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Development of an Engine-in-the-loop Vehicle Simulation System in Engine Dynamometer Test Cell

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ABSTRACT

To meet the ever increasing requirements for engines and vehicles in the areas of performance, fuel economy, emission, and meanwhile reduce product development time, Hardware-in-the-loop (HIL) simulation is increasingly used in automotive control system development. Engine-in-the-loop (EIL) vehicle simulation, which is a specific form of HIL simulation, is an approach in which a physical engine (together with its control unit) is coupled to virtual vehicle and driver models through a high power, low inertia engine dynamometer in the engine test cell environment. EIL can be used to perform powertrain control development, as well as engine and vehicle performance evaluation. Because of its advantages in repeatability and flexibility etc., especially for transient operating mode study, EIL has become a powerful tool and will be more widely used in the near future.

Design and implementation of an EIL vehicle simulation system is described. Driver and vehicle simulation models are developed and executed in real time on a high-speed system controller. A highly responsive permanent magnet AC engine dynamometer and a vehicle acceleration pedal are controlled such that the dynamometer loads the connected engine as a real vehicle would and the simulated vehicle speed trace follows the targeted driving cycle. With this system, developers can perform transient engine control development before whole vehicle integration is available. Vehicle parameters, including driveline configurations can be easily modified and the effect on engine and vehicle performance can be studied. An application example of simulating a 10-15 mode emission test cycle is given. The result verifies the effective performance of the system in simulating vehicle dynamics and shows its great potential in engine and vehicle system development.

INTRODUCTION

The ever increasing requirements for engine and vehicle performance, fuel economy, and especially the pressure for fulfilling stringent emission regulations have pushed OEMs and suppliers to continually put forward new concepts and implement new technologies. At the same time, fierce market competition has driven OEMs to continually shorten the product development time. Under such circumstances, Hardware-in-the-loop (HIL) simulation is increasingly used in automotive control system prototyping, calibration, and validation. For the traditional HIL simulation concept, the control unit is the physical hardware. The engine, or the engine together with driveline and vehicle body, is simulated in the real-time platform and interacts with the control unit through proper interface [1-4]. This type of "controller-in-the-loop" [5] simulation is the most commonly used format in automotive industry. However, in a much broader sense, HIL simulation can be defined as "the operation of real component in connection with real-time simulated component" [6]. It is 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" [5]. HIL basically realizes synergistic combination of the real and virtual

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components, which facilitates system development and greatly reduces development time and cost. In this sense, the "hardware" that is "in the loop" does not necessarily need to be the control unit.

In Engine-in-the-loop (EIL) vehicle simulation, the "real component", or the "faithful physical replicas", is the engine control hardware and software together with a physical engine; while the "real-time simulated component", or the "virtual simulation", is the vehicle and driver. The interaction between the engine and the vehicle system, which includes the driveline, tire and road interface, and vehicle body etc., is replaced by the engine and a transient dynamometer that emulates a real vehicle [5, 7-10]. There are specific reasons why such a combination is used. There have been many studies in which both the engine and the vehicle system are modeled [11-13]. However, high fidelity modeling of engine emission, especially in transient operating mode has been very challenging. For an EIL system, since a physical engine is in the setup, there is no need to make an effort in emission modeling. Moreover, such a system has many other advantages for powertrain control development, as well as engine and vehicle performance evaluation, which are evident by looking into the role of EIL in the whole process of the system development cycle.

Figure 1 shows the V-cycle which is widely adopted in automotive control system development, especially in powertrain control development. This cycle includes all the activities from determination of system requirement to system validation and approval. The horizontal axis represents time, thus a narrower "V" means a shorter development time. The vertical axis basically corresponds to the hardware platform on which various activities of the development process are performed, with the higher position referring more to a system level and vehicle level hardware platform, and the lower position to a subsystem level and component level hardware platform. The left half of the cycle mainly covers the design and prototyping activities, while the right half covers verification, calibration, and validation activities.

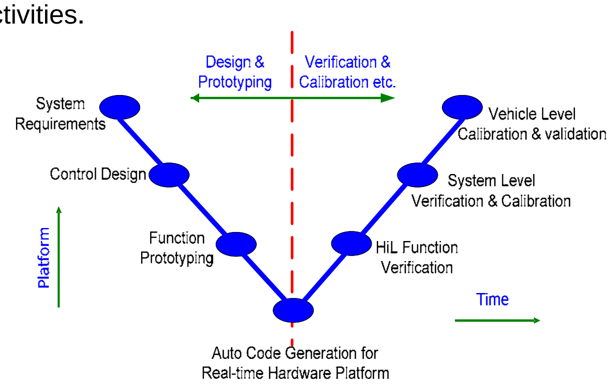

Figure 1. V-Cycle for System Development Process

Usually model-based development methodology is adopted for the design and prototyping portion of the cycle. With this approach, after the system requirements are studied, new algorithms are designed and specified in a high-level graphical language. Then with the aid of an automatic code generation tool, the algorithms are converted and compiled into executables to be implemented and tested on real-time hardware.

In the verification and calibration portion of the V-cycle, various levels of HIL testing may be performed before the system is calibrated and validated at the vehicle level. These HIL tests can be component oriented, subsystem oriented, or function oriented, and are usually started out at the component level and moved on to the system level, i.e., after sufficient confidence is obtained for the component and subsystem functionalities, more system level verification and calibration is performed. During this process, the environment is closer and closer to the reality. EIL is the HIL testing stage in which the physical engine is already in the setup. Moreover, the environment makes it possible that the vehicle and driver behaviors are simulated. It is obvious this system level verification and calibration approach can help not only the overall engine control function verification, but also engine calibration and performance evaluation, especially for transient operations. As increasing emphasis is being placed on engine control performance in transient operating mode to improve fuel economy and emission, an EIL platform shows many advantages. Some of the benefits are as follows:

- EIL provides a platform to rapidly and efficiently evaluate, verify and debug engine control software, find and correct function errors in the early stages of the design process
- Using EIL, developers can perform transient engine control development before whole vehicle integration is available
- EIL can support performance-assured controller design. With its help, developers can perform preliminary calibration targeting driveline and vehicle system with specific parameter values.
- An EIL system is very flexible in that the vehicle system parameters can be easily modified such that their impact on engine performance can be studied.
- An EIL platform provides better monitoring of engine behavior and good repeatability of the test runs. It ensures a reliable and consistent process. Development activities normally executed in highly variable vehicle environment are carried out in controlled engine test cell settings which significantly improve the repeatability.

In summary, with an EIL system, developers can complete as much work as possible for engine control development and performance evaluation in the engine test cell environment, before having to perform at the vehicle level. Because of its numerous advantages, EIL has become a powerful tool and is expected to be more widely used in the near future.

This paper presents the effort of setting up such an environment. ADX simulation and control platform of A&D Co. Ltd. is used in the system, serving as a model-based dynamometer and acceleration pedal controller that includes vehicle and driver models to realize real-time simulation of an actual vehicle. A high power low inertia permanent magnet AC dynamometer is used to load the engine. Application results of simulating a 10-15 mode driving cycle are given.

The paper is organized into four parts. Section I gives an overview of the design and configuration of the EIL system. System hardware including ADX controller is described. Section II provides detailed description of the vehicle and driver models, and the dynamometer control and acceleration pedal control. An application example of using the system to simulate a 10-15 mode driving cycle is presented in Section III. The last section summarizes the paper.

SYSTEM OVERVIEW

Figure 2 shows the overall structure of the EIL system. The engine used in this setup is a 2.4 liter inline 4 cylinder gasoline engine. It has electronic throttle control system — the acceleration pedal position signal is read by the Engine Control Unit (ECU), and the desired throttle opening is consequently determined and set. The engine is coupled to a 265 KW AC dynamometer which uses a synchronous motor with permanent magnet rotor. The dynamometer has a constant motoring and absorbing torque of 506 Nm to 5000 rpm. It has a very low moment of inertia of 0.128 Kg-m^2, which makes it highly responsive and especially suitable for transient testing. The low moment of inertia also makes its impact on the engine perceived load minimal.

Vehicle and driver models, as well as dynamometer and acceleration pedal control algorithms are executed in real time on the ADX controller. The ADX reads in the speed and torque feedback information, and sends out speed or torque setpoint command, which is the result of the driver and vehicle models, to the dynamometer drive through Profibus and consequently controls the operation of the dynamometer. The ADX also sends out acceleration pedal control command to an actuator to control the operation of the pedal. It can be seen that by integrating the virtual system (which includes the driver model, the vehicle model and the control algorithms for dynamometer and acceleration pedal) with the physical hardware (which includes the engine and ECU, speed and torque sensors, dynamometer and drive, and acceleration pedal actuator), the created EIL system makes the dynamometer emulate a vehicle to the connected engine.

The ADX high-speed system controller, which runs the simulation models and controls the dynamometer and acceleration pedal is the central part of the EIL system. Figure 3 shows the hardware framework of this controller. It has a dual CPU architecture, using an Intel PentiumM processor for high-speed simulation and control, and a Renesas SH4 processor for running the human-machine interface, including color touch-screen LCD, function keys, and Ethernet communication with the host PC. A bus controller on the active back plane handles the data transfer between the interface boards and the CPUs. Various function boards can be selected and integrated in the controller to realize the required

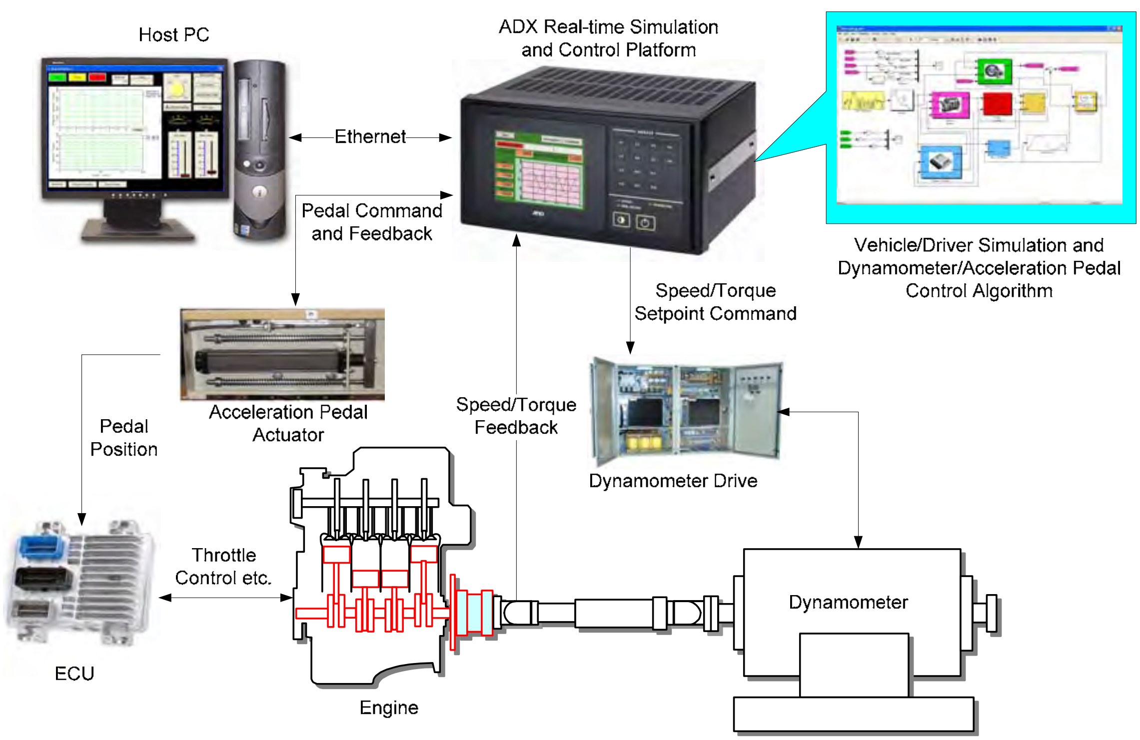

Figure 2. Overall Structure of the EIL System

functions. For the EIL application, analog input and output function boards are integrated in the ADX controller for acceleration pedal control. An encoder board is used for the dynamometer speed and torque feedback. Communication between the controller and the dynamometer drive is fulfilled through a Profibus board.

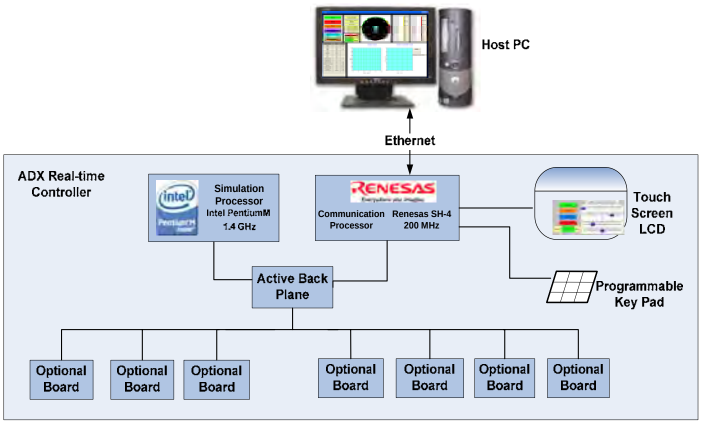

Figure 3. Hardware Architecture of the ADX Real-time Controller

The ADX sends out control commands to the dynamometer drive and pedal actuator at a rate of 1000Hz. Vehicle and driver models, as well as dynamometer and acceleration pedal control algorithms are developed using MATHWORKS products MATLAB®/Simulink®/Stateflow® in the form of model block diagrams on the host PC. The S-functions for system hardware and function modules are developed and integrated in the block diagram. Real-Time Workshop® converts the block diagram into C code, which is then compiled, linked, and downloaded automatically to the ADX hardware for real-time execution under the RT-Linux operating system. VirtualConsole software provides the graphical user interface to the controller enabling the arrangement of various screen elements on the host PC and on the color touch-screen LCD. These screen elements are associated with the variables or parameters of the Simulink® model, enabling real-time parameter setting and signal monitoring.

SIMULATION MODELS AND CONTROLS

EIL simulation of vehicles equipped with automatic transmission (AT) and manual transmission (MT) is different in both the vehicle and driver models. For brevity, this paper only discuss the AT scenario. Figure 4 shows the structure of the virtual system and the relationship among its components. For a given driving cycle, the driver model recognizes the difference between the targeted and calculated vehicle speeds and sends out the target acceleration pedal position value or brake command accordingly. The acceleration pedal control algorithm will subsequently control the action of the acceleration pedal actuator based on the target position value and the position feedback value. The brake command is a virtual command which is sent to the vehicle model, rather than any physical hardware.

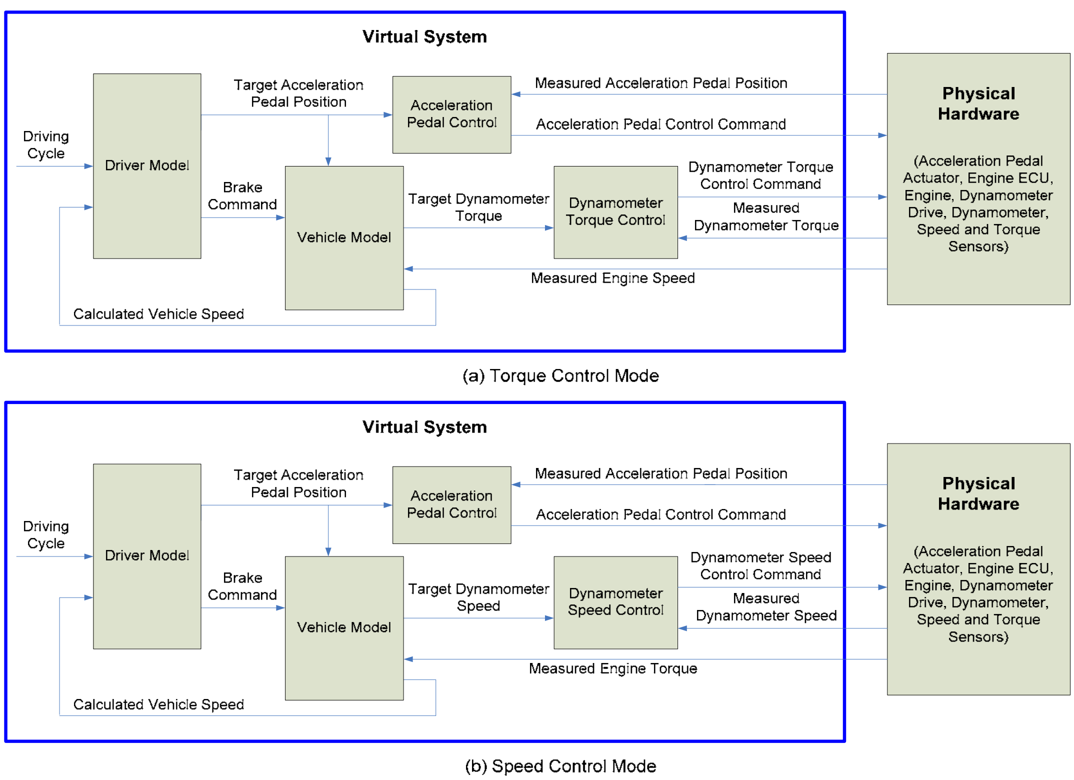

Figure 4. Simulation and Control Model Structure

As to controlling the dynamometer to emulate the engine load, based on different approaches in establishing the connection causality between the physical portion and the virtual portion of the system, two types of simulation and control implementation can be chosen for realizing the setup. The first implementation uses torque control mode of the dynamometer, with which the engine load torque is commanded by the vehicle model, while the engine speed is the result of the torque imbalance between the engine and the dynamometer (Figure 4(a)). An alternative implementation is configured to use the speed control mode of the dynamometer such that the vehicle model commands the dynamometer speed while the engine torque is measured through the dynamometer (Figure 4(b)). Roughly speaking, the first implementation involves higher order control compared with the second and is more challenging [5, 8]. In this paper the first implementation is adopted. For this approach, the engine will generate a specific amount of torque under the engine speed and throttle opening. The engine speed information is read by the vehicle model which calculates the updated vehicle speed. The model also calculates and sends out a dynamometer torque command to the drive to control the operation of the dynamometer.

More details of the driver and vehicle models, which are the most important parts in the EIL system integration, are as follows. A driver model should reflect the human control behavior, which can be very complicated if such factors as response time delay, cognition, preview, adaptive control and learning etc. are all considered [14]. However, since the main focus is vehicle longitudinal dynamics when simulating a vehicle to follow a specific driving cycle, the driver model adopted is very much simplified and only partially mimics human driver control behavior.

Figure 5 shows the longitudinal driver model used for this implementation, which allows the simulated vehicle speed to follow a prescribed schedule. The major function of the model is to calculate the target acceleration pedal position value and brake command value based on the difference between the driving cycle to be realized and the simulated vehicle speed from the vehicle model. A feed-forward algorithm is included in the model which gives a base acceleration pedal position value based on the driving cycle. This feed-forward mechanism basically reflects the driver's understanding of the engine and the vehicle., i.e., for the combination of the engine and the simulated vehicle system, to realize the target speed set by the driving cycle, how much the acceleration pedal needs to be pressed. This base acceleration pedal position value is subsequently adjusted by a PID control algorithm with preview action that uses the information of the target speed profile and the simulated vehicle speed. The resultant value might be positive or negative, indicating whether controlling the acceleration pedal alone is sufficient to realize the speed target, or braking need be applied. Finally the value will be processed by some acceleration/braking logic and a target acceleration pedal position value and a brake command value will be obtained and sent to the vehicle model.

The basic function of a vehicle model is to calculate the simulated vehicle speed and the dynamometer setpoint, either target torque value, or target speed value. Complexity and fidelity of the vehicle model can vary greatly in different application scenarios. Per [15], a vehicle model should be "simultaneously accurate enough to capture key powertrain transients and fast enough to run in real time". Since a major purpose of the EIL system is to develop engine control and evaluate engine and vehicle performance in transient operating mode, the vehicle model should be complex enough to reflect the driveline and vehicle dynamics. Because of the powerful calculation capability and abundant resources, the ADX controller can run very complicated vehicle models in real time, such as Mechanical Simulation Corporation's Carsim®. For this study, vehicle model which is very much simplified but still fulfills the requirement of effectively reflecting vehicle longitudinal dynamics is developed and used.

Figure 6 shows the vehicle model, which consists of torque converter, automatic transmission, shafts and differential, tire and road, and vehicle body etc. Since torque mode is used for dynamometer control, the torque converter model has target dynamometer torque as output, which further dictates that it uses transmission torque as input, measured engine speed as input, and outputs transmission speed as an input for the transmission model. Input and output relationships of the subsystems following the torque converter are as well determined. Each subsystem is briefly discussed below.

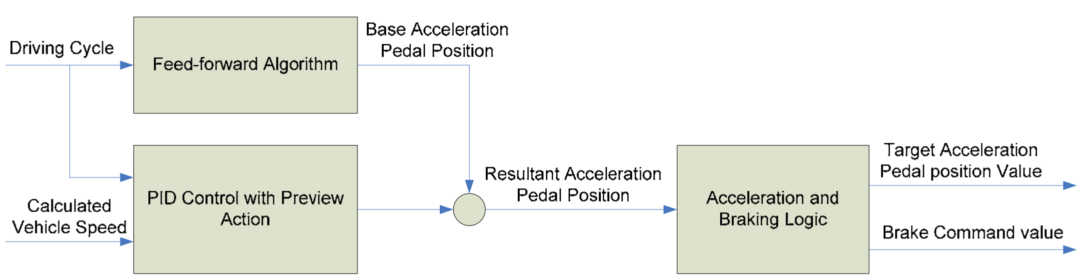

Figure 5. Driver Model

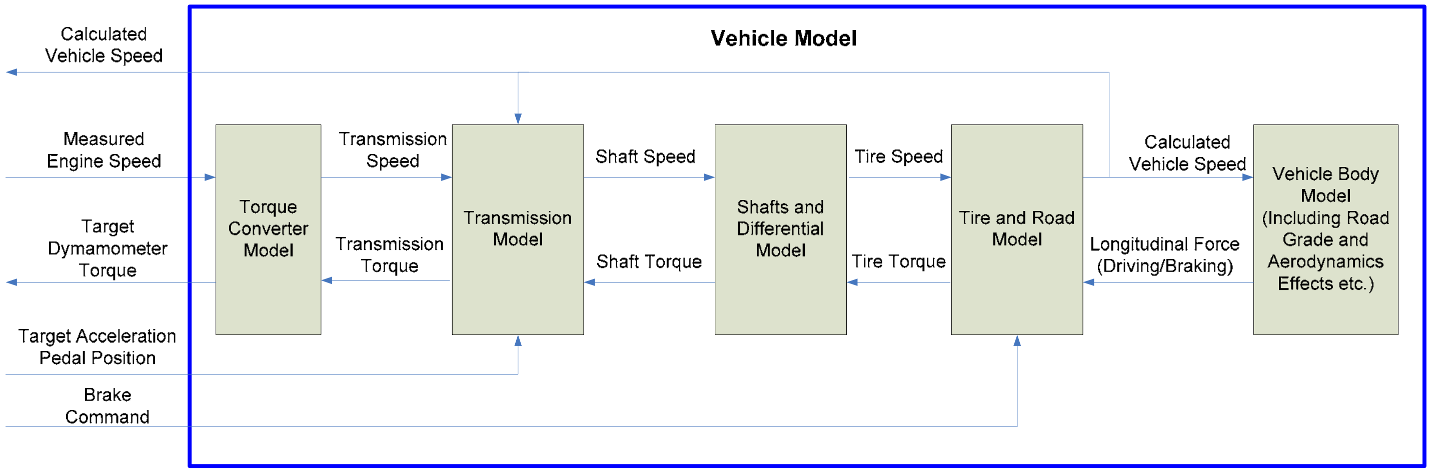

Figure 6. Vehicle Model

TORQUE CONVERTER - A quasi-steady state model is used for the torque converter. The inputs to the model are the measured engine speed (impeller speed) and transmission input shaft torque. A capacity factor is used which is a function of the speed ratio between the transmission input shaft speed (turbine speed) and the engine speed:

$$K_C = f_C(\frac{\omega_t}{\omega_e}) \quad (1)$$

where ω_t is transmission input shaft speed, ω_e is engine speed. Load torque on the engine is calculated using the capacity factor and engine speed:

$$T_e = (\frac{\omega_e}{K_C})^2 \quad (2)$$

Torque multiplication ratio is also obtained as a function of the speed ratio:

$$K_T = f_T(\frac{\omega_t}{\omega_e}) \quad (3)$$

Turbine torque is obtained by multiplying the engine load torque with the torque multiplication ratio:

$$T_T = K_T T_e \quad (4)$$

The transmission input shaft speed is calculated using the relationship among the turbine torque, transmission input shaft torque, and the turbine moment of inertia:

$$T_T - T_{ti} = J_T(\frac{d\omega_t}{dt}) \quad (5)$$

where T_{ti} is the transmission input shaft torque, J_T is the turbine moment of inertia.

AUTOMATIC TRANSMISSION - An automatic transmission model basically takes care of the shift logic, gear ratio, speed reduction, torque multiplication, and transfer efficiency etc. Shift logic is established based on such input information as vehicle speed and acceleration pedal position etc. After the gear position is determined and the gear ratio value obtained, the speed reduction and torque multiplication are calculated subsequently. Usually speed reduction is calculated considering gear ratio only, while the torque multiplication also takes into consideration the efficiency factors:

$$\omega_s = \omega_t / R_g \quad (6)$$

$$T_{to} = \eta_g T_{ti} R_g \quad (7)$$

where ω_s is transmission output shaft speed, which is also speed of the drive shaft connected to it. R_g is the gear ratio, T_{to} is the transmission output shaft torque, η_g is the efficiency factor, which is a function of the gear ratio etc. Effect of moment of inertia of the gear sets is integrated in the model:

$$T_{to} - T_{si} = J_t(\frac{d\omega_s}{dt}) \quad (8)$$

where T_{si} is the drive shaft input torque, J_t is the transmission moment of inertia reflected at its output side.

SHAFTS AND DIFFERENTIAL - Similar to the transmission model, the shafts and differential model takes care of speed reduction and torque multiplication, as well as transfer efficiency. Such influences as moment of inertias etc. are integrated in the model. For this implementation only the vehicle longitudinal dynamics is considered and there is no difference between the left and right driving wheels.

$$\omega_w = \omega_s / R_d \quad (9)$$

$$T_{so} = \eta_s T_{si} R_d \quad (10)$$

where ω_w is the wheel speed, R_d is the final drive gear ratio, T_{so} is the output torque at the wheel end, η_s is the efficiency factor. Effect of moment of inertia of the shafts and differential components is integrated in the model:

$$T_{so} - T_w = J_s(\frac{d\omega_w}{dt}) \quad (11)$$

where T_w is the wheel torque, J_s is the shafts and differential moment of inertia reflected at its wheel side.

TIRE AND ROAD - The tire and road model mainly takes care of the longitudinal force (driving or braking) between the tire and road interface which eventually determines the behavior of the vehicle acceleration, deceleration, and speed. The longitudinal force is calculated based on the wheel slip. It is restricted by the tire normal force and the friction coefficient between the tire and road interface:

$$F_x = f_X(s, F_y) \qquad (12)$$

where s is wheel slip, F_y is the tire vertical load force. The wheel slip is defined by:

$$s = \frac{R_r \omega_w - V}{V} \qquad (13)$$

where R_r is the rolling radius of tire, V is vehicle longitudinal speed.

The brake command from the driver model, and also such factors as whether the vehicle is equipped with an antilock braking system (ABS) and traction control system (TCS) etc. need be taken into consideration for modeling the switching between the driving and braking actions. Dynamics of the tire is integrated in the model as:

$$T_w - T_B - T_r - F_x R_r = J_w(\frac{d\omega_w}{dt}) \qquad (14)$$

where T_B is the braking torque on the wheel, T_r is the rolling resistance moment, J_w is the moment of inertia of the wheel and tire.

VEHICLE BODY - The vehicle body model includes such components as road grade effect and aerodynamic drag etc. It can be as simple as a point mass model, or as complex as a detailed multi-body dynamics model. The simplified model adopted for the implementation is:

$$F_x - F_s - F_a = m(\frac{dV}{dt}) \qquad (15)$$

where m is vehicle mass, F_s is the slope resistance defined by:

$$F_s = mg \sin\theta \qquad (16)$$

with θ to be the slope angle. F_a is air resistance:

$$F_a = \frac{1}{2} C_d \rho V^2 A \qquad (17)$$

where C_d is the air drag coefficient, ρ is air density, A is the vehicle frontal projection area.

Above are the vehicle subsystem models. In short, the degree of complexity of a vehicle model might vary greatly. Proper modeling of a vehicle should satisfy the purpose of the EIL settings and meanwhile fulfill the real time requirement.

Finally, the acceleration pedal control and dynamometer control are briefly discussed. After the target values for the acceleration pedal position and dynamometer torque are obtained from the driver and vehicle models, PID controls are implemented using the measured acceleration pedal position and measured dynamometer torque values for feedback. Necessary filtering of the measured signals and tuning of control gains need to be performed. Setting of proper model parameters that represent the vehicle and driveline characteristics is critical for good simulation results. Validation of the EIL vehicle simulation needs to be performed by comparing the simulation results against the test data collected on real vehicle during chassis dynamometer testing or road testing.

APPLICATION EXAMPLE

The EIL setup can be a very powerful tool in powertrain control development, function verification, calibration and validation, especially for emission evaluation in transient operating mode. Detailed usage of the system in these areas will be covered by separate papers. Here the application results of simulating a Japanese 10-15 mode test cycle are given, which serve as a verification of the system performance in simulating vehicle dynamics.

The 10-15 mode emission test cycle is currently used in Japan for emission certification and fuel economy evaluation for light duty vehicles. The entire cycle includes a sequence of warm-up, idle, and multiple 10-mode and 15-mode segments. Emissions are measured over the final duration which consists of three 10-mode and one 15-mode segments. In this application a passenger car with a curb weight of 1400 kg and equipped with a 5 speed automatic transmission is simulated. For brevity, the following figures only show the results of the time duration approaching the end of the test cycle, which includes one 10-mode segment and one 15-mode segment. Figure 7 shows the driving cycle speed (target) and the simulated vehicle speed. It is obvious the simulated vehicle speed follows the target very well. Figure 8 demonstrates the commanded and measured dynamometer torque, which serves as the engine load torque. It can be seen both motoring and absorbing modes are incurred during the process, reflecting the interaction between the engine and the driveline in transient operations. Figure 9 shows the engine speed and the automatic transmission gear position in the simulation process. In Figure 10 the acceleration pedal control behavior and the brake command are shown. It is clear the acceleration pedal follows its commanded position well and the acceleration command and brake command are in coordination.

The application example indicates the EIL setup fulfills the design requirement of reflecting the vehicle dynamics in real time and can be used for powertrain control development in transient operating mode.

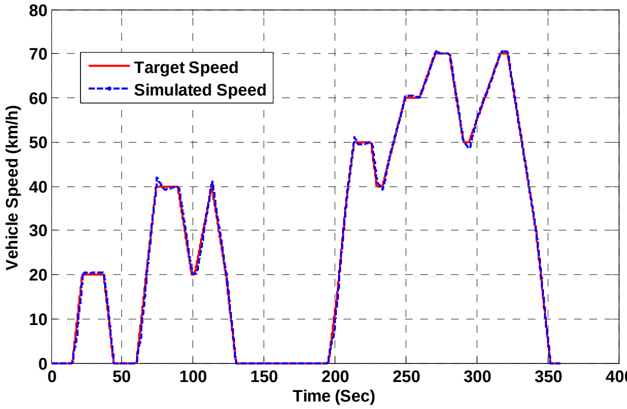

Figure 7. Target and Simulated Vehicle Speed

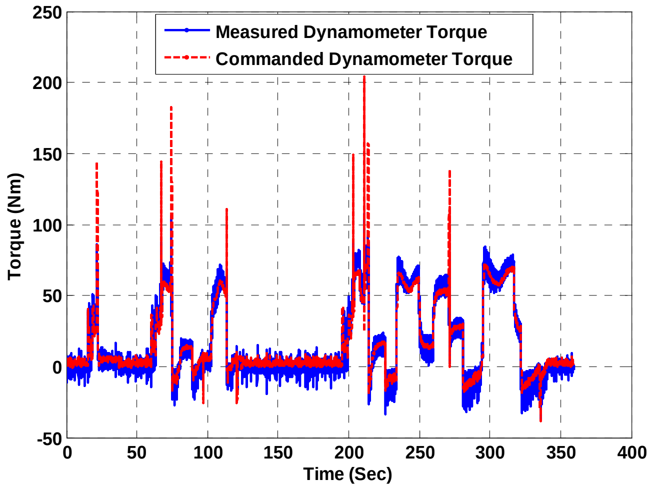

Figure 8. Commanded and Measured Dynamometer Torque

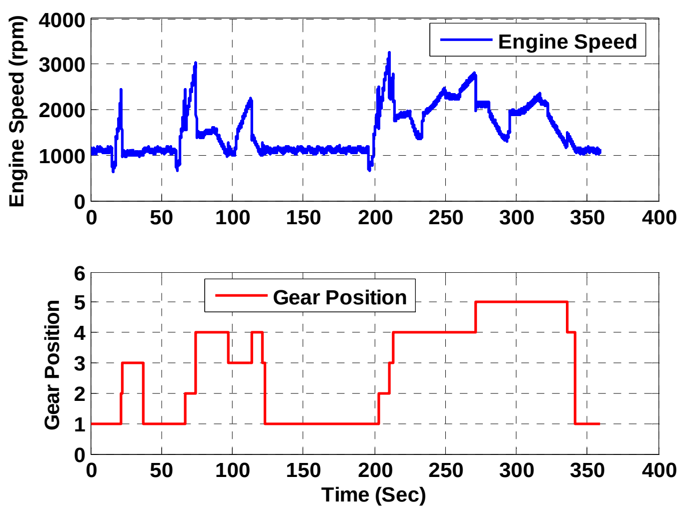

Figure 9. Engine Speed and Automatic Transmission Gear Position

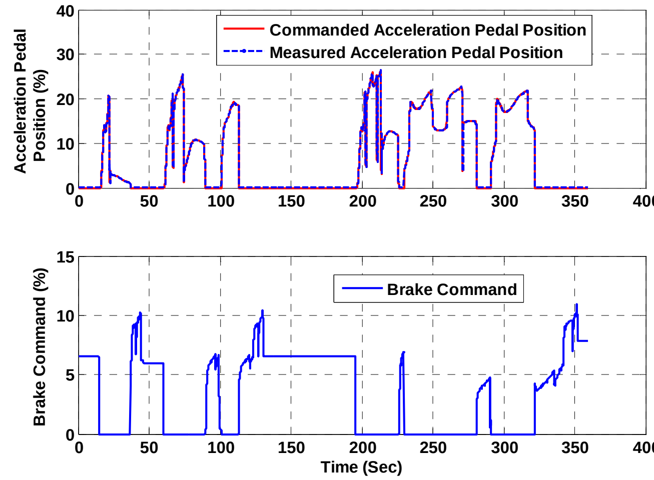

Figure 10. Acceleration Pedal Control and Brake Command

CONCLUSION

HIL simulation has become an indispensable method in automotive system development. As a system level verification, calibration and validation tool, EIL vehicle simulation couples physical engine to virtual vehicle and driver models through a high power, low inertia engine dynamometer in the engine test cell environment. Such a setup has many advantages including repeatability and flexibility, especially for transient operating mode study. Development of such a system centered on ADX high-speed system controller is described. Driver and vehicle simulation models are developed and executed in real time on the controller. A highly responsive permanent magnet AC engine dynamometer and a vehicle acceleration pedal are controlled such that the dynamometer loads the connected engine as a real vehicle does and the simulated vehicle speed trace follows the targeted driving cycle. An application example of simulating a 10-15 mode driving cycle indicates the EIL setup fulfills the design requirement of reflecting the vehicle dynamics in real time and can be used for powertrain control development in transient operating mode. Future work includes development and integration of more comprehensive and higher fidelity vehicle and driver models to obtain simulation results that demonstrate more detailed information of vehicle dynamics effects. Advanced application of the system in powertrain control development, transient operation calibration and validation, and engine and vehicle emission performance evaluation etc. will be reported in future papers.

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