Transportation Research Part C 45 (2014) 138–153

Contents lists available at ScienceDirect

Transportation Research Part C

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

An integrated traffic-driving simulation framework: Design, implementation, and validation

Yunfei Hou [a,*], Yunjie Zhao [b], Kevin F. Hulme [c], Shan Huang [b,1], Yaqin Yang [c,2], Adel W. Sadek [b], Chunming Qiao [a]

[a] Laboratory for Advanced Networking Design, Evaluation and Research (LANDER), Department of Computer Science, University at Buffalo, Buffalo, NY 14260, USA
[b] Transportation Systems Engineering Laboratory (TSEL), Department of Civil and Environmental Engineering, University at Buffalo, Buffalo, NY 14260, USA
[c] New York State Center for Engineering Design and Industrial Innovation (NYSCEDII), University at Buffalo, Buffalo, NY 14260-1810, USA

ARTICLE INFO

Article history:
Received 1 May 2013
Received in revised form 2 January 2014
Accepted 10 February 2014
Available online 11 March 2014

Keywords:
Driving simulation
Traffic simulation
Integrated simulation
Simulator validation
Human-in-the-loop simulation

ABSTRACT

This paper first describes the process of integrating two distinct transportation simulation platforms, Traffic Simulation models and Driving Simulators, so as to broaden the range of applications for which either type of simulator is applicable. To integrate the two distinct simulation platforms, several technical challenges needed to be overcome including reconciling differences in update frequency, coordinate systems, and the fidelity levels of the vehicle dynamics models and graphical rendering requirements of the two simulators. Following the successful integration, the integrated simulator was validated by having several human subjects drive a 2.5 mile long segment of a signalized arterial in both the virtual environment of the integrated simulator, and in the real-world during the evening "rush hour". Several aspects of driving behavior were then compared between the human subjects' driving in the "virtual" and the real world. The comparisons revealed generally similar behavior, in terms of average corridor-level travel time, deceleration/acceleration patterns, lane-changing behavior, as well as energy consumption and emissions production. The paper concludes by suggesting possible extensions of the developed prototype which the researchers are currently pursuing, including integration with a computer networking simulator, to facilitate Connected Vehicle (CV) and Vehicle Ad-hoc Network (VANET) related studies, and a multiple participant component that allows several human drivers to interact simultaneously within the integrated simulator.

1. Introduction

The transportation community has for long used two distinct types of simulator types, but with no true integration. On one hand, the community used microscopic Traffic Simulation (TS) models for evaluating the system performance of transportation networks from an *operational* standpoint (Transportation Research Board, 2000), and on the other, it used Driving Simulators (DS) for evaluating the response of individual human subjects within a virtual in order to study various aspects related to driver behavior, human factors and safety evaluations.

* Corresponding author. Tel.: +1 716 263 8613.
E-mail addresses: yunfeiho@buffalo.edu (Y. Hou), yunjiezh@buffalo.edu (Y. Zhao), hulme@buffalo.edu (K.F. Hulme), asadek@buffalo.edu (A.W. Sadek), qiao@computer.org (C. Qiao).
[1] Present address: Terra Technology, 1515 East Woodfield Road, Schaumburg, IL 60173, USA.
[2] Present address: Bloomberg LP, 731 Lexington Ave, New York, NY 10022, USA.

http://dx.doi.org/10.1016/j.trc.2014.02.004
0968-090X/

Each simulator type, when used independently, has its own set of limitations. While TS models allow for capturing the dynamics of full-scale traffic networks, they lack driver behavioral realism, since vehicle movements are based on idealistic car-following models that are often simplifications of reality. This limits the application of traffic simulators to the analysis of the transportation system mainly from an operational efficiency standpoint, and pays little regard to safety considerations. Archer (2000), for example, noted that existing microscopic simulation models, based on available car following, gap-acceptance, and lane-changing models lack the level-of-detail required for safety evaluations, which demand models that reflect errors in drivers' perception, decision-making, and actions (Saccomanno and Cunto, 2006). Moreover, because human driving behavior is not modeled in detail in TS, it is insufficient to evaluate the effectiveness of eco-driving strategies and applications, which have received increased attention recently and which attempt to encourage drivers to change their driving behavior (e.g., the way they accelerate or decelerate) so to conserve energy.

DS, on the other hand, allow for studying driver behavior by immersing human subjects within a virtual simulation environment and monitoring their reactions. Unfortunately, however, DS often lack traffic authenticity and transportation network realism, since in the majority of DSs, accompanying traffic is often pre-programmed and does not react according to the real-time actions of the human subject who is operating the human-driven vehicle. Moreover, the lack of transportation network realism of many driving simulators limits their application to a small subset of vehicle scenarios (e.g. a single roadway intersection) versus transportation system-level evaluations.

An interesting concept that has emerged over the last decade is the prospect of integrating microscopic traffic simulation and driving simulators (see Section 2.1 for more details). The TS environment provides a realistic representation of the transportation network and the prevailing traffic conditions (e.g., congestion levels, availability of gaps, speeds, and intersection queues), beyond what is currently possible using a standalone DS. Simultaneously, input from the driving simulation provides for authentic driver behavior, which is particularly important for understanding the impact of individual driver behavior on system-level performance. While such a concept has been proposed for several years now, there are still several issues that need to be resolved to provide a complete and accurate integration. Moreover, because integration attempts are relatively recent and largely exploratory in nature, there appears to have been very limited focus on *validating* the resulting integrated simulator. The term "Validation" used in this context refers to the process of determining the degree to which a model or simulation is an accurate representation of the real world from the perspective of the intended uses of the model or simulation (e.g., Balci, 1998).

The current paper contributes to this emerging area of research, by first describing a successful integration of these two heterogeneous simulation platforms and how the challenges encountered were overcome; the result is *a prototype system that allows a human participant to drive a subject vehicle within the virtual driving simulation environment amidst traffic from the microscopic traffic simulation*, *which intelligently responds to the actions made by the human driver*. Following this, the paper describes an exploratory research study aimed at validating the integrated TS–DS platform by comparing the performance of human subjects both within the virtual environment of the integrated simulator as well as in the real-world. The contribution of the current paper is therefore twofold: (1) describing the authors' research on overcoming the challenges of integrating TS and DS; and (2) describing a procedure for the validation of the resulting simulator, and proposing a number of metrics or performance measures for assessing validity.

The paper is organized as follows. Section two provides a brief overview of previous attempts at integrating traffic and driving simulators. The section also cites some examples of previous studies aimed at validating and calibrating *stand-alone* TS models, on one hand, and *stand-alone* DS on the other. Section three describes the main components making up the integrated simulator developed in this study. Note that in addition to the two main components, namely the TS and DS, the integrated simulation framework developed herein includes a detailed emissions model to allow for evaluating green and eco-driving applications. Section four discusses the integration and the validation methodologies. The results from the validation study are then presented in section five. The paper concludes by summarizing the main conclusions derived from the study and describing the authors' future plans for further developments and enhancements to the integrated simulation framework.

2. Literature review

2.1. Integrated traffic/driving simulation

In recent years, there have been a handful of attempts aimed at integrating TS and DS, including previous and ongoing work by the current research team (e.g., Hulme et al., 2010; Zhao et al., 2012). A sampling of the most relevant of those studies is presented here, chronologically.

Jin and Lam (2003) carried out a study on driving behavior with a preliminary integrated traffic and driving simulator. The integration utilized route choices dictated by Variable Message Signs (VMS), however, no validation of the integrated framework was described in the paper (it was just mentioned as a recommendation for future research). Maroto et al. (2006) proposed a micro-simulation model with a user-driven vehicle surrounded by simulated traffic – referred to as the "control zone". The authors proposed two layers to address the surrounding traffic: (1) driver model and (2) vehicle model, respectively. As part of the validation/analysis, the root mean square error (RMSE) of simulation speed versus speeds encountered during the field test was observed.

Similarly, Olstam et al. (2008) proposed a framework in which a driving simulator was surrounded by an inner micro-simulation region and two outer meso-scopic simulation regions. Moreover, a validation study was carried out that investigated: (1) the number of vehicles that came from behind to overtake the driving simulator vehicle; (2) traffic flow both in front of and behind the driving simulator vehicle; no detailed validation of individual driver behavior was attempted however. Yan et al. (2008) investigated the credibility of a driving simulator to address safety issues at a single signalized intersection. Simulation outputs were compared with the field counts in terms of traveling speed and accident/incident occurrences. It should be noted, however, that those studies did not really involve integrating a commercial traffic simulation model with a driving simulator, as is considered herein, but rather focused on enhancing the driving simulator by attempting to make background traffic more intelligent. That and Casas (2011) proposed a framework combining a traffic simulator Aimsun and a driving simulator SCANER, but their integrated framework was not formally validated.

The closest study to the current work is the one by Punzo and Ciuffo (2011), who proposed four main requirements for appropriately integrating TS and DS models. These are: (1) accurate road matching between traffic and driving simulators; (2) synchronization of traffic and driving modules with real time; (3) consistency of the updating calculation frequency; and (4) management of background traffic visualization. Building on the work of Punzo and Ciuffo, the current work addresses additional challenges not previously addressed by them, such as the integration of a an emissions model, and ideas for extension to a multiple-participant driving environment and communication network simulation capacity. Moreover, the current work includes a comprehensive validation component, which was missing from Punzo and Ciuffo (2011).

2.2. Simulator validation

To the best of our knowledge, this is the first attempt at a comprehensive validation of an integrated traffic-driving simulation environment. In this section we review recent researches involving the validation and calibration of *stand-alone* traffic and driving simulators. The approaches and criteria used in those previous researches provided some useful hints for validating the *integrated* simulator.

2.2.1. Traffic simulation model validation approaches and criteria

The primary objective of the validation step in the traffic simulation model development and deployment cycle is to assess the extent to which the simulated traffic network can replicate conditions observed on the real life network. However, the stochastic nature of the transportation system (e.g., in terms of traffic demand and vehicle and driver mix) makes it challenging to capture and quantify the degree of validation or even to arrive at a strict definition of the traffic validation itself. Several previous studies proposed frameworks for validating TS models via statistical methods and hypothesis testing; examples include Horiguchi et al. (1995), Rakha et al. (1996), Fellendorf and Vortisch (2001), Krajzewicz et al. (2002), Sacks et al. (2002), Park and Schneeberger (2003), Toledo et al. (2003), Ni et al. (2004), Brockfeld et al. (2004), Jha et al. (2004), Toledo and Koutsopoulos (2004), Smith et al. (2008), Lawe et al. (2009), and Ciuffo et al. (2012). In addition, COST, an intergovernmental framework for European Cooperation in Science and Technology, has recently initiated the MULTITUDE project whose primary object is support the application of traffic simulation models, and to develop sound methodologies for their calibration and validation (COST, 2012).

Generally speaking, those previous validation efforts either considered macroscopic measures for validation such as aggregate traffic flow, speed and travel time, or microscopic measures in terms of individual driving behavior. For instance, Toledo et al. (2003) validated the MITSIMLab model under congested traffic conditions by first calibrating the traffic simulator with sensor data at aggregate level, and then compared observed and simulated flow, point-to-point travel time and queue length a year later. Wu et al. (2003) describe a case study for how to validate a microscopic simulation model, including the car-following models used, utilizing time series data collected by an instrumented vehicle. Oketch and Carrick (2005) conducted a validation of a traffic network modeled in Paramics through comparing the model results to the field data including traffic volumes, intersections turning movements, average travel time and approach queues. Park and Kwak (2011) proposed an experimental design approach to validate the distribution of travel times. Most recently, Jie et al. (2013) describe the calibration of a microscopic simulation model for use in emissions calculations, which requires the calibration of driving behavior parameters using real trajectories.

2.2.2. Driving simulator validation approaches and criteria

Broadly speaking, DS validation typically focuses on a specific driving task, and usually involves comparing on-road and simulator driving with regards to a specific driving performance measure, such as driving speed (Bella, 2008; Godley et al., 2002), lane position, steering behavior (McGehee et al., 2004; Riener, 2011) and braking performance (Hoffman et al. 2002; Bédard et al., 2010; Karl et al. 2013). Alternatively, some researchers use self-reported questionnaires to assess the measurement validity of data derived from a driving simulator (Reimer et al., 2006; Richer and Bergeron, 2012).

The majority of the validation studies identified in this literature assume that under similar conditions, drivers behave in the simulator as they behave in the real-world (Blana, 1996; Hoskins and El-Gindy, 2006); the current study also makes that assumption when it compares the driving performance (within the integrated simulator) to driving performance in the real-world. Other researchers argue that an external incentive is necessary for simulator studies, because there is a lack of time pressure and the feeling at risk when driving a simulator (Gelau et al., 2011). However, as the objective of our study is to compare simulator driving with actual everyday driving, such incentives may not be necessary. In our experiment, we offer no time constraint for the driver, and we generally assume that there has no more than minimum risk in the field portion of the comparison study.

There are two different groups of criteria for validation of driving simulators. First, from a simulator developer's perspective, the concern is with the difference in a subject's performance between the two environments (i.e., virtual vs. real-world). Within this group, the validation criteria can be classified into those referring to **relative and** to **absolute validity**. Relative validity indicates the subject's performance in the simulator behavior approximates but not exactly replicates the real-world. It requires that the performance difference of a subject driving in the simulator and on the road is of the same order and direction under similar conditions (Blana, 1996). Absolute validity, on the other hand, requires that the performance in the two worlds is about equal or the same. Most researchers have used both the absolute and relative criteria for validating their driving simulators (Shechtman et al., 2009; Underwood et al., 2011; Yan et al., 2008). A number of the metrics used in the current study refer to absolute validity, examples include metrics such as average travel time, acceleration and deceleration distance, whereas other metrics refer to relative validity. Second, from a social scientist's perspective, the concern is primarily with the validity of the driving subject's behavior on a tactical and strategic level, such as evaluating novice driver's performance (Chan et al., 2010; Mayhew et al., 2011), driving behavior after alcohol intake (Helland et al., 2013) and interaction with in-vehicle informational interface design (Wang et al., 2010).

3. Integrated simulator core components

This section provides a brief overview of the core components making up the integrated simulation framework, namely the driving simulator, the traffic simulation model, and an emissions model. The integration of these components is described in Section 4.1.

3.1. Driving simulator: hardware

The driving simulator utilized in the current research study consists of a six degree-of-freedom electrically actuated motion platform. Two passengers are accommodated in a front-seat vehicle passenger cabin (a 1999 Ford Contour). The driver supplies inputs to the simulator using a steering wheel (force feedback, with a 900° rotational stroke), three pressure modulated/adjustable floor pedals (gas, brake, and clutch), and a console gear-shifter with programmable buttons. Additional simulation hardware includes an Emergency-STOP switch, a four-screen (Front, Left, Right, and Rear-view, hexagonally arranged), front-projected XVGA + visualization system (4:3, $8' \times 6'$, 1400×1050 pixel resolution), and a 2.1 channel stereo sound system.

3.2. Microscopic traffic simulation model

For modeling the traffic microscopically, Paramics – version 6.9 (Quadstone Ltd., 2013) was selected for this study. Paramics is a commercial suite of microscopic traffic simulation software for modeling freeway and arterial networks. The primary reason for selecting Paramics for this study is the fact that it has an add-on module called Programmer, which is a comprehensive development Application Programmer Interface (API). Programmer allows the user to retrieve output values, assign input parameters, and augment the core simulation with new functions and driver behavior. This capability was critical for integrating the traffic and driving simulations together.

3.3. Emissions modeling

To allow for using the integrated DS-TS platform to evaluate eco-driving and other green transportation initiatives, the integrated platform was linked to the Environmental Protection Agency's (EPA) MOtor Vehicle Emission Simulator model (MOVES) model (Environmental Protection Agency Office of Transportation and Air, 2011). MOVES2010 is a state-of-the-art emissions model, which was developed by EPA to address the limitations of existing emissions models. One unique advantage of the MOVES2010 model is the ability to perform operational, project-level emissions analysis. Since the release of MOVES in 2010, a number of transportation and environmental researchers have begun to investigate its use in evaluating the impact of transportation improvements, strategies and policies on emissions (Chamberlin et al., 2011; Xie et al., 2011; Papson et al., 2012; Wei et al., 2012).

At the present time, MOVES offer users three different options to define a link's vehicle activity data for the purposes of calculating emissions and fuel consumption. These are:

- *The average speed and road type approach:* This approach utilizes default driving cycles associated with a given speed, grade and road type. The approach is commonly used in the absence of detailed information regarding traffic flow dynamics on a given link, and provides the least resolution because the default driving cycles would not typically be sensitive to project-level traffic improvement for example. Moreover, using an average speed cannot really capture the localized idling, deceleration and acceleration emissions associated with traffic flow at intersections, and hence cannot evaluate the environmental benefits of say signal timing optimization.

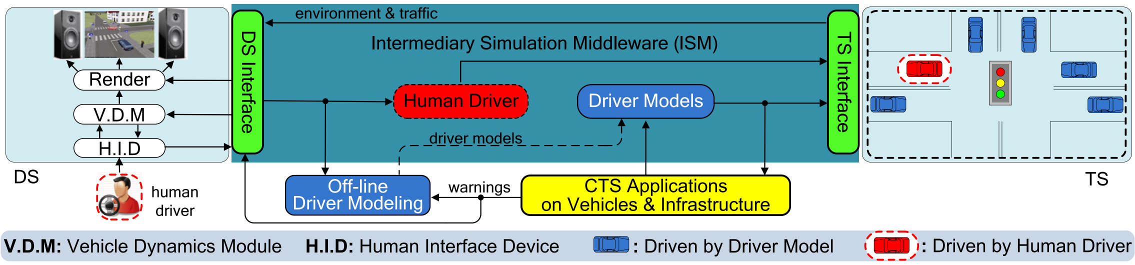

Fig. 1. High-level integration.

- *The link-drive schedule approach:* This approach allows the user to define a second-by-second speed profile for a generic vehicle representative of the driving cycle for multiple vehicles. Specifically, the user is required to define the precise speed and grade as a function of time for a given roadway link. Based on this, MOVES constructs an Operating Mode distribution upon which the link running emissions are then calculated.
- *The direct operating mode distribution approach:* In this approach, the user may specify the operating mode distribution for a given link directly. The supplied distribution will define the fraction of time vehicles would be in a given operating mode.

In linking MOVES to the integrated DS–TS platform, this study used the link-drive schedule approach described above. Second-by-second vehicle trajectory profiles, from both the driving simulator and the microscopic traffic model, served as input to MOVES, thus forming an integrated simulation-based framework. It is to be noted that the researchers have recently researched how to best link simulation models to MOVES using the link-drive schedule approach (the reader is referred to Zhao and Sadek (2013) for more details).

4. Integration and validation methods

4.1. TS–DS integration framework

Fig. 1 serves as the focal point of this discussion, as it illustrates the procedure for the high-level integration between the driving and traffic simulation environments. The integrated simulator consists of three components: DS, TS and Intermediary Simulation Middleware (ISM).

At the DS component, a human driver sits inside the driving simulation vehicle, and provides inputs to the simulation by way of a steering wheel, and both a gas pedal and brake pedal. Those user (i.e., human subject driver) inputs subsequently serve as input to the vehicle dynamics module (VDM), which implements the well-known “Bicycle Model” of an automobile (Milliken and Whitcomb, 1956). This simplified but effective vehicle model treats the pair of tires at each end of the vehicle as a single tire. There is no roll degree of freedom, so the vehicle will not “fall over”. Given the previously described inputs, the state outputs for the VDM include: vehicle position and orientation, velocities (current, maximum, and average), accelerations, tire forces, and tire operating conditions. Those outputs are then used for motion processing and audio rendering. More specifically, for motion processing, the vehicle states are converted into roll, pitch, yaw, heave, surge, and sway (i.e., the six degrees of freedom (DOF) of the motion platform of the simulator). Due to the finite stroke length of each of the motion platform actuators, this conversion involves scaling, limiting, and tilt coordination (e.g., Romano, 2003); sub-processes of a methodology known as washout filtering (e.g., Bowles et al., 1975). For audio rendering, OpenAL is implemented, including: vehicle ignition, engine tone (which varies according to vehicle speed/RPMs), squealing tires (which vary in accordance with the calculated slip angles), hazard/danger cues, and vehicle shutdown.

At the TS component (shown on the right side of Fig. 1), one vehicle is selected to mimic or mirror the behavior of the human subject in the DS (this vehicle is called the “subject” vehicle and is shown in red[3] in Fig. 1). Overriding the default behavior of the subject vehicle is accomplished by utilizing functions from Paramics custom API libraries. Specifically, ISM provides the capacity to seize full control of that vehicle within the TS, and overrides the TS default “Driver Model” with the actions of the human subject in the driving simulator. Moreover, ISM piggybacks dynamic information of the environment from TS component to DS, including background traffic position/orientation and traffic light status. This allows the human subject in the DS to view a realistic picture of surrounding traffic (denoted by the blue color), which now responds to the actions of the live driver, a feature which is most often lacking in stand-alone driving simulator implementations. ISM relays the real-time human input to the traffic simulation such that here, one chosen vehicle’s speed and position/orientation are overridden by the actions of the live driver in the driving simulator.

[3] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

A typical session of the integrated simulator is as the follows: At the starting point, the desired subject vehicle is selected from the traffic simulation vehicles after a network warm-up period, which fills the network with a calibrated level of congestion (traffic demand). From that point onward, the movement of the selected (subject) vehicle mirrors the vehicle dynamic outputs generated from the human driver's inputs, including: timestamp, steering wheel angle, gas pedal position, brake pedal position, vehicle speed, and vehicle heading. Other vehicles that are surrounding the subject vehicle will react according to the driver model specified in ISM. After the session, emission is calculated offline base on the trace output.

ISM is therefore the major component in the design and development of the integrated simulator. It has two major functions: First, it controls and coordinates the communication between DS and TS. Besides information relay, ISM is responsible for synchronizing each component and maintaining the order of each action. For example, whereas the entire data flow loop (Fig. 1) operates at 60 Hz, Paramics, by design, operates at a maximum of 30 Hz due. To overcome this disparity, all dynamic information (e.g., states of the traffic signals, traffic vehicle positions and orientations) sent from Paramics to the driving simulation are linearly interpolated to provide a state "estimate" for each missing data frame.

Second, ISM provides an interface which allows for customized driver models, and additional vehicles and infrastructure elements to be added to the integrated simulator in the future (for example for testing Connected Vehicles (CVs) and other Cyber Transportation System (CTS) applications). As just one example to illustrate the utility of such a design, consider the fact that the driver models in Paramics, and practically the majority of the state-of-the-art traffic simulators currently on the market, are limited to "normal" driving behaviors in which vehicles will strictly follow the car-following and lane-changing model, with "zero" mistakes. Those Driver models do not account for how drivers would respond to collision avoidance warning messages from a CV application, for example. They also do not allow abnormal driving behaviors such that "running red light" and "rear end collision". The ISM design provides the ability to supply the environment with "customized" Driver Models that can reproduce the behavior of interest.

4.2. Design challenges and solutions

Throughout the course of developing the integrated simulator, several challenges were overcome and numerous refinements were introduced in order to improve the performance, authenticity, and reliability of the integrated simulation environment, compared to our initial exploratory study (Hulme et al., 2010; Zhao et al., 2013). Among the various changes that were instituted are the followings:

4.2.1. Graphics rendering

Although Paramics provides a built-in 3D visualization model, in this study, the full virtual environment (i.e., building models, trees, road signs, etc.) was recreated in the DS component. There were numerous reasons for opting not to use Paramics own visualization model, but to recreate the virtual environment from scratch in the DS. Specifically, recreating the environment allowed the study to utilize the multi-screen capability of the DS (including projecting the view from the rear-view mirror). It also allowed for a wide field-of-view graphics scene, and enabled increasing the graphics rendering frame rate from 30 Hz (the maximum afforded by Paramics) to 60 Hz which provided for a much smoother scene. Moreover, recreating the environment allowed the researchers to customize the scene and to make it much more realistic. It also enabled overcoming some limitations in Paramics built-in environment. For example, Paramics environment does not allow for displaying a vehicle's rear braking lights or turning signals. The customized environment designed for the integrated simulator provides for such displays.

4.2.2. TS vehicle behavior

The researchers' preliminary studies (e.g., Hulme et al., 2010) revealed that the maximum update rate provided by Paramics (i.e., 30 Hz) did not provide for a smooth enough movement of vehicles from the standpoint of the human subjects in the DS (achieving this required a minimum of 60 Hz). To address this, one additional feature which was added to the current version of the integrated simulator, is the ability to provide for traffic vehicle path interpolation. Specifically, because the TS operated (maximally) at 30 Hz, and the DS at 60 Hz, the trajectory for each vehicle had to be extrapolated, at every other frame of data, based on the most recently received data points. This simple measure was very effective at increasing vehicle smoothness and decreasing the motion "flutter" that was observed during the preliminary studies.

Another TS challenge involved how to make the turning behavior of vehicles appear smooth to human subjects in the DS. In Paramics, it is only possible to retrieve and override the vehicle location and orientation when a vehicle is traversing a link. For vehicles within the intersection area (i.e. beyond the link), this unfortunately is not possible. This resulted in a sudden change in vehicles' headings at intersections, which was unpleasant for the human subjects in the DS. To tackle the challenge, a routine was designed to generate a smoother turning maneuver via the gradual interpolation between the orientations of the exiting link and the target link. The last modification involves allowing Paramics to "tolerate" driver errors. As is well known, simulated vehicles in Paramics strictly operate under an ideal, error-free driving world, in which vehicles always keep inside lanes and never violate stop lines. When human driver took over the control, and committed driving mistakes, Paramics would lose track of the vehicle. Different Paramics API functions were utilized to override the default, error-free behavior of vehicles in order to make the model "tolerate" such errors.

4.2.3. DS control fidelity

Various issues with controlling the subject vehicle in the driving simulator operated less than optimally in the authors' first pilot study (Hulme et al., 2010). Specifically, lane changing behavior of the subject vehicle acted less as a true steering capacity, and more as a binary, lane-changing feature. This was primarily due to the limitation of the traffic simulator's vehicle dynamics models, since TS are typically not concerned with the exact location of a vehicle within a given lane; just which lane the vehicle is driving in is what is needed. For the DS, however, this is quite significant. Anchoring the scene graphics rendering on the DS side (as described in Section 4.2.1), gave the researchers' the freedom to operate the subject vehicle with a true, smooth steering mechanism. This also allowed for smoother motion of the adjacent traffic vehicles (as described in Section 4.2.2).

4.2.4. Coordinate transformation

There were two subtle challenges regarding the coordinate system. The first challenge was the difference in location representation in the TS and DS. Specifically, in the TS, vehicle location was defined by the link number the vehicle was on, and its distance from the downstream node or intersection. The DS, on the other hand, used a coordinate-based reference system. Routines were thus developed to allow for location translation. After receiving the coordinates from the DS, routines were designed using Paramics APIs whose function was to pinpoint the best match for the link the vehicle was on, the distance to the link end, and current lane the vehicle was driving in. This information was then used to update the subject vehicle's location. The second challenge was with respect to the road network digitization in the virtual environment. Although road network data are publically available online, they usually suffer from low precision and are prone to changes. The current study started with network data from OpenStreetMap, and then manually calibrated and validated the details of the network configuration with the latest Google Map satellite images. While this was a labor intensive task, it ensured the accuracy of the simulated environment.

4.2.5. Computational complexity reduction and load balance

Unlike previous attempts of integrating TS and DS, which performed either partial (Jin and Lam, 2003) or offline integration (Vladisavljevic et al., 2009) due to implementation difficulties, the current study fully integrated the TS and DS by taking advantage of the latest advances in computer hardware and by implementing various steps to reduce computational complexity and balance the workload between TS and DS. First, a "draw-as-you-go" strategy was adopted to render the surrounding objects that were in the "vicinity" of the human subject's vehicle; specifically the "vicinity" of the vehicle was defined as all objects within a circle whose radius was equal to 200 m and whose center coincided with the subject vehicle's location. Information about traffic signal status and surrounding vehicles was only exchanged if they were within that circle, which significantly reduced the computational burden without reducing the visual fidelity.

Second, any large volume of communication data was decomposed into smaller, consecutive packages. For example, while traffic signal status information needed less frequent updates compared to surrounding vehicles' location, they created a surge of communication workload. To address this, the communication workload was first buffered and then spread into consecutive packages. Third, the simulator's computational efficiency was improved by simplifying unnecessary details. For example, Chebyshev distance (also known as chessboard distance) was used, instead of the Euclidean distance, to calculate frequently performed distance related tasks (e.g., collision detection, testing of whether an object is within participant's sight etc.); this reduced the computational complexity of such tasks from polynomial to linear.

4.3. Simulator validation framework

With the modified environment designed and tested, the research team was ready to attempt a validation effort based on the integrated components of the traffic and driving simulators. A framework was developed to perform a preliminary "validation" of the integrated simulator, whose basic premise was to compare drivers' performance data collected within the simulation environment, to analogous performance data collected when the same drivers drove an actual vehicle on the same (physical) roadways that had been modeled within the simulator. For this study, 15 participants were recruited, 11 males and 4 females, ranging in age from 21 to 39 years, with an average of 26.13 years. All participants were graduate students or staff members from the University at Buffalo, and had a minimum of 2 years driving experience. The validation experiment thus involved two parts: (1) Road Test; and (2) Simulator Test, as described below.

4.3.1. Road Test

In the road test, participants were asked to drive their own vehicle along a 2.5 mile path of Bailey Avenue and Millersport Highway, consisting of a total of 10 signalized intersections (as shown in Fig. 2). The Northbound excursion began (on the South end) at Balley-Winspear intersection, and concluded (on the North end) at just beyond the intersection of Millersport Highway and Hartford Avenue. The entire trip was divided into 4 courses (i.e. two round trips from north to south). Each test vehicle was equipped with an on-board diagnostic device called Car Chip Pro (Davis Instruments, 2012) to serve as a driving and engine performance monitor. The device was plugged into the vehicle's on-board diagnostics (OBD-II) port (located on most vehicles, under the dashboard). Once connected, a driver operates the vehicle normally, and then data from the device can be downloaded to a PC by way of a standard USB cable.

Fig. 2. Driving excursion.

In this experiment, the Car Chip Pro units were used to record second-by-second vehicle data that included the time stamp, distance traveled, speed, instances of extreme acceleration and braking, and relevant engine parameters (e.g. engine load, fuel pressure, throttle position, and emissions status). As an auxiliary location tracker, a low-cost GPS receiver was also used. The GPS provided the study with a timestamp, location information and GPS traces at 1 Hz; the location information helped complement the data collected from the Car Chip Pro units.

When conducting the field tests, one observer rode with the participant (i.e. the driver) to record participant's driving behavior data that could not be collected easily from the Car Chip Pro or the GPS receiver (e.g., to count the number of lane changes). The observer also provided navigation guidance to the driver. In order to retain a consistent traffic condition, all the experiments were conducted during rush hour in weekday afternoons, specifically, between 4:00 pm and 6:00 pm Tuesday to Thursday. The entire road test took two weeks.

4.3.2. Simulator Test

The same corridor driven by the drivers in the field test (see previous section) was then modeled in great detail in the Paramics traffic simulation model. Before conducting the validation study in the simulator, the signal timings and traffic flow data were carefully calibrated to replicate the real-world traffic condition, so that the testing participants can experience similar driving experiences in the driving simulator as they do in the field. Specifically, for the ten intersections, the turning movement data were manually collected, translated into Origin–Destination demand matrix using Paramics Estimator, and then implemented in the micro-simulation Model. Exact signal timings and phases were also manually collected and coded in the model to replicate the exact traffic condition in the field.

While the researchers did their best to capture real-world conditions, it should be noted that it is almost impossible to guarantee that each individual testing driver would experience exactly the same traffic conditions in the real-world and in the simulator due to the complex and stochastic nature of the transportation system (for example, the same driver may arrive on green at a given intersection in the real-world, but arrive on red at that same intersection in the simulator). Given this, some of the validation metrics the study utilized looked at the aggregate system behavior or average driver performance (e.g., comparing the average corridor-level travel time for all drivers in the field and in the simulator), whereas others looked at measures that are not specific to a given intersection (e.g., comparing acceleration behavior from a stop to the corridor speed limit). This will be explained in more detail later in Section 5.

With the corridor modeled in the integrated simulator, the same group of participants was then asked to drive the same path in the integrated simulator. In an effort to authenticate the driving environment, major structures and landmarks were modeled in great detail, along with road signs and vegetation. During the simulator tests, a variety of useful data (pertaining both to individual driver performance and to vehicle performance) were collected in real-time, and at a high frame rate (i.e., typically 60 Hz). The data channels included the following: elapsed time (seconds), longitudinal vehicle force (i.e., "throttle"), (lb.), vehicle velocity (ft./s), vehicle position (XYZ) (ft.), vehicle heading (degrees), longitudinal and lateral acceleration (ft./s^2), front and rear tire slip angles (degrees), and a variety of other output channels.

5. Validation results

For the present research study, the performance evaluation compared the following aspects of driver's behavior between the real-world and the simulator: (1) the average corridor-level travel time for all 15 drivers (from Point A to Point B); (2) the acceleration and deceleration profiles of individual drivers; (3) the number of lane changes for individual drivers while driving the course of the test segment; and (4) the trip's energy consumption and vehicular emissions for individual drivers. The results are briefly summarized below.

5.1. Average travel time

As previously mentioned, each participant was asked to drive the test corridor *twice* in each direction (for a total of four courses per driver) and the corridor-level trip travel time for each participant was recorded; in the subsequent discussion, courses 1 and 3 refer to driving from the north end to the south end (i.e. southbound travel), and courses 2 and 4 to driving in the other direction (i.e. northbound travel). Because the exact traffic conditions are likely to vary from one run to another, the comparison looked at the *average* trip travel time for all 15 drivers. However, we distinguish between driving in the northbound and southbound direction, and between the first and second run for a given direction. The results are shown in Fig. 3.

As can be seen in Fig. 3, the average total trip travel time in the simulator and the field appear to be quite close to one another. Specifically, the percent difference between the travel times in the field and the simulator were 7.6%, 4.3%, 8.8% and 3.5% for courses 1 through 4, respectively. While the differences were small, the travel time in the simulator was consistently slightly shorter than in the real road test. This could be explained by the fact that the perception of risk in the simulated road is lower than in the real road (this is in fact consistent with previous studies such as those conducted by Bella (2008) and Törnros (1998)). Moreover, it can be seen that the travel time from the north to the south end (course 1, 3) was slightly larger than from the south to north, and that both the road test and simulator test showed the same trend. This is obviously because of different signalization and traffic conditions in each direction.

To better quantify the difference between the simulation and field travel time, Table 1 below provides the mean and standard deviation for each test. In this case, the results from the two runs were combined in order to have a larger sample size that allows for statistical testing (i.e. the results from courses 1 and 3 were combined to represent travel time from the north to the south ends, and the same was done with courses 2 and 4). Hypothesis testing was then conducted for the southbound (courses 1 and 3) and northbound (courses 2 and 4) directions separately, with the null hypothesis being that the mean travel time in the simulation test equaled the mean travel time in the field. An unpaired two sample t-test confirmed that the population mean of the simulation travel time is not statistically different from the population mean in the field, at a significance level of 0.01 and 0.05, for traveling to the south and north ends, respectively.

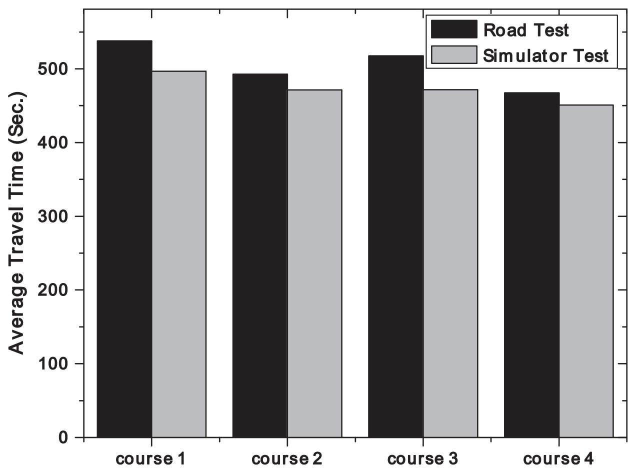

Fig. 3. Average travel time in each course.

Table 1
Travel time statistics.

	Sample size	Mean (s)	Standard deviation (s)
(a) Travel from north to south end (courses 1 and 3)			
Road	30	527.7	60.6
Simulation	30	484.3	65.6
(b) Travel from south to north end (courses 2 and 4)			
Road	30	480.0	52.7
Simulation	30	461.2	50.0

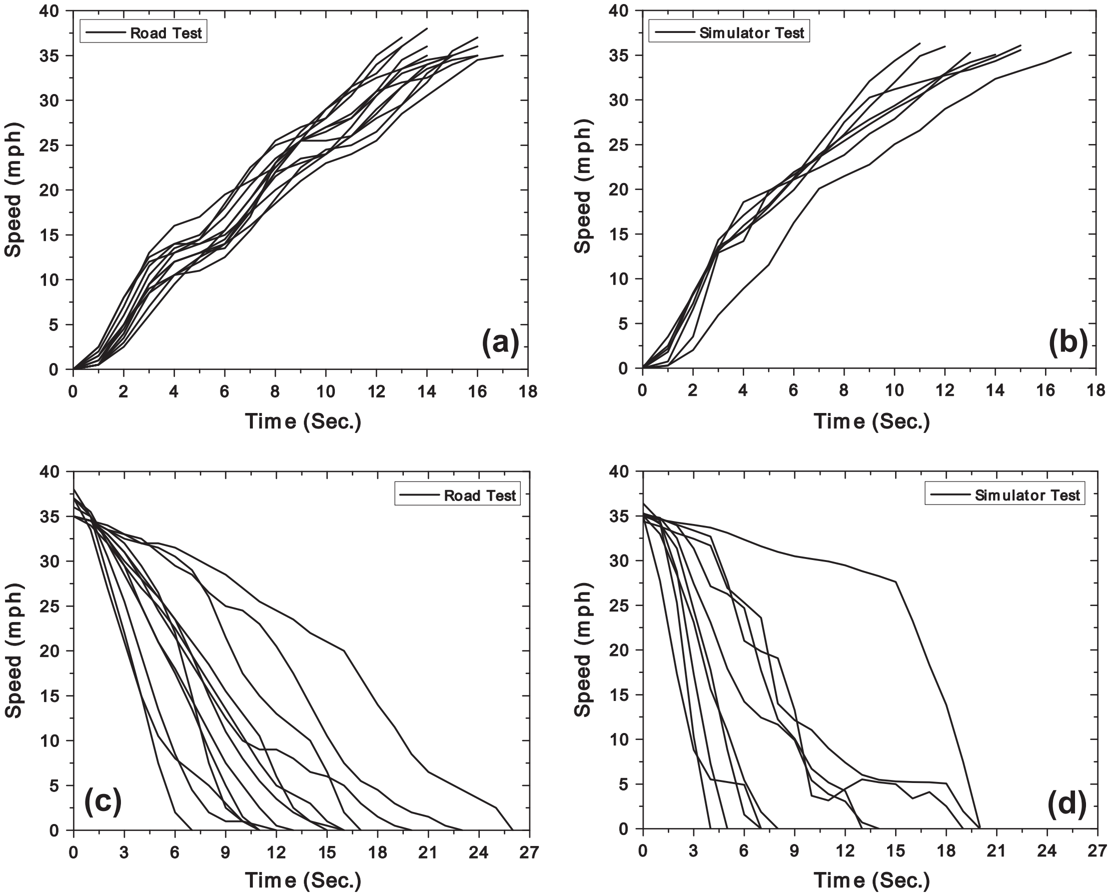

Fig. 4. (a–d) Acceleration and declaration profiles for a given participant.

5.2. Acceleration and declaration profiles

Besides comparing the average travel time, another important aspect of driver behavior that was validated was the acceleration and deceleration profiles of drivers in the simulation environment compared to the field. Fig. 4(a–d) compares those profiles in the simulation against the field-observed profiled. Given space limitations, the profiles of only one test participant are shown in the figure, and only "smooth" accelerating/decelerating profiles were selected for comparison (e.g., acceleration profiles that were "interrupted", perhaps because of a vehicle in front for example, are not included). For acceleration, the speed trajectory was truncated when the speed reached 35 mph, whereas for deceleration, the trajectories compared all started from the same speed.

Comparing Fig. 4(a) and (b), a relatively close match between the road and simulation acceleration profiles can be discerned. Specifically, most of the acceleration profiles, in both the road and simulation tests, required approximately 12–18 s in order to reach a speed of 35 mph. Moreover, they share a similar trend – a fast start at the beginning followed by a gradual increase. The similarity was also observed in the deceleration profiles described by Fig. 4(c) and (d), although it was noticeable that the test driver tended to take a slightly shorter time to come to a full stop in the simulator test, ranging from 4 to 20 s, compared to a time period ranging between 7 and 26 s in the field. Such a difference might have been caused by the resolution projection of the test bed in the simulator environment, which made its look-ahead distance not look as long as it is in the real world. This in turn meant that the distance from which test drivers could see and acquire the signal information was slightly shorter in the simulation compared to the field.

For a more aggregate comparison of acceleration and deceleration behavior, the study also compared the *average* acceleration and deceleration distance of all participants. It should be noted that in calculating the average acceleration and deceleration distances, there were at least two technical issues that had to be addressed. The first is that the deceleration or acceleration distances happened at different intersections throughout the corridor since we had no control of where exactly each participant would come to a full stop (i.e., at which intersection). The second is that the maximum speed reached could be different from one acceleration instance to another, since the speed limit varied slightly over the simulated corridor (there are sections that had a 40 mph speed limit, others that had a 35 mph, and a third group that had a speed limit of only 30 mph). To address these problems, while the profile selection was not restricted to a particular intersection (to increase the sample size), the profiles were truncated at a ceiling value of 30 mph (i.e. we only considered that part of the profile where the speed was below 30 mph to calculate the deceleration or acceleration distance). In addition, the study once again only considered the smooth profiles where the driver accelerated from/decelerated to a full stop in a gradual manner (i.e. without changing from acceleration to deceleration or vice versa).

The results are shown on Fig. 5, which again confirms that the driver's acceleration and deceleration behavior on the road are very similar to those in the integrated simulator. Specifically, as can be seen, the average acceleration distance was 0.0565 mile (or 299 feet) in the road test, compared to 0.0575 mile (or 303 feet) in the simulator, a difference of only around 1.7%. On the other hand, the deceleration or stopping) distance was 0.0504 mile (or 266 feet) in the field, compared to 0.0501 mile (or 265 feet) in the simulation, a difference of only 0.6%. It is also worth noting that the road test was conducted using a variety of different vehicles (each driver used his/her own vehicle), which meant that the acceleration/deceleration ability

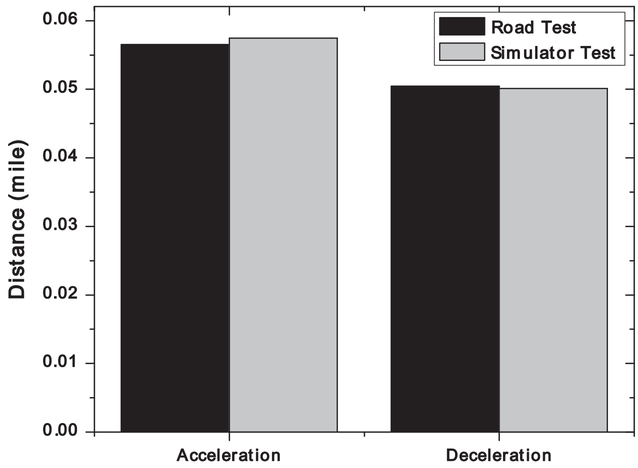

Fig. 5. Average acceleration and deceleration distance of all participants.

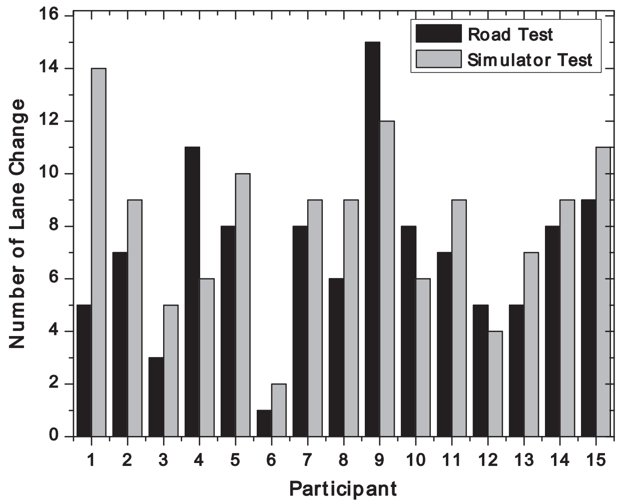

Fig. 6. Total number of lane for each participant.

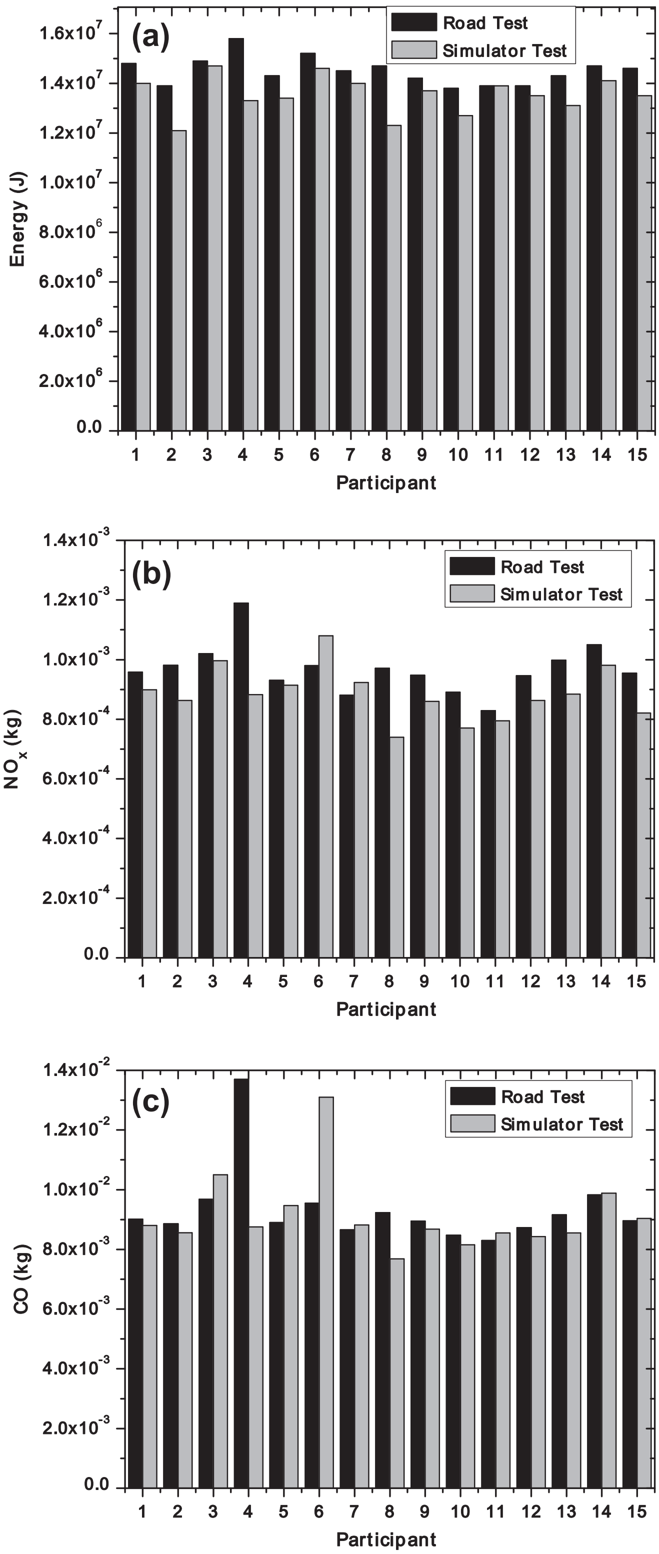

Fig. 7. (a–c) Average emission of each participant.

could have affected the acceleration/deceleration distance. The fact that the average distance was almost identical between the field and simulation confirm the intuition that, while traveling along a congested arterial (the experiments were conducted during the evening peak hour), the acceleration or deceleration distance are primarily dependent upon traffic

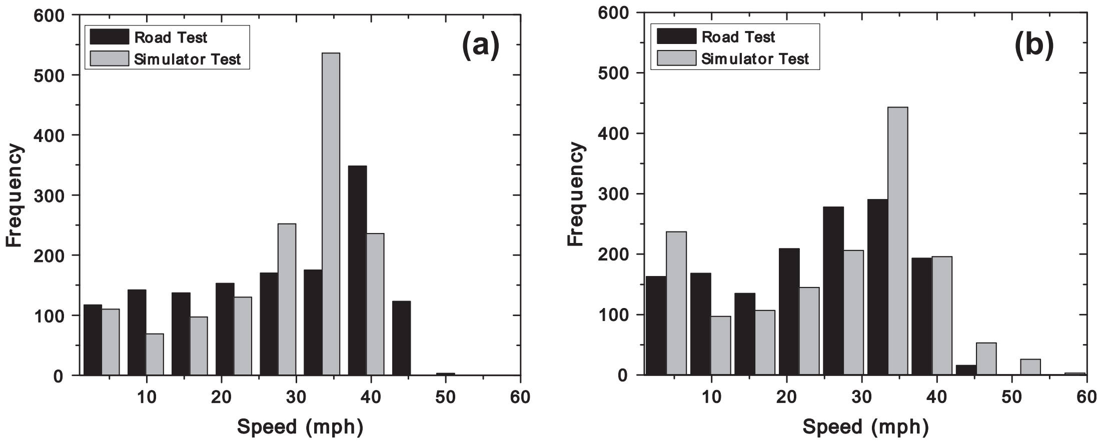

Fig. 8. (a) Driver 4, (b) driver 6 speed frequency distribution.

conditions and the congestion level and not upon the vehicle type, because a participant's driving speed is usually constrained by the vehicle ahead.

5.2.1. Lane change behavior

Another validation metric which the study looked at was the total the number of lane changes which each participant made both in the simulator and during the road test. Fig. 6 shows the total lane change count during the entire 2.5 miles trip (for all four courses) for each of the 15 test drivers. As can be seen, for the majority of the participants, the difference between the total number of lane changes in the simulation and the field was equal to or less than 3 lane changes. The exception however was participant No. 1 and No. 4, where there was a significant difference between the number of lane changes they made between the simulation and the field. The cause of such significant difference is unclear and cannot be easily explained. Several factors may have differed in those instances such as traffic condition and the participant's adaptability to the simulator.

5.3. Vehicle emissions and energy consumption

Since one of the applications of the integrated simulator was its use to evaluate eco-driving and green transportation applications, it was deemed important to validate the energy consumption and emissions estimates computed based on the participants' driving trajectories in the simulator against their trajectories in the real-world. To do this, the energy consumption and selected emissions (NO_x and CO) for each participant during the 2.5 miles trip were calculated using the MOVES model. This was done by providing the MOVES model with the second-by-second vehicle trajectory of the participant, whether driving in the simulator or in the real-world, and using the link schedule approach (described in Section 3.3) to calculate the emissions or energy consumption. The results are shown on Fig. 7(a–c), where the dark bars represent the energy or emissions estimates from the road test trajectories, and the light bars represent the corresponding estimates for the simulator. The values shown are the averages for the four courses and for each driver. As can be seen, for the majority of the drivers, their energy consumption and emissions estimates based on their driving trajectories in the simulator are quite comparable to those based on the field trajectories. The only exceptions were drivers 4 and 6. Specifically, Driver 4's road test profile produced 25.9% and 35.9% more NO_x and CO than those produced by the corresponding simulation profile, whereas Driver 6's field test generated a CO amount that was 37.4% less than the simulation test.

To better understand the nature of such difference, the study next looked at the second-by-second speed profiles for these two drivers, which provided the basic input to the MOVES model. Fig. 8(a) and (b) gives the speed distributions of Driver 4 and Driver 6, respectively. As can be seen from Fig. 8(a), for example, the distribution of the road test speed for Driver 4 weighted more heavily on the high speed tail with a maximum speed at 50 mph, and with the most frequent speed being at 40 mph. This is in contrast to the simulator trip speed distribution which had a maximum speed of only 40 mph (as opposed to 50 mph in the field) and which peaked at 35 mph (as opposed to 40 mph in the field). In other words, a slightly more aggressive behavior was observed in the field which explains the higher emissions and energy consumption rates. On the contrary, Driver 6 was observed to be more conservative in the field test, which was confirmed by the emission results.

6. Conclusions and future work

6.1. Conclusions

This paper has summarized the researchers' efforts in designing, implementing and validating an integrated traffic and driving simulation framework, where the TS captures the microscopic traffic dynamics and the DS brings in the human inputs and converts them into vehicle dynamics. Following successful implementation, the integrated simulator was validated through a comparison study that compared various aspects of driver behavior in the simulator environment to their behavior while driving in the real-world. The integrated TS–DS system was also paired to the MOVES emission model to evaluate its capability to capture driver behavior impact on fuel consumption and emissions. The major findings are summarized as the following:

1. The proposed integrated traffic and driving simulator system was found to be capable of accomplishing the intended two way communication between the traffic and the driving simulator. Specifically, the research succeeded in making the subject vehicle in the TS mimic the behavior of the human subject in the DS. Moreover, the background traffic, which the human subject interacted with in the DS, was made to be responsive to the actions of the human subject.
2. The methods used in this study to overcome the integration challenges (see Section 4.2) appear to have allowed for a high-fidelity simulation environment that closely resembled reality and hence resulted in driving behavior close to that observed in the field.
3. The travel time in the virtual environment was observed to be comparable to the field test, although the road test travel time was slightly higher.
4. The acceleration profiles recorded in the simulation platform were almost identical to those from the road experiments. It generally took between 12 and 18 s for the test participants in both the real and virtual world to reach a desirable cruise speed, i.e. 35 mph. For deceleration, the profiles in the simulator were generally close to the field observed ones, although it was noticeable that the test driver tended to take a slightly shorter time to come to a full stop in the simulator. This is probably because of the limited look-ahead distance in the simulator platform.
5. In terms of the *average* acceleration and deceleration distances, the average distance was almost identical between the field and simulation. This demonstrates that for congested conditions, the acceleration or deceleration distance are primarily dependent upon traffic conditions and the congestion level and not upon the vehicle type.
6. In terms of lane changing behavior, the number of lane changes observed in the simulator was close to those recorded in the real world, with the difference in most cases not exceeding three lane changes for a ten-mile trip (2.5 miles/course x 4 courses.
7. For the majority of the test drivers, their overall trip fuel consumption and NO_x and CO emissions were consistent in the virtual simulation environment versus real-world driving.

6.2. Future and ongoing work

The integration framework presented in this paper is certainly a work in progress. There are numerous potential avenues for its extensibility and expansion, and these are summarized here.

6.2.1. Integration that includes network simulation

The proposed TS–DS integration has been the first step towards the development of a more complete integrated simulation environment for transportation research. Already tested and refined is an integration that includes an additional link to a Communications Networking Simulation (NS), which can simulate the delivery of warning messages among vehicles, and between vehicles and the infrastructure, within a Connected Vehicle environment. While there have been numerous studies that have attempted to develop integrated TS/NS simulators and a handful that attempted to integrate TS/DS as previously described in Section 2.1, none has attempted to integrate all three types of simulators. Fig. 9 shows an overall architecture of the authors' 3-in-1 Integrated Traffic-Driving-Network Simulator (ITDNS) currently under development and enhancement (Zhao et al., 2012, 2013).

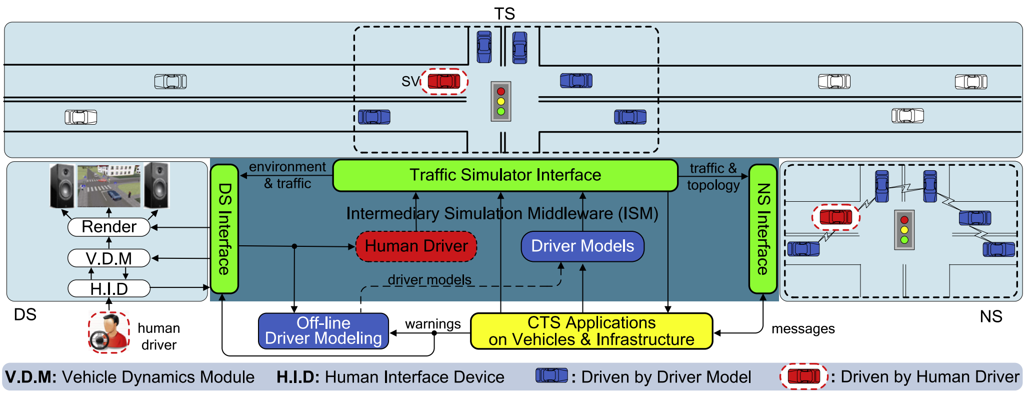

Fig. 9. Integrated Traffic-Driving-Network Simulator (ITDNS).

As previously alluded in Section 1, the integrated 3-in-1 simulator will provide a unique research, development, testing and evaluation platform for CTS applications which have the potential to dramatically improve transportation safety, efficiency, and energy consumption/vehicle emissions. Specifically, the inclusion of the human-in-the-loop within such a simulation environment, through the integration of the DS, will allow for studying the very important topic of human factors in CV and CTS research.

6.2.2. Multi-participant networked vehicle simulation

When analyzing real-time driver decisions based upon the actions of others (e.g. a driver swerving into another lane), it is useful to allow simulation participants to interact in real-time with other human participants located within the same simulation environment. To facilitate such research, we designed a multi-participant component in our integrated simulator which allows multiple driving simulators to be connected across the network.

The design of our integrated simulator allows for the TS, DS and ISM to run on different physical machines, and thus multiple DSs can be added to the simulator. Logically, the system follows the server-client architecture: TS and ISM work together as the server, and each DS is a client. All simulation-relevant information to be exchanged between participants (clients) is relayed through the ISM. A few modifications are currently under investigation to reduce communication overhead. These include using UDP instead of TCP for high frequency communication on vehicle position and orientation, and interpolation between each TS update to hide network latency.

Acknowledgements

The authors would like to acknowledge funding support from the National Science Foundation's Cyber-Physical Systems (CPS) program (CNS-1035733, PI: Qiao), and ongoing hardware, software, and technical support from Moog, Inc.

References

Archer, J., 2000. Developing the potential of micro-simulation modeling for traffic safety assessment. In: Proceedings of the 13th ICTCT, Workshop, p. 44.
Balci, O., 1998. Verification, validation and testing. In: Banks, J. (Ed.), The Handbook of Simulation. John Wiley, New York (Chapter 10).
Bédard, M., Parkkari, M., Weaver, B., Riendeau, J., Dahlquist, M., 2010. Assessment of driving performance using a simulator protocol: validity and reproducibility. Am. J. Occup. Ther. 64 (2), 336–340.
Bella, F., 2008. Driving simulator for speed research on two-lane rural roads. Accid. Anal. Prev. 40, 1078–1087.
Blana, E., 1996. Driving Simulator Validation Studies: A Literature Review.
Bowles, R.L., Parrish, R.V., Dieudonne, J.E., 1975. Coordinated adaptive washout for motion simulators. J. Aircraft 12 (1), 44–50.
Brockfeld, E., Kühne, R.D., Wagner, P., 2004. Calibration and validation of microscopic traffic flow models. Trans. Res. Rec. J. Trans. Res. Board 1876 (1), 62–70.
Ciuffo, B., Punzo, V., Montanino, M. (2012). The calibration of traffic simulation models. Report on the assessment of different goodness of fit measures and optimization algorithms. MULTITUDE Project-COST Action TU0903. JRC Scientific Report.
Chamberlin, R., Swanson, B., Talbott, E., Dumont, J., Pesci, S., Analysis of MOVES and CMEM for evaluating the emissions impacts of an intersection control change. In: 91st Annual Meeting Compendium of Papers, Transportation Research Board, 2011.
Chan, E., Pradhan, A.K., Pollatsek, A., Knodler, M.A., Fisher, D.L., 2010. Are driving simulators effective tools for evaluating novice drivers' hazard anticipation, speed management, and attention maintenance skills? Trans. Res. Part F Traffic Psychol. Behav. 13 (5), 343–353.
Cost (European Cooperation in Science and Technology), 2012. MULTITUDE: Methods and tools for supporting the Use, caLibration, and validaTIon of Traffic simUlation moDEls. <http://www.multitude-project.eu/> (retrieved 12.30.13).
Davis Instruments, 2012. Car Chip Pro – Driving and Engine Performance Monitor. <http://www.carchip.com/Products/8226.asp> (retrieved 04.22.12).
Environmental Protection Agency Office of Transportation and Air Quality, 2011. Introduction to MOVES2010. <http://www.epa.gov/oms/models/moves/Introduction-to-moves2010webinar.pdf> (retrieved 04.22.13).
Fellendorf, M., Vortisch, P. (2001). Validation of the microscopic traffic flow model VISSIM in different real-world situations. In National Research Council (US). Transportation Research Board.
Gelau, C., Sirek, J., Dahmen-Zimmer, K., 2011. Effects of time pressure on left-turn decisions of elderly drivers in a fixed-base driving simulator. Trans. Res. Part F Traffic Psychol. Behav. 14 (1), 76–86.
Godley, S.T., Triggs, T.J., Fildes, B.N., 2002. Driving simulator validation for speed research. Accid. Anal. Prev. 34 (5), 589–600.
Helland, A., Jenssen, G.D., Lervag, L.E., Westin, A.A., Moen, T., Sakshaug, K., Slordal, L., 2013. Comparison of driving simulator performance with real driving after alcohol intake: a randomised, single blind, placebo-controlled, cross-over trial. Accid. Anal. Prev. 53, 9–16.
Hoffman, J.D., Lee, J.D., Brown, T.L., McGehee, D.V., 2002. Comparison of driver braking responses in a high-fidelity simulator and on a test track. Trans. Res. Rec. J. Trans. Res. Board 1803 (1), 59–65.
Horiguchi, R., Kuwahara, M., Nishikawa, I. (1995). The model validation of traffic simulation system for urban road networks:'AVENUE'. In: Proceedings of the Second World Congress on Intelligent Transport Systems, vol. 95, pp. 1977–1982.
Hoskins, A.H., El-Gindy, M., 2006. Technical report: literature survey on driving simulator validation studies. Int. J. Heavy Veh. Syst. 13 (3), 241–252.
Hulme, K.F., Huang, S., Sadek, A.W., Qiao, C., 2010. Next generation, integrated hardware-in-the-loop transportation simulation modeling. In: The Interservice/Industry Training, Simulation and Education Conference (I/ITSEC), Orlando, FL.
Jin, M., Lam, S.H., 2003. A virtual-reality based integrated driving-traffic simulation system to study the impacts of intelligent transportation system (ITS). Proc. Cyberworlds 2003, 158–165.
Jha, M., Gopalan, G., Garms, A., Mahanti, B.P., Toledo, T., Ben-Akiva, M.E., 2004. Development and calibration of a large-scale microscopic traffic simulation model. Transp. Res. Rec. 1876, 121–131.
Jie, L., Van Zuylen, H., Chen, Y., Viti, F. Wilmink, I. (2013). Calibration of a microscopic simulation model for emission calculation. Transportation Research Part C, 31, 172–184.
Karl, I., Berg, G., Ruger, F., Farber, B., 2013. Driving behavior and simulator sickness while driving the vehicle in the loop: validation of longitudinal driving behavior. Intell. Trans. Syst. Mag. 5 (1), 42–57.
Krajzewicz, D., Hertkorn, G., Wagner, P., Rossel, C., 2002. An example of microscopic car models validation using the open source traffic simulation SUMO. In: Proceedings of Simulation in Industry, 14th European Simulation Symposium, pp. 318–322.
Lawe, S., Lobb, J., Sadek, A.W., Huang, S., Xie, C., 2009. TRANSIMS implementation in Chittenden county, vermont. Trans. Res. Board Rec. 2132, 113–121.
Maroto, J., Delso, E., Felez, J., Cabanellas, J.M., 2006. Real-time traffic simulation with a microscopic model. Trans. Intell. Trans. Syst. 7 (4), 513–527.

Mayhew, D.R., Simpson, H.M., Wood, K.M., Lonero, L., Clinton, K.M., Johnson, A.G., 2011. On-road and simulated driving: concurrent and discriminant validation. J. Saf. Res. 42 (4), 267–275.
McGehee, D.V., Lee, J.D., Rizzo, M., Dawson, J., Bateman, K., 2004. Quantitative analysis of steering adaptation on a high performance fixed-base driving simulator. Trans. Res. Part F Traffic Psychol. Behav. 7 (3), 181–196.
Milliken, W.F., Whitcomb, D.W., 1956. General introduction to a programme of dynamic research. Proc. Inst. Mech. Eng. Automobile Div. 10 (1), 287–309.
Ni, D., Leonard, J.D., Guin, A., Williams, B.M., 2004. Systematic approach for validating traffic simulation models. Trans. Res. Rec. J. Trans. Res. Board 1876 (1), 20–31.
Oketch, T., Carrick, M., 2005. Calibration and validation of a micro-simulation model in network analysis. In: Proceedings of the 84th TRB Annual Meeting, Washington, DC.
Olstam, J.J., Lundgren, J., Adlers, M., Matstoms, P., 2008. A framework for simulation of surrounding vehicles in driving simulators. ACM Trans. Model. Comput. Simulat. 18 (3), 9.
Papson, A., Hartley, S., Kuo, K. L., 2012. Analysis of emissions at congested and uncongested intersections using MOVES2010. In: Transportation Research Board 91st Annual Meeting No. 12-0684.
Park, B.B., Schneeberger, J.D., 2003. Microscopic simulation model calibration and validation: case study of VISSIM simulation model for a coordinated actuated signal system. Trans. Res. Rec. J. Trans. Res. Board 1856 (1), 185–192.
Park, B., Kwak, J., 2011. Calibration and validation of TRANSIMS microsimulator for an urban arterial network. KSCE J. Civil Eng. 15 (6), 1091–1100.
Punzo, V., Ciuffo, B., 2011. Integration of driving and traffic simulation: issues and first solutions. Trans. Intell. Trans. Syst. 12 (2), 354–363.
Quadstone, Ltd., 2013. Quadstone Paramics. <http://www.paramics-online.com/> (retrieved 05.13.13).
Rakha, H., Hellinga, B., Van Aerde, M., Perez, W., 1996. Systematic verification, validation and calibration of traffic simulation models. In: 75th Annual Meeting of the Transportation Research Board, Washington, DC.
Reimer, B., D'Ambrosio, L.A., Coughlin, J.F., Kafrissen, M.E., Biederman, J., 2006. Using self-reported data to assess the validity of driving simulation data. Behav. Res. Meth. 38 (2), 314–324.
Richer, I., Bergeron, J., 2012. Differentiating risky and aggressive driving: Further support of the internal validity of the Dula Dangerous Driving Index. Accid. Anal. Prev. 45, 620–627.
Riener, A., 2011. Assessment of simulator fidelity and validity in simulator and on-the-road studies. In: International Journal on Advances in Systems and Measurements, 3(3 and 4), pp. 110–124.
Romano, R., 2003. Non-linear optimal tilt coordination for washout algorithms. In: Proceedings of the AIAA Modeling and Simulation Technologies Conference and Exhibit.
Saccomanno, F., Cunto, F.J.C., 2006. Evaluation of safety countermeasures at intersections using microscopic simulation. In: Transportation Research Board 85th Annual Meeting No. 06-1117.
Sacks, J., Rouphail, N.M., Park, B., Thakuriah, P., 2002. Statistically-based validation of computer simulation models in traffic operations and management. J. Trans. Stat. 5 (1), 1–24.
Shechtman, O., Classen, S., Awadzi, K., Mann, W., 2009. Comparison of driving errors between on-the-road and simulated driving assessment: a validation study. Traffic Injury Prevent. 10 (4), 379–385.
Smith, M.C., Sadek, A.W., Huang, S., 2008. Large-scale microscopic simulation: toward an increased resolution of transportation models. ASCE J. Transport. Eng. 134 (7), 273–281.
That, T.N., Casas, J., 2011. An integrated framework combining a traffic simulator and a driving simulator. Proc. Soc. Behav. Sci. 20, 648–655.
Toledo, T., Koutsopoulos, H.N., 2004. Statistical validation of traffic simulation models. Trans. Res. Rec. J. Trans. Res. Board 1876 (1), 142–150.
Toledo, T., Koutsopoulos, H.N., Davol, A., Ben-Akiva, M.E., Burghout, W., Andréasson, I., Johansson, T., Lundin, C., 2003. Calibration and validation of microscopic traffic simulation tools: Stockholm case study. Trans. Res. Rec. J. Trans. Res. Board 1831 (1), 65–75.
Törnros, J., 1998. Driving behaviour in a real and a simulated road tunnel—a validation study. Accid. Anal. Prev. 30 (4), 497–503.
Transportation Research Board, 2000. Highway Capacity Manual. TRB, National Research Council, Washington, DC.
Underwood, G., Crundall, D., Chapman, P., 2011. Driving simulator validation with hazard perception. Trans. Res. Part F Traffic Psychol. Behav. 14 (6), 435–446.
Vladisavljevic, I., Cooper, J.M., Martin, P.T., Strayer, D.L., Vladisavljevic, I., Cooper, J.M., Strayer, D.L., 2009. The importance of integrating driving and traffic simulations, illustrated through a case study that examines the impact of cell phone drivers on traffic flow. In: Proceedings of 88th Transportation Research Board Annual Meeting.
Wang, Y., Mehler, B., Reimer, B., Lammers, V., D'Ambrosio, L.A., Coughlin, J.F., 2010. The validity of driving simulation for assessing differences between in-vehicle informational interfaces: a comparison with field testing. Ergonomics 53 (3), 404–420.
Wei, H., Liu, H., Lu, M., Yi, P., 2012. Integrating Traffic Operation with emission impact using dual-loop data. 2011 Ohio Transportation Consortium Research Project Report.
Wu, J., Brackstone, M., McDonald, M., 2003. The validation of a microscopic simulation model: a methodological case study. Trans. Res. Part C 11, 463–479.
Xie, Y., Chowdhury, M.A., Bhavsar, P., Zhou, Y., 2011. An integrated tool for modeling the impact of alternative fueled vehicles on traffic emissions: a case study of Greenville, South Carolina. In: Transportation Research Board 90th Annual Meeting, No. 11-3880.
Yan, X., Abdel-Aty, M., Radwan, E., Wang, X., Chilakapati, P., 2008. Validating a driving simulator using surrogate safety measures. Accid. Anal. Prev. 40 (1), 274.
Zhao, Y., Sadek, A.W., 2013. Computationally-efficient approaches to integrating the MOVES emissions model with traffic simulators. In: Proceedings of the 2nd International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications.
Zhao, Y., Wagh, A., Hou, Y., Hulme, K. F., Qiao, C., Sadek, A.W., 2013. Integrated traffic-driving-networking simulator for the design of connected vehicle applications: eco-signal case study. J. Intell. Trans. Syst. Technol. Plan. Oper.
Zhao, Y., Wagh, A., Hulme, K. F., Sadek, A.W., Qiao, C., Xu, H., Huang, L., 2012. Integrated traffic-driving-networking simulator: A unique research and development tool for connected vehicles. In: ACM/IEEE/IFAC/TRB International Conference on Connected Vehicles and Expo, Beijing, China.