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On the Need for Novel Tools and Models for Mixed Traffic Analysis

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Abstract

Field operational tests provide invaluable insight into the performance of self-driving vehicles, however, information on the transportation system level requires large-scale analysis, usually carried out by means of simulation. Unfortunately, available models and tools are not sufficient to fully evaluate mixed traffic scenarios: models for human drivers are collision-free and models for autonomous vehicles largely focus only on the low-level control of the vehicle. In this paper we present the first version of the BEHAVE (Behaviour Evaluation of Human-driven and Autonomous VEhicles) simulator that enables the evaluation of different integration scenarios. We discuss the required changes in microscopic mobility models for both manned and autonomous vehicles, and present solutions that can pave the way for meaningful and reliable simulation of safety and efficiency aspects on a system level. BEHAVE can be used as test suite for AV mobility models and to derive certifications, insurance guidelines as well as operational policies.

Keywords:
Microscopic traffic simulation, car-following model, autonomous vehicles

Introduction

Autonomous mobility will bring a diverse range of benefits: faster commuting times, less pollution, and a more flexible transportation system. However, Autonomous Vehicles (AVs) are not going to replace ordinary cars overnight. There will be an extended period during which the roads will be shared by AVs and human drivers. The effects of such a mixed traffic situation are hard to predict, and thus safety must be rigorously analysed.

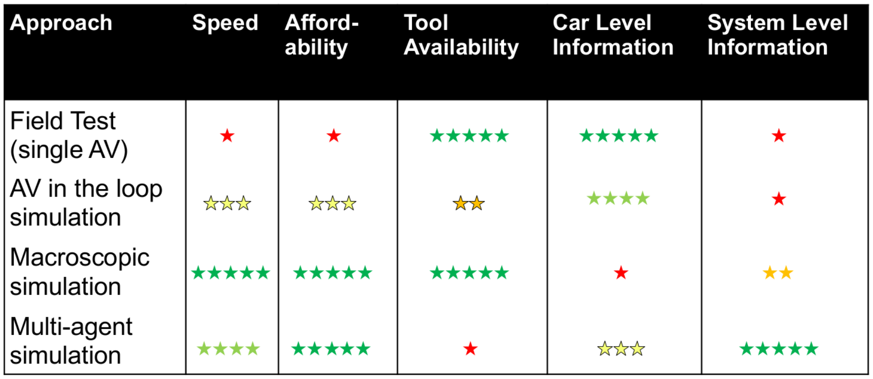
Unfortunately, as a result of real-life tests, numerous accidents with AVs on the road have already been reported, sadly also fatalities [7, 9]. This has caused an unprecedented level of attention from government regulatory bodies to the safety of these vehicles. In order to achieve a reasonable amount of certainty for the safety properties of AVs, hundreds of millions of kilometres have to be driven [6] and a large variety of known and yet-to-be-discovered dangerous test scenarios have to be evaluated. Unfortunately, field operational testing, albeit necessary today, requires a large amount of time and cost and is also potentially dangerous when carried out outside of closed test tracks.

Moving test scenarios from the real-world to a simulation environment can make the integration of AV technology in the transportation system more feasible. With this approach, the time and cost requirements for real-life tests can be drastically reduced as in a simulation environment, millions of kilometres can be driven in a matter of days or even hours. The biggest challenge for this kind of traffic simulation is to provide reliable and meaningful results. It comes down to the question whether the simulation is realistic enough and whether it can be trusted.

In Figure 1, we have listed the current approaches for the evaluation of mixed traffic scenarios. While information at the car level can be obtained using rather expensive field testing or AV in the loop simulation, we observe that approaches to obtain system level information are still scarce. Macroscopic simulation models cannot provide sufficient insights on the safety of mixed traffic, as they do not model the microscopic interaction between vehicles.

Microscopic multi-agent simulation seems to be the only alternative in this regard. There exists a range of microscopic traffic simulations tools, e.g. VISSIM [2], SUMO [10], AIMSUN [1], CityMoS [15]. However, results obtained with this kind of simulators heavily depend on the utilised mobility models. If vehicles do not behave as they would in real life, then conclusions drawn can be misleading or even wrong. Current simulators focus on using existing mobility models rather than serving as a platform to develop new ones. As almost all of today's mobility models are collision-free, they do not capture human behaviour from a safety perspective. We argue that models should be able to take into account a sometimes seemingly irrational and highly unpredictable behaviour. Models for autonomous vehicles should be able to follow different AV policies such as regulations regarding platooning or dedicated AV lanes. At the same time they should be generic enough to allow easy extension to more specific AV strategies and yet complex enough to capture the wide spectrum of AV functionality. Second, the mentioned simulators serve as general purpose traffic simulators which might not be accurate and flexible enough to study certain mixed traffic situations in detail.

In this paper we contribute to closing this gap by identifying the requirements for a mixed-traffic simulation framework and by introducing the BEHAVE framework. This microscopic traffic simulator focuses on model development, model validation and the evaluation of all aspects of mixed traffic scenarios.



Approach	Speed	Afford-ability	Tool Availability	Car Level Information	System Level Information
Field Test (single AV)	★	★	★★★★★	★★★★★	★
AV in the loop simulation	☆☆☆	☆☆☆	★★	★★★★	★
Macroscopic simulation	★★★★★	★★★★★	★★★★★	★	★★
Multi-agent simulation	★★★★	★★★★★	★	☆☆☆	★★★★★

Figure 1: Overview of current approaches to evaluate the performance of autonomous vehicles

Our contributions can be summarised as follows:

- BEHAVE, a microscopic traffic simulator for mixed traffic.
- Necessary extensions to mobility models for both human drivers and autonomous vehicles.
- Research directions that can be explored using BEHAVE which we deem necessary to be studied to pave the way for the safe integration of AV technology.

Microscopic Traffic Simulation

The basic principle of agent-based microscopic traffic simulation is that every vehicle is an *agent* that acts autonomously based on behavioural models and the environment around the agent. Agents can sense other agents that reside within their sensing range (e.g., 300 meters in front and behind of an agent on a road) and act accordingly.

Agents in traffic simulation incorporate models that describe the logic of vehicle movement. Movement is considered in two dimensions: longitudinal and lateral. The longitudinal axis movement is described using car-following models which determine the acceleration and deceleration of a vehicle depending on the speed and position of vehicles in front. The lateral axis movement is formalized using lane-changing models that take as input information about the vehicles on adjacent lanes. Lateral movement is usually modelled discretely, meaning the vehicle cannot move continuously on the lateral axis but is bound to be on a specific lane.

The existing traffic simulation platforms mentioned before feature well-known car-following models such as the Intelligent Driver Model (IDM) [13], the model by Gipps [3], the Krauss model [11] or Wiedemann [14].

Using Gipps' model allows agents to maintain a safe speed to always avoid collision, leaving a big enough gap to come to a full stop if needed. Krauss' model is a stochastic extension of the Gipps' model to introduce human imperfection using a single random variable.

Both Gipp's and Krauss' model are unable to produce traffic instabilities or hysteresis effects for vanishing fluctuation [13]. The IDM is also based on the concept of safe distance, however, approaching slower vehicles and obstacles is smoother as there is no fixed deceleration but rather a gradually increasing deceleration. The explicit differentiation between safe time gap, speed adaptation time and reaction behaviour makes the IDM unable to capture differences between classic Cruise Control (CC) and pure human behaviour. Furthermore, it does not model different nuances in driving style.

In terms of lateral movement, one of the most used lane-changing model is MOBIL, first introduced by Kesting et al. [8]. The primary goal of MOBIL is to minimize the overall induced braking by a lane change.

All of the above models are collision-free. The consequence of being collision-free is that under unexpected critical conditions, introduced either by lane changes or due to an inappropriately large simulation time step, unrealistic and physically infeasible decelerations will be exhibited by the simulation. This constitutes a critical limitation when investigating traffic safety as road accidents are not only a major cause for the formation of traffic congestion but also the main concern when mixing autonomous vehicles with human-controlled cars.

With BEHAVE (short for Behaviour Evaluation of Human-driven and Autonomous VEhicles), we develop a simulation framework for the design, validation, and evaluation of novel vehicular mobility models to allow the analysis of mixed traffic when AVs and human drivers share the roads. In the following section, we present BEHAVE and how it can contribute to more realistic traffic simulation.

BEHAVE

Unfortunately, most of today's approaches to evaluate the safety and efficiency of autonomous vehicles focus solely on the low-level control algorithms and disregard the transportation system as a whole. While microscopic traffic simulation is not, in our opinion, the best candidate to evaluate whether the sensing and controlling functions of an autonomous vehicle are working correctly, it can provide tremendous value when it comes to evaluating the impact of autonomous vehicle on a larger scale.

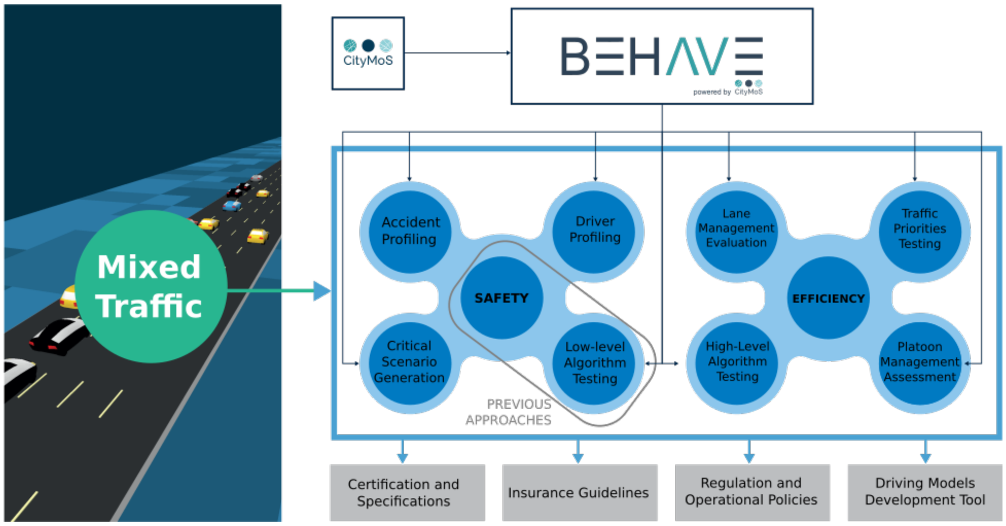


Figure 2: BEHAVE allows different ways to study safety and efficiency of AVs in mixed traffic scenarios where previous approaches focus more on low-level algorithm testing.

Figure 2 shows the two pillars, safety and efficiency, of mixed traffic analysis along with four important subcategories for each of them. For safety evaluation, it is important to understand why a certain situation has happened. Only if the cause is understood, can a proper solution be provided. Therefore, accident and driver profiling as well as the creation of tailored critical scenarios is of utmost importance to analyse safety-critical situations. In terms of traffic efficiency, the simulation tool should provide methods to analyse different policies regarding lane-management and traffic priorities. Additionally, platooning configurations need to be rigorously studied to fully understand their impact on the traffic system. This includes high-level algorithms for autonomous vehicles which can also affect route planning.

If the simulation environment is able to answer all these questions in a reliable and realistic manner, it can be used to derive certifications, insurance guidelines as well as regulation and operational policies. It can then furthermore be used as a development and test suite for new AV driving models.

Main Features of BEHAVE

BEHAVE is powered by the microscopic agent-based traffic simulator CityMoS [15]. In its current form, BEHAVE simulates an infinite stretch of highway road with a customisable traffic volume. This small-scale and specific situation allows for more controlled conditions for the analysis and evaluation of numerous traffic scenarios. Additionally, a virtual camera in the graphical user interface dynamically follows a tagged vehicle to allow for easier evaluation of the traffic situation.

During the simulation, the framework supports the existence of different types of agents allowing the creation of mixed traffic scenarios. We refer to these sets of agents as *populations*. A population is characterised by the set of mobility models it uses. For example, there could be IDM+Mobil population as well as a Gipps population in the same simulation.

The interface of the BEHAVE tool consists of three main modules that allow the user to perform run-time changes to the simulation and to observe and analyse the results of those changes. Those modules are indicated in Figure 3 and are referred to as: model control, environment control and traffic state monitoring.

Desired agent count 100

acceleration 0.4031
attention 0
current speed 14.66
lane change last 15 min 15

agent count 99
avg. no. lane changes last 15 min 4
avg. speed 13.51
crashes last 15 min 0
total no. crashes 0

Population1 0.1
Population2 0.1
Population3 0.8

Figure 3: Graphical User Interface of BEHAVE

The model control module allows the user to add and remove populations, change the models that define the population's behaviour, and change the parameters of those models at run-time. The population model parameters can be either set to constant values or specified from a standard set of distributions, so that the specific parameter of every member of the population is sampled from the chosen distribution.

The environment in the simulation can also be controlled at run-time. First, traffic density can be modulated by increasing the number of vehicles spawning on the road, thus allowing the user to perform tests in both free flow and congested traffic conditions. Second, the weather conditions can be altered, which affects the driver behaviour models accordingly and alters the way both human controlled and autonomous vehicles perceive their environment and behave on the road.

Lastly, the data monitoring module of BEHAVE allows for state monitoring of the traffic simulation. General traffic characteristics such as average speed, number of accidents, and average acceleration are displayed and can be plotted as a function of time by the user. The plotting tool in BEHAVE can also be used to visualise the evolution of agent-specific parameters as opposed to averages. For example, the current speed, acceleration, aggression or the attention levels of single agents can be plotted as a function of time in order to analyse possible reasons for the occurrence of accidents and near-miss situations.

With this user interface, we enable researchers as well as non-domain experts to meaningfully interact with the simulation environment, easily identify regions of interest, and explore capabilities and limitations of various mobility models.

Extending human driver models

Existing car-following and lane-changing models for human drivers do not fully capture the essence of human behaviour. For example, they do not allow for collisions and are largely predictable, contrary to human behaviour. We therefore believe that existing driver models should be extended to include some characteristics of human driving that allow collisions by taking into considerations non-deterministic manoeuvres.

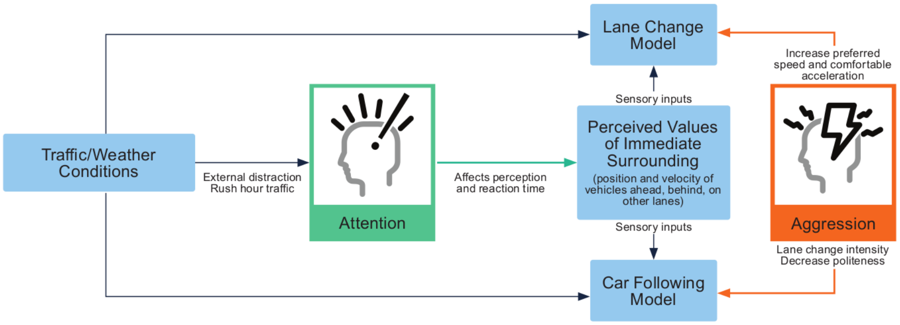


Figure 4: Introduction of stochastic elements (attention-aggression) to model irrationalities and recklessness of human behaviour.

We believe that a stronger focus should be set on stochastic elements in the models to incorporate unpredictable and even irrational human behaviour. This includes factors like aggression, attention, and perception in the decision-making process both in the car-following and lane-changing models. Manipulating these elements also allows modelling changing driving behaviour because of external factors such as weather conditions, darkness, stress factors, and recklessness. As shown in Figure 4, concepts such as attention, aggression, and perception can be modelled in terms of random processes, which can affect each other and are affected by the current state of the driver and the external conditions.

To explain the difference between this approach and the state of the art, we discuss how we compute the preferred speed of a driver. Preferred speed is one of the parameters of all existing widely used car-following models. It is typically a constant value throughout the simulation. Instead, we model it as an autoregressive stochastic process, which is coupled to other, both external and internal, parameters, thus allowing its value to dynamically change throughout the simulation. External events like reduced visibility would also reduce the preferred speed parameter of the driver and would increase the minimum safety gap that drivers leave when they follow other cars. Additional factors such as driver aggressiveness, which is also a behaviour parameter modelled as a stochastic process, increase the preferred speed and decrease the time gap to the vehicles ahead.

0.1 Modelling Autonomous Vehicles

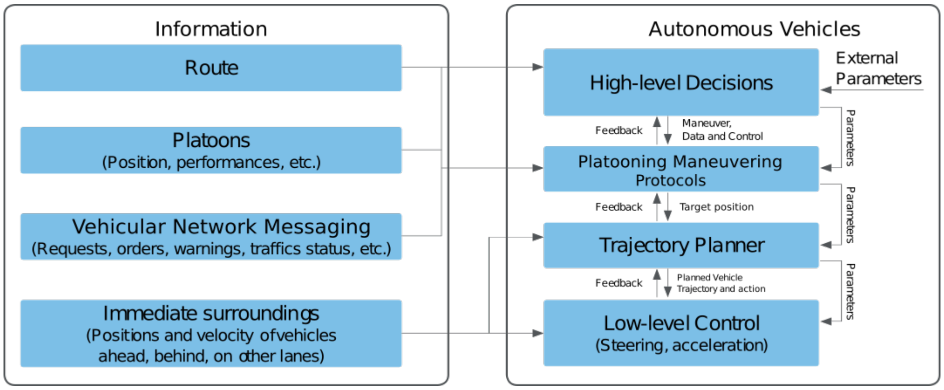


Figure 5: Hierarchical command-and-control structure for autonomous vehicles.

Although existing driving models already represent AV behaviour to some extent, they are not sufficient to capture the entire spectrum of AV mobility, as they do not include high-level planning and control. For example, the action of locating platoons and taking the necessary manoeuvres to join them is missing in present modelling efforts. Such high-level planning and control is, in our opinion, necessary in order to evaluate AV strategies and their performance. We believe that an autonomous vehicles model should consist of a hierarchical command-and-control structure which includes high-level planning, platooning manoeuvring protocol, trajectory computation, and low-level control. A possible structure is shown in Figure 5.

Low-level control refers to the car-following and lane-changing models. It takes as input the description of the immediate surrounding of the agent and determines the autonomous control of the vehicle. At a higher level of the control hierarchy, the trajectory planer model provides inputs to the low-level control to take into consideration broader traffic state information. The planner performs the manoeuvres needed to achieve the goals set by the platooning manoeuvring protocols module. This module allows advanced platoon formation, merging, and splitting. This enables the AVs to perform key manoeuvres unique to this class of vehicles and thus study the implications of AVs on traffic and the safety properties of platoons.

At the high-level of the control hierarchy, the agents will use optimisation techniques to choose the most promising strategy of platoon-related actions, incorporating global as well as current platoon performance information. The optimisation is constrained by the planned route of the agent. In this hierarchical model, information can travel up and down the hierarchy, which ensures that the lower modules can send status information and potentially supplementary restrictions which must be taken into account by the upper-level modules.

Research and analysis capabilities for mixed traffic scenarios

In this section we provide several more specific examples of possible use cases for the BEHAVE platform in order to give an insight into the capabilities of the BEHAVE platform.

Faster environment for experiments compare to real-life deployments: Using simulation decreases drastically the time required for real-life testing. For example, 24 hours of simulation using BEHAVE allow one vehicle to drive over $58,000km$ with a average velocity of $20m.s^{-1}$ ($72km.h^{-1}$). In real-life, it would take up to 34 days for a vehicle to drive this distance with the same speed. Since more than one agent is simulated, a total of 7.5 millions of kilometres have been driven during the simulation. This result has been obtained with a Lenovo ThinkPad T460s with an Intel Core i7-6600U CPU @ 2.6GHz, using only one core.

New human driving behaviour model design: Researchers can use the BEHAVE platform for the development of new driver behaviour models to improve the level of accuracy of their simulation studies. Model development is facilitated by 1) permitting run-time parameter changes to the models and immediate visual feedback of the results of those changes, and 2) having a modular software architecture, which allows adding a new driver behaviour model by simply creating a new model class and thus requires no in-depth knowledge of the internal working mechanism of the simulation platform itself. The models can then be calibrated and validated in the BEHAVE environment with real data and their performance can be evaluated. An overview of a possible calibration procedure using BEHAVE has been presented in [12].

Analysis of platooning manoeuvres and their effects on traffic: Changes to platooning protocols and platooning manoeuvre parameters can be analysed by policy-makers and AV manufacturers in a systematic way to study the effects of platooning on traffic conditions. Furthermore, the BEHAVE tool can be used for the comparison of different execution protocols for manoeuvres of the same class to find optimal execution protocols in terms of both safety and efficiency.

Design of socially-aware single AV control logic: AV manufacturers and researchers can use BEHAVE to study the system-wide impact of single AVs that have additional objectives on top of taking people from A to B such as the overall improvement of traffic conditions. For example, single AV control models can be designed to use AVs as local traffic optimizers in mixed traffic conditions. In this way, AVs can mitigate congestion waves and increase the resilience of traffic flow by acting as “dampeners” among human drivers with imperfect behaviour. A step in this direction has been made in [4].

New traffic law regulations testing: Regulators can use BEHAVE to test new traffic regulations concerning the introduction of AVs. One example study could be whether the introduction of an exclusive AV lane on highways would help traffic conditions and at which penetration rate of AVs does it make sense, if at all [5]. Another study could entail the built-in procedures of AVs in case of extreme weather conditions and poor visibility and how such situations will affect both the safety and efficiency of the transportation system.

Identification of dangerous driver behaviours: Insurance companies can use existing driver behaviour models with different parametrization to identify drivers that pose a higher risk in mixed traffic conditions. Furthermore, they can also use BEHAVE to compare the safety features of different high level control logic of the AVs on the road and thus develop pricing models for AV insurance packages.

Conclusion

In this paper, we identified the shortcomings of today's models and tools for the evaluation of mixed traffic scenarios to support the integration of autonomous vehicles into existing traffic systems. We discussed changes and directions for the microscopic mobility modelling of both manned and unmanned vehicles, focusing on stochastic elements to capture the sometimes unpredictable nature of human drivers and on the need for higher level driving strategies for autonomous vehicles. We presented BEHAVE, a simulation platform that can be used to verify the safety and efficiency of transportation systems where autonomous vehicles co-exist with human-controlled vehicles. The platform has multiple uses: it offers support for the development of additional models for humans and AVs, it provides regulators with a tool to assess the effects of traffic regulations, it allows the testing of control policies for AVs, and it enables insurance companies to develop pricing models by identifying the effects of human behaviour in traffic. Such a simulation framework can significantly contribute to the cost and time-efficient evaluation of future transportation systems.

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