Review of Hardware-in-the-Loop Simulation and Its Prospects in the Automotive Area

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ABSTRACT

Hardware-in-the-loop (HIL) simulation is rapidly evolving from a control prototyping tool to a system modeling, simulation, and synthesis paradigm synergistically combining many advantages of both physical and virtual prototyping. This paper provides a brief overview of the key enablers and numerous applications of HIL simulation, focusing on its metamorphosis from a control validation tool into a system development paradigm. It then describes a state-of-the art *engine-in-the-loop (EIL) simulation* facility that highlights the use of HIL simulation for the system-level experimental evaluation of powertrain interactions and development of strategies for clean and efficient propulsion. The facility comprises a real diesel engine coupled to accurate real-time driver, driveline, and vehicle models through a highly responsive dynamometer. This enables the verification of both performance and fuel economy predictions of different conventional and hybrid powertrains. Furthermore, the facility can both replicate the highly dynamic interactions occurring within a real powertrain and measure their influence on transient emissions and visual signature through state-of-the-art instruments. The viability of this facility for integrated powertrain system development is demonstrated through a case study exploring the development of advanced High Mobility Multipurpose Wheeled Vehicle (HMMWV) powertrains.

Keywords: HIL simulation; engine-in-the-loop simulation; transient diesel emissions; HMMWV

1. INTRODUCTION

Synthesizing a modern engineering system invariably entails some degree of prototyping. Virtual prototyping can support initial system design work rapidly and efficiently, but as a system's design matures, the need for prototyping it physically increases. *Hardware-in-the-loop (HIL)* simulation can be viewed as a synergistic combination of physical and virtual prototyping (a.k.a. "modeling and simulation"). Various definitions of HIL simulation exist in the literature[1,2]. This paper defines a HIL simulator as "a setup that emulates a system by immersing faithful physical replicas of some of its subsystems within a closed-loop virtual simulation of the remaining subsystems". This definition highlights a key characteristic of a HIL simulator, namely, that it must capture the *closed-loop* or *bidirectional* interactions between its physical and virtual constituents. It is often possible to assume *unidirectional* interactions between the physical and virtual constituents of a given simulation setup with little loss of fidelity. When simulating the response of a virtual building to a physically measured earthquake signature, for example, one typically neglects the building's influence on the earthquake signature, as shown in Figure 1.a. Similarly, when simulating the response of a physically prototyped car chassis to a virtual road profile, it may be possible to neglect the influence of the chassis's vertical motion on the road profile, as shown in Figure 1.b. In both cases, this furnishes a setup with a *driving subsystem* that can be simulated or measured offline, and a *driven subsystem* that can be simulated using the driving subsystem's outputs. The challenges involved in realizing such *decoupled* simulators are quite distinct from the challenge of building a *closed-loop* HIL simulator such as the one sketched in Figure 1.c. This paper focuses on closed-loop HIL simulation and its unique challenges and potential.

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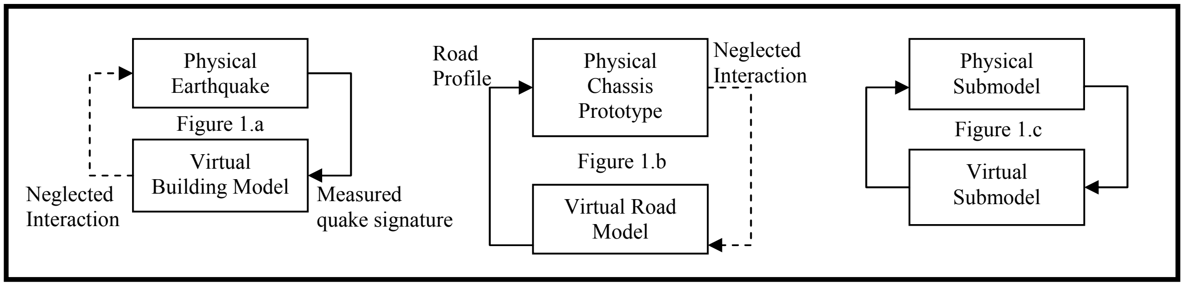


Figure 1: Combined physical and virtual prototyping with (1.a) driven virtual models; (1.b) driven physical prototypes; (1.c) bidirectional, closed-loop HIL Simulation

HIL simulation has become indispensable to the aerospace, automotive, marine, and defense industries. It plays a pivotal role in the development of powertrain controllers, automotive safety systems, unmanned underwater vehicles, and defense systems (Section 3). A sizable global HIL industry supports these development activities[3-6], and universities are rapidly integrating HIL simulation into their curricula[7-9]. This growing prevalence of HIL simulation attests to its many advantages, including:

1. Cost effectiveness: HIL simulation often requires significantly less hardware than physical prototyping, thereby costing less.
2. Rapid prototyping: Because they often require less hardware than fully physical prototypes, HIL simulators can also be considerably quicker to build. Controller prototypes, for instance, can be built rapidly and evaluated in the loop utilizing the appropriate software platform.
3. Fidelity and verisimilitude: By prototyping in hardware those components whose dynamics or other attributes (e.g., transient emission formation in diesel engines) are not fully understood, HIL simulators often achieve fidelity levels unattainable through purely virtual simulation.
4. Simulation speed: HIL simulations of complex physical phenomena run faster than purely virtual simulations of the same phenomena (e.g. IC engine simulations based on Computational Fluid Dynamics).
5. Repeatability: Systems that normally operate in highly variable environments (e.g., off-road vehicle suspension systems) can often be tested in controlled lab settings through HIL simulation, which may significantly increase repeatability.
6. Non-destructive nature: HIL simulation often makes it possible to simulate destructive events (e.g., vehicle accidents, missile interception, etc.) without incurring the costly destruction.
7. Comprehensiveness: HIL simulation often makes it possible to simulate a given system over a much broader range of operating conditions than what is feasible via purely physical prototyping.
8. Safety: HIL simulators can often be used to train human operators (e.g., airplane pilots) of safety-critical systems (e.g., supersonic aircraft) in significantly safer environments (e.g., flight simulators).
9. Concurrent systems engineering: Finally, HIL simulation allows different teams to develop different parts of a system in hardware without losing sight of integration issues, thereby enabling concurrent systems engineering.

In summary, a HIL simulator is a setup that prototypes parts of a given system in hardware and virtually emulates the rest while maintaining *bidirectional* information flow between these physical and virtual subsystems. The more traditional application of the HIL concept is controller design and testing, in which a control unit in hardware is integrated with virtual models of the devices and systems being controlled. This type of HIL simulation could be termed *Controller-In-the-Loop (CIL) Simulation*, and has become a mainstay of the automotive, aerospace, marine, and defense industries. However, advances in both simulation and testing capabilities have opened the door for HIL simulation to metamorphose from a control validation tool to a system synthesis paradigm. In this case, major pieces of hardware performing physical tasks are integrated with virtual devices emulating realistic operating conditions based on predictions of a high-fidelity simulation. This paradigm shift is particularly important for modern automotive propulsion systems. The increasing complexity of such systems, coupled with the need to evaluate many options before finalizing a vehicle concept, motivates application of the HIL system synthesis paradigm as an essential new tool for concurrent engineering.

This paper surveys the evolution of HIL technology and enablers (Section 2), before focusing on exciting applications that such technologies and enablers have made possible (Section 3). In particular, the paper investigates different aspects of the HIL metamorphosis and explores the power of HIL simulation as a vehicle system synthesis paradigm (Section 3). To illustrate this power, Section 4 presents an engine-in-the-loop (EIL) setup that integrates a fully instrumented diesel engine with accurate real-time driver, drivetrain, and vehicle models of the High Mobility Multipurpose Wheeled Vehicle (HMMWV) through a state-of-the-art electric dynamometer and its controller. Section 5 then demonstrates the use of this setup for quantifying the influence of powertrain transients on dynamic diesel engine performance and emissions. The setup's V8 6L diesel engine, manufactured by International, is a new product significantly more powerful than the standard HMMWV engine, and it is being considered for propulsion of heavy up-armored versions of the HMMWV vehicle. The study emphasizes fidelity and verisimilitude of EIL by offering insight into transient soot emissions that are otherwise difficult to simulate on the system level. The driveline and vehicle models can be easily replaced by different designs; hence this research takes HIL simulation beyond its traditional automotive applications, such as control calibration and validation, and capitalizes on its full potential as a system development paradigm. The paper concludes with a brief discussion of the progress of HIL simulation in the past several decades, and the potential areas of growth of HIL simulation in the years to come (Section 6).

2. KEY ENABLERS OF HIL SIMULATION

Numerous key enablers must come together seamlessly to furnish a synergistic HIL simulation setup. Figure 2 presents a simple pictorial summary of some such enablers (in ovals) in relation to a HIL setup's main components (in rectangles).

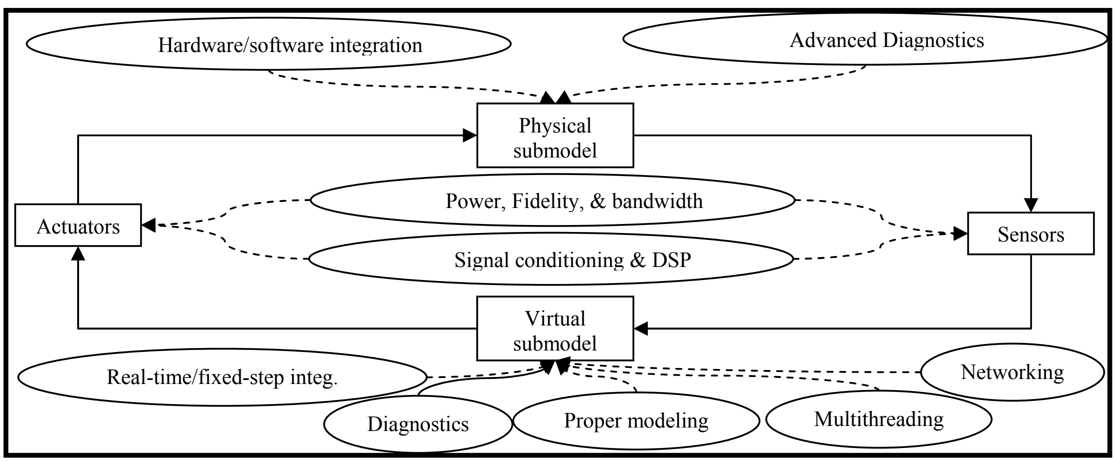


Figure 2:Key Enablers of HIL Simulation

The illustration in Fig. 2 groups the key enablers of HIL simulation into eight main categories:

1. Sensor and actuator fidelity, bandwidth, and unobtrusiveness: Examination of Figure 1 reveals that a HIL simulator is in essence a *control system* whose virtual components command its hardware to "track" a hypothetical reference "system". This observation is recognized in the literature, as evident from Frangos' proposed control-theoretic framework for analyzing HIL simulators[10]. An important consequence of this observation is that the ability of a HIL simulator to capture the behavior of a system rests on the fidelity, bandwidth, and unobtrusiveness of the simulator's sensors and actuators. Zhang and Alleyne provide an insightful proof of this result for a class of HIL simulators using linear control theory[11]. Furthermore, a significant portion of the HIL simulation literature focuses on developing sensors and actuators that are accurate,

fast, and "unobtrusive" in the sense of not altering the dynamics of the underlying hardware. Examples of such sensors and actuators include hydraulic dynamometers often used for engine-in-the-loop research because of their low inertia and high bandwidth[12-15].

2. Signal conditioning and digital signal processing (DSP): A HIL setup's sensor measurements must often undergo significant processing before they can be fed into the setup's virtual simulation. Typical processing tasks include digital signal decoding, anti-alias filtering (for analog signals), noise attenuation, etc. Such signal conditioning tasks are often performed separately by a *digital signal processor* within a HIL interface board to free the main HIL microprocessor for virtual simulation.

3. Fast processors, real-time operating systems (RTOS), and fixed-step integration: Since the interactions between the physical and virtual components of a HIL simulator are bidirectional, it is crucial that the time frames of these components match exactly. This implies that the virtual components must run in *real time*, which places tight requirements on the HIL simulator's microprocessor, operator system, and integration routine. Specifically, fast microprocessors and – in some cases, even faster *field-programmable gate arrays (FPGAs)* – are often used by HIL simulators to enable real-time virtual simulation[6,16]. Furthermore, even with such fast processors, running a HIL simulator in real time necessitates a special kind of operating system that executes integration steps at regular intervals signaled by clock interrupts. Such *real-time operating systems* are a mainstay of HIL simulation, and Liu[17] provides a thorough review of their different types (e.g., "soft" vs. "hard") and architectures. Finally, the solver used for simulating the virtual component of a HIL setup should conduce to real-time simulation by ensuring the completion of every integration step within the "real time step" corresponding to it. This can be difficult if the solver uses variable step-size integration, which explains the prevalence of fixed step-size integration routines in the context of HIL simulation. Fixed step-size integration introduces an interesting challenge for HIL simulators of *hybrid discrete/continuous systems*, namely, that the transitions between the discrete states of such systems may occur during integration time steps. A clutch in a car transmission may, for instance, engage halfway through an integration step. The HIL simulation literature discusses this difficulty in depth and explores some of its possible remedies[18-21].

4. Advanced diagnostics of physical devices: The expanded use of HIL simulation as an effective system synthesis paradigm critically depends on advanced laboratory instrumentation and diagnostic systems. In particular, the sensor and transducer requirements for HIL simulation-based system synthesis often significantly exceed the requirements for merely establishing a functional HIL setup. The types, fidelities, and bandwidths of HIL instruments are often dictated by the selection of hardware immersed in the virtual system and the need for detailed insight into the behavior of this hardware under realistic dynamic conditions. In the context of EIL simulation, for instance, a good example is a fuel injector needle lift sensor and fast exhaust emission analyzers. As engine load and speed change rapidly during a drive cycle, these sensors and instruments offer essential information about the dynamic behavior of the vital engine subsystem and its consequences. To fully utilize such sensors, one must choose a data acquisition system commensurate with their number and response times, and must also tightly integrate it with the main test cell controller.

5. Proper modeling: The virtual models within a HIL simulator must typically meet two important requirements. First, they must capture the dynamics of the virtually prototyped systems accurately enough to enable the HIL simulator to achieve its required simulation and design goals. Secondly, they must run in real time: a requirement that stems from considerations described in item 3 of this list and often translates into a bound on model complexity. These two requirements, fidelity and simplicity, typically conflict. The literature recognizes this conflict and deems a dynamic system model *proper* if it optimally balances these two requirements. A companion to this paper provides a thorough review of both the proper modeling literature and the growing use of proper modeling in the context of HIL simulation[22-25].

6. Multithreading and multirate integration: A common problem in HIL simulation is virtual model *stiffness*, defined as a large disparity between the characteristic speeds of different components of a virtual model. Stiff models can be found in many disciplines, particularly mechatronics, where mechanical and electrical components typically exhibit markedly disparate response speeds. Proper modeling techniques can often alleviate model stiffness by eliminating "fast" dynamics from a given model in favor of "slower" dynamics[22]. This may not be feasible if capturing the relatively fast dynamics of, say, the electronic components of a mechatronic system is a simulation requirement. When the disparity between the fast and slow dynamics in a virtual model cannot be eliminated, it is common to integrate these dynamics separately at different integration rates. Such *multirate integration* may take place on one processor via multithreading, but is more often

achieved using multiple processors[18-20]. The HIL literature describes multirate integration issues in depth, with particular focus on different methods that each processor can use to synchronize with other processors or extrapolate their outputs[18-20].

7. High-bandwidth networking: The possibility of distributing a HIL simulator's physical and virtual components over a network can be quite attractive for three reasons. First, the different pieces of hardware needed for a particular HIL simulation may not be physically collocated or mobile. Secondly, distributing the virtual components of a HIL simulator can provide increased virtual simulation capabilities compared to the use of a single processor. Finally, the ability to network the various components of a HIL simulator makes it possible to build different HIL simulators of different components of a system independently and then combine them into a larger, system-level HIL simulator. This can provide superb concurrent systems engineering capabilities to designers. For these reasons, researchers have recently begun to examine the distribution of a HIL simulator's components over a network. Results of this research are promising[20,26], but significant further progress can be made in the area of distributed HIL simulation as network *quality of service (QoS)* increases. El-Gendy *et al.* provide a thorough review of network QoS research, details of which are omitted from this paper for brevity[27].
8. Hardware/software integration: An effective HIL simulator comprises more than just a hardware prototype and a virtual model interacting bilaterally in real time. *Synergy* between the prototype and model must also be achieved for successful HIL simulation. To achieve such synergy, the designer of a HIL simulator must pay close attention to issues such as *partitioning* and *connection causality*. Partitioning, in this context, refers to the breaking-up of a system into subsystems to prototype in hardware and others to simulate virtually using HIL technology. In performing such partitioning, one should seek synergy by prototyping in hardware those components that require direct experimental insight. Partitioning a system into two subsystems further leads to the question of how to choose their *connection causality*, defined as the direction of flow of various signals between them. For instance, in an engine-in-the-loop simulator consisting of a physical engine and a virtual vehicle model, one may ask whether the virtual model should command the engine torque and measure its speed, or vice versa. As will be explained in Section 4, such a decision can strongly affect the tractability of a HIL simulator's virtual model and the effectiveness with which its physical components can be controlled.

The above enablers can be seen both as essential prerequisites to effective HIL simulation and as key reasons behind the viability of modern HIL simulation. In fact, a careful examination of the history of HIL simulation reveals that as each of these critical enabling technologies evolved, so did the state of the art in HIL simulation. Section 3 section briefly reviews the history of HIL simulation, focusing on its different applications and highlighting its evolution from a control *calibration tool* to a *system design paradigm*.

3. APPLICATIONS OF HIL SIMULATION

As explained in Section 2, a HIL simulator is in essence a control system whose virtual components command its physical components to track a hypothetical fully physical system. This implies that the key enablers for both HIL simulation and electronic control are quite similar. Progress on HIL simulation and embedded control has therefore often been closely linked in the early days, and achievements in development of HIL simulation have led to more extensive application to electronic control design. Consequently, HIL simulation can be an excellent framework for *control prototyping, calibration, and validation*, as shown in Fig. 3. More recently, the role of HIL simulation expanded in response to a need to study physical devices immersed into complex virtual systems. The advanced *system synthesis HIL setup* includes major pieces of hardware such as an IC engine, transmission, missile or a torpedo, and supports design and validation of components and complete systems. The following sub-sections examine the history and evolution of the HIL simulation concept in more detail.

Control prototyping applications: Figure 3 presents an example of how HIL simulation can aid in the design of a hypothetical control system, in this case, for an combined active/passive car suspension. This particular hypothetical HIL setup consists of a simple virtual quarter-car suspension model connected to an embedded linear quadratic Gaussian (LQG) active suspension controller. The plant model captures vehicle inertia, suspension stiffness, suspension damping, road characteristics, and sensor/actuator dynamics. As the suspension's design matures, this model may also mature into capturing more details of the vehicle system's dynamics. Suspension stroke and sprung mass acceleration measurements are assumed, and fed into a physical microprocessor that uses LQG control to estimate and command the states of the virtual suspension. This hypothetical example illustrates the importance of HIL simulation to modern control prototyping. In this case, the physical active suspension microcontroller is tested against a virtual vehicle to calibrate and validate it before installation in a real vehicle. This makes it possible to debug and optimize the controller offline before incurring the large costs of testing it in a real vehicle. The literature provides many examples similar to Figure 3, where HIL simulation is used to design, calibrate, and validate physically prototyped controllers by embedding them within virtual simulations of the underlying plants. Some of these examples date back almost a century, thereby predating the advent of modern electronic control systems. In particular, one may consider a *flight simulator* to be a HIL setup where a physical control system consisting of a human pilot and a physical cockpit is immersed within a virtual simulation of the rest of the airplane. The purpose of such a HIL simulator is primarily to "calibrate" the human controller by training him/her to fly safely and proficiently. With this in mind, one of the earliest "HIL simulators" may have been the "Sanders Teacher" built around 1910[28]. This was a flight simulator consisting of an actual airplane gimbaled to the ground and mounted facing the prevailing wind[28]. Pilots, or human "controllers", trained on this setup by adjusting its control surface positions to regulate its "virtual" flight against the wind[28]. Such a primitive HIL simulator was not particularly useful, however, due to the erratic nature of the "virtual simulator" – in this case, the prevailing wind[28]. This led to the development of the Antoinette trainer: a more sophisticated flight simulator whose motion was generated by human instructors as opposed to the prevailing wind[28]. By mentally simulating and manually imparting the motion of a real airplane onto the trainer, these instructors provided a cognitive "virtual model" for this HIL simulator and also provided its "instrumentation" and "actuation"[28]. Further technology leaps led to pneumatically actuated flight simulators, computerized flight simulators, and ultimately the advanced flight simulators available today[28]. The airplane and its aerodynamics are simulated with a computer code. Baarspul gives a fascinating and thorough survey of this evolution of flight simulators, of which we only mention some of the earlier highlights in this paper for brevity[28].

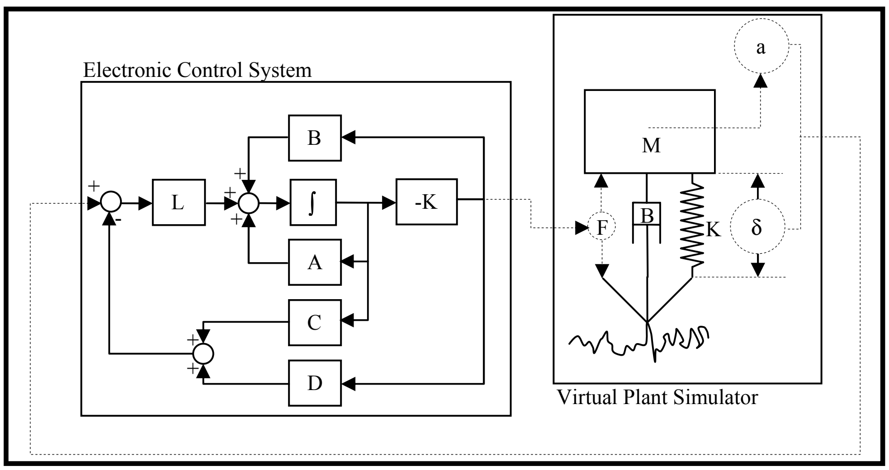


Figure 3: Example of HIL Simulation for Control Validation

With the advent of modern embedded electronic control systems, both the need for and potential capabilities of HIL simulators grew considerably, especially in the automotive context. In particular, the advent of microprocessor-based *electronic control units (ECUs)* for car engines created a need for new tools for testing, calibrating, and validating these ECUs. HIL simulation quickly fulfilled this need, and is now a key technology for engine ECU testing and calibration. Wagner and Furry describe a virtual simulation environment that can enable such HIL simulation[29], and Kimura and Maeda use such HIL simulation for engine ECU development[30]. Lee *et al.* delineate the requirements that a HIL simulator must satisfy to be effective for ECU development[31]. Furthermore, they present a formal process for developing such a HIL simulator that uses *automatic code generation* to streamline the transition of control system designs from pure simulation to commercial embedded code[32]. Finally, Song and Grigoriadis utilize HIL simulation to validate the design of an advanced linear parameter-varying (LPV) engine control system[33]. These papers show that HIL technology can be seamlessly used to develop, validate, and calibrate different control schemes for different engines. Furthermore, the fact that industrial corporations have put together formal processes for HIL simulator development highlights the degree to which HIL technology has become an integral part of automotive engine control system design and development. The use of HIL simulation for automotive ECU development is not limited to engine applications. In fact, HIL simulation has been used effectively for the development, calibration, and validation of transmission and driveline electronic control units. For instance, Raman *et al.* describe in detail the process of developing a HIL simulator for the purpose of transmission ECU development[34]. Similarly, Hagiwara *et al.* describe in depth the design of a HIL simulator for automatic transmission ECU development[18]. Schupbach and Balda demonstrate the versatility of HIL simulation by using the same HIL setup to simulate the transmissions and drivelines of several distinct vehicles[35]. Many transmissions and drivelines use hydraulics as a means for actuation. With this in mind, Ferreira *et al.* develop a HIL simulation setup for a hydraulic system, paying particular attention to the inherent numerical stiffness of hydraulics models and the proper modeling efforts necessary for simulating such models in real time[36, 37].

<u>Immersing major pieces of hardware in the loop</u>; In addition to the above powertrain applications, HIL technology has proven viable for the development of automotive brake and stability control systems. An interesting challenge arises in this context, namely, that tire dynamics and brake hydraulics can be both numerically stiff and difficult to model accurately. This challenge, coupled with the fact that hydraulic circuits and tires are relatively easy to prototype in hardware compared to other automotive systems, has spawned an interesting trend in chassis HIL simulation. It is common in chassis HIL simulation studies to prototype not only ECUs but also hydraulic circuitry and sometimes even tires in hardware. This represents an important evolution versus the more "traditional" use of HIL simulation where only the ECU of a given system is prototyped in hardware. *Over the past 15-20 years, HIL simulator designers have begun to immerse major pieces of hardware into their HIL setups beyond just ECUs. This has allowed HIL simulation to metamorphose from a control validation tool to a system synthesis paradigm.* Because of this evolution, Isermann *et al.* and the present authors advocate terms such as *controller prototyping* or *controller-in-the-loop simulation* to describe the more traditional applications of HIL simulation[1] described in the previous sub-section. Such terms underscore the fact that HIL simulation has metamorphosed considerably beyond its traditional role in ECU development. For example, Lam and Liao model an entire vehicle virtually except for its suspension's magneto-rheological damper and the damper's ECU, which they prototype in hardware[38]. This allows them to capture the MR damper's characteristics more accurately than would be possible in pure simulation. Similarly, Kim *et al.* develop an active roll stability control system and validate it using a HIL simulator that prototypes not only the control system's ECU but also its hydraulics in hardware[39]. This makes it possible to simulate the roll stability control system in real time without encountering the numerical stiffness typically associated with virtual models of hydraulic circuitry. Lee and Suh[40], Lee *et al.*[41-42], and Li *et al.*[43] use a similar strategy to simulate antilock braking and torque control systems for different vehicles. They prototype the hydraulics of these systems as well as their ECUs in hardware, thereby mitigating the problem of simulating stiff hydraulics models in real time. Similarly, Noomwongs *et al.* develop a vehicle handling and stability system using a HIL simulator that prototypes the vehicle's tires in hardware, thereby eliminating the need for potentially inaccurate virtual tire simulation[44]. Setlur *et al.* take this approach a step further by including a real driver "in the loop" of a steer-by-wire system's HIL simulator, thereby improving the potential accuracy with which this simulator captures the dynamics of human driving[45]. Finally, Geitelink *et al.* and Verhoeff *et al.* take this approach yet another step further by prototyping an entire vehicle in hardware to test its collision avoidance system[46, 47]. The vehicle is placed on a chassis dynamometer that measures its velocity and feeds it to a simulator that estimates the vehicle's proximity to other vehicles on a virtual road[46, 47]. Using this virtual proximity information, the HIL setup physically moves robotic obstacles in front of the vehicle to new positions relative to the vehicle[46, 47]. This makes it possible to thoroughly evaluate the response of the given vehicle's collision avoidance system to realistic road conditions[46, 47].

In summary, the past 15-20 years have seen a metamorphosis in HIL simulation from a control development method to a system synthesis paradigm. The driving force behind the HIL metamorphosis into system synthesis methodology has been the fact that many system components beyond just ECUs can more accurately be built and simulated in hardware rather than virtually. The testing and diagnostic technology has advanced to levels that allow integration and *bidirectional* interaction between real components and virtual sub-systems. In addition, expanding the frontiers of selected technologies became critically dependent on the ability to study them *experimentally* under *highly dynamic conditions* experienced in real life. Evidence for this metamorphosis can be found not only in the automotive brake and stability control literature but also in the broader automotive, aerospace, military, robotics, and naval HIL simulation publications, to name a few. For instance, Aghili and Piedboeuf use HIL simulation to develop a robotic manipulator suitable for zero-gravity celestial applications[48]. Prototyping such a robot faithfully in hardware and testing it terrestrially is difficult because the robot is too weak to operate against the force of gravity, so Aghili and Piedboeuf simulate it virtually[48]. However, because the mechanics of contact between the robot and the objects it handles are difficult to model accurately, the authors prototype these contact mechanics in hardware[48]. This furnishes a HIL simulator that prototypes part of a robotic system in hardware and the rest virtually in a synergistic fashion that ensures the most accurate simulation results[48]. Ganguli *et al.* adopt the opposite approach when building a HIL simulator for machine tool chatter: they simulate the cutting and contact forces in the machine tool virtually, but prototype its spindle in hardware as a beam[49]. This makes it possible to emulate chatter using the HIL setup without performing actual machining operations[49]. Huber and Courtney provide a thorough description of how HIL technology can be used to evaluate heat-seeking surface-air missiles in a controlled environment[50]. The heat-seeking missiles are placed in a HIL simulator containing infrared sources that emulate real targets and their defense mechanisms, e.g. thermal flares[50]. Motion of the seeker and targets in space is then virtually simulated to assess the seeker's capabilities[50]. Kelf describes a conceptually similar HIL setup for torpedo design[51]. The setup places the torpedo of interest inside a water tank and instruments the torpedo to measure its control surface positions[51]. Based on these control surface position measurements, a virtual simulator predicts the motion of the torpedo relative to a virtual marine environment[51]. This is one of two HIL simulation "loops" in this particular setup[51]. The second HIL simulation loop is built around the torpedo's sonar system, which emits sonar signals into the laboratory tank[51]. The tank is instrumented to measure these signals, and a computer model predicts how the torpedo's virtual environment would reflect these signals[51]. Sonar actuators in the tank then emit "virtually reflected" sonar signals back to the torpedo[51]. This makes it possible to evaluate the ability of the torpedo to navigate underwater, track targets, and destroy them, without actually firing a single torpedo[51]. Takashima *et al.* discuss an important issue in the HIL simulation of missile technologies, namely, how one can generate a "virtual scene" for a missile with artificial vision[52]. Two alternative approaches are presented, namely, either projecting an artificial image on a screen or directly injecting the virtual scene into the missile's microprocessor[52]. Arguing that the latter option is better-suited to indigenous Japanese technology, the authors describe in depth the development of a Japanese missile HIL simulation system[52]. Finally, Yeo and Kim show that immersing major pieces of hardware into a HIL simulator can be very valuable in the automotive powertrain context[53]. In particular, they develop a hybrid electric vehicle HIL simulator with a real regenerative brake, real brake controller, and real human driver[53]. The remainder of the vehicle is simulated virtually, and the resulting HIL setup provides interesting insights into regenerative braking performance[53].

The literature cites more examples of HIL simulation in the automotive, aerospace, military, naval, and robotics industries. A thorough evaluation of that literature, omitted for brevity, reaffirms the conclusions of the above review. HIL simulation is a powerful tool for *control prototyping*, but its potential uses encompass much more. In fact, HIL simulation can be used as a *synergistic system synthesis paradigm*, where different physical parts of a system beyond its ECU, are prototyped in hardware, tested, and possibly optimized within a virtual simulation of the rest of the system. Section 4 describes an *engine-in-the-loop* setup developed at The University of Michigan that highlights the value of HIL simulation as a research tool and a system development paradigm.

4. THE ENGINE-IN-THE-LOOP FACILITY

<u>Overview and Motivation:</u> Modern automotive systems are increasingly complex. New technologies offer unparalleled opportunities for improving vehicle attributes, but benefits depend on integration of new components in a way that maximizes synergies at the system level. Hence, evaluating the potential of candidate technologies and optimizing their designs requires effective system analysis tools. Studying novel concepts relies heavily on predictive simulation tools, since decisions often have to be made before physical prototypes are available. While simulation has proven to be effective in predicting and optimizing the performance and fuel economy of conventional and hybrid powertrains[54-57], the accurate prediction of transient emission formation in internal combustion engines remains a challenge. In particular, simulations of soot emission formation in a diesel engine are too slow for systems work, since they require the coupling of sophisticated Computational Fluid Dynamics (CFD) and chemical kinetics models[58,59]. Therefore, building the EIL capability is seen as the most viable alternative for accurately assessing the impact of powertrain design and control on emissions. Locating the engine in the test cell allows application of very sophisticated diagnostic techniques, hence providing not only the overall evaluation of emissions, but also in-depth insight into critical conditions producing high soot or NOx emissions. Therefore, the results will be essential for development and refinement of novel designs and strategies.

The engine- (or powertrain-) in-the-loop testing paradigm is used in academia and industry, but mostly for the design and calibration of transmission and engine controllers[60]. Recent research at the universities of Bath and Wisconsin, for instance, has focused on the development of hydraulic dynamometers with exceptionally high bandwidths conducive to control system work[12-15]. Similarly, Fleming *et al.* describe the development of a powertrain-in-the-loop setup that enables control design and implementation specifically for parallel hybrid electric vehicles[61]. Finally, the Argonne National Laboratory (ANL) is heavily investing in HIL capabilities, and serves as the primary site for technology validation for the U.S. Department of Energy. ANL's focus is on enabling the testing of various powertrain components in an emulated vehicle environment[62]. Recent work at the ANL has also utilized HIL simulation to investigate tradeoffs between fuel efficiency and NO_x emissions in a hybrid vehicle with CVT[63], but relied primarily on analysis of the time spent at given engine regimes and steady-state emission maps. The setup presented in this paper differs from the above EIL-related literature in three important ways. First, a primary goal of our EIL research is to study fundamental aspects of *transient* diesel emissions in the context of realistic in-vehicle conditions. We seek a realistic characterization of powertrain dynamics, and a fundamental understanding of the influence of such transient dynamics on emissions. Secondly, we support the use of EIL as an integrated system-level methodology for powertrain design and control with extensive driveline/vehicle modeling effort. Prior research in the Automotive Research Center produced a comprehensive set of engine and vehicle simulation tools for design and analysis of advanced vehicle systems. The resulting system modeling platform, dubbed VESIM for Vehicle Engine SIMulation, runs in SIMULINK with emphasis on high-fidelity and predictiveness of fully integrated system simulations. Various subsystems have been integrated in SIMULINK as a common simulation environment to produce a tool for a baseline conventional vehicle[54]. This platform has subsequently been extended and utilized for investigating a number of research issues related to hybrid propulsion for trucks, such as evaluation of the fuel economy potential of selected hybrid electric and hydraulic hybrid configurations[55,56]. A methodology for combined, sequential optimization of hybrid propulsion system design and power management has been proposed and applied to a 6x6 medium truck[57]. Performing studies with different objectives stimulated systematic evaluation of tradeoffs between computational speed and fidelity and ultimately furnished an extensive library of *proper* vehicle system models[22, 24]. Thirdly, our focus is on medium-duty diesel engines and trucks, rather than passenger cars.

The challenges associated with development of high power-density clean automotive propulsion are especially relevant to the modernization of the High Mobility Multipurpose Wheeled Vehicle (HMMWV): a dual-use medium-duty truck. There is a growing need for increasing the power of the HMMWV, both because its current engine is not especially powerful and because of the need for up-armoring the HMMWV, thereby potentially increasing its weight. Competing with these needs is the impetus for improving the fuel economy of the HMMWV, both in order to address rapidly escalating fuel prices and in order to reduce the need for battlefield fuel shipments. Fuel comprises 70% of the tonnage moved when the U.S. army is deployed, and any savings attained through improvements in fuel economy would be further amplified through the reduction of resources dedicated to the transport of supplies[23]. Last but not least, there is an additional strong need to reduce HMMWV NO_x and particulate emissions, both in order to comply with the 2007-2010 EPA emissions standards and in order to reduce battlefield visual signature[23]. Addressing these challenging needs simultaneously is only possible through a synergistic powertrain development approach that carefully optimizes not only the different components of a HMMWV powertrain but also their interactions. Figure 4 summarizes the structure of a state-of-the-art engine in the loop (EIL) simulator built by the authors and their colleagues to make such synergistic systems engineering possible. The simulator connects a powerful 6-liter V-8 direct-injection diesel engine manufactured by the International Truck and Engine Corporation to accurate real-time VESIM-based driver, driveline, and vehicle models through a state-of-the-art AC electric dynamometer[23].

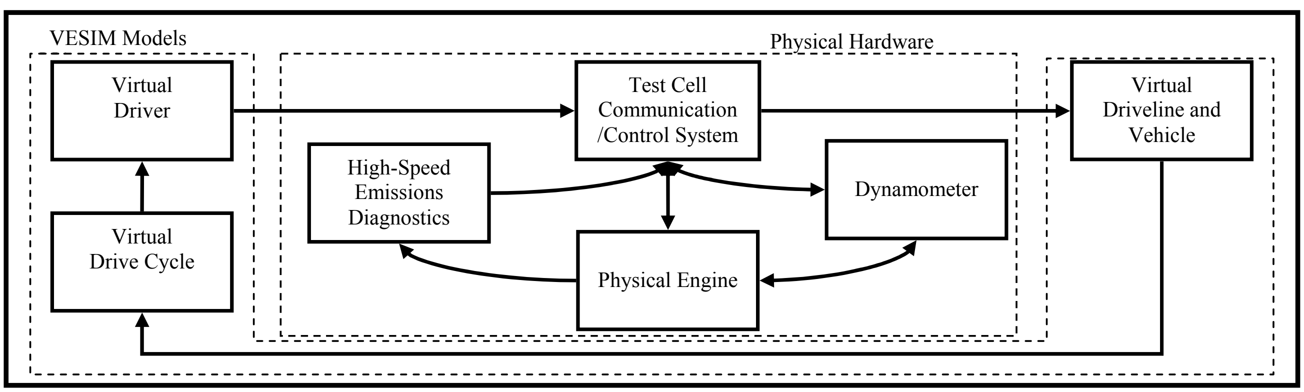


Figure 4: Engine-in-the-Loop Setup

The remainder of this section describes the setup's engine, dynamometer, and emissions instruments in depth. The section concludes by explaining how the setup uses some of the recent advances in HIL technology to enable synergistic powertrain system development.

Test cell hardware: The engine used in this setup is a 6 L V-8 direct-injection diesel engine manufactured by the International Truck and Engine Corporation. The engine bore and stroke are 95 mm and 105 mm, respectively, and the compression ratio is 18. An exhaust gas recirculation (EGR) circuit is used to introduce cooled exhaust gases into the intake manifold in order to decrease NO_x emissions. EGR flow rate is controlled through modulation of the EGR valve and the setting of the variable geometry turbocharger (VGT). The engine is intended for a variety of medium duty truck applications covering the range between Classes IIB and VII. By replacing the standard 145 kW 6.5 L turbocharged IDI engine with the modern 250 kW International 6 L DI engine, the EIL setup makes it possible to obtain experimental insight into performance, fuel economy and emissions characteristics of a high-performance HMMWV that has not been built yet. The particular engine used in this setup was chosen because it is a potential candidate for the propulsion of future up-armored (and thus heavier) HMMWVs[23].

The above engine is coupled to a 330 kW AVL ELIN series 100 APA Asynchronous Dynamometer. This is a very highly responsive machine capable of providing a 5 ms torque response time and a -100% to +100% torque reversal time of 10 ms. The main test cell control system is AVL PUMA Open. The test cell controller incorporates a virtual driver and dynamometer controller (EMCON 400) and its extension ISAC 400. The latter enables interfacing with user-defined vehicle, powertrain, and driver models implemented in SIMULINK®. Interfacing with the engine's powertrain control module (PCM) and monitoring of control functions is accomplished through the use of ETAS INCA software. The injection parameters, as well as EGR valve and VGT vane setting, can be observed and adjusted. The engine is fully instrumented for time-based measurements of pressures, temperatures, and flow rates at various locations in the system. The time-based signals are acquired with the use of AVL fast front end modules (F-FEMs). Crank-angle resolved measurements include in-cylinder pressure, fuel injection pressure and needle lift. Data acquisition and combustion analysis is performed via an AVL Indimaster Advanced 671 indicating system[23].

The above EIL setup combines many of the key enablers delineated in Section 2 to furnish a truly synergistic powertrain system development capability. In particular, the following list shows how the setup capitalizes on each HIL enabler listed in Section 2:

1. The particular dynamometer furnished by AVL possesses a very low inertia that minimizes its influence on perceived engine inertia, thereby minimizing obtrusiveness[23]. Furthermore, both the dynamometer and emissions sensors have fidelities and bandwidths sufficient for the accurate measurement and control of highly transient engine dynamics and responses[23].
2. The particular communication system used in the setup (EMCON) was designed by AVL to ensure maximum bandwidth, thereby ensuring high-fidelity HIL simulation[23].
3. The setup also employs finely tuned lead-lag filters to both minimize the effect of measurement noise and maximize its bandwidth. Such signal conditioning has proven critical to the integration effort and effective exploitation of the setup's capabilities[23].
4. Advanced engine diagnostics include specialized fast-response analyzers for measuring critical engine-out emissions during very dynamic events characteristic of powertrain operation in an off-road vehicle. Accurate and fast measurements of NO_x are provided by a CLD 500 Fast NO_x analyzer made by Cambustion Ltd. It consists of a chemiluminescent detector with a 90% ->10% response time of less than 3 ms for NO, and less than 10 ms for NO_x. Temporally resolved particulate concentrations are obtained using a differential mobility spectrometer (DMS) 500 manufactured by Cambustion Ltd. DMS measures the number of particles and their spectral weighting in the 5 nm to 1000 nm size range with a time response of 200 ms. Instantaneous measurements of NO_x concentrations and particle number-size distributions can be converted to mass flow rates in (g/s) using appropriate formulas for integration and conversion to mass units[23].
5. The setup uses state-of-the-art microprocessors and real-time operating systems to ensure real-time simulation[23]. Furthermore, the setup uses a fixed step-size integration routine within the Matlab® Real-Time Workshop® to ensure that its virtual simulator is constantly in synch with real time[23].

6. Even though the setup does not currently employ networked simulation or multirate integration, ongoing work seeks to increase its viability by evolving it in that direction.
7. The setup uses proper virtual driveline and vehicle models to ensure that the dynamics of the driveline and vehicle are captured both accurately and in real time. The extraction of such models from more complex ones using energy-based model reduction techniques is described in depth in other publications by the authors[22-24]. The vehicle mass was set at 5112 kg, and the driveline comprises a torque converter, four-speed automatic transmission, central transfer case, front and rear torsen differentials and in hub final gear reduction.
8. Finally, the setup is designed with synergistic hardware/software integration in mind. In particular, the setup is *partitioned* to prototype the engine in hardware and the rest of the vehicle system virtually. This partitioning synergistically maximizes the setup's accuracy and simulation speed by prototyping in hardware only those processes (namely, emission formation) that are critical for accurate and reliable analysis. Furthermore, this partitioning enables the *rapid prototyping* of different vehicle driveline options. In particular, the setup makes it possible to quickly swap and compare different transmission options, including manual, automatic, hybrid electric or hydraulic options. Analysis of alternative propulsion system designs will be omitted here for brevity, but the integration of EIL with the parallel electric hybrid driveline has been demonstrated by Filipi *et al.*[23], while on going work focuses on a series hydraulic hybrid concept. After partitioning and setting up the interface between the real and virtual elements, the success of running EIL proved to be dependant on establishing a proper *connection causality* between its virtual and physical constituents. In particular, the setup is configured to allow the virtual driveline model to command engine speed and measure engine torque through the dynamometer[23]. This connection causality was found to be significantly superior to the reverse, because it is much harder to measure and control torque than speed. Therefore, a *forward* connection causality where engine torque is measured and engine speed is controlled through the dynamometer provides stable operation and is superior to the backward alternative[23].

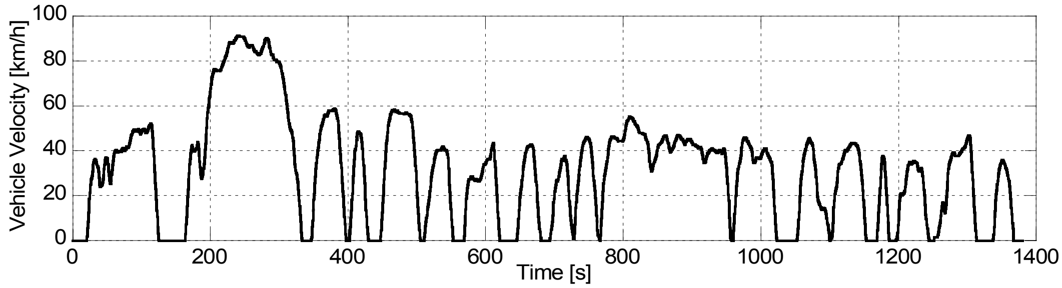
5. CHARACTERIZING DYNAMIC INTERACTIONS IN THE POWERTRAIN SYSTEM AND TRANSIENT EMISSIONS

The EIL setup described in the previous section provides a concrete example of how advances in the key enablers of HIL simulation have allowed it to become a synergistic system development tool. This section demonstrates immersion of a major piece of hardware, namely, a multi-cylinder diesel engine together with its accompanying subsystem controller, in the loop. The resulting *engine-in-the-loop* capability enables synthesis of a selected powertrain configuration, and the use of the EIL and the accompanying advanced test cell diagnostic systems for in-depth study of transient emission characteristics.

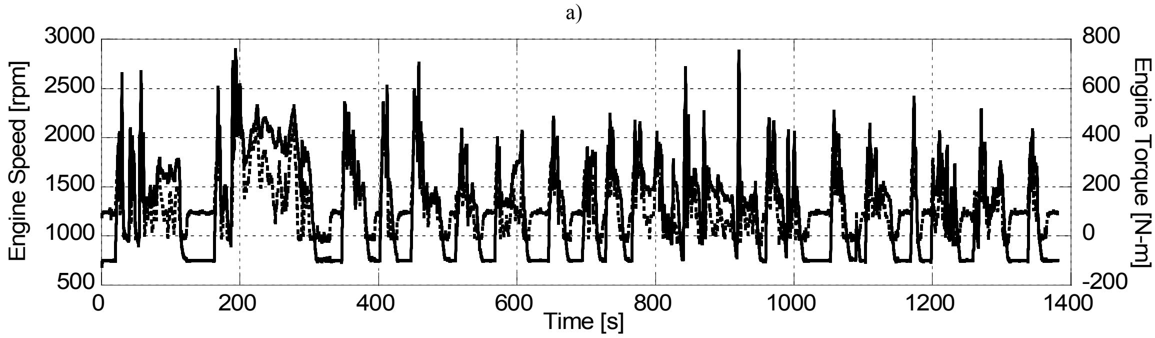
In particular, this section assesses the impact of powertrain transients on emissions of the HMMWV equipped with a *real* high-performance V8 6L diesel engine and a *virtual* 4x4 driveline. It describes the drive cycle and examines interactions in the powertrain systems and dynamic responses of critical sub-systems and components. Particular attention is focused on the effect of engine system transients on exhaust emission trends and visual signature. The transient contribution to overall particulate emission is quantified, thus enabling future development of strategies for clean and efficient HMMWV propulsion.

<u>Typical measurements obtained over a transient driving schedule</u>; Figure 5 investigates the interactions between powertrain subsystems and components over an aggressive driving schedule typical for city or secondary road conditions. The schedule is a Federal Urban Driving Procedure, and while it was originally designed to represent typical use of a passenger car, it is commonly used for evaluating light and medium trucks as well. The vehicle speed profile is shown in Fig. 5a, and this is the only input for a particular transient test run. The rest of the time-resolved profiles given in Fig. 5 represent measurements obtained in the EIL facility. Figure 5b illustrates engine speed and torque profiles. The engine speed history is much more dynamic than the vehicle speed history, due to interactions with the torque converter and the transmission. The engine is idling while the vehicle is stopped. The torque profiles (see also Fig. 5b) display even more dynamic behavior, with very sharp and frequent fluctuations between relatively low and extremely high values. It is important to note that the torque fluctuations depend not only on vehicle parameters and driving conditions, but also driver aggressiveness in correcting errors. For instance, in the process of addressing integration challenges, it was observed that the cyber-driver with shorter preview had difficulties following the schedule accurately and often behaved more aggressively, thus causing increased fluctuations of engine torque[23]. Figure 5c allows going one level deeper and

characterizing the behavior of the turbocharging system during transient in-vehicle operation, as well as the repercussions for the in-cylinder conditions, namely the Air-to-Fuel (A/F) ratio. Every increase in engine command from the driver leads to increased fueling, higher enthalpy in the exhaust and thus increased boost pressure delivered by the compressor. However, the dynamics of filling and emptying the manifolds, as well as the dynamics of the turbocharger rotor cause a lag in the response of the air-charging system, and this has a profound effect on in-cylinder processes, e.g. mixing, combustion and emission formation. The instantaneous NO_x and Particulate emission trends are shown in Fig. 5d. The emissions profiles demonstrate a very transient behavior, with sharp high-frequency fluctuations, and while the A/F ratio is obviously an important factor, the fluctuations of either NO_x or Particulates are not necessarily correlated directly with A/F. More information is needed to fully understand the transient emissions spikes and identify additional factors affecting their magnitude.



a)



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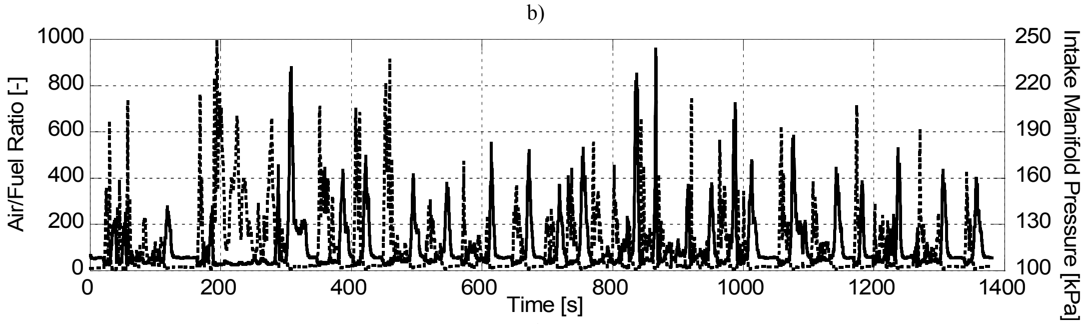

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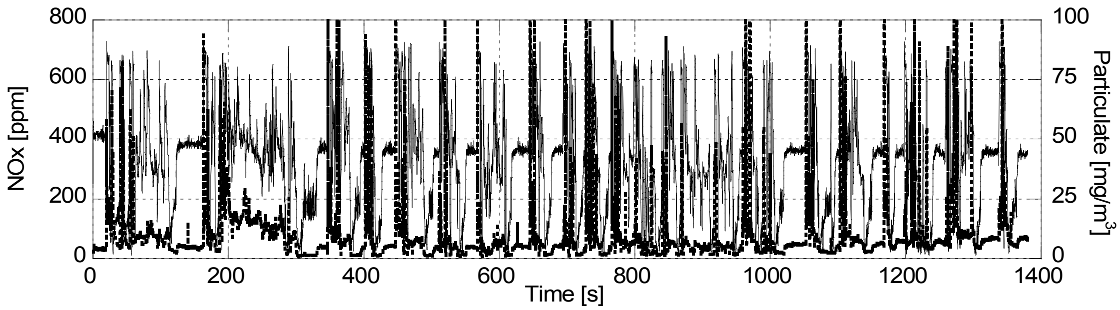

d)

Figure 5: Results of the Engine-In-the-Loop test over a FTP75 driving schedule: a) vehicle speed, and measured histories of b) engine speed and torque, c) boost pressure and Air/Fuel ratio, and d) instantaneous NOx concentration and Particulate mass in the exhaust.

<u>Characterizing transient emissions</u>; A close up of a shorter interval given in Figure 6 provides more details. The instantaneous flow rates of particulates, measured during the interval between 180s and 220s using the fast Differential Mobility Spectrometer, are shown in Fig. 6a. The particulate emissions are emphasized for two reasons. The preliminary analysis led to a hypothesis that the transient contributions to total particulate emission might be dominant under very dynamic operating conditions. Secondly, particulate emission is tied directly to the visual signature and is consequently equally important for the military and the commercial sector. Selected engine variables are plotted for the same time interval in Figure 6b. The engine command shows driver behavior, and the intake manifold pressure illustrates turbocharger response to the commanded load changes. Interestingly, the sharp spike of the particulate emission occurs very early, as soon as the load transient is initiated, and does not align with the peak engine command. While the command often shows very rapid increases to 100%, the intake manifold pressure buildup is delayed due to turbocharger inertia and manifold filling dynamics. This is a period of irregular conditions, where the engine air supply limits the amount of fuel that can be burned, mixing is poor and the A/F ratio can be significantly higher than under more steady operation. In addition, exhaust residual might still be present in the manifold even if the Exhaust Gas Recirculation (EGR) valve is instantly closed. In summary, transient departures have the most effect on particulate emissions, since the phasing of instantaneous PM spikes aligns well with the initiation of the load transient. The transient effect is most prominent when the transient load increase is initiated from idle.

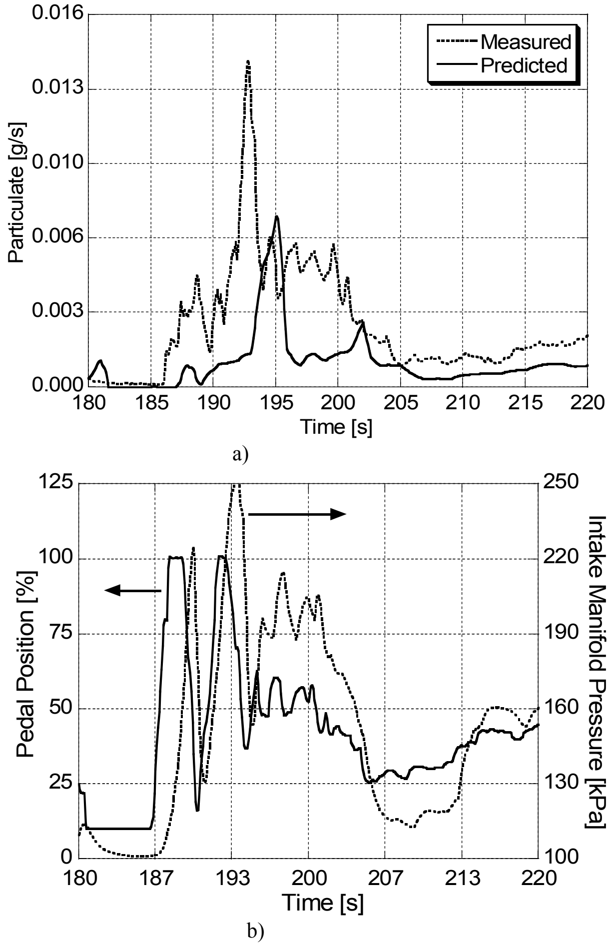

Figure 6: Engine system behavior during a 180 – 220 sec. interval of the FTP 75 vehicle driving schedule : a) comparison of measured transient particulate mass emissions and predictions based on quasi-steady assumptions, and b) pedal position and measured intake manifold pressure.

Quantifying the transient effect requires establishing of the reasonable baseline first. This is accomplished utilizing a simple engine model in SIMULINK and a map of steady-state engine particulate emission measured in the same test cell. When *transient* speed and fueling trajectories measured in the EIL facility are provided to the SIMULINK engine model as input, the emission histories corresponding to assumed quasi-steady conditions are obtained as output[23]. In other words, the quasi-steady baseline represents estimates of what the emissions would have been had we marched through the driving schedule point-by-point and allowed conditions to settle at every step. This baseline is contrasted to real instantaneous measurements obtained in the EIL facility, as shown in Fig. 6a. The spike of instantaneous particulate emission is higher and it precedes the quasi-steady predictions. The quasi-steady profile basically follows the load, its peak aligning closely with the peak in boost pressure. This confirms the hypothesis about irregular conditions at the initiation of the transient being the primary cause of transient particle emissions. The transient contribution to the total emission during the given interval is very tangible, as the integrated area under the transient trace is much greater than the area under the quasi-steady line. Consequently, the transient contribution can easily dominate the overall emission trends in case of very aggressive driving condition, such as those specified by the FTP75 procedure. In addition, the large transient spikes in soot emission are linked to black smoke and visual signature and hence need to be addressed regardless of the cumulative emission.

The EIL tests are currently the only reliable way to obtain such deep insight and hence are an essential tool in the quest for developing clean and efficient propulsion for trucks. The advanced test cell capabilities correlate engine state variables with transient emissions and offer guidance for reducing their magnitude. As an example, characterization of transient emissions for different tip-in functions performed by Hagena *et al.*[64] offers detailed insight into causes of transient spikes and identifies strategies for diminishing their effect. On-going work is aimed at expanding this knowledge and applying it for addressing transient emissions with engine-level strategies (e.g. multiple injections, Variable Geometry Turbine and Exhaust Gas Recirculation strategies) or vehicle level strategies such as drive-by-wire systems, tailoring of the torque converter or transmission characteristics.

The vehicle-level analysis is particularly important in case of hybrid propulsion. While hybrid systems offer more flexibility in controlling the engine, optimizing the powertrain supervisory control for fuel economy can lead to sharp load increases. Indeed, initial study of the parallel hybrid electric system[23] demonstrated the tendency of the stochastic dynamic programming algorithm to frequently switch between the engine and electric motor as the sole power source, rather than to use the electric motor for power assist. Every switch to engine-only operation was accompanied by a spike in soot emission. Hence, follow up work will use lessons learned in the EIL facility for optimizing the trade-off between fuel economy and emissions. In addition, new hybrid architectures are being explored, e.g. an electric power-split system with two planetary gears and a series hybrid system, each bringing unique benefits and challenges. These are but a few examples of the potential applications of the EIL capability for assessing advanced propulsion systems. The immersion of additional hardware, e.g. electric motor/generators, power electronics and energy storage, will expand the EIL concept to powertrain-in-the-loop studies and enable equal fidelity in evaluating transient behavior of these sub-systems and components.

6. DISCUSSION AND CONCLUSIONS

Hardware-in-the-loop (HIL) simulation is a process of emulating a system by immersing selected hardware within a closed-loop virtual simulation of the remaining subsystems. It provides a powerful "middle ground" between purely virtual simulation and full physical prototyping, thereby combining the rapidness of the former with the verisimilitude of the latter. It is a mainstay of the electronic control system development, calibration, and validation industries. Such traditional control prototyping or controller-in-the-loop simulation is an important application of HIL technology, but the technology has evolved to permit much more. In fact, HIL simulation is rapidly becoming a system synthesis methodology that allows engineers to immerse major pieces of hardware beyond just electronic controllers "in the loop". This paper reviews key enablers of the HIL simulation and its historical metamorphosis from a control prototyping tool to system integration and optimization tool. The new HIL paradigm opens up attractive possibilities in many areas, including automotive propulsion. The latter is particularly relevant due to increased complexity of concepts being considered for future ground vehicles, including hybrids, and growing pressures for improving fuel economy and emissions. Therefore, this work documents development of the engine-in-the-loop (EIL) setup that immerses a physical engine system within a virtual simulation of a vehicle system. Having the engine in the test cell allows application of sophisticated diagnostics, including ultra-fast emissions analyzers. The power of the EIL simulation is highlighted by showing how it provides detailed insight into the transient interactions between powertrain components and their influence on transient emissions. Armed with such insights, automotive systems engineers can effectively optimize tradeoffs between fuel economy, performance and transient emissions and evaluate new technologies before physical prototypes become available. In commercial applications this is critical for meeting future stringent exhaust emission regulations, while in military trucks particulate emissions have direct impact on visual signature.

The researchers are expected to increasingly use HIL simulation for system design, particularly in the automotive context. Ongoing work expands the use of the EIL setup for the integration and development of advanced hybrid propulsion systems. Virtual prototyping of the vehicle facilitates rapid changes of the propulsion system architecture and evaluation of a number of very different configurations, e.g. a hybrid electric power split system or a series hydraulic hybrid system. The HIL capability will facilitate simultaneously optimization of engine control strategies, hybrid system design and its supervisory control, based on analysis of realistic, transient operating conditions. In this context, virtual scaling will rapidly become an essential part of HIL simulation. Virtual scaling is the process of wrapping a virtual model around a physical component in a HIL simulator in order to make it "appear" bigger or smaller to the rest of the simulator – a capability essential for making design decisions regarding complex hybrid systems.

As a further longer term trend, networked HIL simulation is likely to rapidly gain pace in the coming years. The potential power of networked HIL simulation is evident from promising research by investigators including Brudnak *et al.* [26]. Networking different HIL simulators will allow different engineering teams to design selected subsystems independently and then integrate their design efforts through the Internet, thereby demonstrating global concurrent systems engineering. Suppliers, OEMs and customers will have an opportunity for much more reliable evaluations of designs and concepts early in the development stage, thus facilitating strategic decisions and partnering. On the theoretical front, the conceptual similarities between HIL simulation and automatic control are expected to stimulate the control community to develop a fundamental understanding of the power and limitations of HIL simulation. Apart from the proposed control-theoretic framework for HIL simulator analysis by Frangos[10] and the insightful theoretical analysis of HIL simulators by Zhang and Alleyne[11], the literature still lacks a fundamental analysis of the capabilities and limitations of HIL simulation.

7. ACKNOWLEDGEMENTS

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