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Impact of human drivers on automated vehicles' traffic flow: An integrated and reproducible driving simulator study

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Abstract

We design an integrated and reproducible driving-simulator experiment to study human factors involved in take-over maneuvers and their consequences on the Automated vehicles' traffic flow properties. The experiment design aims to help investigate drivers' response time and take-over quality during take-over maneuvers in relation to factors such as mental workload, risk perception and traffic conditions. In this experiment, participants will be exposed to automated-driving and human-driving modes while interacting with other automated vehicles through car-following and lane-changing maneuvers for a wide range of traffic conditions. The experiment design is programmed in webots, a robot simulation software, where all automated vehicles are programmed to follow the full velocity difference model (FVDM) coupled with a cooperative lane-changing driving strategy. The proposed experiment design stands out from the existing ones in that it enables studying impacts of drivers' take-over of AVs on the safety and traffic flow properties of surrounding AVs. To promote reproducibility, we make available all the software and programming codes as well as the data collection within this paper.

1. Introduction

Automated vehicles (AVs) are expected to fully populate traffic stream and autonomously control vehicles through automated driving systems in a few decades. In the meantime, automated vehicles will not be autonomous, and requires human drivers' supervisions. Automated driving's system may request drivers to take over the vehicle in certain situations, e.g., when exiting motorways or when detecting safety-critical situations. Such take-over maneuvers are classified as mandatory in the literature as the request is issued by the vehicles' system.

A major question in researching into driver interactions with AVs is how quickly drivers can take over the vehicle when a mandatory take-over request is issued by the system.

Depending on the underlying human psychological factors, drivers' intervention with AVs may have significant consequences for the safety and traffic flow dynamics of the preceding and surrounding AVs. However, despite its importance, not much research has been conducted into this area to date. For instance, most of the studies analyzed in the meta-analysis by Zhang et al. (2019) focus primarily on the behaviour of the subject vehicles, where only a few surrounding AVs with simplified driving rules are considered. In such experiment designs, the information obtained from human factors cannot be explicitly utilized to study consequences for the surrounding AVs.

This research gap can be in part explained by the difficulties in designing realistic and robust simulation environments, particularly designing AVs with radar detector and cooperative automated driving strategies, capable of responding to the participant's take-over behavior.

We develop a driving simulator experiment design framework based on the integrated simulation platform recently proposed in Jia et al. (2021). We utilise the proposed framework to design a driving-simulator experiment with focus on studying how drivers' take-over maneuvers may affect traffic flow of AVs. The experiment encodes major determinants of drivers' take-over time (e.g., headway setting, presence/absence of messages, etc.) in a simulation environment, where participants actively interact with the surrounding AVs. The proposed design stands out from the existing ones in that all AVs are fully equipped with sensors that detect the surrounding vehicles and objects and can adapt their driving strategies accordingly. The AVs are programmed to follow a cooperative adaptive cruise control driving strategy, based on the full-velocity car-following model (Jiang et al., 2001) and a lane-changing cooperation strategy with the surrounding vehicles recently proposed in (Shladover et al., 2015; Xiao et al., 2017). The proposed experiment design enables studying how traffic flows of AVs can be affected by a single driver, from both flow efficiency and safety perspectives.

As an additional contribution, this paper presents an automated implementation framework to facilitate fast and practical refinements of experiment designs based on new evidence or feedback during the pretesting stage. To promote reproducibility, we make available all the software and programming codes as well as the data collection within this paper.

2. Experiment design

In this section, we elaborate on the experiment design. There are two motivations behind the proposed experiment:

(1) to accommodate the human psychological factors underlying the drivers' take-over manoeuvres
(2) to capture the impacts of drivers' take-over manoeuvres on the traffic flow of AVs

With respect to (1), a comprehensive review by Zhang et al. (2019) has been conducted to investigate factors main factors underlying drivers' take-over time. The outcomes suggested that drivers' engagement in the non-driving related tasks (NDRT) and headway are among the major determining factors. Therefore, in our experiment, we accommodate both of these factors to provide a comprehensive set of scenarios of drivers' take-over occurrence.

With respect to (2), we implement a cooperative automated-driving strategy based on the full-velocity difference car-following model (Jiang et al., 2001), and lane-changing cooperation as in (Xiao et al., 2017, Shladover et al., 2015).

The entire experiment is programmed and implemented in the webots, which is a software heavily used to meachnical engineers to reproduce realistic simulations of solid bodies based on real-world's physical properties (Michel, 2004). We utilize webots and design numerous AVs and program controllers to control them with desired automated-driving strategy. Figure 2 presents the simulation environment as well as the driving simulator set up.

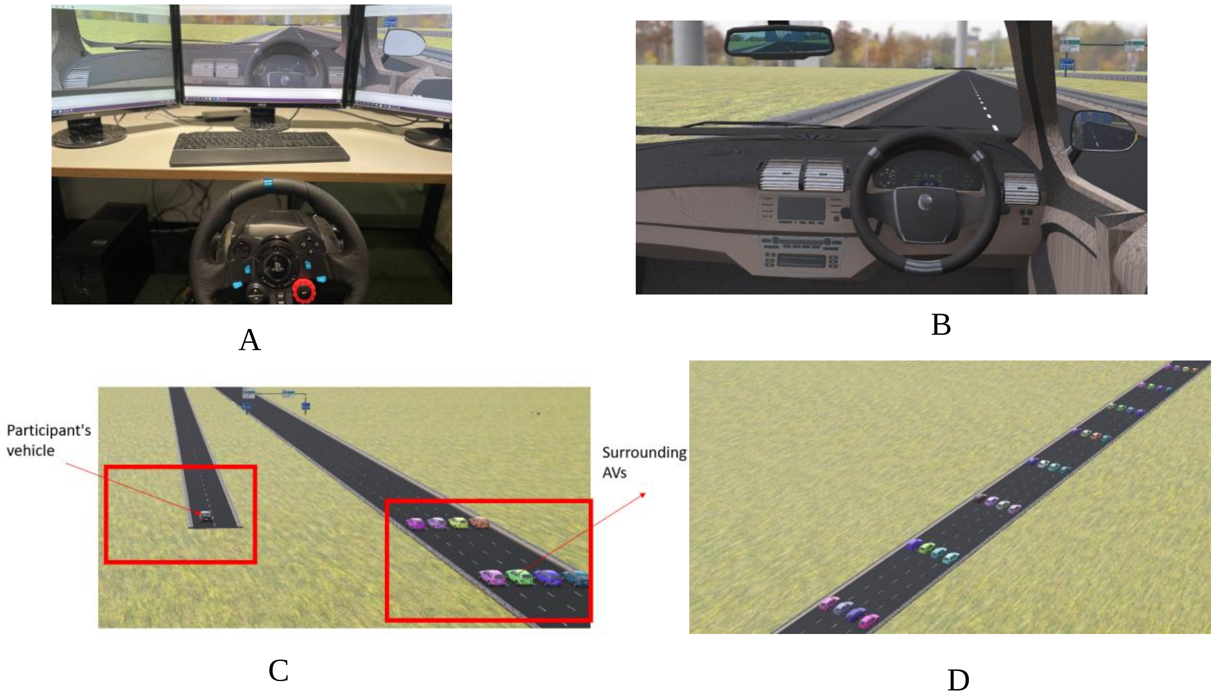

Figure 1- snapshots of the driving simulator setup and simulation environment. A) The experiment set up for participants, B) close-up of participant's view, C and D) illustration of a large number of AVs programmed in this experiment design

2.1. The experiment's schematic

The experiment design consists of 3 multi-lane motorways, which are connected to one another. The motorways have the same geometrical design, which is illustrated in Figure 2. On each motorway, driving route consists of different phases which are explained in detail, later on.

Upon experiment starts, participants vehicle starts driving through a single-lane road for $250m$ after which, vehicle's system will generate an auditory message, asking the drivers to take over the vehicle due to a red traffic light in $250m$ distance. After taking over the vehicle, the participant will drive the remaining distance up until slowing down and stopping behind the red traffic light, which is the entry point to the first motorway. Once traffic light turns green, participants will speed up and merge into a multi-lane motorway with the length $L = 8500m$, which consists of a 5-lane merge section with $L = 500m$, a 4-lane homogenous section, and a 5-lane diverge section (see Figure 1).

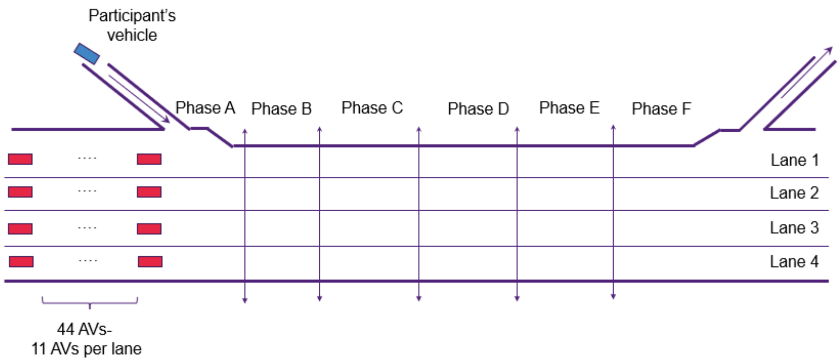

Figure 2- Schematic the motorway section in the experiment design. Refer to the main text for the descriptions of different phases.

Drivers route on each of the three motorways consist of 6 major phases described as follows:

Phase A: Participants vehicle enters the motorway through the merge section, where they have to indicate and perform one-mandatory LC manoeuvre to merge into main freeway. Once merged, the participant's vehicle will be following an AV, and will have multiple AVs in the adjacent lanes.

Phase B: This phase is designed to expose the participants to the stop-and-go driving in the current lane and better driving condition in the adjacent lanes. After a few hundred meters of driving in the motorway section, the participant's leader will exhibit a stop-and-go car-following behaviour. Traffic condition in the adjacent lanes will get better incrementally, and it is expected that the participant decides to perform voluntary LC manoeuvres to get to the rightmost lane.

Phase C: In this phase the participants vehicle will be following its leader at a steady speed for roughly 2 minutes. This phase is designed to collect data on participant's gap acceptance behaviour in the steady-state traffic conditions.

Phase D: This phase is designed to expose drivers to auto-driving mode. After having derived under the steady-state traffic condition for a while, participants will be asked to activate the automated driving mode by pressing a button via an auditory message. During this phase participants may either be observing traffic or engage in non-driving-related tasks such as reading news on iPad.

Phase E: This phase is designed to study participants' take-over time and quality of their take-over makeovers. After having been kept out of the loop for a while, participants will be asked to take-over the vehicle to complete LC manoeuvres and exit the motorway.

Phase F: This phase is designed to study participants' take-over quality and LC manoeuvres after having been kept out of the loop for a while. During this phase, participants will indicate to complete several LC manoeuvres and exit the freeway.

The entire experiment consists of three motorways, where traffic conditions and headway settings will be different on each. For each participant, the experiment will be run twice, where the first time, participants will only be supervising the vehicle during the auto-driving mode. In the second time, participants will be asked to work with an iPad during the auto-driving mode. Table 1 summarizes the factors considered in this experiment.

Table 1- Factors considered in this driving simulator experiment and their places in each motorway

Factors	situations considered	Places in the experiment and description
Headway setting for AVs	• Steady-state under human-driven mode	During the stead-state condition (phase D) on each motorway, different headway settings will be adopted.
Car-following scenarios	• Stop-and-go • Steady-state under human-driven mode	Left-most lane in each motorway

	• Steady-state under auto-driven mode	
Lane-changing scenarios	• Non-mandatory: Drivers will perform LC manoeuvres to reach better driving condition • Mandatory: Drivers will have to perform LC manoeuvres to diverge from each motorway	On each motorway
Drivers' engagement in non-driving related tasks during auto-driving mode	• No engagement • Reading breaking news	The entire experiment is repeated twice to accommodate these factors

2.2. Automated vehicles' driving strategy

All automated vehicles in the experiment design in webots are controlled by a controller that takes their (Jiang et al., 2001)

$$a_n(t) = \frac{v_{opt}(t) - v(n)}{T_{adap}} + \lambda\big(v_{n-1}(t) - v_n(t)\big),$$

where T_{adap} is the adaptation time (i.e., the time required to recover the steady-state speed), and λ is driver sensitivity, v_n and v_{n-1} are the subject vehicle's and the leading vehicle's speed, respectively, and

$$v_{opt}(t) = \max\left(0, min\left(V_{max}, \frac{(S_n(t) - S_{min})}{T_{gap}}\right)\right)$$

is the $v_{opt}(t)$ is the 'optimal' or steady-state speed, with V_{max} being the maximum speed, S_{min} being the minimum inter-vehicular gap between vehicles under stopped traffic, and T_{gap} being the 'desired' time gap. Besides, the immediate AV follower of the participant on the adjacent also adopt a lane-changing cooperation strategy in case the participants indicate and decide to perform a lane-changing maneuvers as in (Xiao et al., 2017, Shladover et al., 2015). The mathematical details are not presented to save space.

3. Data collection

Huge amount of data will be collected in this experiment. More specifically, the main data collected from participants and AVs are summarized in Table 2 and Table 3, respectively.

Table 2-Description of the data extracted from participants

Field Name	Definition	Field type
Local_time	Local time from the beginning of the experiment, recorded every 0.05s	Decimal
Main_road	Check whether participant drives in the freeways or not 1: Driving in the freeway's sections 0: Otherwise	Boolean
Road_ID	The ID of the current road, participant is driving. e.g.,: RR# if the participant is in road 1 'None' if the participant is not driving in the main road	String
Lane_ID	The ID of the current lane: e.g., RR#_Lane01= the leftmost lane in the first road	String

Participant_Position_x	Participant's lateral position (m)	Decimal
Participant_Position_Z	Participant's longitudinal position (m)	Decimal
Participant_Speed	Participant's speed at any point in time (m/s)	Decimal
Participant_leader_ID	The ID of the participant's immediate leader: 'none' if there's no leader ahead	String
Participant_follower_ID	The ID of the participant's immediate follower: 'none' if there's no follower behind	String
Message_Played	Checks whether a message has been played: 0= if no; 1= if yes	boolean
Message_ID	records which message has been played	String
Participant_Presses_button	Records whether participant has pressed the ACC button: 0= if not (human driving mode) 1= if participant activates the ACC 2= if participant deactivates the ACC	Integer
Participant_Indicates	Records whether participant has turned the indicator on: 0= if not (default) 1= if the participant indicates right 2= if the participant indicates left	Boolean
Participant_Indicate_back	Records whether participant has turned the indicator off: 0= if not (default) 1= if the participant turns off the indicator	Boolean
Participant_Brakes	Indicates whether the participant has pressed the brake pedal	Boolean
Participant_is_hit_from_behind	records whether participant crashes with its follower from behind 0= if not; 1= if yes	Boolean
Participant_crashes_its_leader	records whether participant crashes its leader 0= if not; 1= if yes	Boolean

Table 3-Description of the data extracted from AVs

Field Name	Definition	Field type
Local_time	Local time from the beginning of the experiment, recorded every 0.05s	Decimal
Road_ID	The ID of the current road, participant is driving. e.g.,: RR1 if the participant is in road 1 'None' if the participant is not driving in the main road	String
Lane_ID	The ID of the current lane: e.g., RR1_Lane01= the leftmost lane in the first road	String
AV_Leader_ID	The ID of the AV's immediate leader: 'none' if there's no leader ahead	String
AV_follower_ID	The ID of the AV's immediate follower: 'none' if there's no leader ahead	String
AV_ID	The AV's ID	String
AV_Position_X	AV's lateral position (m)	Decimal
AV_Position_Z	AV's longitudinal position (m)	Decimal
AV_Speed	AV's speed at any point in time (m/s)	Decimal
AV_Brake	Records if the AV starts to decelerate 0: if not (default); 1: if yes	Boolean
AV_LC_Coop_status	Records if the AV cooperates with the participant's LC manoever: 0: If not (default); 1:if yes	Boolean

4. Conclusion and ongoing research

We design an integrated and reproducible driving-simulator experiment to study human factors involved in take-over maneuvers and their consequences on the Automated vehicles' traffic flow properties. The experiment design aims to help investigate drivers' response time and take-over quality during take-over maneuvers in relation to factors such as mental workload, risk perception and traffic conditions. In this experiment, participants will be exposed to automated-driving and human-driving modes while interacting with other automated vehicles through car-following and lane-changing maneuvers for a wide range of traffic conditions. The experiment design is programmed in webots, a robot simulation software, where all automated vehicles are programmed to follow the full velocity difference model coupled with a cooperative lane-changing driving strategy. The proposed experiment design stands out from the existing ones in that it enables studying impacts of drivers' take-over of AVs on the safety and traffic flow properties of surrounding AVs. To promote reproducibility, we make available all the software and programming codes as well as the data collection within this paper.

The ethics clearance for this driving simulator experiment has been obtained. The actual data collection using the designed driving simulator experiment will start soon.

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