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Dyno-in-the-Loop: An Innovative Hardware-in-the-Loop Development and Testing Platform for Emerging Mobility Technologies

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Abstract

Today's transportation is quickly transforming with the nascent advent of connectivity, automation, shared-mobility, and electrification. These technologies will not only affect our safety and mobility, but also our energy consumption, and environment. As a result, it is of unprecedented importance to understand the overall system impacts due to the introduction of these emerging technologies and concepts. Existing modeling tools are not able to effectively capture the implications of these technologies, not to mention accurately and reliably evaluating their effectiveness with a reasonable scope. To address these gaps, a dynamometer-in-the-loop (DiL) development and testing approach is proposed which integrates test vehicle(s), chassis dynamometer, and high fidelity traffic simulation tools, in order to achieve a balance between the model accuracy and scalability of environmental analysis for the next generation of transportation systems. With this DiL platform, a connected eco-operation system for the plug-in hybrid electric bus (PHEB) has been developed and tested, which can optimize the vehicle dynamics (and potentially powertrain control via smart energy management) to reduce the operational energy consumption as well as tailpipe emissions of the target PHEB. The system performance has been evaluated on the DiL platform with respect to a variety of traffic congestion levels. The results have shown that the developed system can save fuel by more than 13% while reducing the electricity consumption by 2% in the test scenarios.

1. Introduction

1.1. Emerging Mobility Technologies

The emergence of nascent concepts, technologies and services associated with Intelligent Transportation Systems (ITS), such as connected and automated vehicles (CAVs), cybersecurity, electric vehicles and smart grids, and Mobility as a Service (MaaS), has placed our contemporary transportation system on the cusp of a seismic shift. It is predicted that more than 18 million new automated vehicles (with different levels of automation) will be added to the global market by 2030, and the autonomous driving market will be valued at about $173 billion, 65.31% of which will be contributed by the shared mobility service [1].

Many practitioners and decision-makers wonder how these emerging technologies and services will affect our daily travel patterns (such as demand, travel mode, and route choice), land use, energy consumption, and climate change; and what public policies (encourage or restrict their use) should be enacted to steer their development in a favorable direction [2]. As a result, it is of unprecedented importance to develop appropriate development and testing approaches to understand the system impacts in terms of safety, mobility, and environmental sustainability due to the introduction of these emerging technologies and concepts.

1.2. State-of-the-Art Development and Testing Approach

Over the past decade, a variety of approaches and tools, especially numerical/simulation software, have been developed to evaluate the intelligent transportation systems. They can model the target transportation systems from different perspectives (such as vehicle simulator, driving simulator, and traffic simulator) at different scales (i.e., microscopic, mesoscopic, and macroscopic). However, any of these numerical/simulation tools, if used exclusively, has its own limitation. For example, it is deemed as a great challenge to calibrate the state-of-the-art microscopic traffic simulators to properly model detailed vehicle dynamics, not to mention autonomous vehicles' behaviors [3]. On the other hand, although the vehicle simulator is well able to model an individual vehicle including its powertrain components and on-board sensors as well as evaluate their performance, it is overwhelming to integrate the interaction with other road users or roadway infrastructure. All these lead to some major hurdles to accurately and reliably evaluate the energy efficiency of these emerging technologies, and even more difficulties to scale up the assessment on a larger spatial scale (e.g., statewide, nationwide) or project the impacts over a longer temporal span.

To address these issues, some studies have proposed multi-resolutioned simulation approaches. For example, Argonne National Laboratory's POLARIS regional transportation simulation tool was coupled with the Autonomie vehicle-scale simulation to evaluate the impact on regional travel demand and energy consumption due to the introduction of privately-owned vehicles with high level of automation [4]. DLR's microscopic traffic simulator, SUMO, was connected with the Unity game engine to evaluate V2X communication-based advanced driver assistance systems [5]. Despite its relatively low cost, this type of approach relies on the simulation models heavily which sometimes may not be able to accurately capture the situation in the real world.

Other researchers take advantage of various "X-in-the-Loop" (XiL) concepts, such as Hardware-in-the-Loop (HiL), Software-in-the-Loop (SiL), Model-in-the-Loop (MiL), Vehicle-in-the-Loop (ViL), and Human-in-the-Loop (HuiL), as the testing approaches to evaluate the emerging transportation technologies. Federal Highway Administration developed an HiL testbed to evaluate the Eco-Approach and Departure application with the consideration of queue where a real test vehicle and communication equipment were integrated with a microscopic traffic simulator [6]. The University of Michigan resorted to their M-City physical environment laboratory in conjunction with PTV VISSIM to evaluate connected and automated vehicle applications [7]. However, these experiments are usually overwhelming due to the resource constraints (e.g., costs, dedicated test sites).

1.3. Contributions and Innovations

In this paper, an innovative HiL development and testing platform, called Dyno-in-the-Loop (DiL) is proposed, where the chassis dynamometer is coupled with real test vehicle(s), microscopic traffic simulator, to perform cost effective system evaluation of emerging transportation technologies and services, such as connected and automated vehicle (CAV) applications.

Besides the advantages of a generic HiL development and testing platform, such as higher fidelity than pure simulation platform and flexibility to fuse other elements (in the form of either hardware or software), the proposed DiL platform has the following key innovations:

1. There is no need to reserve a dedicated testing track which may be too costly for the operation and maintenance. On the other hand, different roadway networks and traffic scenarios can be created for modeling and evaluation, by using the same hardware setup.
2. It provides a perfect balance between model accuracy and evaluation scalability for the *environment-oriented* emerging technologies, e.g., CAV-based eco-driving. As a cost effective approach, the platform can keep the emerging technologies tangible on a limited scale, based on which the effectiveness can be reasonably gauged and extrapolated to a larger scope.

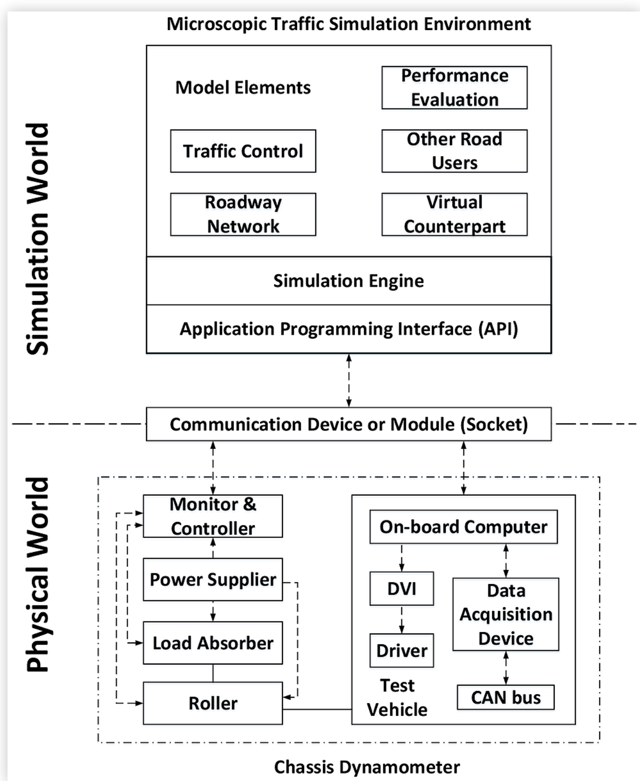
1.4. Paper Organization

The remainder of this paper is organized as follows. Section II details the system architecture of the proposed DiL development and testing platform, followed by the case study of connected eco-operation for plug-in hybrid electric bus in Section III. Section IV further discusses on the opportunities in the application of DiL platform, and Section V concludes this paper along with future steps.

2. Dyno-in-the-Loop System Architecture

Figure 1 presents the general system architecture of the proposed Dyno-in-the-Loop (DiL) development and testing platform, which basically consists of physical world and simulation world with the communication device or module (e.g., sockets) being the connection between two worlds.

FIGURE 1 System architecture of DiL platform.



In the physical world are the chassis dynamometer and test vehicle. Major components in the chassis dynamometer include rollers, load absorbers (e.g., brake), power supplier, and monitoring and control system, besides the structural steel frame and auxiliary system (e.g., cooling system). On the test vehicle are the data acquisition system (via OBD or J1939 CAN bus, depending on the type of vehicles), and on-board computer. The on-board computer may process the information retrieved from CAN bus and/or send control signals back if any real-time vehicle/powertrain control algorithm is running. If an advanced driver assistance system is developed, the advisory information can be delivered to the driver through the driver-vehicle interface (DVI).

Using the Application Programming Interface (API), the information of test vehicle and chassis dyno (e.g., roller speed) can be transmitted to the microscopic traffic simulator (i.e. the simulation world) where a virtual counterpart of the test vehicle is synchronized in real time with the test vehicle in terms of vehicle dynamics (at least the longitudinal speed). The simulation engine governs the operation of other road users (including surround vehicles, pedestrians, and bicyclists) and the traffic control modules (such as traffic signals). The system level performance can be evaluated with embedded functions or via user-defined plug-ins. As aforementioned, one critical feature of the DiL development and test platform is its flexibility in modeling and evaluation under different roadway networks and traffic conditions which can be easily adjusted in the simulation environment. Also, if different market penetration rates of the target emerging technology need to be tested, this can be achieved by modifying the other vehicles' behaviors through APIs.

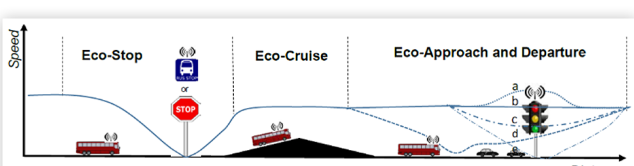
3. Case Study

3.1. Connected Eco-Operation for PHEB

In this paper, an innovative Connected Eco-Operation System for Efficient Plug-in Hybrid Electric Buses (PHEBs) was evaluated with the proposed DiL platform. By leveraging the CAV technology, this system can perform the co-optimization of vehicle dynamics (longitudinally) and powertrain control (mainly the determination of power split) to reduce the energy consumption and tailpipe emissions of the target PHEB [8].

More specifically, the system integrates three CAV applications: 1) Eco-Stop; 2) Eco-Cruise; and 3) Eco-Approach and Departure as illustrated in Figure 2. The *Eco-Stop* application determines the most energy-efficient longitudinal speed profile for decelerating to and accelerating from bus stops and stop signs whose locations are predefined. Based on the look-ahead traffic and terrain (e.g., road grade) conditions, the *Eco-Cruise* application identifies the speed profile with least energy consumption. The *Eco-Approach and Departure* application utilizes the signal phase and timing (SPaT) information of upcoming signals and downstream vehicular queue length to calculate the eco-friendly speed trajectory for passing through the intersections [9].

FIGURE 2 Illustration of the Connected Eco-Operation System for a PHEB, including Eco-Stop, Eco-Cruise, and Eco-Approach and Departure.



3.2. Vehicle Dynamics Optimization Algorithm

The vehicle dynamics optimization is formulated as a shortest path problem in a weighted directed graph model $G = (V, E, C)$ where V, E, C represent the set of nodes, edges and costs, respectively, and the time and space are discretized into fixed time step Δt and distance grid Δx. Therefore, the speed is also discretized with the step of $\Delta x/\Delta t$ for consistency. For each node, a 3-tuple (t, x, v) is assigned which describes the dynamic state of the subject vehicle, where $t \in (0, T]$ is the time (in second); $x \in [0, L]$ is the traveled distance (in meter) along the entire route with the length of L; and $v \in [0, v^{\text{Limit}}]$ is the speed (in m/s). The edge defines the connectivity between two nodes, and $e_{V_i \to V_j}$ is created from $V_i(t_i, x_i, v_i)$ to $V_j(t_j, x_j, v_j)$ if and only if the following rules are satisfied:

1. Consecutive in time, i.e., $t_j = t_i + \Delta t$;
2. Consistency between distance and speed: $x_j = x_i + v_i\Delta t$
3. Boundary on acceleration and consistency between speed and acceleration, i.e.,

$$a_{min} \le \frac{v_j - v_i}{\Delta t} \le a_{max}$$

where a_{min} and a_{max} are the maximum deceleration rate and maximum acceleration rate for the subject vehicle, respectively. The jerk constraint can be applied in a similar manner.

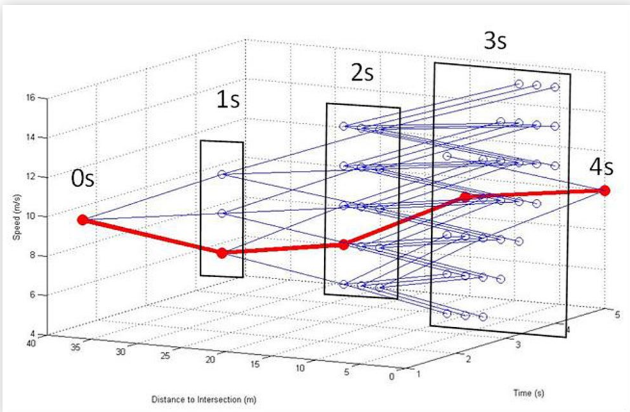
The energy cost between node i and node j, $c_{V_i \to V_j}$ on edge $e_{V_i \to V_j}$ is estimated by:

$$c_{V_i \to V_j} = \begin{cases} Q_t\left(v_i, \dfrac{v_j - v_i}{\Delta t}, \theta_i\right) & \text{if } \dfrac{v_j - v_i}{\Delta t} > a_{coast} \\ Q_{idle} & \text{if } \dfrac{v_j - v_i}{\Delta t} \le a_{coast} \end{cases} \quad (1)$$

where the road grade θ_i can be estimated by the elevations between nodes V_i and V_j; a_{coast} represents the coast-down acceleration; and Q_{idle} and $Q_t(\cdot)$ denote the energy consumption rate for idling and in motion, respectively. Readers may refer to [10] for detailed derivation of a_{coast}, Q_{idle}, and $Q_t(\cdot)$.

Upon the completion of this directed graph model, the Dijkstra's algorithm [11] (or other heuristic path searching algorithm, e.g., A* search algorithm [12]) can be applied to solve this single source shortest path problem with non-negative cost, where the computational complexity is $O(\log(N)*E)$. Figure 3 depicts an example where the target vehicle travels along a road segment (36 meters long) in 4 seconds with both the initial and final speed being 10 m/s. The time step Δt is 1

FIGURE 3 An example to illustrate the vehicle dynamics optimization algorithm by constructing the graphic model and formulating into the shortest path problem.



second, the distance grid Δx is 2 meters, and the maximum and minimum acceleration rates are 2 m/s^2 and -2 m/s^2, respectively.

3.3. Setup for DiL Test Platform

As a valuable laboratory resource at the Bourns College of Engineering - Center for Environmental Research and Technology (CE-CERT) at the University of California, Riverside (UCR), the Mustang heavy-duty chassis dynamometer (HDCD) is used in this study. The 48-inch HDCD is capable of absorbing continuous loads of 600 hp, with vehicle inertia simulated in the weight range of 10,000-80,000 lb [13].

A PC with PowerDyne software is interacting with HDCD, running frontend program with graphical user interface (GUI). It allows the user to create/select vehicles in order to keep track of the vehicle parameters (e.g., road load coefficients, horsepower, and curb weight) which can be used to simulate the situations as in the real world. In addition, to enable the connection between HDCD and traffic simulation environment, the PowerDyne API is used to create customized frontend to set the parameters, extract the real-time states of chassis dynamometer, and send them to the simulation environment to update the states of virtual counterpart.

The PHEB in this case study is a converted (hybridized) compressed natural gas (CNG) bus to a plug-in hybrid electric one. For the testing, it needs to be positioned and chained down to the HDCD. If a relatively high state of the charge (e.g., SOC >30% to actively engage the electric motors) needs to be maintained throughout the test, a charging cable is required to keep connecting with a 220V electric power supply. The detailed specifications of the test PHEB are listed in Table 1 below.

An on-board data acquisition system from Vector Informatik (CANcaseXL) [14] is used to receive (and transmit if needed) J1939 messages from (and to) the in-vehicle network bus. An on-board computer installed with Vector CANalyzer is connecting to CANcaseXL and used to record the data (and create desired CAN messages if needed).

TABLE 1 Specifications of the CNG plug-in hybrid electric bus.

Make / Model	US Hybrid / PHEB
CNG Engine	Cummins ISB6.7 G 240
Horsepower	240 hp @ 2400 RPM 300 hp peak with electric assist
Weight	34,760 lb (curb weight, no passengers)
Length	44 ft 10 in (including frame extension)
Width	102 in
Height	134 in (including CNG roof tanks)
Wheelbase	274.6 in

In the following, the test with driver assistance is elaborated.

3.4. Test with Driver Assistance

The system architecture of the scenario with driver's assistance is outlined in Figure 4. The upper left quadrant represents the test PHEB on the chassis dynamometer. The speed information is communicated with the simulation engine (PTV VISSIM [12] in this study) on the upper right quadrant. The downstream traffic states (including both vehicles and traffic signals) and network geometry of the simulation model are delivered to the Matlab routine (i.e., the lower right quadrant) for calculating the most energy-efficient vehicle dynamics. The optimal advisory speed profile and instantaneous speed are delivered to the driver (in the lower left quadrant) through a driver-vehicle interface (DVI) mounted on the vehicle dashboard. In this case, full longitudinal control is handled by the driver by using the throttle and brake. Lateral maneuvers are not simulated.

Regarding the microscopic simulation model with PTV VISSIM, a real-world traffic network is coded, including a 3-mile signalized corridor along the University Ave. between Lime St. and Canyon Crest Dr. at Riverside, CA, as shown in Figure 5. The simulated corridor consists of eleven signalized intersections and seven bus stops on the eastbound bus route

FIGURE 4 System architecture of the test scenario with driver assistance.

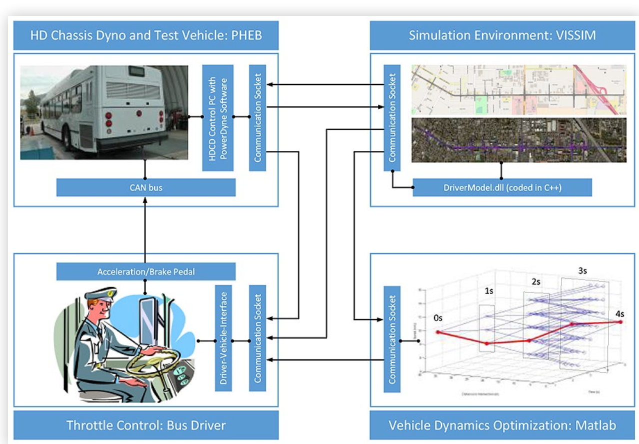
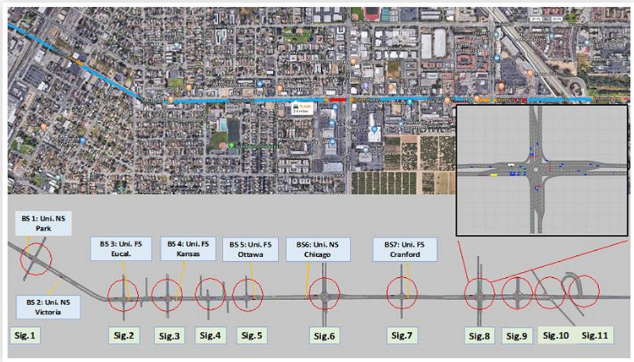


FIGURE 5 Simulated network in PTV VISSIM for PHEB testing (BS: bus stop) [15].



(see Figure 5). The traffic volumes and signal timing settings (from the City of Riverside) represent the traffic conditions on a typical weekday in the early Summer of 2016. The bus schedule and passenger information are fed into the simulation network based on the survey data from the Riverside Transit Agency (RTA). The baseline bus dynamics (i.e., functional relationship between speed and acceleration) has been calibrated by using the real-world data collected from RTA buses serving along the same route.

In addition, to create an immersive environment for the driver to respond naturally in real-time to the surrounding traffic and upcoming signal lights, a large display is positioned in front of the PHEB with the PTV VISSIM model configured in the first-person view. Figure 6 illustrates the developed mixed-reality environment where the driver's perspective and bird's-eye view of the roadway in the simulation environment as well as the advisory information shown in the DVI (in the real world) are present. To maintain realistic and natural behavior from the driver, the latency between driver's input and simulation response needs to be minimized.

As described earlier, the PowerDyne API is used in the DiL testing and a customized routine is created to enable the speed of the dynamometer to be sent to the VISSIM simulator in real-time via a UDP socket. With the receipt of dynamometer's states, the VISSIM model can control the virtual counterpart within the simulation environment in real time via the DriverModel.dll.

3.5. Test Scenarios and Result Analyses

To evaluate the performance of the developed Connected Eco-Operation System for PHEB, two scenarios including the baseline PHEB without the technology and the optimal PHEB equipped with the technology are tested in the driver assistance mode by using the DiL platform. Five different congestion levels of traffic are created: a) very light traffic (volume to capacity or v/c is 0.17); b) light traffic (v/c is 0.35); c) moderate traffic (v/c is 0.52); d) heavy traffic (v/c is 0.7); and e) very heavy traffic (v/c is 1.0).

Figure 7 presents some example speed profiles (concatenating five simulation runs with different seeds) of the PHEB from the testing under the baseline and optimal scenarios at the heavy traffic condition. As can be seen from the figure, due to the availability of downstream traffic information via connected vehicle technology in the optimal scenario the equipped PHEB is able to avoid coming to a full stop in many situations (including at signalized intersections) and the standard deviation of speed is reduced by 21%), compared to the case in the baseline scenario.

Table 2 summarizes the results of energy savings (both fuel and electricity) for the PHEB in the optimal scenario across different traffic congestion levels. As can be observed from the table, the fuel savings for the optimal scenario increase as the traffic gets more and more congested, but the electricity consumption may vary depending on the baseline energy management logic. For example, under the moderate traffic condition, the equipped PHEB can reduce the fuel consumption by around 12% at the expense of a 23% increase in electricity consumption. It is noted that all the values are measured with J1939 CAN messages and the fuel consumption here is diesel equivalent. For fair comparison, the initial states of charge (SOCs) for baseline and optimal scenarios have been maintained similar for each test case of different traffic

FIGURE 6 PHEB on HDCD (upper-left panel); driver's perspective (upper-right panel); bird's-eye view of the road network (lower panel); Advisory information on DVI (middle panel).

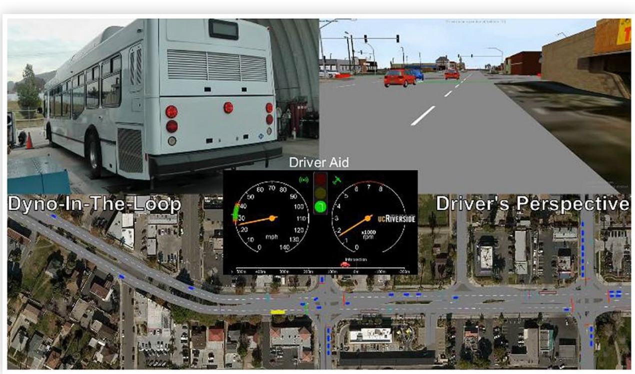


FIGURE 7 Example speed profiles (concatenating 5 simulation runs with different seeds) under the heavy traffic condition (baseline vs. optimal).

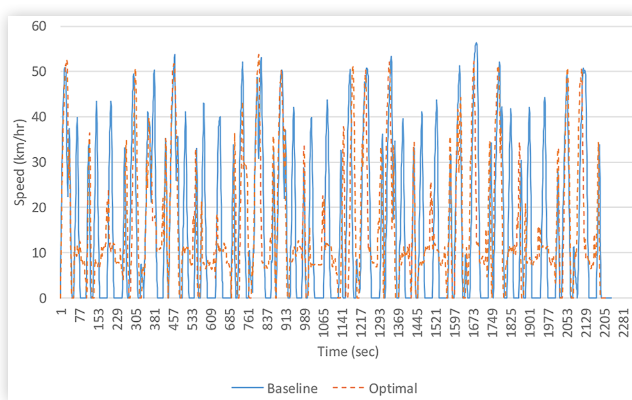


TABLE 2 Comparison of energy consumption by the test PHEB between baseline and optimal scenarios.

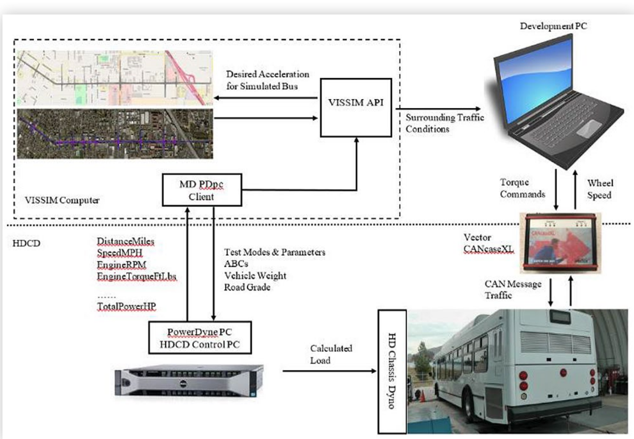
Traffic Condition	Scenario	Fuel (L/km)	Electricity (kWh/km)
Very Light Traffic	Baseline	0.57	1.86
	Optimal	0.57	1.66
	Change (%)	*-1.30*	*10.84*
Light Traffic	Baseline	0.65	1.86
	Optimal	0.59	1.57
	Change (%)	*8.06*	*15.28*
Moderate Traffic	Baseline	0.62	1.44
	Optimal	0.55	1.78
	Change (%)	*11.88*	*-23.25*
Heavy Traffic	Baseline	0.65	1.67
	Optimal	0.57	1.63
	Change (%)	*13.10*	*2.21*
Very Heavy Traffic	Baseline	0.73	1.29
	Optimal	0.60	1.58
	Change (%)	*17.29*	*-22.95*

conditions. In addition, these energy savings are results of the vehicle dynamics optimization only, and greater benefits are expected when the powertrain control optimization is combined.

4. Discussion

Besides the connected vehicle technology evaluation (as shown in the use case of driver assistance), the Dyno-in-the-Loop (DiL) platform can also provide a safe development and test environment for (partially) automated vehicle technology. Figure 8 gives a possible setup for the DiL test of PHEB's Connected Eco-operation System with longitudinally automatic control. In this configuration, the human driver is replaced by the development PC which can access all the required information from simulation environment and ego bus, calculate the optimal torques of internal combustion engine (ICE) and electric motors, respectively, and send the powertrain control signals in real-time to the J1939 CAN bus for execution.

FIGURE 8 Experiment setup for DiL testing with partially automatic control.



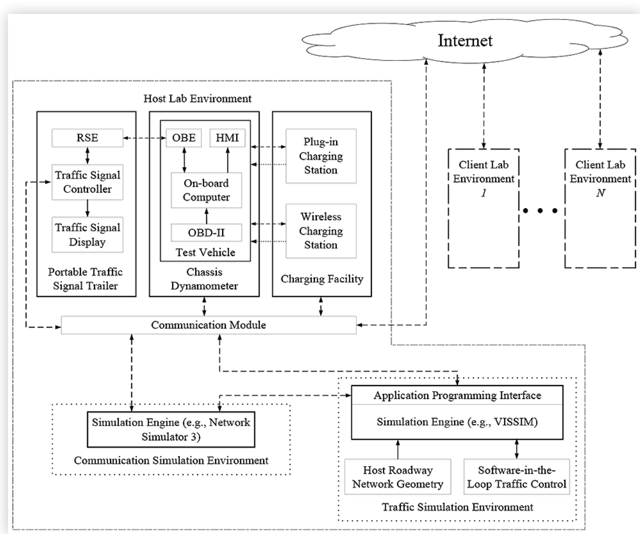
As aforementioned, the DiL approach is a type of Everything-in-the-Loop (XiL) testing, where the platform is open and flexible enough to fuse other elements such as wireless communication devices (or communication network simulation environment), portable traffic control devices (or signal control emulators), and charging stations (or corresponding simulators). In addition, the proposed platform has the potential to:

1. Leverage the existing resources including hardware (e.g., test vehicle, lab facilities or test track), software (various simulation tools), computational power, and communication capability, to push the limit of modeling various emerging technologies in transportation systems and assessing their energy efficiencies.
2. Maximize the utilization of resources available from multiple laboratories or test sites, and support collective testing efforts on the system development and evaluation in a common mixed-reality environment (see Figure 9 as an example).

5. Conclusions and Future Work

In this study, an innovative hardware-in-the-loop development and testing platform, i.e., Dyno-in-the-Loop (DiL), is

FIGURE 9 An example of potential DiL platform extension to fuse other resources from different test sites.



proposed for the modeling and evaluation of emerging transportation technologies. The Connected Eco-Operation System for Plug-in Hybrid Electric Buses (PHEBs) with driver assistance is used as a case study to illustrate the configuration of DiL platform. Compared to pure numerical or traffic simulation, results from the DiL approach have higher fidelity and can provide further insight into the system performance when deploying in the real world environment. Test results on a simulated bus route are very promising, showing that the target application can help the equipped PHEB reduce more than 13% of fuel and 2% of electricity consumption in heavy traffic conditions. It is noted that these savings in energy may be at the expense of extra auxiliaries added into the equipped vehicle. In addition, possible extensions of the DiL platform for partially automated control testing and multi-lab facilities with fusion of various elements are discussed. These potential extensions may point out some future steps to explore the opportunities and challenges of the proposed DiL development and testing platform.

6. Acknowledgement

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Definitions/Abbreviations

API - Application programming interface
CAV - Connected and automated vehicle
CV - Connected vehicle
DiL - Dynamometer-in-the-Loop
DVI - Driver-vehicle interface
EAD - Eco-approach and departure
GUI - Graphic user interface
HDCD - Heavy-duty chassis dynamometer
HiL - Hardware-in-the-Loop

HuiL - Human-in-the-Loop
MiL - Model-in-the-Loop
PHEB - Plug-in hybrid electric bus
RTA - Riverside Transit Agency
SiL - Software-in-the-Loop
SOC - State of Charge
SPaT - Signal phase and timing
ViL - Vehicle-in-the-Loop
XiL - Everything-in-the-Loop

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