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# Simulation Based Testing and Evaluation Tools for Transportation Cyber-Physical Systems

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*Abstract*—**Transportation Cyber-Physical Systems (TCPS) requires simulation-based testing and evaluation due to the prohibitive cost of building realistic test beds. Given the trans-disciplinary nature of TCPS, various simulation models and frameworks have been proposed in civil engineering, computer science, and related fields. Traditionally, researchers in different areas have developed their own set of simulation tools, which provide limited capability for TCPS research. In recent years, we are witnessing a growing interest of combining two or more features of traditional simulators in order to capture the unique characteristics of TCPS. In this paper, we describe several mainstream simulation models used in transportation, communication and human factor studies in TCPS research. Moreover, we present our unique design and implementation of an Integrated Traffic Driving Network Simulator (ITDNS). Finally, we discuss future enhancements that will promote best simulation practices for TCPS research.**

*Index Terms*—**Driving Simulator, Integrated Simulator, Network Simulator, Traffic Simulator**

## I. INTRODUCTION

The integration of advanced communication technology into the transportation system holds promise to revolutionize the future of public transit. Transportation Cyber-Physical Systems (TCPS) (that encompasses Vehicle-to-Vehicle (V2V) & Vehicle-to-Infrastructure (V2I) technologies) is expected to bring about transformative improvements in the highway transportation system's safety, efficiency and sustainability. TCPS has also been referred to as Cooperative Intelligent Transportation System (CITS).

The latest TCPS advances present enormous opportunities to change the transportation system with increased levels of connectivity among vehicles and the infrastructure (e.g., the Connected Vehicle (CV) initiative), increased levels of vehicle automation (e.g., automated vehicles (AV) and self-driving cars), and more accurate sensing and monitoring (e.g., vehicle detection, adaptive traffic lights). TCPS is becoming an active area of research standardization and development, and has received a lot of interest in the US, Japan and the European Union [1].

Like any emerging and future technologies, the design, infrastructure and applications of TCPS must be evaluated and validated before their implementation and deployment. The need for conducting extensive testing of TCPS applications is especially prominent because: 1) human drivers or travelers will always constitute a major component of the system and as such, human lives are at stake; and 2) the development and deployment of applications will be evolutionary, and accordingly, in the foreseeable future, vehicles will have varying degrees of connectivity (with respect to V2V and V2I communications) and automation (with respect to general autonomous driving capability). It is therefore critical to have a versatile platform for hybrid simulation and experimentation involving both Hardware-in-The-Loop (HaTL) and Human-in-the-Loop (HuTL) testing.

While field tests such as SHRP2 [2] initiative provide potentially useful naturalistic driving data, such data alone are not directly suitable for TCPS experimentation. This is because the SHRP2 data is acquired by way of today's vehicles and technologies, and cannot be used to evaluate emerging or unproven TCPS technologies (which may expose the drivers to risky or otherwise dangerous situations). This is also true of some of the latest USDOT CV test-beds, such as the Safety Pilot experiment currently taking place in Ann Arbor, Michigan [3], and test-beds in New York, California, Virginia, and Florida [4]. While those tests are designed to evaluate the feasibility of wireless V2V and V2I communications, they are costly and, because they cannot expose drivers to risks, are limited to testing mature technologies. Finally, to date, we have not seen large-scale field tests of connected vehicles and their interactions with regular traffic.

In contrast, a simulation-based study provides a flexible and economical way to evaluate TCPS technologies, and enables human factor studies in a safe and authentic environment. Along with the development of TCPS research, many simulators are available within the research community. However, it is difficult for researchers to choose among the various simulation tools. Additionally, there is no clear picture for how simulation should evolve to satisfy the requirements of future TCPS research. This void has motivated us to review previous and ongoing developments relating to TCPS simulation.

This paper is organized as follows. Section 2 presents an

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overview of models and tools that can be used *only* to analyze traffic mobility, wireless channel, or human behavior. The state-of-the-art pertaining to the integration of two distinct simulations (i.e. combining traffic simulation with either driving or network simulation) is described in Section 3. Section 4 presents our recent efforts relating to the integration of all three types of simulations, and presents potential use cases of such a 3-in-1 integrated simulator, with discussions on how it can be used to evaluate various emerging TCPS technologies and applications. Finally, Section 5 concludes the paper with suggestions for future work.

## II. OVERVIEW OF DOMAIN-SPECIFIC SIMULATORS

Challenges in the design of future TCPS exist in three aspects: a) the transportation systems, which manage the transport network and mobility (i.e., traffic control, intersection design, etc.); b) the cyber systems that handle sensing, computing and communications, and c) human factors that are concerned with interaction among human and other elements of the TCPS. Accordingly, researchers from respective areas adopt different tools and models that can be categorized as follows: 1) a traffic simulator, which models traffic mobility; 2) a network simulator that models wireline and wireless channels; and 3) a driving simulator that is used to study human behavior. In the remainder of this section, we review the major tools in each of these three areas. Our goal is to provide an overview of simulators that are available for TCPS research.

### *A. Traffic simulator*

The transportation community has been using simulation tools for a wide range of applications from urban planning, traffic monitoring, management and operation, to performance evaluation and decision-making. A Traffic Simulator (TS) is typically categorized as macroscopic, mesoscopic or microscopic by its level of detail. Similarly to the fluid dynamics model, macroscopic simulation considers traffic flow as a whole with characteristics like speed, flow and density, instead of tracking individual vehicles. In comparisons, microscopic model simulates each vehicle's movement on a sub-second or second-by-second basis. The methodology behind microscopic model is usually based on car-following models. For the car-following model, each simulated vehicle is either under the free-flow mode (where the vehicle accelerates to a desired target speed and cruises) or car-following mode (where it tries to follow the preceding vehicle). Last but not least, mesocopic model lies in-between regarding the level of detail, which analyzes transportation elements in small groups.

For the purpose of TCPS research, vehicular communication layers require high-fidelity vehicle movement (e.g., vehicle location, heading and speed) on a secondly basis. Such trajectory detail is only deliverable by the finest microscopic traffic simulation. Therefore, in this paper, we focus only on the state-of-the-art microscopic traffic simulation. The most popular packages in both industry and research communities include: CORSIM, Paramics, Vissim, SUMO, Aimsun and so forth [6] [7] [8] [9] [10].

SUMO gains its popularity in the research community by its open source and highly portable nature, and its convenient network import capability from map providers or other simulators, such as OpenStreetMap, ArcGIS Shape files, Vissim, and others [11] [12] [13] [14]. CORSIM, Vissim, Paramics, and Aimsun are commercially available TS packages. Despite differences in network representation, graphical user interface, car-following models, and related features, all of these TS models are extensible to operate with a network simulator (NS) by simulating and exporting vehicle trajectories (either online or offline). For example, Paramics, Vissim and Aimsun [15] [16] [17] [18] [19] provide an extensive API to their traffic simulator, so that users can get access to the network topology and vehicle dynamics during the simulation, and manipulate the corresponding vehicle movements according to the needs of the TCPS. CORSIM's Run-Time Extension was originally coded to support signal control analysis by introducing HaTL, but it can still generate high fidelity vehicle traces for TCPS research purposes [20] [21] [22].

However, a simple one-way information flow from the TS to NS is not sufficient for most TCPS research. For example, driving behavior or routing choices are expected to adapt themselves en-route as CV applications may recommend, which requires a feedback loop from the NS to the TS. Another major limitation of the TS is the lack of realistic driving behavior and human perception, especially when evaluating CV applications. Such a gap in functionality is usually accommodated by integrating driving or networking models. Previous integration efforts will be reviewed in Section 3.

### *B. Network simulator*

In this section, we review the major communication Network Simulator (NS) used in TCPS research. A network simulator is commonly used to evaluate routing protocols or analyze wireless channel usage. In a TCPS scenario, a vehicle is usually modeled as a wireless router or node, thus nearby vehicles create a mobile network. V2V communication or Inter-Vehicular Communication (IVC) [23] is generally referred to as Vehicular Ad Hoc Network (VANET)[24]. While VANET is a unique feature of TCPS, the cellular and optical communications are also critical components for V2I and between-infrastructure communications. The following is a list of network simulators that are capable of performing evaluation in VANET scenarios, and are under active development:

ns-2 [25] is virtually the standard network simulation tool, and has been used extensively for vehicular network research. The major components of ns-2 are written in C++, while oTcl scripts are used to control the simulation. This design choice was originally made to avoid frequent recompilation time of the C++ code. However, it compromised simulation performance, which limited ns-2 simulations to no more than a few hundred nodes. To build a scalable simulation, ns-3 [26] was introduced as a successor. In ns-3, simulations can be implemented entirely in C++, while Python replaced oTcl to provide a scripting capability. Unfortunately, ns-3 decided to abandon backward-compatibility with ns-2, which means feature sets of vehicular network from ns-2 have to be imported manually.

Unlike ns-2, OMNeT++ [27] is a generic C++ simulation library and framework that is primarily used for building network simulators. It provides a component architecture for domain-specific models (e.g., wired and wireless communication networks, on-chip networks, queuing networks), and each are developed independently of OMNeT++. Similar to ns-2, OMNeT++ uses a description language, called NED, to set up simulations. Major models that have VANET simulation capacities include: INET and MiXiM that provide propagation models for a V2V channel, and the Veins framework that is composed of a network simulator and a traffic simulation model (refer to section 3.2).

### C. *Driving simulator*

A Driving Simulator (DS) is commonly used to study human driving behavior for a variety of transportation scenarios. It provides a HuTL capability for evaluating unproven technologies, in a low-cost yet safe environment. The "safety" feature is particularly important because of the exploratory nature of TCPS research. The types of driving simulators used in the research community can be classified into three categories according to their initial cost (which is typically proportional to its feature-set): low-cost, medium-cost and high-cost [28]. Here, we describe a number of representative driving simulators in service within the transportation research community.

#### 1) *Low-cost driving simulators*

Low-cost driving simulators are the most popular setting for TCPS research. With the recent advances of PC hardware and 3D-gaming engines (e.g. OGRE and Unity3D) researchers can easily construct a low-cost driving simulator with a desktop computer and gaming control devices. Its major advantage is to have a flexible virtual environment with an inexpensive graphic display, a moderate fidelity control interface, and basic auditory cueing.

STISIM Drive [29] is a commercial driving simulator from Systems Technology, Inc. that allows users to customize driving scenarios, and develop their own plug-in modules using COM compatible programming languages such as C++ and VB. The hardware component supports a 60-180 degree driver field-of-view, a steering wheel with dynamics based feedback, and foot pedals.

OpenEnergySim [30] developed by Japan's National Institute of Informatics, is an online multi-user 3D driving simulator. It is designed to provide smooth visualization of a large-scale multi-user simulation that is accessible by the Internet. A unique feature of OpenEnergySim is that users can participate as drivers, pedestrians or as traffic engineers, which makes it convenient for conducting behavior studies in the transport domain.

#### 2) *Medium cost driving simulators*

The medium-cost driving simulators employ advanced field-of-view by adopting large curved screen, and usually provide basic motion cueing (e.g. normal vibrations while driving, and pitch during turning). Most of the driving simulators that used for TCPS research fall in this category.

The driving simulator at the University at Buffalo consists of a six degree-of-freedom motion platform and a four-screen (hexagonally arranged) projection system. Details about its research applications and its current technical configuration can be found in [31].

The Research Driving Simulator of the University of Porto [32] consists of a full-size SMART car with all controls, three-projectors, a curved screen visualization system and a sound system. The platform also provides a "Head's Up" display and a portable display system for multimodal interactions inside the cockpit.

SCANeR [33] is a driving simulator software developed by the French company OKTAL. The company also manufactures simulator hardware, and most of their products are low-medium cost simulators (an obvious exception is an 8 degree-of-freedom driving simulator that has recently been built at Tongji University). SCANeR adopts modular configuration, whereby the users can select and add modules for creating driving environments and scenarios. It offers the capability to link physiological measurements (e.g., eye movement tracking) with the simulation.

#### 3) *High-cost driving simulators*

Typical high-cost driving simulators provide advanced imaging which usually contains a full 360 degree field-of-view, and a complete vehicle cabin that includes all typical driving controls. The state-of-the-art motion system usually includes more than six degree-of-freedom (e.g., a full-fidelity motion platform on a moving track) and permits linear movement, examples in the research community are: VTI [34], UoLDS [35] in Europe and NADS [36] in the U.S. Automotive manufacturers such as Toyota, Honda, General Motors, Ford, and BMW also have interactive simulation facilities with full motion systems. A more complete list can be found in [37].

High-cost driving simulators are out of the scope of this paper, because both the hardware and software for these advanced systems are typically developed in house. It is therefore difficult and not practical for other researchers to adopt such systems for external implementation. As alternative choices, the OpenDS [38] project funded by the European Commission provides an extensible and open-source driving simulator software environment to the research community. MiniSim [36], developed at the University of Iowa, also provides a commercialized version of their NADS, which contains lower-cost hardware and tailored software components.

## III. 2-IN-1 SIMULATORS

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 often simplifies the reality. A NS commonly provides detailed simulation of communication protocols, but does not have a realistic vehicle mobility model since there is no feedback from the network simulation to the traffic simulation (e.g. they are incapable of

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studying safety applications that can affect the mobility of nodes). Moreover, a typical DS allows for studying driver behavior by immersing human subjects within a virtual simulation environment and monitoring their reactions. Unfortunately, however, a DS often lacks traffic authenticity and transportation network realism, since in the majority of simulators 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.

Given these observations, an interesting concept that has emerged over the last decade is to combine two conventional simulators for TCPS research. Several works proposed to integrate traffic and network simulators in order to adopt realistic mobility models for the evaluation of vehicular network protocols and applications. Additionally, integrating traffic and driving simulators has also attracted attention, since understanding individual driver's perception and decision-making would be beneficial to the evaluation of system-level performance.

When it comes to integrating two simulation modules, there are two general approaches: 1) the Composite Mode, that leads to tighter integration by adding the main function of one simulator to the other, or developing main functions for both from scratch; and 2) the Federated Mode, in which different simulators exchange information with each other via inter-process communications.

### A. *TS-DS integration*

The advantage of integrated Traffic/Driving Simulation is two-fold: 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 DS provides for authentic driver behavior, which is particularly important for safety-related studies, and for understanding the impact of individual driver behavior on system-level performance. A sampling of the most relevant attempts of integrating a TS with a DS is presented here, chronologically.

In [39], Jenkins et. al. described an architecture for integrating TS and DS, but did not elaborate on many technical details pertaining to the development. Later, Jim and Lam [40] carried out a study on driving behavior with a preliminary integrated driving-traffic simulator. Ikeuchi et al. [41] described an ambitious research program in Japan aimed at constructing a "Mixed Reality Traffic Experiment Space", which involved linking driving simulators with traffic simulation models. Maroto et al. [42] proposed a micro-simulation model with a user-driven vehicle surrounded by simulated traffic - referred to as the "control zone". Similarly, Olstam et al. [43] proposed a framework in which a DS was surrounded by an inner micro-simulation region and two outer mesoscopic simulation regions.

It should be noted, however, that those studies did not really involve integrating a commercial traffic simulation model with a driving simulator but rather, focused on enhancing the driving simulator by attempting to make background traffic more intelligent. Punzo and Ciuffo [44] discussed the challenges of integrating driving and traffic simulation. They proposed four main requirements for appropriately integrating TS and DS models: (1) accurate road matching between traffic and driving simulators; (2) synchronization of traffic and driving modules with real time; (3) consistency of the update calculation frequency, and (4) management of background traffic visualization.

That and Casas [45] proposed a framework combining TS Aimsun and DS SCANeR. Arturo et al. [30] introduced OpenEnergySim: a multi-user DS that is capable of integrating with a TS (X-Roads) using the OpenScience framework. Around the same time, the Utah Traffic Laboratory Driving Simulator [46] was designed to integrate Vissim with a low-cost DS called ARCHER. Gomes et al. [32] developed a coupling architecture between the TS DIVERT and the Research Driving Simulator of the University of Porto. An interesting note is that DIVERT was later upgraded to integrate with ns-3 (refer to the VNS in the next section), however it is not clear if it continues to support online integration of a DS.

### B. *TS-NS integration*

Realistic vehicle movement is the essential key to study the connectivity and communication metrics under TCPS environment. At early stages, researchers deployed TS as a trace generator to evaluate the communication layer in an offline fashion. They also tried feeding the network simulator with real vehicular traces collected in the field. The major limitation of the offline approach was that the movement of vehicles was pre-defined, and there was no two-way interaction between the communication network and the vehicle movements. In other words, drivers would not respond to the mobility or safety application that is enabled by TCPS. The same limitation also applies to the real trace approach, additionally, real traces usually only cover a certain area, date or type of vehicle, which further limited their usage.

The research community seems to converge towards using online integration of TS and NS [47]. Most of the tools discussed in this section are often considered as a VANET or IVC simulator. Recent active and ongoing projects are summarized below, for comparison studies please refer to [24, 48, 49].

NCTUns [50] is a composite simulator for vehicular network research with a closed loop between network simulation and traffic simulation. After version 6.0, the project went commercial under the name EstiNet. EstiNet provides an advanced graphic user interface, and is capable of simulating a wide range of networks and protocols. A unique feature of EstiNet is that it directly uses real-life UNIX network protocol stack. It is capable of running real UNIX compatible application programs without any modification. However, this feature may also limit its adoption, because EstiNet only runs on Fedora.

GrooveNet [51] originally known as GrooveSim, is another composite simulator. Besides integrating traffic and network simulation, GrooveNet supports interactions and communications between real vehicles and simulated ones.

This unique ability allows it to function as a test-bed software as well as a simulator. However, implementing customized modules in GrooveNet requires a complete knowledge of the simulation platform, and thus developers may find doing this somewhat difficult, especially with the limited documentation available.

Veins [52] is an open source framework that integrates OMNeT++ and SUMO via TCP connections. The Traffic Control Interface (TraCI) [14] is used as the communication protocol. Veins achieves bidirectional coupling of both simulators such that the movement of vehicles in SUMO are reflected in the movement of the nodes in OMNeT++, and vice versa.

iTETRIS [53] is an EU-funded simulation platform that combines SUMO and ns-3. The central block of this open source platform is referred to as iTETRIS Control System (iCS). The modular architecture of iCS allows the platform to interface with modules written in different programing languages through sockets; such modular design is also beneficial for future upgrades. Additionally, iTETRIS is designed to support large scale simulation, and is compliant with ETSI Technical Committee on ITS Communication Architecture.

VSimRTI [54] provides a generic integration between traffic, and network simulation which allow user to choose from different simulators. Currently supported simulators including: JiST/SWANS [55] (a NS that no longer officially maintained), OMNeT++, ns-3, SUMO and VISSIM. VSimRTI's design is based on the simulation runtime infrastructure concept in IEEE standard for modeling and simulation high-level architecture [56]. By adopting this architecture, VSimRTI is capable of integrating other time-discrete simulation models, so as to directly integrate with commercial software.

Simulation development is an active area in the research community, and new software and tools are always under development. Some of the most recent developments include: VACaMobil [57] which provided new mobility manager for OMNeT++ by running in parallel with SUMO. BHU-VSim [58] combined mobility models and routing protocols to simulate the delay tolerant network features in the vehicular environment. Within the VNS [59] framework, DIVERT 2.0 was redesigned from scratch to integrate with ns-3. Finally, HINT [60], focused on improving the efficiency of the integration between SUMO and ns-3. It demonstrated improvements in terms of reduced simulation time and computational cost.

## IV. 3-IN-1 INTEGRATED TRAFFIC, DRIVING AND NETWORKING SIMULATION (ITDNS)

### *A. Motivations*

To address these challenges, the authors of this paper propose to use 3-in-1 simulators which integrated both traffic, driving and network models for TCPS testing and evaluation. Specifically, the unique advantage of 3-in-1 simulator stems from its HuTL design which allows for observing and understanding the drivers' perceptions and responses to a given TCPS application, and the implications of the observed response with respect to improving (or worsening) the transportation system safety or sustainability. For example, observing human subjects' response in the 3-in-1 simulator can provide answers to questions such as: (1) what kind of alert or warning messages is more effective and easy to perceive by drivers? (2) To what level are drivers willing to comply with the alerts or advisory messages (e.g. slow down when receiving an incident alert without physically seeing the incident scene for themselves)? (3) Are eco-driving tips and feedback messages truly effective in changing driver patterns to make them more eco-friendly? Addressing these very important human factors issues appear to be missing in many of the previous simulation-based studies.

There is a second important reason which underscores the importance of understanding and correctly accounting for human factors issues when designing and evaluating TCPS applications, which is the evolutionary nature of the likely deployment path of TCPS. In the case of autonomous vehicles, for example, transitioning from a driving environment in which the human driver is the primary responsible agent for controlling the vehicle, as is the case today, to an environment in which vehicles are fully autonomous cannot happen immediately. Instead, the transition would have to take place in phases, in which incremental levels of human control are relinquished to automation over time. This means that in the short- and medium- term, TCPS systems would be designed to basically provide human drivers with advisory and alert messages, leaving the final driving control decision to the human driver.

Moreover, in terms of market penetration of TCPS applications, in the early stages, only a small portion of vehicles will be equipped for TCPS applications via wireless communications and on-board driving assistance devices. It thus becomes essential to study the interactions between equipped and non-equipped vehicles at both the microscopic and macroscopic levels. Once again, the 3-in-1 simulator may be ideal for studying such situations (e.g., how human drivers in non-equipped vehicles interact with equipped vehicles).

The third unique advantage of including the human element in the 3-in-1 simulator is the ability it provides for modeling the salient features of TCPS. To the authors' knowledge, there are currently no commercial simulation packages that explicitly model the impact of TCPS messages on driver behavior (e.g., safety warnings communicated via V2V and V2I communications). With the 3-in-1 simulator, the response of human subjects to various TCPS warning or advisory messages may be observed, analyzed and finally used to build new driver behavior models that explicitly accounts for the impact of TCPS messages on driving behavior. As mentioned before, these models could then be integrated within the 3-in-1 framework.

### *B. 3-in-1 simulators*

The authors of this paper have developed a 3-in-1 Integrated Traffic-Driving-Network Simulator (ITDNS) [61]. The simulator consists of: Paramics, ns-2 and the driving simulator

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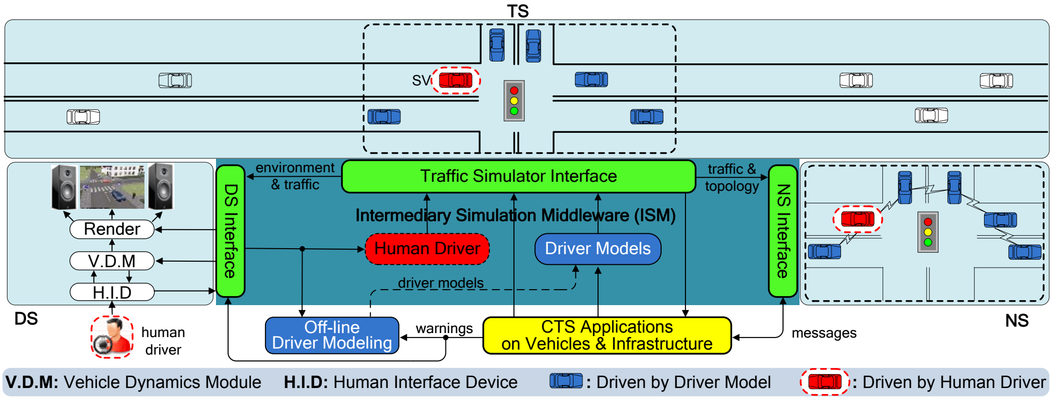

Figure 1. Integrated Traffic-Driving-Network Simulator (ITDNS)

at the University at Buffalo. Fig. 1 shows the overall architecture of our ITDNS. 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 ITDNS. Some of the technical issues and their solutions were discussed in [69], the details of the overall development deserve a separate paper, and we state that as the future work. From users' perspective, the ITDNS works as follows:

TS is used to generate a fairly realistic driving environment (e.g. road, traffic lights), and background traffic consisting of vehicles controlled by microscopic agent-based car-following, lane-changing modes. It also uses one or multiple DSs, which consist of an instrumented vehicle with realistic cuing (graphic, motion and audio) that is operated by a human participant, thus supporting both HaTL and HuTL environment. Finally, ITDNS uses a NS capable of simulating various V2V and V2I communications as well as other wireless/wireline communication infrastructures.

The integration of Paramics and DS is implemented via a two-way data exchange, which allows the actions of the human subject in the DS to be reflected or mimicked by one chosen vehicle in Paramics. Simultaneously, Paramics and ns-2 are integrated to allow them to run in parallel, a complete feedback loop is implemented to send results from the NS back to the TS for further action. By leveraging the advantages unique to each stand-alone simulator, we believe our 3-in-1 simulator is the future trend in TCPS simulation. To the best of our knowledge, ITDNS is the first 3-in-1 simulator that has been developed.

A unique feature in ITDNS is that it allows for implementing new driver behavior models within the TS, which reflects how drivers are likely to react to warning messages coming from a TCPS application (e.g. collision warning message). Moreover, the ITDNS is capable of linking to the MOVES emission model for research on sustainability [62].

Note that at the time of writing this article, we came across a very recent project that develops the so-called Cyber-Physical System Simulator (CPSS) [63]. CPSS, a joint project between Japanese and Australian researchers, appears to be attempting to develop a tool similar to our own ITDNS. The key features of CPSS include: simulate multiple drivers in a 3D environment named DiVE, and integrating traffic, driving and network simulation through a dedicated middleware called OpenV2X.

The multiuser driving simulator DiVE is extended from OpenEnergySim with improved user capacity. It is reported to be capable of supporting 100 simultaneous user-driven cars and 200 low-cost traffic simulator-controlled cars. An interesting note is that DiVE also runs on an iPad. The middleware OpenV2X integrates DiVE with the traffic simulator OpenTraffic, and also provides connection with OMNet++ by utilizing MiXiM (which is an OMNet++ extension under the INET Framework).

Compared with ITDNS, CPSS allows researchers to study the behavior of large groups of travelers (including both driver and pedestrians) that share the same simulation space. However, the tradeoff has been made to reduce simulation fidelity. Compare with its counterpart in CPSS, ITDNS has an advantage in terms of its TS and NS capacities, thanks to the well-established developments within the ns-2 and the Paramics communities.

### *C. Case studies*

Since the development of the prototype ITDNS, we have been taking advantage of its unique capabilities, and in particular its *human-in-the-loop* simulation capability in several research studies related to TCPS applications. In this section, we will briefly review three of those studies which focused on evaluating: (1) an eco-signal application; (2) human perception of autonomous driving, and (3) data fusion for a safety application.

#### *1) Eco-Signal application*

One of the first applications to which we applied ITDNS is an evaluation of the likely benefits of the eco-signal concept [70]. Eco-signals are designed to provide vehicles approaching a signalized intersection with an advisory speed which allow them, if possible, to arrive at the intersection on green, thereby avoiding the need to stop at the intersection [18, 64]. The unique aspect of our study, however, was that, thanks to the HuTL capability of ITDNS, we were able to explicitly account for driver reaction to the advisory speed and to assess the likely fuel and emissions savings resulting from a humanly-controlled approach speed trajectory.

To implement the eco-signal application in the ITDNS, a speed panel was projected at the DS display. As soon as the vehicle entered the communication range of the eco-signal, the panel showed a recommended speed to the driver. The speed

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was calculated based on the signal phasing and time information as well as safety considerations (i.e., collision avoidance). In the experiment, each participant was asked to perform two test runs, one with the eco-signal application and one without it. Their second-by-second speed trajectories were then imported to MOVES2010 model for energy and emission calculations.

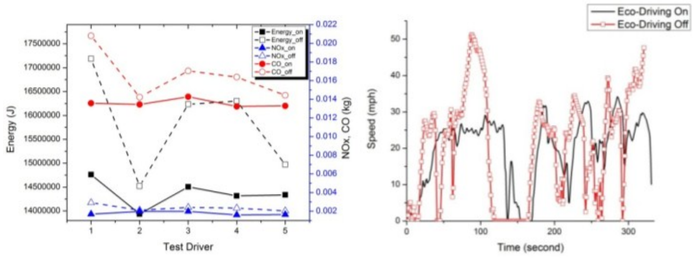

Figure 2. (a) Energy, NOx, CO w/ and w/o Eco-Driving (b) Speed-Time Diagrams w/ and w/o Eco-Driving

Based on experimenting with a rather small sample of drivers, the preliminary results indicated the potential of the eco-signal concept to result in tangible reductions in fuel consumption and emissions, even when manually implemented (i.e., when the vehicle's approach speed is controlled by the human driver in response to the advisory speed provided by the application). Specifically, depending upon the aggressiveness level of each driver, our results indicated savings between 4% to 14% percent in fuel consumption, between 6% and 35% in Carbon Monoxide (CO) emissions, and between 6% and 42% in Nitrogen Oxides (NOx) emissions. Refer to Fig. 2, the average savings for the sample of drivers tested were 9% for energy consumption, 18% for CO and 25% for NOx.

### *2) Driver acceptance of an autonomous speed control system*

Instead of investing in high-cost instrumentations, ITDNS provides a low cost simulation environment with decent fidelity to conduct research on autonomous vehicles. Our recent study has focused on the minimum acceptable headway and driver acceptance associated with an autonomous speed control system.

In general, all the autonomy features related to the control of the vehicle's speed are referred to as the Autonomous Speed Control System (ASCS). Compared with adaptive cruise control which is capable of maintaining a fixed headway by adjust speeding, ASCS has advanced functions such as bringing the vehicle to a complete stop, exchanging information with the surrounding vehicles via wireless communication, or predicting environmental factors such as wind speed and road slope. Besides the improved driving experience, comfort level and reduced workload of the driver, ASCS also have the potential to dramatically reduce vehicle headway. This in turn could result in significant increases in roadway capacity, without additional infrastructure capital investment.

In [65], we conducted simulation experiment with ITDNS to answer the following two questions: (1) What is the minimum headway with which the driver would feel comfortable when driving in an autonomous environment? and (2) What would affect the driver's acceptance of the autonomous speed control system in free flow traffic?

To explore the gender difference with the ASCS, 30 participants were recruited, 15 males and 15 females with an average age of 26.7 years and an average annual driving mileage of 5,300 miles.

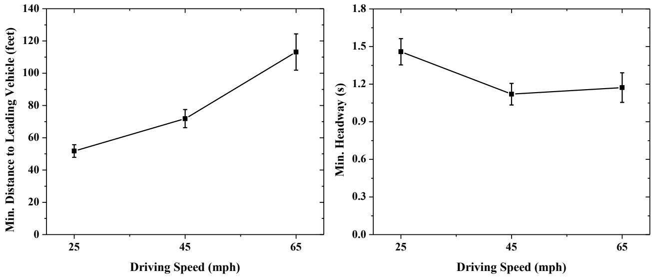

Figure 3. (a) Effect of speed on the minimum headway (b) Effect of speed on the minimum distance to leading vehicle

The results showed that headway has a significant effect on the participant's opinion of the autonomous speed control system (i.e., workload, confidence, comfort, safety and acceptance), whereas no significant effect of the driver's gender or traffic speed was observed on the driver's opinion. At different driving speeds (i.e. 25, 45, 65 mph), the headway assigned by the participants remained stable (refer to Fig. 3 (a)) with an average of 1.12 - 1.26s (Standard Derivation .47 - .65s). This study also demonstrated that most drivers maintain spacing between vehicles relying on their judgment on distance (Fig. 3 (b)), and their judgment on headway is unreliable (i.e., most drivers are unable to jointly consider both speed and distance).

### *3) Human centric data fusion for safety application*

It can be said that the effectiveness of safety applications depends heavily on how a human driver interact with them. An application that overwhelms or confuses the driver with either too much information or by providing complicated warnings will be ignored, if not turned off completely, even if the information is generally accurate. It is crucial not only to consider networking and transportation issues when designing such applications, but also to keep the human factors aspects in mind. ITDNS is an ideal platform for conducting safety related research when it comes to such multi-perspective experiments. It allows for realistic HuTL testing while ensuring the test subject's safety.

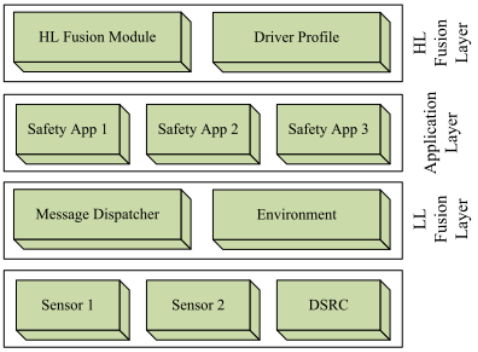

Fig.4 Multi-Layered Architecture for Data-Fusion

In [66], we proposed a multi-layered data fusion architecture to incorporate the human factors perspective into the design of connected vehicle system. As shown in Fig. 4, we address this issue at two different levels: we place one fusion layer between the applications and the human driver to process the application-generated warnings before they are delivered to the driver, and another layer between the applications and the communication network to optimize the information that is being exchanged over the wireless channels. The first of the two layers is referred to as the High Level (HL) fusion layer; its main task is to capture all the messages that are generated by the on-board applications and optimize the way in which this information will be presented to the driver. A three-step algorithm housed in this layer processes the messages by removing redundancy and content that has no significant impact on the specific driver and delivers only the most useful information on the appropriate modality (audio/visual/tactile or some combination). The algorithm considers the driver's possible evasive maneuvers, the locations of the potential hazards, familiarity with various warnings and past reactions to them, and also their message presentation preferences. We used warning messages such as Speeding, Forward Collision, Hard Braking, and Intersection Violation in our pilot study to test our algorithm [66].

We tested the response to violating cross traffic in three scenarios where the subject vehicle was equipped with: 1) No warning system; 2) A warning system without data fusion; and 3) A warning system with data fusion. Test drivers drove the subject vehicle in an urban environment. They encountered a total of 29 intersections along the way with the violating cross traffic vehicles at 9 of them. We programmed surrounding vehicles, and buildings lined on each side of the road, such that it was difficult for the test driver to spot the cross traffic until she had driven into the intersection. When a violation occurred, we observed the reaction of the human drivers.

We found that the quality and timeliness of the drivers' reaction were improved when they were only warned about the most pertinent threat as compared with warning them about multiple possible threats or not providing any warnings (to simulate our present day scenario where such systems are not installed) as seen from Fig. 5.

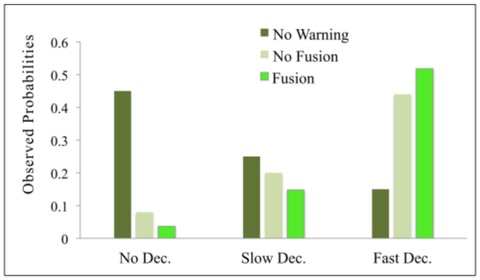

Fig.5 Observed probabilities for No Deceleration, Slow Deceleration, and Fast Deceleration responses at intersections with violating cross traffic in Fusion, No Fusion and No Warning scenarios

Unlike the HL fusion layer, which works at the message level with information generated by the applications, the other layer (referred to as the low level or LL fusion) deals with raw data in the form of discrete data elements. Each data element represents a discrete piece of information (to model the SAE's Data Dictionary concept) that represents one specific datum about the scenario. E.g. speed, acceleration, heading, and position are all discrete data elements that can be put together to form a beaconing message that can be broadcast periodically. In [67], we used the message dispatcher concept [68] as our starting point and developed techniques that could: 1) break up messages by removing information that was not absolutely critical and 2) fuse multiple outgoing messages by considering not only their content but also their utility to other drivers. Multi-sender and receiver scenarios were also examined. In general, we found that using our algorithm provided improvements in terms of the overall utility that could be exchanged between multiple vehicles given the scarce nature of the wireless resources that are available in connected vehicle networks.

### *D. Validation*

It is widely recognized that simulation results are only significant with proper validation and calibration. In the context we are considering herein, the major concern is with the subjective difference between the virtual and real-world in terms of variables, such as traffic density, packet lost rate and vehicle dynamics. It is worth noting that the validity of the driving subject's behavior on a tactical and strategic level, such as evaluating novice driver's performance and driving behavior after alcohol intake, deserves additional attentions from social scientist.

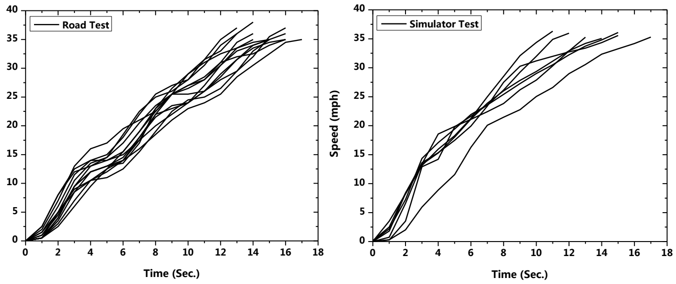

Fig.6 Acceleration profiles for a given participant from the validation study

Given the federated structure of ITDNS, it is nature for us to divide the validation task into two parts: TS-DS, and TS-NS validation. The TS-DS component in ITDNS was first validated, the TS-NS component is currently under enhancement and calibration. Our validation on TS-DS was reported in [69]. Several human subjects were recruited to drive a 2.5 mile long segment of a signalized arterial in both the virtual environment and the real-world during evening "rush hours". A few 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. As an illustrative example, Fig. 6 compared the acceleration profile of driver in the simulation environment compared to the field. Given space limitations, only one test participant is shown in the figure.

## V. FUTURE WORK

The integration frameworks introduced herein, including TS-DS, TS-NS and our current 3-in-1 simulator, can be viewed as the initial steps towards the development of a comprehensive simulation environment for TCPS research. The potential avenues for their extensibility and expansions can be expected in three directions:

(1) Implementing customized human behavior model to enhance the traffic mobility: This is target at override driver's model in a traffic simulator with experiment-specific human behavior models. Human factors and ergonomics researcher have been studying how a driver may response to different scenarios, which have so far been largely underutilized in commercial traffic simulation. Given a particular set of driver profile and environment settings, researcher could customize different human response models to mimic human behavior (e.g., response to warning messages) thus improving the realism of their experiment.

(2) Providing high-fidelity, multiple-participant capability to facilitate research that involves interaction between human participants. Two or more driving simulators should be able to connect in real-time, which allow human drivers to interact with each other. Despite the success of driving simulators such as DiVE that has already provided certain level of multiple driver capacity, there is still room for improvement in terms of functionality and fidelity. Multiple-participant environment would be essential when studying the incremental development of TCPS (i.e., when both automated and human-driven vehicles are on the road). For example, in a platoon research, two-participant capability would help to guide the design of how vehicle join/leave a platoon, and provide insight of how other human drivers interact with platoon vehicles.

(3) Developing a generic programming interface to promote collaboration among different research groups: This involves the design of a common standard for the 3-in-1 integration. Most of the tools reviewed in this paper can only establish linkage between a particular pair of simulations. Although VSimRTI provides a generic interface for TS-NS integration, developers may still find it challenging, if not impossible to connect their in-house DS to VSimRTI. With a generic 3-in-1 interface, researchers would be able to choose a simulator they prefer, and easily set up their experiments.

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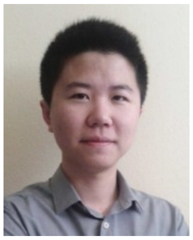

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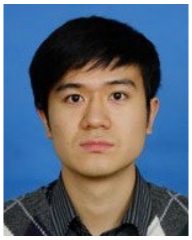

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