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The use of microscopic simulators for safety assessment in automated and partially automated scenarios: a comparison

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Abstract

In the field of safety assessments, the use of simulators to predict unknown scenarios is becoming crucial, due to the ability of predicting conflict points. The microscopic simulators, accountable for modeling single-vehicle interactions, differ for the type of car-following and lane-changing model, hence for the number of definable parameters. The possibility of modifying all the parameters inside the model equations makes them suitable for simulating autonomous vehicles too. To evaluate the road safety of a site, the output of traffic simulators can become the input of the SSAM (Surrogate Safety Assessment Model), which relies on surrogate safety measures (SSMs). Thus, the choice of the simulator is fundamental. The focus of this dissertation concerns the comparison of the car-following and lane-changing models at the basis of the most used commercial microscopic simulators (VISSIM, AIMSUN, PARAMICS) and the related SSAM outputs in the automated and partially automated traffic environment. The Gipps Model, valid for the car-following and the lane-changing model, aims at always achieving the safety distance, intervening on kinematic parameters like the acceleration, speed, and distance. It is possible to intervene on a limited number of parameters of this model. The Wiedemann model belongs to the family of psycho-physical one and it is governed by several parameters, which makes it useful to remodel complex situations, simulating the human mental workload in driving. The Gipps model and the Wiedemann one (implemented respectively in AIMSUN and VISSIM) have already been used for safety purposes, while the Fritzsche one (implemented in PARAMICS) has been currently used only for environmental issues related to automation. It is possible to modify up to 16 parameters in the Gipps and Wiedemann model to simulate the automated and partially autonomous vehicles, even if these models belong to different car-following model family. Based on the site variables, each simulator showed potential strengths. Scenarios involving automated vehicles, which do not account for human behaviors, might be better represented by the Gipps model, which aims at reproducing only the safety distance and not the human mental behavior. Thus, this model could also be the most suitable for the general purpose of crash analysis above mentioned.

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1. Introduction

The need of assessing the performance of road networks, to design new roads or enhance existing road connections is an everyday problem in transportation engineering. Commonly, transportation analyzes rely on traffic simulators to predict traffic conditions in case of significant modifications in the infrastructure system, which may impact travel time and costs. In this latter case, the use of traffic simulators is crucial since there are no other ways to predict modifications in route choice and driving behavior.

Similar concerns arise for road safety assessments, which should predict the benefits or the potential issues of given future scenarios (i.e., specific countermeasures) on the safety of the analyzed road sites. To predict safety performances of the hypothesized countermeasures it is practically impossible to rely on specific on-site experiments. Hence, a possible help for making reliable predictions is to use crash prediction models (i.e., safety performance functions -SPFs- and crash modification factors -CMFs-, see AASHTO, 2010), which may provide estimates for future conditions. Hence, the use of traffic simulators can be crucial, to simulate future traffic conditions and perform safety assessments. Given the previous remarks, in the recent years, traffic simulators were used for predicting traffic improvement schemes (Chimdessa et al., 2013), safety assessments (Coropulis et al., 2021; Guido et al., 2019), design purposes (Oktech et al., 2004), by providing reliable results (Tettamanti et al., 2018). In this study, we focus on this specific case, considering future scenarios of traffic automation, since there is still no complete automation on roads and on-road tests may require complex procedures, depending on country-specific regulations. Thus, it is not possible to count on several real-world studies, useful for safety assessments. Several traffic simulators are available, having different features and working at different scale (macro, meso, and micro). The most useful simulators to analyze the interactions among the vehicles, also for simulation of future scenarios with different traffic components, are the microscopic ones.

All traffic simulators have embedded specific car-following models and lane-changing models to simulate how drivers behave in traffic. In fact, these models are calibrated for human driving experiences, and their parameters account only for human-based driving. Despite this assumption, the chance of modifying all the baseline parameters inside the model equations makes the microscopic simulators adaptable to new traffic conditions (Lee et al., 2019; Morando et al., 2018) Hence, micro simulators are likely capable of simulating traffic scenarios from SAE level 0 to SAE level 5 (SAE J3216, 2021).

1.1. Traffic simulation outputs and surrogate safety measures for safety assessments

The outputs from traffic microscopic simulations include the trajectories of vehicles throughout the simulation period, which can be used for safety assessment purposes, that is estimating the frequency and severity of collisions as based on conflict analyzes (Surrogate Safety Measures, SSMs). In particular, the SSAM (Surrogate Safety Assessment Model) is among the most used for those evaluations (Pu et al., 2008), starting from traffic simulations to estimate crash frequency and severity. The SSAM has been widely validated by comparing simulated results with observed crash data (Astarita et al., 2021; Guido et al., 2019). The outputs of the SSAM are the number of collisions and the number of conflicts.

A conflict is defined as an observable dangerous situation in which two or more drivers approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged (Gettman et al., 2008). Hence, a collision is a step forward than the conflict, it is defined as an unavoidable crash between two or more vehicles, and it happens or might happen only when the time to collision (TTC) is equal to 0 s, hence when there is no more time for evasive maneuvers. The TTC is an indicator for traffic conflict and is related to crash risk: low TTC means a higher crash risk and high TTC means a lower crash risk.

The relation between collisions and crashes can be treated with an extreme value statistical approach (Tarko, 2021). Nevertheless, it is possible to compare the SSAM outputs to real crash data for validation purposes, thanks to several approaches depending on the availability of the dataset and the accuracy of the expected conflicts and collisions (Zheng et al., 2020). Hence traffic simulators outputs must be accurate, to obtain accurate and reliable predictions.

1.2. Objective of the study

The main objective of this study is to compare the performance of the microsimulation baseline models determining which one is the most suitable for the automated/autonomous vehicles (AVs) scenarios. This comparison is crucial to have reliable safety assessments by the SSAM, based on the output derived from the traffic simulations (Gettman et al., 2008), since the SSAM analysis is based on trajectory data retrieved by the simulations. The safety analysis for AVs based on traffic simulations is the only reliable way currently available to know the crash risk related to the AVs for a site, since there is a lack of real crash dataset for this kind of vehicles. Hence, selecting the appropriate traffic simulation framework becomes crucial.

2. Methodology

2.1. Traffic simulation models comparison

The analysis is based on the comparison of the simulators. The choice of the most suitable traffic simulator is dependent on the analysis of the models implemented in each software. These models are crucial to realistically depict driving behaviors.

Each simulator aims at virtually reproducing what happens on different types of roads (motorways, rural, urban, and so forth). There are several available simulators, but it is also possible coding own algorithms to modify and obtain the desired output parameters for specific analysis and purposes by using APIs (Rahman et al., 2019). APIs are a set of functions and procedures allowing the creation of applications that access the features or data of an operating system, application, or other service. The focus of this dissertation mainly concerns the most widespread and suitable models implemented in the main simulators and their outputs to be used in the SSAM. Gipps, Wiedemann, Intelligent Driving Model (IDM2000), Fritzsche and TEXAS intersection model (Gettman et al., 2008) are among the most common models. A simulator which embeds all the models is Tritone, which was already analyzed for safety assessments and traffic outputs (Astarita et al., 2019). The main difference among all the microscopic simulators mainly consists in the car-following and lane-changing model used for the simulation, hence in the number and type of parameters to define. The greater is the number of parameters, the greater is the computational effort, but also the possible accuracy.

The car-following models simulate how the vehicles behave in the same lane, interacting with other adjacent vehicles (Olstam et al., 2004), but also in free-flow conditions when the distance between two following vehicles do not have consequences on their behavior; the lane-changing models simulate how vehicles behave in changing lanes to overtake other vehicles or simply to move from one lane to an adjacent one, considering speed, distance, and acceleration of the approaching and existing vehicles on the target lane (Balal et al., 2014).

2.2. Influencing parameters for AVs simulation

Parameters that typically are used in the models are reaction time, acceleration/deceleration, speed, sight distance, aggressive behaviors, headway, cooperative behaviors. There is a great change of the parameters themselves whether the driver is human or automatic.

The set of characteristic parameters possibly modifiable for each of the compared models (Gipps, Wiedemann, Fritzsche and TEXAS intersection model) is summarized in the following table.

Tab. 1: Comparison of the modifiable parameters for each model.

	Reaction time	Acceleration/deceleration	Speed	Sight distance	Aggressive behaviors	Headway	Cooperative behavior
Wiedemann '74	✘	✓	✓	✓	✓	✓	✓
Fritzsche '94	✓	✓	✓	✘	✓	✓	✓
Gipps '81	✓	✓	✓	✓	✓	✓	✓
IDM2000	✓	✓	✓	✓	✓	✓	✓

TEXAS '77 intersection model	✓	✓	✓	✓	✗	✓	✓
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3. Results

3.1. Car-following models

Clearly, the study of the different baseline model equations, variables, and parameters helps in understanding the different potentialities of simulators.

In summary, Wiedemann and Fritzsche are psycho-physical models, which mainly rely on different flow regimes (as shown in Fig. 1), according to the set thresholds. This kind of models depend on the desired driving behavior, being able to simulate precisely and reliably what currently happens on roads.

Psycho-physical models consider the vehicle velocity as a variable dependent on the perceptive thresholds such as the minimum velocity difference between follower and leader. The following driver monitors changes in the behavior of the leader and will react by modifying his/her motion only if thresholds are reached. These models aim at simulating what happen in the driver’s mind and so they are based on two key assumptions:

- for large distance, the following driver is not influenced by the speed difference
- for a small distance, for a specific speed or distance that marks a threshold, the following driver may not react.

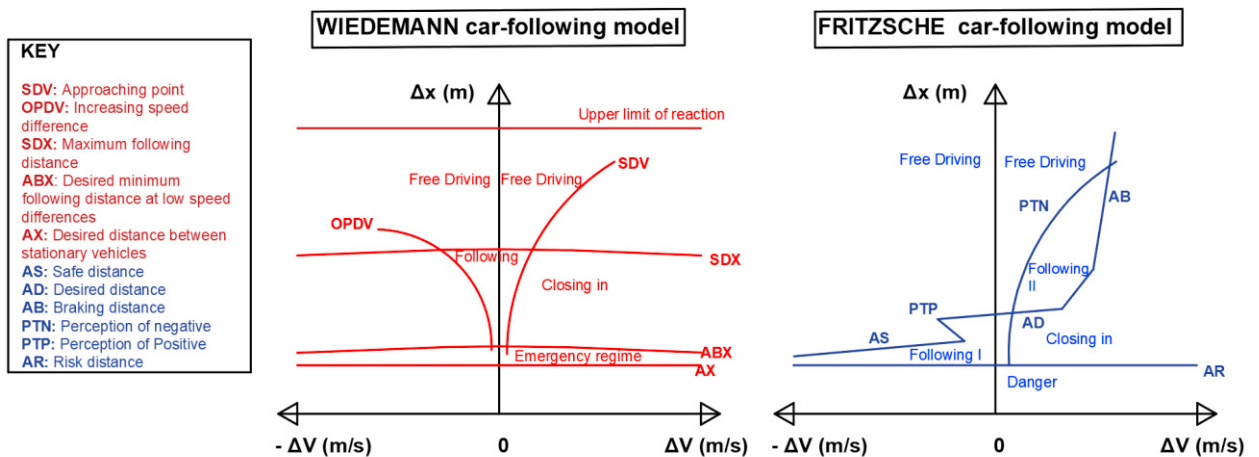


Fig. 1: Wiedemann and Fritzsche car-following models according to their thresholds.

In the following regime, the acceleration is a function of the normally distributed driver dependent variable (speed difference and space headway) according to a linear relation. In the free driving regime, the acceleration is proportional to the exponential of the desired speed. Considering the closing in regime the deceleration of the follower vehicle varies quadratically with the speed difference, while it is inversely proportional to $ABX(t)$, defined in Fig. 1, and the distance. The emergency regime links the squared speed difference to the deceleration and the inverse of the distance.

The Fritzsche model has the same structure as the Wiedemann one, and it simulates five different flow regimes according to the exceeding of some thresholds. It sets two thresholds for the perception of negative (PTN) and positive (PTP) speed differences. Drivers are assumed to be more inclined to observe positive speed differences, so PTP is greater than PTN.

In the danger regime, the drivers use the maximum deceleration because they have no space to change maneuvers. Contrary, in the closing-in regime, the acceleration is directly proportional to the squared difference between the vehicle speed and inversely proportional to the constraint distance between the two vehicles.

The following behavior relates the deceleration to the speed and distance between vehicles. The free driving regime relates the acceleration to the desired speed, but also contemplates the chance of not maintaining the desired

speed constant. The other two models, the Intelligent Driver Model, IDM, and the Gipps model are related to the vehicles and their interactions in the traffic flow, focusing on the impact that the leader vehicle has on the kinematic parameters of the follower. According to these assumptions, the set of variables can be entirely modified to address more specifically some of the fundamental aspects of the simulated scenario.

The IDM belongs to the family of those derived from the Gazis-Herman-Rothary model (GHR) (1959), which has been optimized at microscopic and macroscopic levels several times during years (Brackstone et al., 1999). In these models, the acceleration is a function of the velocity of the front vehicle and the distance to the front vehicle. The IDM parameters which are updated each step of the simulation are acceleration, maximum deceleration, and time gap. Moreover, other car-following models exist and are used for commercial purposes, for instance, the TEXAS (Lee et al., 1977) software uses an ad hoc model, belonging to the GHR family, hence it considers the same parameters of the IDM 2000. However, this car-following model has been developed for intersections only. Another family of car-following model is the safety distance or collision avoidance one, which essentially relies on the safe following distance. The Gipps Model (Casas et al., 2010) is one of the most used of these types of models. The IDM and the Gipps car-following models despite belonging to different families, provide comparable results (Ims et al., 2021). The Gipps car-following model considers only the speed of the leader and follower vehicles, their acceleration, and deceleration on a single lane.

In this sense, the safety distance models, like the Gipps one, can replicate the human behavior, not simulating the mental workload, as the Psycho-physical ones, but just thanks to the parameters which modify the kinematic of the vehicles: safety margin factor, speed limit acceptance, non-lane-based behavior, aggressiveness. Among all the models, the safety distance one, like the Gipps model, seems to be the most suitable for simulating the AVs behavior, hence it is the most recommended one.

3.2. Lane-changing models

Simulations differ also in the type of lane changing, in the factors that makes it necessary and consequently in the characteristic variables of each model. A traffic modeling tool that fully describes lane-changing is still lacking. Gipps (Gipps, 1986) proposed a lane changing model based on the decision-making process considering the potentially conflicting points and assuming a logical driver behavior. The model highlights the urgency of the lane changing maneuver, modelled through the gap acceptance and braking behavior, according to the kinematic parameters, as the deceleration and the time gap.

Yousif and Hunt (Yousif et al., 1995) investigate the lane changing behavior on multi-lane unidirectional roadways. The assumption of the model is that if the available gap is smaller than the expected acceptable one, no lane changing process will take place.

Wagner (Wagner et al., 1997) defines a set of rules for the car that wants to change lane, emphasizing the need not to obstruct the car behind on the other lane. The model reproduces satisfactorily the lane usage characteristics on multi-lane roads incident-free conditions. Most models were either numerically tested or validated by demonstrating their potential to produce outcomes consistent with certain macroscopic traffic flow features.

All the main variables for each simulator are summarized in the table below, together with the flow regimes of the models.

Tab.2: A comparison of the different model

Model	Type	Main Variables	Regimes
Wiedemann 74 (Wiedemann et al., 1992; PTV, 2018)	Psycho- physical	Minimum desired distance	Free flow
		Maximum following distance	Emergency
		Minimum following distance at low speed	Closing in
		Desired distance between stationary vehicles	Deceleration
		Approaching point	Following
		Increasing speed difference	
Gipps '81 (Gipps, 1981)	Safety distance	Decreasing speed difference	Free flow
		Maximum desired acceleration	Constrained

Car following models			Maximum desired deceleration	
			Speed	
	IDM 2000 (Treiber et al., 2000)	G-H-R	Reaction time	Free flow
			Desired speed	Cooperative
			Time gap Speed difference between follower and leader vehicle	
	Fritzsche '94 (Duncan, 1997)	Psycho-physical	Desired time gap	Free flow
			Risky time gap	Closing in
			Deceleration parameter	Danger
			Safety time gap	Following I
			Calibration parameter	Following II
Normal acceleration rate				
Perception of positive speed difference				
Perception of negative speed difference				
Lane changing models	Wiedemann and Reiter modified 2018 (Oketch et al., 2004; Moridpour et al., 2010)	Available time lag to collision	Free	
		Safety distance	Necessary	
		Minimum time headway		
		Lead time to collision		
		Speed of the vehicle in the target lane Speed of the lane changing vehicle		
	Gipps '86 (Chao et al., 2020) modified (Tettamanti et al., 2018; Lee et al., 2019)	Desired speed	Discretionary	
		Front gap	Mandatory	
		Speed of the follower vehicle	Forced	
	Fritzsche modified (Cameron and Duncan, 1996; Liu et al., 2020) based on the Gap acceptance theory	Rear gap		
		Front gap	Free	
Rear gap		Necessary		
		Time		

4. Discussion

4.1. AVs in traffic simulations

The mentioned models are globally set to the specific presence of human drivers, but in the case of vehicle automation, these models may be still reliable. The only issue can be aroused by the presence of fully automated vehicles because the psycho-physical car-following and lane-changing models might be globally modified. Acceleration, speed, time, and deceleration drastically change their meaning in the case of not-human drivers, if the model is set to reliably reproduce the human driver-behaviors and so the common laws of vehicle interactions could not be applied (Ims et al., 2021). This is the reason why, in the case of fully autonomous vehicles, Wiedemann (Papadoulis et al., 2019;), especially, and Fritzsche (Rezaei et al., 2021) would not be reliable, unlike important modifications thanks to the use of ad hoc scripts in APIs (Application Programming Interface), to model not the human mental workload but the machine workflow. In the case of the safety distance model, the focus of the algorithms for the driving behavior is on physics parameters: their dependency on the type of driver can be adjusted just by modifying the values of some crucial parameters related to the dynamics of the vehicle. Changing these parameters means accounting for different behaviors from the human one. This enables easier representation of different vehicle behaviors. The Gipps model is used by the AIMSUN software, it only requires 16 parameters to intervene on. Differently from the Gipps model, the Wiedemann one is governed by several parameters and can

remodel complex situations (Vrbanić et al., 2021). The IDM is considered to be accurate more for cooperative behavior than for fully autonomous driving (Whang et al., 2010). Contrary, the TEXAS model is accountable just for intersections and it is not possible to limit the entire AVs scenario to intersections only. The main characteristics of the AVs, when implemented in already existing codes (in absence of APIs), are designed by modifying of values of the main variables of the car-following and lane-changing model (Ims & Pedersen, 2021). The most used models for the AVs safety analysis are the Gipps and Wiedemann ones, due to the reliability of results and their intelligibility by the SSAM software. The default values for human driving are considered stochastic since not all the drivers follow the same behavior. In the case of AVs, the values can be considered deterministic since the lack of experience and real-world dataset made difficult to create a range of variability of the parameters. Despite this assumption, current studies (Hermann et al., 2018) have demonstrated great variability in AVs behavior depending on the manufacturers. Thus, further improvements of this research might consider statistical distribution also for the values related to the AVs, especially to those not fully automated which still rely on human intervention. In that case, there is no certainty about the human driving behavior during the takeover phase. The greater is the grade of automation, the higher should be the technological performance of sensors which might be more reliable than the human behavior and the less should be the dependency by human factors.

4.2. Final discussion and conclusion

This study aimed at finding the most influencing variables in the more widespread traffic simulation models to create a framework for AVs simulation. The study starts from a comparison among all the most common models, which are also implemented in the commercial software packages for traffic simulations, to understand the most suitable one to reproduce AVs scenarios. After having assessed the simulation performance capabilities of all the simulated model which are used in the simulators, it was possible to understand their capabilities in simulating AVs performance. All the possible parameters to intervene on in the different model implemented in the different software packages have been investigated and compared. The analysis of the models was propaedeutic for the safety assessment since the output of the traffic simulator became the input of the Surrogate Safety Measure Analysis through the SSAM. According to this comparison, it was blatant that a perfect simulator does not exist, while it is possible to identify a simulator suitable for different scenarios and case studies.

The safety distance models are the ones which can be most suitable for the AVs scenarios because they rely on kinematic parameters to simulate the vehicle motion, rather than psycho-physical models which aim at reproducing the human mental scheme while driving, or G-H-R ones which aim at representing and simulating the human decisional behavior according to set thresholds. For the Gipps model, intervening on acceleration, safety distance, time gap and speed enables to modify the vehicle behavior according to different user, human, human and autonomous, and autonomous. Contrary, the other two types of models might be more efficient in simulating the human behavior and so to depict the current scenarios of roads since their scope is to reproduce the mental workload in different decisional contexts. Since the recorded trajectories of the vehicles by the simulations became crucial for the safety assessment, providing trajectories more likely to be run by AVs is fundamental for predicting precise and reliable scenarios with different AVs market penetration. Hence, the use of the Gipps model which better represents AV behaviors with low computational efforts and low risk of error propagations is suggested in absence of APIs and to define the different market penetration scenarios. This is justifiable by the fact that it is possible to intervene on physics parameters of the vehicles, so to set different ranges corresponding to specific behaviors, capable of simulating the interaction among different vehicle types, which still follow the same model but with different characteristics, according to each vehicle type. Moreover, this kind of model performs better in case of great variability of traffic demand and high speeds (Gettmann et al., 2008). In absence of previous considerations, it is impossible to define a priori the most suitable model simulating AVs, but it is possible to choose the most suitable according to each specific case to study, the goal of the investigation and the site-specific context.

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