Simulation Modelling Practice and Theory 59 (2015) 1–17

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Development and application of an integrated traffic simulation and multi-driving simulators

Jian Sun *, Zian Ma, Tienan Li, Dening Niu

Key Laboratory of Road and Traffic Engineering in the Ministry of Education, Tongji University, Shanghai 201804, China

A R T I C L E   I N F O

Article history:
Received 20 November 2014
Received in revised form 22 July 2015
Accepted 11 August 2015
Available online 28 August 2015

Keywords:
Driving simulator
Traffic simulation
Integration
Traffic flow
Experiment

A B S T R A C T

Professional virtual reality experiment tools, including driving simulators and traffic simulators, have their strengths and weaknesses. The integration of the two simulators will enhance the ability of both traffic modeling and driving simulation and present a new area of applications. This paper develops, implements, and validates an experimental platform that integrated a traffic simulator with multiple driving simulators (TSMDS). As a connected multi-user framework that allows multiple drivers who are simultaneously handling many driving simulators, it not only allows driver behavior experiments to be more accurate, controlled, and versatile but also simulates special driving behavior or multi-vehicle interactions under more realistic traffic flow environments. To validate the performance of TSMDS, 27 drivers were recruited to attend the lane changing experiments at a recurring on-ramp bottleneck and left-turn experiments at a two-phase signalized intersection in Shanghai. Both experiments required several drivers to drive the TSMDS and fulfill several complicated lane changing/crossing behaviors through their interaction. The results show that both the participants' response and lane changing/crossing data that were obtained from the experiment are consistent with the field observation, which confirms the validity of the integrated platform.

1. Introduction

Driving simulators (DS) are designed to imitate driving a real vehicle by placing human subjects in a virtual driving environment. As professional virtual reality experiment tools, driving simulators, such as CTS [1], SCANeR [2], and VTI [3], have been widely used to study individual driver behaviors. Application fields of DS include novice driver performance, driver distraction, sleep deprivation, intoxication, human–machine interaction, driving practice and training, road design and vehicle design. Because the majority of available simulators are single-user stand-alone systems, traffic engineers cannot easily analyze complex driving behaviors, such as the interaction between multiple human drivers or pedestrians. Furthermore, a simplified traffic flow model in a DS has largely limited its application in studying the impact of different driving behaviors on traffic flow. On the other hand, microscopic traffic simulations (MTS), such as VISSIM [4], PARAMICS [5], AIMSUN [6], and CORSIM [7], are another important tools that are widely used for traffic analysis by modeling individual vehicles and their interaction. MTSs provide realistic traffic flow patterns in terms of density and headway, which can make up DSs' limitation in traffic flow simulation. Moreover, MTSs lack the human-in-the-loop simulation ability that a DS could provide. In summary, both DSs and MTSs have their strengths and weaknesses, and they could complement each other in a variety of ways.

* Corresponding author.
E-mail address: sunjian@tongji.edu.cn (J. Sun).

http://dx.doi.org/10.1016/j.simpat.2015.08.003
1569-190X/

A good virtual reality experiment must be associated with a strong sense of immersion, high environmental fidelity, positive interaction and little negative impact. The integration of the two simulators will fulfill these characteristics and enhance the ability of both traffic modeling and driving simulation, enabling a new direction of controlled virtual reality experiments. For the DS, the integration can generate a more realistic traffic environment and present multi-vehicle interactions, to strengthen the validity of and immersion into the scene and also strengthens the ability to test special driving behaviors. For the MTS, the researchers or engineers can not only calibrate the fundamental traffic flow models in the simulation model by comparing the behaviors of the user-driven vehicles and the simulated vehicles but can also create and test new suitable models.

Based on this idea, the objective of this paper is to develop, implement, and validate an experiment platform that integrates a microscopic traffic simulator with multiple driving simulators (TSMDS) in a real-time environment. When multiple drivers control their vehicles individually through the DS, the MTS enables the control of multiple user-driven vehicles in running environments in full accordance with the drivers' intentions; autonomous vehicles in the driving environment are driven by the traffic flow model (e.g., car-following, lane-changing) of the MTS. Driver behavior research based on the DS will benefit from easy-to-define realistic traffic flow in the virtual driving environment and the ability to study the impact of multi-vehicle interactions on traffic flow. For traffic flow research, the human-in-the-loop element, as well as unconventional driving behavior, both previously unavailable to MTS models, will provide opportunities to include individual driver characteristics in the analysis. The wider range of scenarios that can be studied on a DS will also in turn provide more accurate data for modeling the traffic flow in the MTS. Finally, two complicated experiments (one is the lane changing experiments at a recurring on-ramp bottleneck and another is the left-turn experiments at a two-phase signalized intersection in Shanghai) are conducted to validate the integrated experiment platform.

This paper is organized as follows. Section 2 presents an overview of the research work. Section 3 describes the developed simulation framework and provides a detailed description of its different components. Two case studies for the TSMDS validation are presented in Sections 4 and 5 respectively. Section 6 ends the article with concluding remarks.

2. Literature review

Previous researchers have recognized the demands for integration between the two simulation technologies. One approach is to develop traffic flow models that are specialized for simulation of surrounding vehicles in a DS. Three of the most well-known models following this approach are the ARCHISIM model [8,9], the NADS model [10], and the DRIVERSIM model [11]. Most of them are limited to freeway simulations, and there is little focus on modeling urban networks and on modeling for generation of realistic traffic streams. Olstam et al. [12,13] described a framework for the generation and simulation of surrounding vehicles in a DS. The framework was tested within the VTI Driving simulator III, but the results showed that the agreement was not good for active catch-ups on freeways because of deficiencies in the lane-changing model that was utilized.

Another approach for simulating the surrounding vehicles is to use available microscopic traffic simulation tools. Obviously, this approach is more powerful. Some authors have proposed integrating the DS environment with MTS, such as Jenkins [14], Vladisavljevic et al. [15], Ciuffo et al. [16], Punzo and Ciuffo [17] and Hou et al. [18]. The findings in these papers showed the usefulness of the integration and exposed existing shortcomings. For example, in [15], because of issues concerning the import/export capabilities of the simulation programs and data transfer delays, only a one-way communication flow was established. In [16], although real-time integration between driving and traffic simulation was strongly advised, because of implementation difficulties, the authors only tested offline integration, using results from one instrument as the input to the other. Afterwards, Punzo and Ciuffo [17] overcame the real-time data exchange challenge and described the integration of a DS known as SCANeR and a MTS known as AIMSUN. After several tests, the maximum number of vehicles that was allowed in the SCANeR simulation was set at fifty, and data exchange between the driving and traffic simulator was proved consistent both in time and space. Nonetheless, in their work, autonomous vehicles were controlled by traffic models in AIMSUN, which cannot flexibly simulate specific driver behaviors in different traffic scenarios. Their integration also had no comprehensive validation in practical application cases. Hou et al. [18] extended Punzo and Ciuffo's work [17] in respect of integration of emission model and comprehensive validation. Nonetheless, the implement and practical application cases of the multi-user network simulation has not been mentioned. Furthermore, the aforementioned integration is completely limited to a specific MTS and DS. For other types of MTS or DS, the integration may not be feasible.

To the best of the authors' knowledge, because the majority of available DSs are single-user stand-alone systems, the simulator can only handle a single user at a time and is not available to the general public. Sun et al. [19] and Niu and Sun [20] constructed a multi-user driving simulator platform to evaluate the effectiveness of eco-driving speed guidance strategies, but they did not consider the effect of complex traffic flows. Nakasone et al. [21] presented an experimental framework for integrating MTS and multi-user immersive driving, but they proved that it is extremely difficult to implement and could not be used to complete a complicated driver behavior experiment. Gajananan et al. [22] conducted a driver behavior study in a multi-user network virtual environment based on the Scenario Markup Language. The experiment reproduced an accident and tested the slowing-down behavior of multiple "rubbernecking" drivers on the opposite direction. However, the validation of traffic realism was not mentioned and the behavior was one-dimensional because only the speed of vehicles was under control.