

COMBINING AUTONOMOUS VEHICLES AND CONTROLLED EVENTS IN DRIVING SIMULATOR EXPERIMENTS

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ABSTRACT

Autonomous vehicles can be used to create realistic simulations of surrounding vehicles in driving simulators. However, the use of autonomous vehicles makes it difficult to ensure reproducibility between participants. In this paper an effort is made to solve the problem by combining autonomous vehicles and specific predefined traffic situations, here denoted plays. The problem is to achieve the same initial play conditions for each participant, since the traffic situation around the participant will be dependant upon each participant's actions while driving in the autonomous traffic. This paper presents an algorithm that achieves the transition from autonomous traffic to a predefined start condition for a play. The algorithm has been tested in the VTI driving simulator III with promising results. For most of the ten participants, the algorithm could reconstruct the specified start condition and conduct the transition from autonomous to controlled mode in a non conspicuous way. Some problems were observed regarding moving unwanted vehicles away from the closest area around the simulator vehicle, and this part of the algorithm has to be enhanced. The experiment also showed that the controlled everyday life traffic normally used in the VTI driving simulator makes participants drive faster than in autonomous traffic.

1. INTRODUCTION

A driving simulator is a tool which allows driving in a virtual environment. It is possible to reproduce many types of driving situations, from everyday life driving to specific situations, e.g. risky situations. Just 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. The disadvantages are limited realism regarding the behavior of the surrounding vehicles and limitations in the complexity of the scenario situations, due to both the complexity of the scenario programming and the programming effort required. The complexity of programming can be decreased and realism increased by giving the surrounding road users increased autonomy. This leads to simulated situations with similar advantages and disadvantages to real world experiments, i.e. low reproducibility but realistic surroundings. Our hypothesis is that it is possible to gain in realism without losing too much in reproducibility by combining autonomous and controlled simulated road users.

Earlier work within the field of simulating surrounding vehicles in driving simulators has focused on the development of models for simulation of autonomous vehicles; see for example Al-Shihabi and Mourant (2002), Cremer et al. (1995), Espié (1995), Janson Olstam et al. (2008) or Wright et al. (2002). Ideas and frameworks, but no complete algorithms, for combining autonomous and controlled vehicles are provided by Alloyer et al. (1997), Wassink et al. (2005, 2006) and Janson Olstam and Espié (2007). Inspired by the work of Alloyer et al. (1997) and Wassink et al. (2005, 2006), Janson Olstam and Espié (2007) proposed an alternative design methodology for driving simulator experiments in which periods with autonomous simulated road users are combined with periods with only controlled simulated road users. The basic idea is to let the surrounding vehicles run in autonomous mode between the predetermined situations at which measurements are taken. When a participant approaches a position along the road where a situation is going to take place, the simulation of the surrounding vehicles should change from the autonomous to the controlled mode. The transition from autonomous to controlled mode has to be done in a way which is unnoticeable for the participant. The idea is that the autonomous parts will ensure the necessary realism and the controlled part will ensure the required reproducibility. The controlled events are named *Plays* and the problem of changing from the autonomous to the controlled mode is referred to as the *Play Preparation Problem*. Possible approaches for solving the play preparation problem are discussed and outlined in Janson Olstam and Espié (2007), but no complete algorithms are presented or evaluated. The aim of this paper is to propose and evaluate an algorithm for solving the play preparation problem.

Section 2 gives an introduction to the play preparation problem and its sub problems. The developed algorithm is then presented in Section 3. An evaluation of the algorithm including

results from a driving simulator experiment is presented in Section 4. Section 5 ends the paper with conclusions and outlines for future research.

2. THE PLAY PREPARATION PROBLEM

Janson Olstam and Espié (2007) define a driving simulator scenario as a constellation of the three components everyday life driving, preparations for plays, and plays (see Figure 1 for an example). Everyday life driving refers 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 positions and speeds that they will have when the next play starts. The play is a traffic situation that will be studied.

Janson Olstam and Espié (2007) present the play preparation problem using a theater metaphor, which is an extension of the theater metaphors presented in Alloyer et al. (1997), Espié and Rousseau (1998), and Wassink et al. (2005, 2006). The theater metaphor includes definitions of the terms play, manuscript, role, actor, stage, etc. in the context of a driving simulator experiment. A play in this context includes a *manuscript* and a *role list* and is performed on a *stage*. The *manuscript* defines the scenery (i.e. the road infrastructure, surroundings, road and weather conditions, etc.). The *stage* is defined as a limited area around the simulator vehicle which moves with the speed of the simulator vehicle. The *role list* is a description of all the main and walk-on characters. Each *role* 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 during the play. 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. In this paper the position and speed are specified as relative to the driving simulator vehicle, e.g. 400 meters ahead and 15% slower. There are both *active roles* and *walk-on characters*. The walk-on characters are here referred to as *no-roles*. The no-role characters should not interfere with the main characters. Therefore, they are instructed to keep a minimum distance to the simulator vehicle. An *actor* is defined as a road user, e.g. a vehicle or pedestrian, that behaves or acts at some level of autonomy between “fully” controlled and “fully” autonomous. A “fully” controlled actor does not take any initiative and only follows the directives that it has been given. A “fully” autonomous actor on the other hand takes initiatives and only considers a request from someone else if it complies with the actor’s own goals.

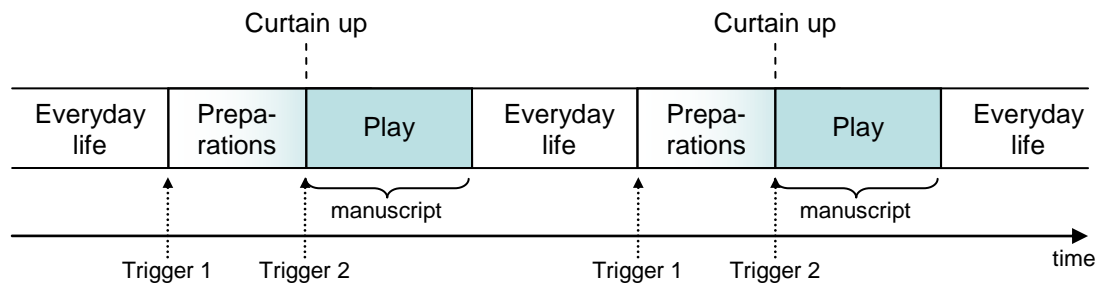


Figure 1: Illustration of an example combination of the three components in a driving simulator scenario.

The three basic components (everyday life driving, play preparation and plays) have different purposes in a driving simulator experiment. The plays are used to study driving behavior in some specific driving situation. The everyday life driving parts are used to get the participant to the awareness level, mood, etc. that he or she has in their normal everyday life driving in the current driving context. These parts are also used to “reset” the participants between the plays. The play preparation is used to ensure that the plays start at the right time or at the right place and that the conditions at the start of the plays are comparable between participants. In this paper autonomous vehicles are used for the everyday life driving to increase realism, while controlled vehicles are used during the plays to ensure reproducibility. The play preparation problem is defined as the problem of changing from the autonomous everyday life driving to a controlled play.

2.1. The play preparation sub problems

The play preparation problem can be divided into three sub problems: estimation of the start time of the play; casting; and transportation of actors. The transition from autonomous everyday life driving to a controlled play includes two trigger points, see Figure 1. The first point triggers the start of the play preparation and the second point triggers the hand over from the autonomous to the controlled mode. *The start time estimation problem* consists of estimating when the simulator driver will reach the second trigger point. *The casting problem* consists of finding actors that can play the roles in the upcoming play and assigning the roles to the most suitable actors. *The transportation problem* consists of moving each actor to the right initial position (either a role position or a no-role minimum distance) in a non conspicuous way. If there are no suitable actors on the stage, new ones have to be created out of sight of the simulator driver. The casting and transportation sub problems are strongly connected to each other and neither of the sub problems are trivial. The casting problem is difficult since the casting has to be done in such a way that the needs of transportation and reordering of actors are minimized. The transportation sub problem is difficult since the transportation of actors has to be done in a non conspicuous way.

The transportation problem implies that 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_a , which is dependent on the participant's future actions and especially on the speed of the simulator vehicle until the start of the play. The second constraint is that the actor's speed at the estimated play start time, \hat{t} , should be equal to the initial role speed, v_R . The problem of reaching the initial role position and speed can be described as:

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

$$v(\hat{t}) = v_R \quad (1)$$

and

$$\int_0^{\hat{t}} (v(t) - v_a) dt = 0. \quad (2)$$

3. ALGORITHM

The algorithm developed consists of three phases, which are related to the estimation of the play start time, the casting, and the transportation of actors. Figure 2 shows how the algorithm is integrated in the simulation time step. An initial casting is done when trigger 1 is reached. The play start time estimation, the transportation part, and a check that actors still can reach their assigned role, are run in each time step of the simulation. The "still able to reach role" control is currently only done for actors that are assigned a no-role. The following sections will describe the casting and transportation phases in more detail.

3.1. Casting of active roles

When the first trigger point has been reached, the play preparation starts with the casting of the roles in the role list. The roles closest to the simulator vehicle could in some sense be compared to the leading actors of the play and consequently it is most critical to find suitable actors for these roles. The casting algorithm therefore starts with the casting of the roles closest to the simulator vehicle and then continues with the ones further away. The casting of a role is a process in which actors are evaluated one at a time. The procedures for the casting of actors behind and in front of the simulator vehicle are equivalent. The procedure for the casting of roles behind the simulator vehicle are done according to the following algorithm

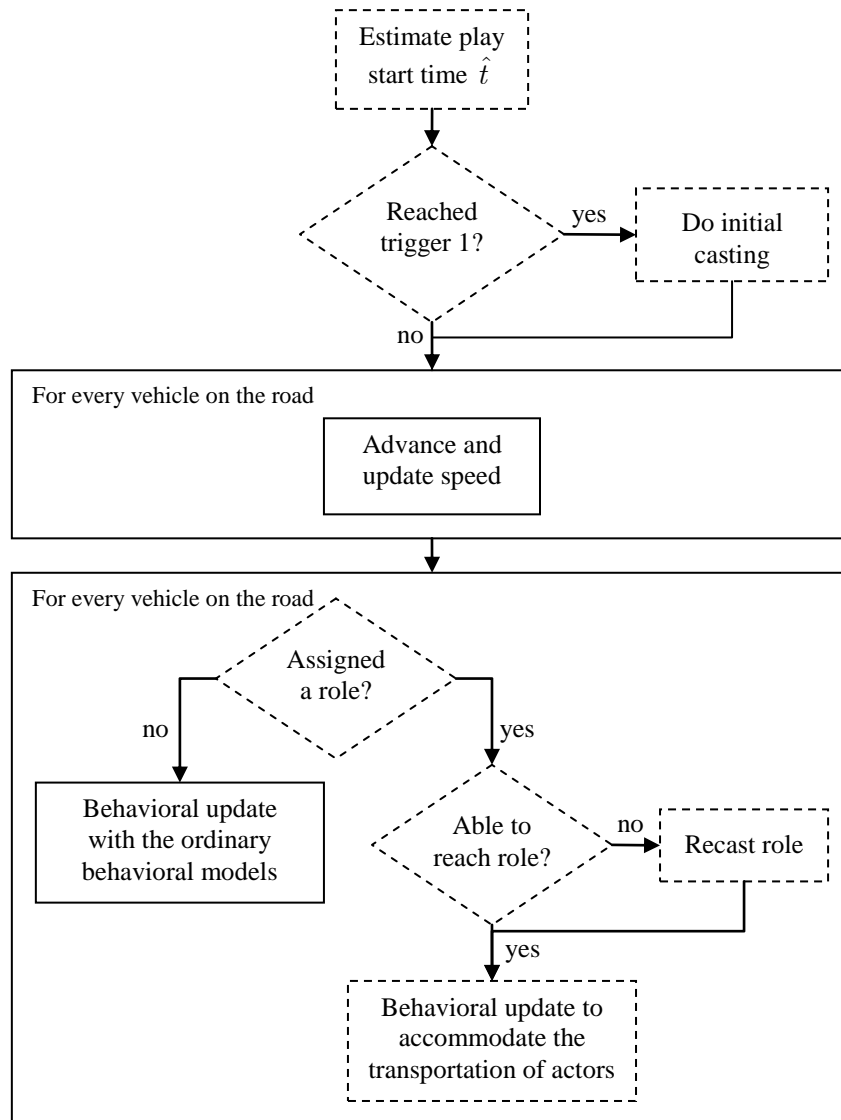


Figure 2: Illustration of how the play preparation problem algorithm (dashed line boxes) is working in each simulation time step.

0. Set the role-to-be-assigned equal to the closest role behind the simulator vehicle and go to step 1.
1. Set the actor-to-be-evaluated equal to the closest actor behind the simulator vehicle and go to step 1.a.
 - a. Check if the actor-to-be-evaluated is already assigned a role. If so, go to step 2. Otherwise go to step 1.b.
 - b. Check if the actor-to-be-evaluated can play the role. If so, go to step 1.c. Otherwise go to step 2.
 - c. Check if the actor-to-be-evaluated can reach the stage in time. If so, go to step 1.d. Otherwise go to step 2.
 - d. Check if the actor-to-be-evaluated is the most suitable actor for the role so far. If so, assign the role to the actor-to-be-evaluated and un-assign the role from any previously chosen actor. Go to step 2.

2. Check if there is any actor behind the actor-to-be-evaluated on the stage.
If so, set the actor-to-be-evaluated equal to the actor behind the current actor-to-be-evaluated and go to step 1.a. Otherwise, go to step 3.
3. Check if it is more suitable to create a new actor off stage.
If so, create a new actor from off the stage and assign the role to this actor and un-assign the role from any previously chosen actor. Go to step 4.
4. Check if there is a role behind the current role.
If so, set the role-to-be-assigned to this role and go to step 1. Otherwise, end the assignment loop.

3.2. Assignment of no-roles

The actors that are not assigned any active role are assigned a no-role. These actors are instructed to achieve and maintain a specified minimum distance to the simulator vehicle. An actor can either be assigned a no-role behind or in front of the simulator vehicle. The actor's should be assigned the no-role that leads to the least conspicuous transportation from the simulator driver's point of view. This is generally the no-role on the same side of the simulator vehicle as the actor, e.g. an actor behind the simulator vehicle is in general assigned the no-role behind the simulator vehicle. The difficulties in the no-role assignment have to do with actors driving relatively close to the simulator vehicle. The approach developed estimates whether an actor behind the simulator vehicle will be able to catch up with the simulator vehicle or not and whether an actor in front will be caught up by the simulator vehicle or not within half the preparation time. For example, an actor in front of the simulator vehicle will be assigned a no-role behind if

$$\hat{t}_{catch} < 0.5 \cdot (\hat{t} - t), \quad (3)$$

where

$$\hat{t}_{catch} = \begin{cases} \frac{x - x_{DS}}{\hat{v}_{DS} - v}, & \text{for } \hat{v}_{DS} > v \\ \infty, & \text{otherwise.} \end{cases} \quad (4)$$

These conditions are also used to continuously test if an actor that is assigned a no-role can still reach this role or if she has to be assigned another no-role, in the "still able to reach role" algorithmic step in Figure 2.

3.3. Longitudinal transportation strategy for active roles

For the longitudinal transportation of actors, the actor's strategy is to reach a speed on the necessary side of the required average speed, i.e. the side opposite to the initial role speed. The actor can then smoothly regulate towards the initial role speed. The acceleration that an actor applies in order to reach an assigned role is calculated as

$$a = \begin{cases} \frac{v_a - v}{t_c}, & \text{if } \text{sign}(v - v_a) \neq \text{sign}(v_R - v_a) \text{ and } t_c \leq 0.5 \cdot \tilde{t} \\ \frac{v_a - v_R + v_a - v}{0.3 \cdot \tilde{t}}, & \text{otherwise,} \end{cases} \quad (5)$$

where

$$t_c = \frac{v_a - v_R}{v - v_R} \cdot \tilde{t}. \quad (6)$$

Here v is the current speed, v_a is the required average speed, v_R is the initial role speed, the function $\text{sign}(x)$ gives the sign (negative or positive) of x , and \tilde{t} is the estimated time left to the play, i.e. $\tilde{t} = \hat{t} - t$. The time t_c is the time at which the actor should pass the required average speed in order to fulfill the conditions given by equation (1) and (2), given that constant acceleration rates is used.

3.4. Longitudinal transportation strategy for no-roles

Actors that are assigned no-roles use a straightforward and rather simple strategy to transport themselves off the stage and to the specified minimum distance to the simulator vehicle. Actors that have not yet reached the minimum distance decrease or increase their desired speed to the necessary level. In this way, only the actor's driver characteristics are changed and there is no need for changes in the underlying behavioral models for acceleration, lane-changing, etc. If the underlying behavioral models give realistic driver behavior, the conspicuity regarding the remove transportation should not be a problem. In order to avoid conspicuously quick changes in speed, the actors are only allowed to change their desired speed by 3 km/h per second. Actors that have reached the minimum distance will gradually change their desired speed towards the speed of the simulator vehicle, in order to keep at least the minimum distance, but not go too far away from the simulator vehicle.

3.5. Lane changing strategy

The basic idea behind the transportation algorithm is that the actors should as much as possible act according to their underlying behavioral models. However, it is sometimes necessary for the actors to deviate from their normal behavior in order to reach their assigned role or to help other actors to reach their roles. It is sometimes preferable to not make a desired lane change. This can be for example if the actor in front is assigned a role in front of the current actor or if by changing lane the actor will go away from the specified initial role lane. Sometimes, it can also be preferable to change lane even if the actor normally does not estimate this lane change as desirable or necessary. This can be for example if the actor in front is assigned a role behind or if the actor's current lane differs from the initial role lane.

3.6. Actor collaboration

To simplify the rearranging of the actor sequence and to decrease the risk for conspicuous actions, the actors are instructed to collaborate. The primary goal of an actor is of course to reach his initial role conditions but the actor should as much as possible try to help the surrounding actors in their striving to reach their roles. For example, an actor can send a request to a preceding actor that is assigned a role behind him to change lane to the right or keep to the right so that the actor can pass. Actors trying to reach a no-role in front are often constrained by other no-role actors that have already reached the minimum distance. These actors can be asked to accelerate in order to make it easier for the actors that have not yet reached the minimum distance. Another example of collaboration is that actors that need to change lane can ask the actors in the target lane to increase the gap if it is too small.

4. ALGORITHM EVALUATION

A driving simulator experiment has been conducted in order to test the developed algorithm. The simulator experiment had two main aims. The first aim was to test if the algorithm is able to reconstruct equal play start conditions for each participant in a non conspicuous way. At the end of each play preparation, the actors' position, speed, etc. were measured and compared to the role specifications. The result of this comparison is presented in Section 4.4.1.

The second aim was to test if the type of traffic (autonomous or controlled) during the everyday life driving affects the participants' driving behavior and/or experience of the drive. One hypothesis is that the kind of controlled everyday life traffic that has been used on freeways in the VTI driving simulator III makes participants drive faster than they normally do. The assumed reason for this is that they feel pressured by the fast cars coming from behind. These cars will drive faster than the participant independent of how fast the participant drives (the faster the participant drives, the faster will the vehicles behind drive). The result of this comparison is presented in Section 4.4.2.

4.1. Testbed

The algorithm developed has been implemented in the traffic simulation framework for surrounding vehicles in driving simulators presented in Janson Olstam et al. (2008). As suggested in Janson Olstam et al. (2008), the lane changing model has been replaced by a lane changing model that includes anticipation. The new lane changing model is a combination of the ARCHISIM (El hadouaj and Espié, 2002) and the MOBIL (Kesting et al., 2007) lane-changing models. In order to achieve a better integration of the lane-changing and car-following model, the car-following have been replaced by a version of the HDM/IDM car-

following model (Treiber et al., 2000, Treiber et al., 2006) which is commonly used together with the MOBIL lane-changing model. The lateral position update algorithm has been replaced by the steering model presented in Salvucci et al. (2001). The simulation framework has been integrated with and tested in the VTI driving simulator III (VTI, 2008). This driving simulator is a vehicle cabin and motion based driving simulator with a 120 degree field of view in front and three back mirrors.

4.2. Scenario description

The scenario consisted of three plays along a 72 km long freeway stretch. The speed limit was 110 km/h and there were two lanes in each direction; see Figure 3 for an illustration. There were on- and off ramps along the road but no entering or exiting vehicles. The road was dry but there was some mist in the air.

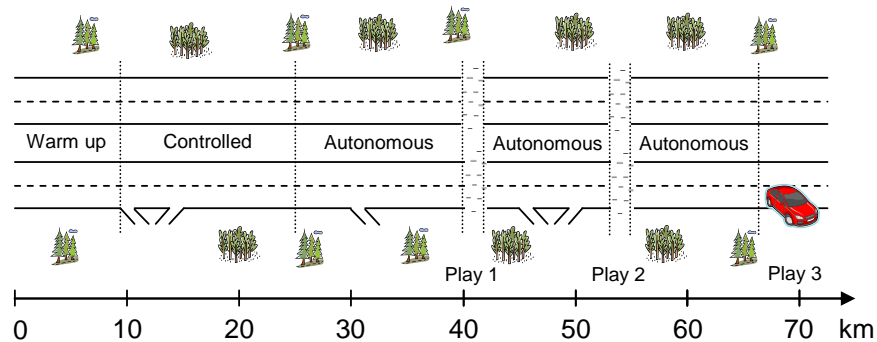


Figure 3: Illustration of the scenario.

The scenario started with a 10 km long warm-up section without any surrounding traffic. It continued with a 15 km long section with controlled everyday life traffic followed by a 15 km long part with autonomous everyday life traffic. The traffic during the controlled everyday life part was designed in the same way as in earlier freeway experiments in the VTI driving simulator, e.g. the DIWITSA project (IVSS, 2008). The controlled everyday life traffic was defined so that the number of active and passive catch ups that the participants experienced would be the same for all participants. This implies that there would be vehicles driving faster and slower than the participant independent of how fast or slow the participant drove. The controlled everyday life traffic consisted of nine catch up situations, in which the participant caught up with a slower vehicle platoon. In six of the cases, a faster vehicle platoon arrived in the left lane at the same time. The participant then had to decide whether or not to change lane and overtake the slower platoon or to let the faster platoon pass first.

The traffic conditions during the autonomous everyday life driving part are defined in terms of flow and vehicle type shares, in this case set to 1200 vehicles/h/direction and 92 % cars, 6 % trucks and 2 % buses. The 15 km long autonomous everyday life driving part is followed by the first play preparation and play. The play consists of a 1 km stretch with dense fog in

which no surrounding vehicles should be closer to the participant than 300 meters. The reason for using this kind of low complexity play is to test the remove transportation of no-role actors separately. For the first play the play preparation length is set to 1 km. This play is followed by 10 km of autonomous everyday life driving and an identical play but now with 2 km of play preparation. This makes it possible to investigate how the length of the play preparation period affects the algorithm’s ability to achieve the play start condition. The preparation of the third and last play starts after another 10 km of autonomous everyday life driving. The preparation length for this play is 2 km. This play includes four active roles. The leading star role is a car in front of the participant that after some driving has a car brake down and has to decelerate and park on the shoulder. At the same time and in order to prevent the participant from immediately changing lane the participant is passed by a platoon of three vehicles. The start condition for the front car is a relative position of 400 m and a relative speed of 0.78. The start conditions for the three cars behind are relative positions of 250 m, 300 m, and 350 m, and a relative speed of 1.15. The no-role actors should have a minimum distance of 400 m to the participant.

4.3. Participants and experiment procedure

All of the ten participants were in-house VTI personnel with no previous insight into or knowledge of this particular study. Data about the participants is presented in Table 1. Upon arrival at the simulator facility, the participants were directly asked to take a seat in the driver seat of the simulator. The participants were told that they would drive on a freeway with a speed limit of 110 km/h for approximately 40 minutes and that the first 10 km was a warm-up stretch without any surrounding vehicles. The participants did not get any further instructions but were asked to drive as they normally would on a similar freeway. During the whole simulator drive, the test leader took notes on traffic situations or driving behavior that deviated from the test leader’s expectations of realistic traffic situations and driving behavior. The main focus was the behavior of the surrounding vehicles during the play preparations.

Table 1. Background data about the ten participants.

	Participant number									
	1	2	3	4	5	6	7	8	9	10
Gender	F	M	M	F	F	F	M	M	M	F
Age	36	37	53	50	60	29	43	58	25	32
Years with license	18	20	32	32	41	11	23	32	6	13
Mileage last year	1000	1200	1500	500	1000	3000	1500	1600	300	1000
# of drives in simulator	0	15	3	0	3	0	0	4	1	0
Desired speed	115	125	120	110-120	110-120	120	120	110	120	120

After the drive, the participants were asked to fill in a questionnaire with questions regarding background data, driving style, and the general impression of the simulator with respect to steering, accelerating, and braking, etc. The participants were then interviewed by a trained psychologist with regard to the traffic situation and the behavior of the surrounding vehicles

during the different parts of the drive. The participants were asked questions regarding their general impression of the drive, questions related to the different parts of the drive, i.e. the first fog, the second fog and the car that surprisingly stopped at the end of the drive. As a mnemonic device, a line-out of the drive was used, similar to the one in Figure 3 (without the information on controlled and autonomous traffic). The participants’ impression of the traffic situation during the period (play preparations) just before the first and second fog and the car break down was also discussed. The interview guide is available upon request. The interviews were taped and transcribed for further analysis.

4.4. Results

Actor’s ability to reach roles and no-roles

The first aim of the driving simulator experiment was to test if the algorithm is able to reconstruct the same play start conditions for all participants. At the end of each play preparation, the actors’ position, speed, etc. were measured and compared to the role specifications. The no-roles only included a specification of the minimum distance to the driving simulator vehicle (300 m for play 1 and 2 and 400 m for play 3). Table 2 - Table 4 display the distance between the participant and the first no-role actor in front and behind the participant. In connection with play 1, (Table 2) the minimum distance was for all participants reached by the actors behind the simulator vehicle, while the actors in front only succeeded for two of the participants. For play 2 (Table 3), the minimum distance was reached more or less for all participants with some exceptions and the situation was similar for play 3 (Table 4). The difference between plays 1 and 2 can most likely be explained by the difference in preparation length.

Table 2. Distance in meters to the driving simulator vehicle for the first no-role actors in play 1 (fog event with 1 km preparation period and 300 m minimum distance).

Distance in m	participant number									
	1	2	3	4	5	6	7	8	9	10
First no role behind	-372.2	-480.1	-305.9	-383.3	-350.8	-396.0	-407.7	-377.1	-352.8	-356.6
First no role in front	179.1	142.8	112.4	177.2	339.5	240.3	135.9	29.7	309.8	232.1

Table 3. Distance in meters to the driving simulator vehicle for the first no-role actors in play 2 (fog event with 2 km preparation period and 300 m minimum distance).

Distance in m	participant number									
	1	2	3	4	5	6	7	8	9	10
First no role behind	-268.8	-448.0	-299.5	-449.9	-298.7	-548.0	-286.9	-256.3	-297.1	-351.5
First no role in front	340.6	296.9	380.7	344.2	473.4	333.8	318.0	388.6	314.8	243.7

Table 4. Distance in meters to the driving simulator vehicle for the first no-role actors in play 3 (braking car event with 2 km preparation period and 400 m minimum distance).

Distance in m	participant number									
	1	2	3	4	5	6	7	8	9	10
First no role behind	-402.0	-500.9	-399.7	-398.8	-979.9	-402.0	-398.4	-400.2	-485.0	-335.0
First no role in front	466.9	341.8	641.5	665.8	577.0	454.7	344.4	419.4	379.3	521.2

Play 3 also included active roles. The difference between the achieved distance and the specified distance to the participant for each active role is presented in Table 5. The difference is less than 1 meter for all participants and roles, which is acceptable.

Table 5. Difference between actual and specified distance in meters to the driving simulator vehicle for active roles in play 3 (braking car event with 2 km preparation period).

Difference in m	participant number									
	1	2	3	4	5	6	7	8	9	10
Behind role 350 m	0.14	-0.21	-0.13	-0.13	-0.13	-0.15	0.17	-0.14	-0.49	-0.14
Behind role 300 m	0.15	-0.29	-0.14	-0.14	-0.15	-0.16	-0.07	-0.15	-0.40	-0.14
Behind role 250 m	0.24	-0.14	-0.13	-0.14	-0.11	-0.16	-0.14	-0.14	-0.33	-0.14
Front role 400 m	0.74	0.18	0.21	0.18	0.24	0.20	0.12	0.22	0.12	0.26

Besides the relative position, the active roles also included a specification of the relative speed to the driving simulator vehicle, specified as $\frac{v_R}{v_{DS}}$. The difference in percent units between the achieved relative speed and the specified relative speed, i.e. $100 \cdot \left(\frac{v}{v_{DS}} - \frac{v_R}{v_{DS}} \right)$, is presented in Table 6. The difference is less than 0.5 percent units, i.e. less than 0.15 m/s at 30 m/s, for all experiment runs except for the runs with participants 1, 7, and 9. For the experiment runs with participants 1, 7, and 9 the differences are of the magnitude 2 – 5 percent units, i.e. less than 1.5 m/s at 30 m/s, which is less good but still workable. The conclusion is that the speed differences are within acceptable limits.

Table 6. Difference in percent units between actual and specified speed relative to the driving simulator vehicle for active roles in play 3 (braking car event with 2 km preparation period).

Difference in %-units	participant number									
	1	2	3	4	5	6	7	8	9	10
Behind role 350 m	2.87	-0.38	0.49	0.42	0.42	-0.15	3.55	0.14	-5.01	-0.12
Behind role 300 m	2.71	-0.65	0.21	-0.14	-0.02	0.01	-1.40	-0.03	-2.81	0.04
Behind role 250 m	3.54	0.24	0.69	-0.40	0.55	-0.71	-1.75	0.09	-2.08	0.17
Front role 400 m	2.09	-0.43	-0.27	0.00	-0.19	0.33	0.15	0.11	-0.30	-0.11

Participant’s mean free speed

The hypothesis regarding the participants’ speed choice is that the controlled everyday life traffic made the participants drive faster than they normally do. The average speed as free vehicle (time headway > 6 s and |acceleration| < 0.5 m/s²) has been used as a test variable for investigating this hypothesis. Table 7 presents the participants mean free speed during the

warm-up, controlled and the three autonomous parts while Table 8 presents the difference in the participants’ mean free speed between the controlled part and the warm-up part and the three autonomous parts, respectively. The difference is generally positive and varies from -0.32 to 4.64 m/s.

Table 7. Mean free speed with 95%-confidence intervals [m/s].

	Participant number									
	1	2	3	4	5	6	7	8	9	10
Warm up	30.9± 0.05	32.4± 0.08	32.8± 0.09	30.9± 0.09	30.3± 0.03	30.3± 0.02	34.8± 0.15	30.4± 0.03	31.6± 0.06	32.6± 0.06
Controlled	32.2± 0.09	33.4± 0.08	34.9± 0.13	32.5± 0.07	30.8± 0.07	31.1± 0.11	34.7± 0.12	30.4± 0.04	31.7± 0.06	32.8± 0.06
Autonomous 1	31.4± 0.15	32.4± 0.08	32.2± 0.19	30.9± 0.11	29.2± 0.09	30.0± 0.05	33.9± 0.13	30.3± 0.03	31.6± 0.06	32.5± 0.09
Autonomous 2	30.4± 0.08	31.9± 0.14	30.6± 0.11	30.8± 0.18	29.4± 0.07	30.1± 0.04	31.8± 0.16	30.3± 0.05	32.0± 0.05	32.2± 0.16
Autonomous 3	30.8± 0.05	31.6± 0.10	30.2± 0.27	30.5± 0.08	29.5± 0.08	29.9± 0.03	34.4± 0.10	30.0± 0.04	31.9± 0.06	30.5± 0.10

Table 8. Difference in mean free speed [m/s] between controlled and autonomous everyday life driving or warm-up driving.

	Participant number									
	1	2	3	4	5	6	7	8	9	10
Controlled – Warm up	1.22	0.91	2.11	1.64	0.44	0.85	-0.04	0.04	0.09	0.23
Controlled – Autonomous 1	0.80	0.99	2.70	1.66	1.52	1.18	0.84	0.06	0.16	0.27
Controlled – Autonomous 2	1.76	1.48	4.28	1.76	1.36	1.00	2.93	0.05	-0.32	0.61
Controlled – Autonomous 3	1.39	1.72	4.64	2.01	1.24	1.20	0.34	0.40	-0.19	2.28

One sided t-tests have been conducted with the hypothesis that the participants’ mean free speed during the controlled part is higher than during the warm-up part and the three autonomous parts. This gives four t-tests: controlled – warm-up ($t(9) = 3.24; p = 0.0051$); controlled – autonomous 1 ($t(9) = 4.01; p = 0.0015$); controlled – autonomous 2 ($t(9) = 3.50; p = 0.0034$); and controlled – autonomous 3 ($t(9) = 3.52; p = 0.0033$). The difference in mean free speed is significant at the 95 % confidence level for all tests. The conclusions are that the participants drive about 1 m/s faster during the controlled everyday life driving part than during the autonomous everyday life driving parts and than during the warm-up period.

Participant comments and test leader observations

In this section, the results from the interviews and observations made by the test leader are summarized. The test leader observed some problems with the casting and transportation of no-role actors. The problems were mainly related to the transportation of actors that are close to the simulator vehicle when the play preparation starts. The problems seem to be more severe in connection with the shorter preparation length of 1 km. There were for example, situations in which an actor in front of the participant had been assigned a no-role behind the

participant and therefore started to decrease her speed in order to give the participant a reason to pass. However, the decrease seemed to be too rapid and the participant observed the change as a strong deceleration and started to decelerate instead of changing lane. This sometimes resulted in the actor no longer thinking that the participant would catch up with her. The actor would then be re-cast to a no-role in front, and thereby start to accelerate. This may have been a problem of inconsistency in the no-role casting, i.e. that the casting of a no-role changed back and forth from a no-role behind and a no-role in front. Unfortunately, there was no recording of data regarding the changes in no-role casting during the experiment. It may also have been a problem of bad tactical behavior in the no-role transportation model.

Several participants commented on the catch up situations during the controlled everyday life traffic in which the participant caught up with a slower platoon at the same time as a fast vehicle platoon caught up with the participant. Some participants gave comments like “*The overtakings were not normal*” or “*These situations happen more often than in real traffic*”. One participant also commented on the fact that he drove faster than he normally does due to the fact that the other vehicles drove fast. Other comments did not include any value judgment. However, the fact that these traffic situations were commented on indicates that these situations, or their frequent appearance, differ from real freeway traffic.

Many participants thought that the autonomous everyday life traffic drove slower than real world freeway traffic, leading to too many active catch-ups and too few passive catch-ups. Similar comments were given during the study presented in Janson Olstam et al. (2008). One explanation is probably that the speedometer in the driving simulator shows the actual speed and not a speed 5-8 km/h higher than the actual speed, which is the case in most real cars. However, the test leader also observed that the autonomous vehicles never, or seldom, were able to reach their desired speed. The reason for this was found to be the design of the IDM car-following model (Treiber et al., 2000), more precisely, the function for calculating acceleration due to interactions with a preceding vehicle. The observed deficiency leads to a lower average speed than what is expected for a specific distribution of desired speeds. This is probably an additional explanation to why the participants thought that the autonomous vehicles drove slowly.

There were observations about autonomous cars that passed the simulator driver really slowly or vehicles that did not seem to be able to decide if they should pass or not. The autonomous vehicles were sometimes considered to drive irregularly, i.e. change speed without reason. These observations seem to be in connection with play preparations. Some strange lane changes and speed changes were observed during the play preparations. Some of the observations may concern situations during autonomous everyday life traffic. Several participants observed that there was no or little traffic around them when they entered the foggy parts.

5. CONCLUSIONS AND FUTURE RESEARCH

In the present paper, an algorithm for combining autonomous surrounding traffic and controlled events is presented and evaluated. The algorithm has been tested in the VTI driving simulator III with promising results. For most of the participants the algorithm could reconstruct the specified start condition and conduct the transition from autonomous to controlled mode in a non conspicuous way. However, some problems were observed, for example regarding transporting no-role actors to the specified minimum distance to the participant. The conclusions from the driving simulator experiment are the following:

- The casting and transportation of active roles works satisfactory.
- The casting and transportation of no-roles do not always work as intended. This part has to be enhanced in order to ensure reproducibility.
- The platoon situations that frequently appeared during the controlled everyday life traffic were considered different to real freeway traffic situations by the participants. The behavior of the surrounding vehicles during this part had a significant effect on the participants free driving speed, which was higher than during autonomous everyday life traffic and during warm-up without any traffic.
- The participants experienced the autonomous everyday life traffic as slower than real freeway traffic.
- The underlying autonomous behavior models have to be enhanced with regard to the problems observed with slow overtakings, strange lane-changing behavior and vehicles that are not able to reach their desired speeds.

The problem with the transportation of no-role actors is more severe in connection with the shorter preparation length of 1 km. It seems that a 1 km preparation period is too short for clearing an area of 300 meters around the participant at a traffic flow of 1200 vehicles/h. One solution could be to use a variable length of the preparation period that depends on the current traffic situation around the simulator vehicle.

The algorithm has only been tested for two types of plays and for one traffic condition. Further tests with different kinds of plays and traffic conditions (especially more dense conditions) are needed. The algorithm should also be tested within a “real” driving simulator experiment and not only in an experiment designed to test the algorithm. However, before any additional testing is done the problems observed regarding casting and transportation of no-role actors have to be solved. Future research should also include enhancements of the IDM car-following model which was found to have deficiencies regarding the calculation of interaction accelerations.

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