Designing a Balanced Order Driving Simulator Study with OpenSCENARIO and Esmini

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Abstract *– Designing driving simulator studies with human drivers in a balanced manner is important for reducing biased results. Simulator scenarios should also preferably be easy to share between simulators and an enabler for this is standardized scenario formats. In this work the scenario standard OpenSCENARIO was tested in an XR-based driving simulator study including a balanced order. The scenarios were run within the simulator software using the open-source OpenSCENARIO player Esmini. The used road network was designed by combining multiple blocks of 8 base road building blocks into two roads with approximately 30 blocks each, where a scenario only occurs within one base block. Using this block structure, a total of 48 scenarios split on two roads with 24 scenarios each was performed. The study using this block concept was successfully completed with 44 participants.*

Keywords: *OpenSCENARIO, Esmini, simulator study design, simulator scenarios, balanced order*

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Introduction

Driving simulators with realistic road environments are widely used to study human behaviour and test new vehicle technologies. To reduce development time and support collaboration, it is important to enable scenarios to be run across different simulator platforms. This makes standardized approaches for generating road networks and describing scenarios essential.

OpenSCENARIO, developed by ASAM, is an open standard for describing dynamic driving scenarios in a structured, machine-readable XML format. It defines elements such as actors, manoeuvres, triggers, and environmental conditions, supports modularity through catalogues, and integrates with OpenDRIVE for road network generation (ASAM, 2022). The standard is widely used for large-scale scenario generation in virtual testing of ADAS and automated vehicles (Li et al., 2023; Baker et al., 2024; Kim et al., 2025), and methods for generating scenarios from traffic databases have been proposed (Karunakaran et al., 2023). However, most applications focus on short scenarios for offline simulations with limited experience on its use in driving simulator studies involving multiple participants, where scenario reordering is important for balanced designs. Our approach in this work is to combine several smaller scenarios in a balanced order for a longer driving simulator study.

Study design

The simulator study focusing on driver interactions with cyclists and pedestrians was conducted in a fixed-base driving simulator equipped with a vehicle mock-up and an XR headset providing 360° field of view, see Figure 1. This setup allowed participants to view the physical vehicle controls, their own body and hands, and to freely look around the virtual environment implemented using Unreal Engine 5.

Figure 1. Fixed-base driving simulator used in the study, equipped with a vehicle mock-up and an XR headset.

The study included 16 versions of a cyclist-related scenario, 12 variations of a pedestrian scenario, and 4 versions of a car-following scenario, all requiring randomization to reduce order effects. Additionally, failures in individual scenarios should not affect

subsequent ones. OpenSCENARIO was used to implement scenarios where each scenario was linked to an OpenDRIVE road with the tag RoadNetwork. Thus, each scenario is tightly connected to a road network. To enable reordering of the 48 scenarios without creating separate road networks for each participant, the road layout was constructed using five specific blocks implementing the targeted events, see Figure 2. Block 1 consists of two four-way intersections used for the car-following events; block 2 is a pedestrian crossing for pedestrian events; block 3 is a T-junction used to clear traffic; block 4 is a four-way intersection used for cyclist events; and block 5 is an additional four-way intersection used to clear traffic. These blocks were combined into a road segment repeated 20 times to create two road networks. Because cyclist events were more frequent, some segments omitted scenarios in blocks 1, 3, and 5. In such cases, one, two, or all three of these blocks were removed to shorten the overall route and reduce participant fatigue and simulator sickness.

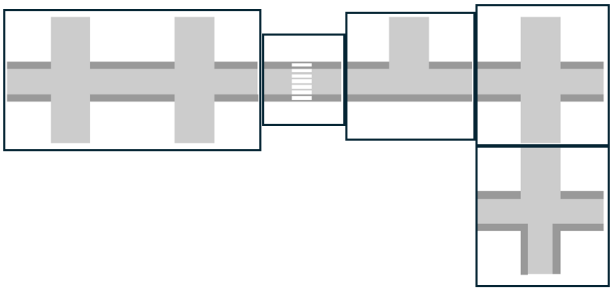

Figure 2. The study's repeated road segment, composed of five event-specific blocks.

Esmini was integrated into the VTI simulator using esminiLib, which provides a C++ API. Esmini is a lightweight, open-source simulator for running OpenSCENARIO and OpenDRIVE files (GitHub 2025). The workflow involved loading a scenario at the start of a road block, running it, and ensuring it finished before the end. Otherwise, it was forcefully stopped. As a result, Esmini was restarted multiple times during a run for different scenario variations.

When loading a scenario, which required about one second, parameters (via the OpenSCENARIO ParameterDeclarations tag) were used to select variants and adjust road IDs, enabling scenarios to be relocated and varied. Only the ego vehicle was synchronized with Esmini, meaning no interaction occurred between scenario vehicles and surrounding traffic—this was handled through careful scenario and traffic design.

Results and discussion

A driving simulator study with immersive XR visualization was conducted using OpenSCENARIO scenarios. Event ordering was balanced across participants and executed smoothly. Scenarios started and stopped around the road block borders, resulting in a tight design with often only seconds between scenarios. By repeatedly stopping Esmini, failures in one scenario could not affect subsequent ones.

However, limitations in Esmini constrained the study design. At the time, it lacked support for traffic lights, and the surrounding traffic didn't use indicators and brake lights. Also, since Esmini runs as a separate process, any data to be logged must be explicitly sent to the main system, meaning internal data not exposed by Esmini, such as vehicle acceleration states, could not be recorded.

Conclusions/implications

This paper presents a structured approach to scenario and road design using OpenSCENARIO and Esmini to address challenges associated a balanced study design. The method works well when all traffic participants can enter and exit within a single block without affecting surrounding traffic. The proposed method enabled the successful execution of a study with 44 participants, incorporating a randomized sequence of 48 scenarios. Limitations in Esmini are expected to diminish in future versions.

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