accurate compared to microscopic simulation. Specifically, individual road segments or junctions cannot be recreated in a sufficient level of detail.

Mesoscopic models, in contrast, try to bridge the gap between macroscopic and microscopic simulation by using individual vehicles that are being actuated through macroscopic control variables. Sub-microscopic models, the fourth group, provide the highest level of detail, but are computationally expensive and take strong efforts to be calibrated. They are, therefore, most often used for single vehicle simulation in the automobile industry.

The choice of a microscopic approach for BABSIM was motivated by the need to granularly simulate vehicle motion, especially in the vicinity of highway junctions, where more strategic inter-vehicle interactions have to occur. BABSIM uses a time-step based system, with time steps adjustable between 0.1 to 1.0 seconds.

Behavioral models
Six different simulation behaviors have been included into BABSIM. In the implementation phase, our goal has been to leave the underlying algorithms untouched as far as possible, and to adapt them only when model changes or obsolete traffic assumptions force alterations.

In the following, the term driving behavior describes all vehicle movements in axial direction, i.e. accelerating or decelerating along a current road lane. All models stated below consider only the next vehicle in front of a car. In addition, all model realizations try to accurately emulate realistic acceleration rates.

Lane change behaviors describe the strategy for lateral transitions of a vehicle from one road lane to an adjacent one. In contrast to the car following behaviors described above, where only the preceding and following vehicles have to be taken into account, a lane change requires a far more complex consideration of the interaction between the car and all its neighboring vehicles. Each vehicle has to decide whether it wants to change lanes, whether such a change would be safe, and whether the security of other cars would be affected in the process. Furthermore, vehicles have to assist other cars that try to change lanes, which complicated the decision finding process even more.
The kinematic model uses a very elementary kinematic equation to calculate the maximum degree of acceleration/deceleration that a vehicle must exert to prevent a collision with the preceding vehicle. At each time-step, the new deceleration rate $a_{n+1}$ must be high enough to prevent a collision for a predefined time interval (called time-to-collision, $t_c$). Also, it has to adjust the current following distance $D_x$ to attain a targeted optimal following distance (called $d_x$). The velocity is being clipped such that it remains in the interval $[0..v_{\text{max}}]$.

$$a_{n+1} = a_n + (D_x - d_x) \cdot \frac{2}{t_c^2} + d_v \cdot \frac{2}{t_c}$$

As the model relies on only two parameters, the calibration effort is rather small – but the simulation obviously does not attain high levels of reality, either. Due to its limitations, the kinematic model is of little significance in modern traffic simulation and not recommended for road dimensioning tasks. It has been included, however, for educational purposes.

Wiedemann’s concept was to define a driver’s perception threshold, that, if exceeded by a visual stimulus (e.g. an approaching vehicle), triggers a behavioral reaction. The reaction is dependent on the relation between the car and the preceding vehicle. Several regions of interaction are defined (Approaching, Following, Emergency and Uninfluenced). Each driver-vehicle unit (DVU) is provided with an individual set of attributes that define his driving behavior, e.g. his alertness, reaction time, need for safety or willingness to accelerate. The advantage of the psycho-physical model lies in its high level of realism. Furthermore, it is proven and shows a reasonable robustness.

In 1995, Bando et al. introduced the Optimal Velocity Model (OVM), a velocity-density-model that belongs to the group of deterministic driving models and relates a vehicle’s target velocity to the macroscopic traffic density. Bando introduced an optimal velocity such that every vehicle tries to follow the relation

$$a_{n+1} = \alpha \left(v_{\text{opt}}(dx) - v_n\right)$$

where:

- $a_{n+1}$ = acceleration for the next time-step
- $\alpha$ = sensitivity factor (inverse of the driver’s reaction time)
- $v_{\text{opt}}$ = optimal velocity function
- $dx$ = distance headway to preceding car
- $v_n$ = current vehicle velocity
Bando’s team proposed a monotonically increasing optimal velocity function with an upper bound of $v_{\text{max}}$.

\[
v_{\text{opt}}(dx) = \frac{v_{\text{max}}}{2} \left( \tanh(0.086 \cdot (dx - 25)) + 0.913 \right) \leq v_{\text{max}}
\]

Since that time, several modified optimal velocity functions have been developed, e.g. using different functions for the acceleration and deceleration cases (Asymmetric Optimal Velocity Functions) or differentiating between a vehicle’s free-speed (uncongested traffic flow) and the speed-at-capacity (congested traffic) with a four-parameter-equation (Van Aerde, 1995). The original Bando version and the Van Aerde modification have been included into BABSIM as well.

**Driving behavior GAZIS.** The so called car following theory, based on research by Gazis, Herman and Rothery (1961), attempts to emulate the vehicle behavior by determining the car following distance by considering a driver’s reaction time to certain stimuli (speed difference to preceding car, velocity and headway) according to the formula

\[
a_{n+1} = a_0 \cdot \frac{v_{n+1}^m}{dx} \cdot dv
\]

where:

- $a_{n+1}$ = acceleration after a fixed reaction time $T$
- $a_0$ = sensitivity factor
- $m, l$ = calibration parameters
- $dv$ = velocity difference to preceding vehicle

For German highways, values for the parameters $m$ and $l$ have been established in the study by Hoefs (1972) for different scenarios (falling back or closing in on the car in front, with or without brake lights). But, due to the steady increase of traffic on European roads, a recalibration of the model parameters has been performed during the development of BABSIM, resulting in a new parameter set for more realistic simulation results.

**Lane change behavior SPARMANN.** Based on the work of Wiedemann, Sparmann developed a lane change algorithm for two-lane highway traffic (Sparmann, 1978). Taking into account all six potential interaction partners (i.e. each vehicle in the front and back on the current lane as well as its two neighbors), a vehicle might develop the desire to change lanes by using a variation of Wiedemann’s regions of relation. Once the need for a lane change has been established, the vehicle checks whether such a transition would endanger either him or its interaction partner. If the safety of all vehicles can be ensured, the lane change behavior initiates the change process, and the vehicle is set on the neighboring driving lane.

One disadvantage of Sparmann’s model is the lack of a more anticipatory strategic approach. Only the neighboring vehicles are being considered, ignoring the need to assist other vehicles that might change lanes. As a consequence, a cooperative interaction, especially in the proximity of highway junctions, can not be represented.
For a better emulation of on-ramp and off-ramp behavior, therefore, Theis has created an improved model.

**Lane change behavior THEIS.** Theis (1997) added a strategic component to Sparmann’s model: If a vehicle is trying to reach a certain lane, it has to ask conflicting vehicles for their assistance. Vice versa, the assisting vehicle has to decide whether to accelerate or to fall back to create a gap for the changing vehicle, or to change lanes by itself to make room. Theis differentiates between on-ramp and off-ramp behavior. When no strategic interaction planning is necessary, the “classic” Sparmann behavior is used instead.

**Implementation notes**
A simulation package targeted to be used in public road planning offices needs to provide a high level of usability. Traffic engineers cannot be expected to spend countless hours learning to use a simulation program. Performing a simulation should be a rather straightforward process: design your road network, set traffic densities and measurement points, start the simulation run, and evaluate the results. To increase productivity, an intuitive graphical user interface (GUI) is mandatory.

To this effect, BABSIM provides a graphical network editor that serves as sole environment for design, simulation and visualization. The GUI is inspired by familiar CAD user interfaces and offers a variety of tools to generate complex road networks in a short time. Existing maps and satellite photos can be used as references for road design. Single or multiple lane roads can be created and connected via on-ramps and off-ramps, forming complex highway junctions. The traffic density and truck rates can be user-defined for each route between a given source and sink.

![Figure 1. The network editor in 2D and 3D view](image)

As the simulation system was targeted to run on different operating systems, an object-oriented, platform-independent approach using the programming language Java has been taken. The first step of the design phase was to identify, classify and model the basic classes of the model, e.g. vehicles, traffic lanes, obstacles etc. Complex highway networks can then be emulated by associatively linking numerous traffic lane elements together. Vehicles are being generated by sources and placed onto the road elements. Controlled by the chosen behavioral model, the vehicles
move through the network until they reach a sink, upon which they are being removed from the simulation.

Figure 1. Class diagram of the main simulation classes (overview)

For visual and numerical evaluation of simulation runs the user can choose between several possible tools. He may choose individual vehicles and follow them through the road network, while watching vehicle velocity and its interaction with neighboring vehicles. Measuring points can be inserted into the existing road network to create distance/time-diagrams and velocity/density-diagrams of the traffic flow. For each road segment, the level of service is recorded during simulation. Travel time and mean velocities for each route are also provided. Thus, a thorough analysis of all data generated by the simulation is possible.

Figure 2. Input of traffic volumes (left) and generated q-v-diagram (right)

Calibration and testing
Some of the models, especially the conventional Wiedemann and Gazis behaviors, require an extensive recalibration phase to update their parameters to modern traffic conditions. To this end, a series of real-life measuring runs has been conducted to gather data on vehicle velocities, accelerations and following distances in different traffic situations. To ensure results unbiased by individual driving attitudes, the measuring vehicle was being driven by different test drivers. In total, a distance of more than 800 kilometers on German highways has been covered. All measurement runs were recorded on time-coded video to identify following and lane change processes. Using the obtained data sets, optimization runs have been performed using BABSIM to define appropriate parameter sets for all driving behaviors.
Conclusion
A short overview of traditional traffic simulation strategies in general and microscopic behavioral models in particular has been given. It has been discussed that these models can be integrated into a unified simulation system. The design of the program model and its user interface has been presented. BABSIM has evolved into a complex, yet easy to use open-source alternative to commercial traffic simulation systems that can be applied to both scientific research projects and road design tasks.

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References


