Combination of autonomous and controlled vehicles in driving simulator scenarios

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Abstract—This paper presents a design methodology for driving simulator scenarios in which autonomous and controlled surrounding vehicles are combined. The main motives are to achieve both a high realism and high reproducibility. The methodology is introduced using a theater metaphor in which a driving simulator scenario is defined as a constellation of: everyday life driving, preparations for plays, and plays. Advantages, disadvantages and difficulties with the proposed methodology are discussed.

Index Terms—Driving simulators, Driving simulator scenarios, Traffic simulation, Autonomous actors.

I. INTRODUCTION

Many traffic accidents are caused by failures in the interaction between the driver, the vehicle, and the traffic system. Thus, knowledge about these interactions is essential and this is especially true nowadays since the number of driving related interactions is increasing. Today drivers also interact with different intelligent transportation systems (ITS), advanced driver assistance systems (ADAS), in-vehicle information systems (IVIS), and NOMAD devices such as mobile phones, personal digital assistants, and portable computers. These technical systems influence drivers’ behavior and their ability to drive a vehicle.

To get knowledge on how these kinds of systems influence drivers, researchers conduct behavioral studies and experiments, which either can be conducted in the real traffic system, on a test track, or in a driving simulator. The real world is of course the most realistic environment, but it can be unpredictable regarding, for instance, weather-, road- and traffic conditions. The limited control possibilities often make it hard to design real world experiments with equivalent conditions for all subjects. Test tracks offer a safer environment and the possibility of giving test drivers more equivalent conditions, but they have drawbacks regarding notably the variety and complexity of the driving context. Driving simulators on the other hand offer a less realistic environment than the real world, but in which test conditions can be fully controlled and varied in a safe way.

A driving simulator is a tool which allows driving in a virtual environment. It is possible to reproduce driving situations from everyday life driving to specific situations, e.g. risky situations. As in real traffic situations, a main component of the driving context is the behavior of other road-users. The main reason for choosing driving simulators for conducting driving behavior experiments is often to get increased controllability and reproducibility. In order to ensure high reproducibility, the behavior of the surrounding road-users is often strictly controlled. This comes with the price of limited realism regarding the surrounding vehicles’ behavior and limitations in the complexity of the scenario situations, due to both the complexity of the scenario programming and the required programming effort. The complexity of programming can be decreased and realism increased by giving the surrounding road-users more autonomy. This leads to simulated situations with similar pros and cons as real world situations, i.e. low reproducibility but realistic surroundings. However, this environment is both safer and still more controllable than the real world.

We propose an alternative design methodology for driving simulator experiments in which periods with “fully” autonomous simulated road-users are combined with periods with only controlled simulated road-users. A “fully” controlled road-user is a road user which only follows instructions from some supervisor while an autonomous road-user is a road-user that tries to achieve its own goals. The presented methodology can for some type of driving simulator experiments imply a gain in realism without too large losses in reproducibility. The basic idea is to let the surrounding vehicles run in autonomous mode between the predetermined situations at which measurements are taken. When getting closer to the place where a situation is going to happen, the simulation of the surrounding vehicles should, in an unnoticeable way for the subject, turn from autonomous to controlled mode.

The aim of this paper is to discuss advantages, disadvantages, and difficulties with combining autonomous and controlled simulated vehicles in driving simulator scenarios and to present means and methods for how the transition from autonomous to controlled mode can be done. For illustrating this we will present and use a theater metaphor in which a scenario is broken down into three base elements: everyday life driving, play preparations, and plays.

The paper starts in Section II with an introduction to driving behavior experiments and a comparison between experiments in the real world, on test tracks and in driving simulators. Section III then gives an introduction to driving simulator scenarios followed by a presentation of the developed theater metaphor. In Section IV is the problem of combing autonomous and controlled vehicles presented and possible solutions strategies are outlined. Section V ends the paper with concluding remarks and future research.
II. DRIVING BEHAVIOR EXPERIMENTS

Driving behavior experiments are used to assess hypothesis on how drivers behave in some specific driving context. Driving behavior experiments follows traditional experimental design. In order to increase the knowledge of some scientific question a specific measurable instance of this question is studied. The experimenter choose which modalities or independent variables that should be used and sets up an experimental design, e.g. a within, between, or mixed group design, describing how many subjects that will be tested for each combination of the independent variables. The modalities can for example be: fatigue or not fatigue; with or without an ADAS; urban or rural road environment. As in all types of experiments the experimenter wants to limit the number of confounds, this in order to avoid that an observed change in any of the dependent variables is due to something else than a change in one of the independent variables. Due to the complex and dynamic nature of traffic, limiting confounds is difficult and consequently a key issue in design of driving behavior experiments.

The lack of controllability often makes it difficult to limit the number of confounds in real world experiments. The difficulty also increases with increasing complexity of the situation to be studied. Some experiments are also too dangerous or impossible to conduct in the real world due to ethical reasons. Test tracks offer a safer environment in which subjects can be given more equivalent conditions. However, even if the realism of driving the vehicle is high, the realism with respect to the surroundings and the surrounding traffic is quite low. Driving simulators on the other hand offer a less realistic environment than the real world, but in which test conditions can be controlled and varied in a safe way. Table 1 presents a comparison of driving behavior experiments in the real world, on test tracks and in driving simulators with respect to “Sense of Realism” and “Reproducibility”. The table includes rough judgments and should be viewed as a way of illustrating pros and cons for the different environments. The estimations are made under the assumption of “perfect” models for simulation of surrounding vehicles and “perfect” hardware and software for creating driver sensations. “Traffic - Micro level” refers to individual actions while “Traffic - Macro level” refers to traffic in form of aggregated measurements as average speed, density, distribution of vehicle types, etc.

![Table 1 Comparison of sense of realism and reproducibility in driving behavior experiments for real world, test track, and driving simulator (DS) experiments.](image)

Thus, it is hard to achieve reproducibility, at least at a micro level. Realism is a wide and subjective term. In this paper we refer to a realistic model (for the behavior of the surrounding vehicles, the vehicle cabin, the vehicle motion, etc) as a model that induce realistic subject driving behavior at operational, tactical and strategical level (using the definitions of operational, tactical, and strategical level presented in [1]). For example, a realistic simulation of surrounding vehicles is a simulation that results in that the subject accelerates, steers, choose lanes, overtakes, etc. as he or she does when driving in real traffic. “Medium” classification of “Sense of Realism – Vehicle” is due to that driving in a driving simulator is only almost as realistic as driving a real vehicle.

III. DRIVING SIMULATOR SCENARIOS AND A THEATER METAPHOR

A driving simulator scenario is a specification of the road and traffic situation along a road in a driving simulator experiment. This includes specification of how the road and its environment look like, e.g. specification of road geometry, road surface, weather conditions, and surroundings as trees and houses, etc. A scenario must also include a specification of other road users and their actions, predetermined or not. A scenario is more or less a description of the driving context. In [2] is a scenario defined as a constellation of consecutive traffic situations, or using the theatrical terminology in [3] a constellation of scenes, which starts when a certain condition is met and ends when another condition is met. We will use the word play instead of scene in order to capture that the actors live their everyday life between the plays and thus may not always be at the theatre. If they are cast for a role in a play they have to transport themselves to the stage before the play starts. The word scene is also problematic since the word is ambiguous and can refer to either the stage or a part of a play.

One of the strengths with driving simulators is that several situations easily can be studied after each other. However, the situations cannot follow each other too fast. A subject’s awareness, mood, etc are affected by a critical situation and to expose a subject for another situation just after a situation will not be comparable to only studying the second situation. When studying several situations in a row, we need to “reset”
the subject between the situations. That is, we need to get the subject to the awareness level, mood, etc. that he or she has in their normal everyday life driving in the current driving context. This is also important even if only one situation is studied. The time required to “reset” a driver is an interesting research question, but this is out of scope of this paper. With this in mind, we would like to widen the earlier scenario definitions and define a scenario as a constellation of the three components everyday life driving, preparations for plays, and plays, see Fig. 1. With everyday life driving we refer to the “normal” driving context on the present road type, i.e. the traffic conditions on the present road type when there are no exceptional events. The play preparation part refers to the moving of the surrounding vehicles to some pre-specified position and speed that they should have when the next play starts. The play is a traffic situation that will be studied. Plays, manuscript, roles, actors, etc. will be further introduced in the forthcoming sections.

For scenarios with only or mainly everyday life driving the requirements on reproducibility is generally lower. Thus, it is often convenient to use surrounding vehicles with a high level of autonomy in the simulation of everyday life driving, e.g. by using the model presented in [4] or [5], [6]. The plays are also referred to as directed plays, thus it seems like strictly controlled vehicles are the best alternative in order to maximize reproducibility and thereby minimize confounds. However, depending on the complexity of the traffic situations in a play, the surrounding vehicles may need a higher level of autonomy. This can be compared to that human drivers need more driving skills (at both cognitive and vehicle control level) in order to be able to drive well in complex traffic situations. The level of autonomy can actually be viewed as the driving skill of a simulated driver. As in [7], we consider the level of autonomy as a continuous variable between “fully” controlled and “fully” autonomous. The design of a driving simulator scenario can in this sense be seen as a problem of choosing a level of autonomy that give the best compromise between realism and reproducibility and that fulfills minimum requirements regarding traffic complexity and controllability. Our hypothesis is that both realism and reproducibility can be maximized by varying the level of autonomy during a scenario. Our suggestion is to use a high level of autonomy in the modeling of everyday life driving and then gradually decrease the autonomy during the play preparation to a suitable level for the upcoming play. We will refer to this transition from autonomous everyday life driving to less autonomous directed plays as the play preparation problem.

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A. **Play**

A play is the performance of some actors acting on a stage according to a manuscript, e.g. a vehicle actor that brake due to that a bus actor enters the road from a bus stop. A play has a specified initial setting and ending. The initial setting can include a specific place/infrastructure or not. We will in this paper focus on initial settings including a specific place, i.e. a specific position along the studied road. In plays with an initial setting not including a specific place, the play can be set to start when the initial setting is reached, this is for example utilized in [8] for driver training scenarios. A play can succeed or fail, e.g. due to that actors do not show up at the theatre (e.g. a vehicle are not at the right position) or that actors do not follow the manuscript (e.g. a vehicle or the subject do not behave as expected).

B. **Stage**

A stage is the physical place at which a play is performed. The stage can be fixed or moving. We will in this paper define a stage as an limited area or bubble around the simulator vehicle which moves with the speed of the simulator vehicle, following the notion of bubble originally presented in [9]. The size of the stage or the bubble depends on the visibility distance; the stage must be fixed to what the subject can see from the simulator vehicle. The visibility distance can vary a lot between different roads and also along a specific road, thus the stage size has to be adjusted to the studied road.

C. **Manuscript**

A manuscript is a complete specification of a play; in this case it is the description of the driving context. The manuscript includes:

- A specification of the scenery (in this case the road infrastructure, surroundings, road and weather conditions, equipments, etc.)
- A role list (a description of all characters, e.g. vehicles or pedestrians, that will take active part in the play or which play walk-on characters)

D. **Role**

A role is a description of a character in a play. The role description includes a specification of the character’s characteristics, e.g. vehicle type, brand and color. It also includes acting instructions, which define the driving behavior and can vary from detailed instructions to a “theme”. Last but not least it includes a specification of the character’s entering time and initial state, i.e. its position, speed, acceleration, etc. when the play starts. The position and speed

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![Fig. 1 Illustration of an example combination of the three components in a driving simulator scenario](image_url)
are generally specified as relative to the driving simulator vehicle or the infrastructure.

E. Actor

In this theater metaphor, an actor is a road-user, e.g. a vehicle or pedestrian, which behave or act at some level of autonomy between “fully” controlled and “fully” autonomous. A “fully” controlled actor do not take own initiatives and do only follow the directives that it has been given. A “fully” autonomous actor on the other hand do take own initiatives and do only consider a request if it complies with the actor’s own goals. A “fully” controlled actor can be compared to a driver with low driving skills who need very detailed instructions and much supervision, while a “fully” autonomous actor can be compared to an experienced driver with high driving skills who need few or no instructions. A “fully” autonomous actor can be said to act according to a “theme”, e.g. act as an aggressive car driver, with a high desired speed; driving on a freeway.

IV. THE PLAY PREPARATION PROBLEM

The theater metaphor presented in this paper is inspired by, and in many ways similar to, the theater metaphors presented in [3], [8], [10], [11]. As in [8], [11] we want to capture that the play preparation and the play is the result of things happening both on and off the stage. With the theatre metaphor presented in this paper we want to set the focus on that the play preparation problem consists of four sub-problems: estimation of the start time of the play; casting; transportation of actors to the stage; and transportation of actors from the stage. The start time estimation problem consists of estimating when the simulator driver will reach the place where the play is going to be performed. The casting problem consists of finding actors that can play the roles in an upcoming play, i.e. finding vehicles of the right type that can reach the initial roles’ positions. The transportation problems consist of moving the actors to the right initial position in time. The requirements for being able to play a role depends on if the actor currently is on the stage or not. Off stage (outside the bubble), the actors are allowed to change characteristics (vehicle type, color, etc.). It is also possible to create or move actors in order to simplify the play preparation. However, on the stage (inside the bubble), the actors are required to have the right characteristics and all movements has to be done in a non-conspicuous way. In driving simulators an illusion of real driving is created. If some actors behave in a conspicuous way (non expectable) the illusion may break, resulting in non valid test results. One vague definition of a conspicuous action could consequently be an action that breaks the illusion. It is difficult to give a distinct and precise definition, but a conspicuous action is an action that differs from what you expect from a driver in a specific driving context and which make the subject aware of that something extraordinary is going to happen. An example of a conspicuous action is if a vehicle that you have caught up with and followed for a while, for no reason accelerates and speeds away from you. However, if the vehicle in front starts to accelerate after a preceding vehicle has turned off the road, the action is more plausible. The same action can be conspicuous or not depending on the context. How conspicuous an action is depends on the subject’s earlier observations of the simulated driver’s behavior and the action in relation to the driving context.
One way to limit the risk for conspicuous actions (at operational level) is to ensure that the actors use time headways, longitudinal and lateral accelerations, etc. within the ranges that drivers normally use. It is for example known from experiments that drivers normally use longitudinal accelerations up to around 0.3g and lateral accelerations up to around 0.5g, see example in Fig. 2 and further details in e.g. [12]. To illustrate how this information can be used to limit the risk for conspicuous actions due to the casting or the transportation, the following example will be used. An actor that is assigned a role has to reach the role’s initial position and speed at the start of the play. This implies two constraints on the actor’s speed trajectory. In order to reach the initial position the actor has to travel at an average speed, \( v_e \), which of course is dependent on the subject’s future actions and is consequently dependent on the estimation of the driving simulator vehicle’s average speed until the start of the play, cf. the estimation of the play start time. The second constraint is that the actor’s speed at the estimated play start time, \( \hat{t} \), should be equal to the role initial speed, \( v_e \). The problem of reaching the initial role position and speed can mathematically be described as:

Find a speed trajectory \( v(t) \) which fulfills

\[
v(\hat{t}) = v_e \quad \text{and} \quad \int_0^{\hat{t}} (v(t) - v_e) \, dt = 0.
\]

However there are an infinitive number of solutions to this problem and we want to find the “least conspicuous” solution. Let’s study the following example: assume that there is an actor 1500 m behind the simulator vehicle with \( v(0) = 32 \) m/s and that this actor should reach a role with an initial position 200 m behind the simulator vehicle and with \( v_e \) equal to 2.78 m/s higher than the speed of the simulator vehicle, see illustration in Fig. 3. Further assumptions are that the simulator vehicle is expected to drive at a constant speed of 30.8 m/s and that the estimated start time of the play \( \hat{t} = 180 \) s. This leads to that the actor need an average speed around 38 m/s in order to reach the initial role position. The number of possible speed profiles can be limited by taking into account the knowledge on the highest acceleration and jerk levels used by drivers in normal driving. One possible speed profile (profile 1 in the figure) is to accelerate strongly up to a speed just above the needed average speed and when getting close to the start time decelerate strongly to the initial role speed. This profile imply the smallest changes and variation in speed but a large change in speed during a short time close to the driving simulator vehicle, which may be conspicuous if the speed change seems to happen without any plausible reason. An alternative speed profile (illustrated by speed profile 2) is to accelerate more gently up to a speed higher than the needed average speed and then use the achieved speed marginal to smoothly regulate towards the initial role conditions. It is of course possible to do the opposite (profile 3), but there do not seem to be any pros with this approach only cons like large changes in speed close to the simulator vehicle. The best strategy seems to be to accelerate or decelerate using normally utilized acceleration or deceleration rates to a suitable speed on the “right” side of the needed average speed. Next step is to decide when to start to reach the role speed if normally utilized acceleration and deceleration levels should be used. In the example, this strategy would lead to a profile somewhere between profile 1 and 2, i.e. a stronger acceleration than in profile 2 but smaller than in profile 1. It would also imply a later start of the deceleration towards the role speed than in profile 2, in order to avoid too small (normally not used) deceleration rates. However, the start should not be as late as in profile 1, in order to have some marginal and thereby being less sensitive to speed changes of the simulator vehicle. A possible extension to the problem is to also put requirements on the initial role acceleration rate, or specifying if the acceleration should be less than, equal to, or larger than 0. Speed profile 4 shows an example in which the vehicle reaches the initial role speed with a small positive acceleration.

The longitudinal transportation is only one part of the transportation of an actor to an initial role position. Interactions with other vehicles, especially the need of overtakings, have also to be considered. However, the longitudinal transportation problem can serve as a good base for the casting. It is important that the casting both takes into

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**Fig. 2** Observed longitudinal and lateral accelerations along a curvy 15.4 km long road stretch. The circle is at 0.5g. (Source: Figure 4-9 in [12]).

**Fig. 3** Illustration of the problem of transporting an actor from one speed to a specific speed and position relative to the driving simulator vehicle.
account the conspicuity regarding the transportation of the actors that are cast for a role and the conspicuity regarding the transportation of actors without a role from the stage. We therefore suggest the following casting algorithm:

1. For each role, find the sub-set of actors which are on the stage and have the right characteristics or which are off stage and can change to the right characteristics.
2. For each actor, find the least conspicuous longitudinal transportation profile to each role that it is considered for, according to step 1, and to each “exit” of the stage.
3. Choose the combination of actors and roles that minimizes the total conspicuity given constraints on how conspicuous a specific transportation profile is allowed to be.

The question left is how to define how conspicuous a specific transportation is. The criteria should punish speed profiles in which large and rapid speed changes within sight from the subject is needed, especially profiles in which the actor will use free speeds which are both faster and slower than the subject vehicle. This requires recording of the vehicles’ highest free speed which the subject has been possible to observe. It may also be useful to record if the vehicles has been overtaken by or has overtaken the simulator vehicle. This in order to avoid using an overtaken vehicle for a “catch-up” role or vice versa.

Another important question is when the casting should be conducted. This depends on the latest time at which an actor off stage can start to reach a role in a non-conspicuous way. Note that off stage means areas which are out of sight from the subject, including areas behind or in front of the simulator vehicle and on cross roads.

C. The transportation sub-problems

The transportation of actors with a role to the initial role state can be divided into two parts: longitudinal transportation and overtakings. The longitudinal transportation is the same problem as presented above with the extension that the least conspicuous speed profile has to be updated each time step. This in order to get a feedback regulation which can deal with that the simulator vehicle’s speed may vary, leading to variation in the needed average speed and consequently variation in the role speed and position. For the rearranging of the actors, i.e. overtakings, some sort of collaboration between the actors is needed. For example should actors try to give way to actors which are assigned roles with initial positions in front of the own initial role position. Collaboration between actors is also needed in order to ensure that the subject drives in the lane that the scenario developer intends. For this, the actors need to collaborate in order to create motives for the subject to reach the intended lane, e.g. by creating/closing gaps in order to create motives for/against a lane change.

The transportation of actors without roles from the stage can be handled in a similar way by specifying a minimum distance to the simulator vehicle that they at least have to reach, e.g. the edge of the stage. Other possibilities for the transportation of actors from the stage are to let vehicles turn off the road at off-ramps or intersections.

V. CONCLUSION AND FUTURE RESEARCH

We have in this paper presented a methodology for combining autonomous and controlled vehicles in driving simulator scenarios. Advantages, disadvantages and difficulties with this approach have been discussed and a casting algorithm has been proposed. Future research includes implementation, calibration and validation of the proposed methodology and tests in a driving simulator.

VI. ACKNOWLEDGMENT

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