Modeling the Dynamics of Vehicle Fuel Systems

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Abstract

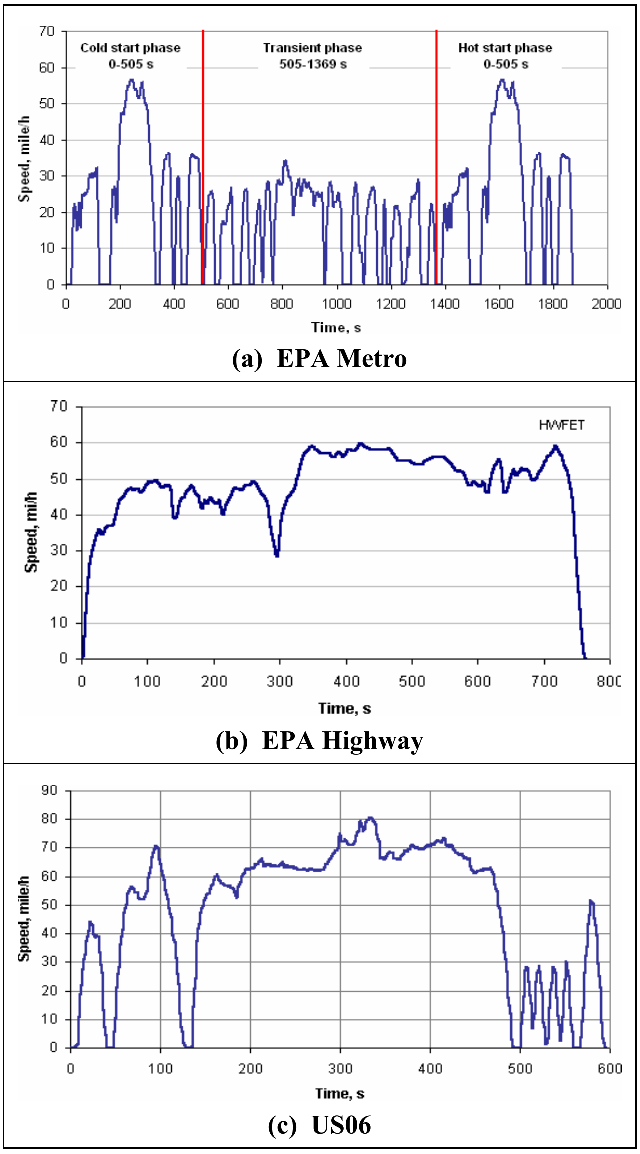
This paper describes the development and application of a multi-domain, physical model in Modelica for the simulation of vehicle fuel systems. The fuel system model includes components from the electrical, mechanical, and hydraulic domains to represent the physical components in the vehicle fuel system. A brief overview of the modeling background and formulation is provided. Following a discussion of the model calibration and refinement effort, sample simulations are shown with the full system model for various transient tests. Additional applications and usage scenarios of the fuel system model are briefly discussed.

Keywords: hydraulics; mechanics; powertrain

1 Introduction

Drivability, emissions, and fuel economy, particularly during transient conditions, are the main drivers for the design requirements cascaded to vehicle subsystems. As gasoline prices become more volatile, vehicle fuel economy has become an increasingly important customer attribute. Fuel economy contributes strongly to customer satisfaction and perceived quality relative to the competition. Achieving fuel economy targets while also meeting increasingly-stringent emissions regulations [1] poses a significant engineering challenge to auto manufacturers. While aggregate fuel economy is a function of many factors, such as engine fuel consumption, vehicle weight, and the fuel control strategy, the basic components of the vehicle fuel system are fundamental pieces in the overall fuel economy picture.

In an effort to improve vehicle fuel economy, there is an increased focus on the design and behavior of the vehicle fuel system components. While the overall design of the fuel system must meet certain steady-state requirements for fueling capacity, *etc.*, transient operation is key for acceptable fueling system dynamic performance, emissions, and fuel economy. In particular, the majority of real world driving is transient as are the drive cycles on which fuel economy and emissions are measured.



(a) EPA Metro

(b) EPA Highway

(c) US06

Figure 1. Common US drive cycles

Figure 1 shows the highly transient nature of three common US drive cycles: EPA Metro, EPA Highway, and US06. The EPA tests are used for emissions certification while the US06 is used to represent a more aggressive driving style with higher speeds. Similar transient characteristics are found in the regulatory New European Drive Cycle (NEDC) and Japanese drive cycles. The speed traces for these and other drive cycles can be obtained from [2].

While customer and regulatory drive cycles point to the importance of transient performance, balancing steady-state and transient design considerations at the fuel system level is a nontrivial task. Cascaded requirements from the system and subsystem level lead to the design of the individual components, such as motors, pumps, and valves, but often the only mechanism to test the transient response of the system is late in the product development cycle when prototype hardware is available. These physical prototypes are expensive and may have long lead times to produce. Information obtained from physical testing may be obtained too late in the design cycle to allow an opportunity for design changes or iterative improvement. Rather than rely on the testing of physical prototypes, it is clearly desirable to develop multi-domain physical models to simulate the transient response of the system upstream in the design process where design changes are most easily accommodated.

This paper describes the development and application of a multi-domain physical model for a vehicle fuel system. Following some background information on this modeling effort, an overview of the physical components from the electrical, mechanical, and hydraulic domains is given. The processes for calibrating the component models from bench data and some model sensitivity results are shown. Furthermore, application and validation of the calibrated model are described including some model improvements to better match the dynamic response of the experimental data. Following the simulation results, some potential usage scenarios of the fuel system model are presented.

2 Fuel System Modeling

Modeling the dynamics of a vehicle fuel system requires physical models that span multiple domains. Figure 2 shows a generic schematic of a vehicle fuel system [3]. The fundamental components of the system are the fuel tank, fuel motor and pump, fuel lines, injector, various orifices such as a fuel filter, and associated regulation valves. A basic, lumped representation of these components requires elements in the mechanical, electrical, and hydraulic domains. This section provides some background information regarding this modeling effort and gives an overview of the component models that comprise a typical vehicle fuel system. The background information provides additional anecdotal evidence of the benefits of component-based physical modeling.

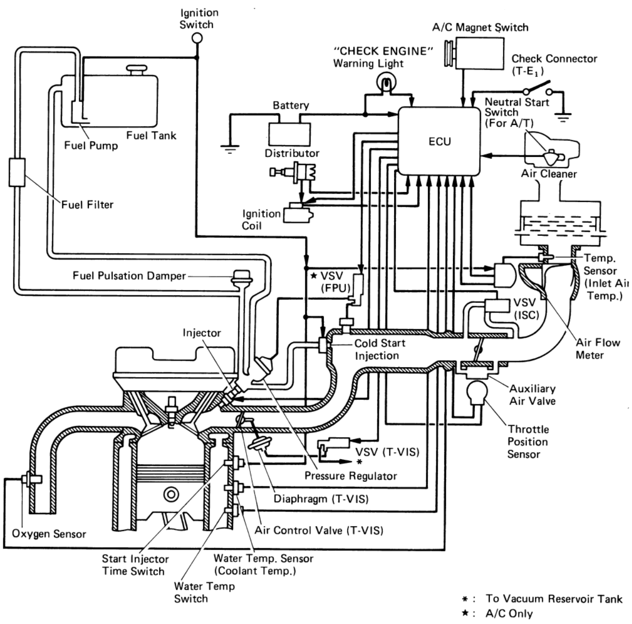


Figure 2. Schematic of a vehicle fuel system [3]

2.1 Background

At its most basic level, modeling involves the mathematical description of the physical behavior. However, great care must be taken in the abstraction of the physical system into its mathematic representation as relevant physical insight can be lost. While Modelica has the advantage of component-based physical models, other approaches that require direct generation of the underlying mathematical equations for use in equation-based solvers can be problematic. To underscore this point, an example relevant to fuel system modeling is presented.

The in-tank fuel pump, shown in the upper left hand side of Figure 2, is a fundamental component of the vehicle fuel system. The fuel pump is typically an integrated motor and pump assembly. The assembly is often characterized by steady-state data consisting of the voltage input to the motor, current in the motor, pressure difference across the fuel pump, pump speed, and pump flow rate. A common approach when using steady-state data to formulate a transient model is to establish a regression equation with unknown coefficients, fit the coefficients with the data, and then establish a semi-empirical transient form of the regression equation using applicable conservation laws. This technique when applied to the motor yields a semi-empirical formulation for

Kirchhoff's current law (with some non-standard units):

$$L\frac{dI}{dt} = V - a_o - a_1 I - a_2 RPM \tag{1}$$

where L is the motor inductance, V is the applied voltage to the motor, I is the current in the motor, and RPM is the motor shaft speed. A semi-empirical conservation of angular momentum for the motor shaft yields the following equation:

$$J\frac{dRPM}{dt} = c_o + c_1 I + c_2 RPM + c_3 RPM^2 + c_4 \frac{VI}{RPM} - c_5 \frac{QdP}{RPM} \tag{2}$$

where J is the shaft inertia, Q is the volumetric flow through the pump, and dP is the pressure difference across the pump. Those familiar with the modeling of DC motors will recognize some of the terms in the two equations above: the c_1 term represents the torque input from the motor, the c_5 term is the work done on the fluid, and the c_2, c_3, and c_4 terms are meant to account for losses in the system. While it is certainly possible to generate values for the a and c coefficients from the pump steady-state data, this approach has severe flaws and can result in unstable behavior. For example, this approach can result in inconsistent formulations since the power supplied by the electrical system is related to the torque input to the shaft (*i.e.* a_2 and c_1 are not independent). Furthermore, losses in the motor represented by the c_4 term should be related to the voltage drop across the motor (*i.e.* the a_2 term) not the voltage input to the system. Using the steady-state regression coefficients based on the formulation above, the transient equations implemented in SIMULINK [4] proved unstable for obvious reasons. Unfortunately, these types of modeling inconsistencies are extremely easy to overlook when formulating the underlying system conservation equations directly rather than modeling the physical behavior of the individual components.

Given the issues with generating a consistent, stable model for the entire system, a more fundamental, component-based approach was started using Modelica. This approach, while still using regressions to describe some physical behavior, ultimately proved more robust by sharply focusing the modeling on the physical behavior of the individual components. An overview of the Modelica models is given in the sections that follow.

2.2 Fuel Pump Assembly

The model for the fuel pump assembly is shown in Figure 3. It consists of a model of the electric motor with components from Modelica Standard `Electrical` library and the fuel pump connected by a shaft. The dynamics of this model are similar to those given by Eqs, (1-2) but with a consistent formulation. The regression coefficients generated for Eq. (1) above were used to specify the parameters for the electrical system.

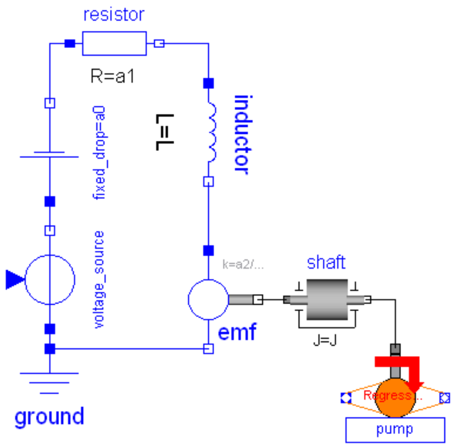


Figure 3. Modelica model of fuel pump assembly

A simple, efficiency-based formulation is used for modeling the pump to account for the various losses such as friction, leakage, *etc.*:

$$\eta_{pump} = \frac{\tau_{fluid}}{\tau_{shaft}} \tag{3}$$

where τ_{shaft} is the pump shaft torque and τ_{fluid} is the torque imparted to the fluid. At steady-state, the shaft torque is equal to the motor torque. Substituting the definitions for the shaft torque and the torque imparted on the fluid yields the following equation for the steady-state efficiency:

$$\eta_{pump} = \frac{QdP}{V_m I} \tag{4}$$

where V_m is the steady-state voltage drop across the emf device and can be calculated from the electrical system model by applying the voltage and shaft speed from the steady-state data. In keeping with the component-based approach, the pump efficiency is regressed from the steady-state data based on the pump operating conditions. A sample functional form for the efficiency equation is as follows:

$$\eta_{pump} = d_o + d_1 dP^2 + d_2 Q + d_3 Q^2 + d_4 RPM^2 \tag{5}$$

Note that this equation is semi-empirical and could be posed with different or additional terms based on the pump operating conditions and available data.

The results from a regression to the pump data are shown in Figure 4 and agree quite well with the experimental data. The R^2 value of the regression can be increased semi-arbitrarily by including additional terms in the regression equation. The flowrate through the pump was also regressed from the steady-state experimental data using the following functional form:

$$Q = b_o + b_1 RPM + b_2 dP \tag{6}$$

The sample pump efficiency map in Figure 5 shows that the efficiency is stable (*i.e.* between 0 and 100%) along the pump operating line shown in blue. Note that while negative efficiencies from Eq. (5) are shown in Figure 5, these regions do not intersect the pump operating line; thus, the pump would never encounter negative efficiencies during simulations. The stability of this formulation was confirmed over the entire pump operating range (*i.e.* RPM and dP).

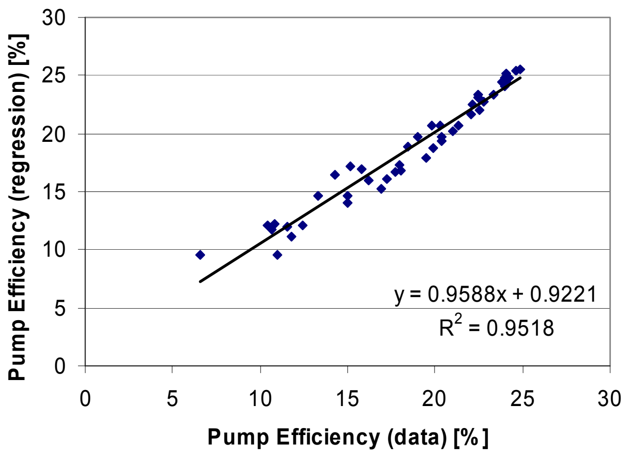


Figure 4. Sample regression for pump efficiency

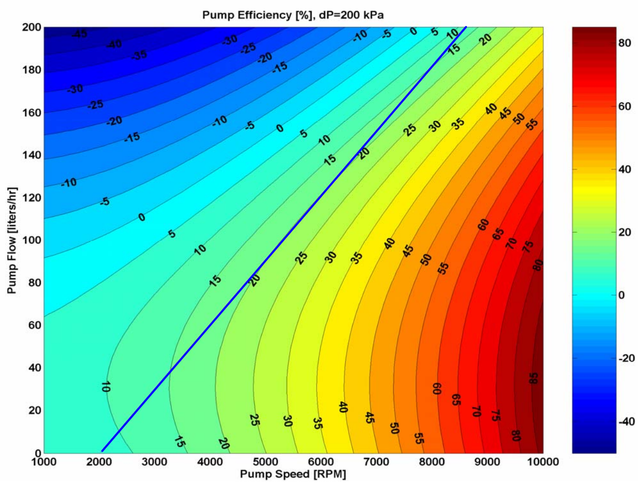


Figure 5. Sample pump efficiency map

2.3 Hydraulics

A `BasicHydraulics` library was developed consisting of accumulators, orifices, pumps, reservoirs, and various valves and flow devices for use in hydraulics modeling. This library is targeted for casual Modelica users and thus intentionally did not employ advanced Modelica concepts such as the `MediumModel`. It employs a standard hydraulic formulation similar to the Modelica `HyLib` library [5] but is targeted at novice users. Given previous work in hydraulics modeling [6], it should be possible to develop a library of this scope from the forthcoming Modelica `Fluid` library [7]. A few of the more interesting components in the vehicle fuel system will be highlighted.

Figure 6 shows an excerpt of the code from the accumulator model including the effects of aeration in the liquid. In lieu of the `MediumModel` a `parameter record` is used for the fluid properties. The model includes the standard conservation equation:

$$\frac{V}{\beta}\frac{dP}{dt} = \sum Q \tag{7}$$

where the effective β is calculated from the liquid compressibility and the mole fraction of gas in the liquid, y_{gas}. Adjustments to these parameters can also be used to account for flexibility in the lines and affect the overall system stiffness as will be shown in subsequent sections.

```
  parameter Modelica.SIunits.Volume volume=1e-6 "Volume";
  parameter Modelica.SIunits.Pressure initP=101325 "initial pressure";
  Modelica.SIunits.Pressure P(stateSelect=StateSelect.prefer)
    "Pressure of fluid in accumulator";
  a;
  parameter Interfaces.FluidProperties fluid_props "fluid property record"
    a;
protected
  parameter Modelica.SIunits.BulkModulus beta_liq=fluid_props.beta
    "fluid bulk modulus";
  parameter Modelica.SIunits.VolumeFraction y_gas=fluid_props.y_gas
    "volume fraction of gaseous component";
  Modelica.SIunits.BulkModulus beta "effective fluid bulk modulus";
initial equation
  P = initP;
equation
  P = a.p;
  1 = beta/beta_liq + beta*y_gas/(1 - y_gas)*1/P;
  volume/beta*der(P) = a.Q;
```

Figure 6. Code excerpt from the accumulator model

The vehicle fuel system commonly contains valves used for pressure regulation. Figure 7 shows the model used for the valves. This model combines elements from the hydraulic and mechanical domains and consists of a pintle mass between two stops. The pintle experiences a force from the hydraulic pressure and opposing preload and spring forces. The dynamic pintle position is used for the variable flow area calculation in the orifice. The mechanical components used in the valve are from the Modelica `Translational` library.

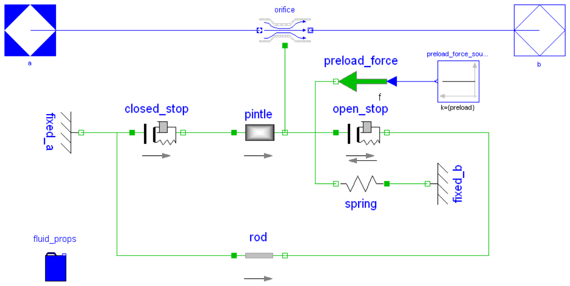
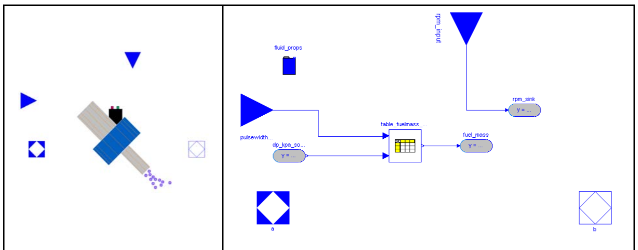


Figure 7. Valve model

A simple model is used for the vehicle fuel injector. The model, shown in Figure 8, contains a table similar to that in the vehicle control system. Given the commanded pulse width and pressure difference across the injector, the fuel injection mass is calculated and converted into a volumetric flowrate based on the engine speed. Consequently, the dynamic pressure upstream of the injector is extremely important as it has a direct impact on the quantity of fuel injected.



(a) Icon **(a) Diagram**

Figure 8. Injector model

2.4 Vehicle Fuel System

Figure 9 shows the vehicle fuel system model. The system model contains the fuel pump assembly shown in Figure 3 in conjunction with hydraulic components for the various lumped volumes in the system, fuel tank, fuel filter, injector, and valves. The single injector model accounts for the cycle-averaged fueling to the entire engine rather than individual pulses for the injector in each cylinder. This formulation is consistent with the overall model formulation and number of lumped volumes considered; the pulsed flow formulation might be required in other applications requiring higher fidelity representations of pressure pulsations in the system (*i.e.* fuel rail dynamics).

The primary inputs to the model are those provided by the control system, namely the voltage input to the electrical system, the engine speed, and the desired amount of fuel to be injected as determined by the fuel pulse width from the engine controller.

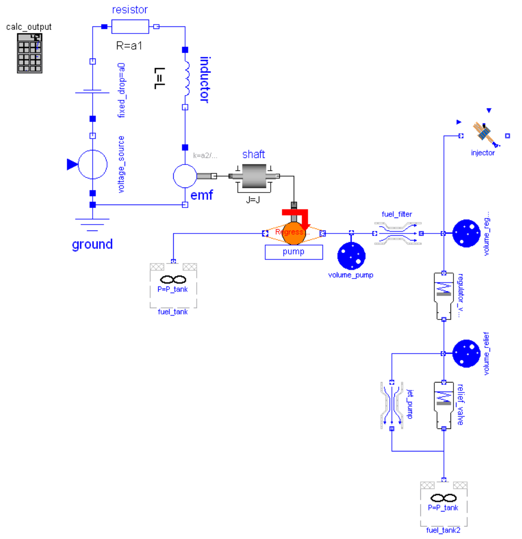


Figure 9. Vehicle fuel system model

3 Results

Prior to the simulation of the fuel system model in Figure 9, the relevant physical system parameters must be provided. These parameters include volumes of the various accumulators; flow areas and discharge coefficients of the various orifices; pintle mass, maximum travel, preload force, and spring constant in the various valves; and bulk properties of the fuel including fuel density and an estimate of the mole fraction of air dissolved in the fuel. While many of these parameters can be obtained from detailed system specifications, some of the parameters require calibration from experimental data. The following section gives an overview of the calibration process for a few selected component models. The simulation results in the following sections were obtained using Dymola [8].

3.1 Model Calibration

Another area where component-based modeling has a distinct advantage over equation-based system models is in model calibration and validation. Efforts to calibrate model behavior at the system level typically prove frustrating and often lead to unphysical calibrations due to multiple calibration knobs and dynamic interactions between components. Component-based physical modeling is ideally suited for calibration on the component or sub-model since unique, isolated test models can be easily constructed to replicate experimental bench tests.

Due to the timing of the vehicle fuel system model development effort, the only data that was available for model calibration resulted from a bench test of the entire fuel system. Careful extraction of the relevant experimental data and construction of unique test models allowed both the steady-state and transient calibration of vital fuel system components.

While the regression provided in Eq. (6) provides good overall agreement with the pump data provided, there can be small differences that arise in steady-state values due to point-by-point regression accuracy and prototype hardware variation. To dial in the steady-state pump flow calculation at a given operating condition, the test model in Figure 10 was constructed. This model prescribes the pump speed and pressure difference from experimental data and allows for precise calibration of a flow multiplier to match the steady-state experimental data. A small adjustment in the flowrate gives the results shown Figure 11 where good steady-state agreement is achieved on each side of the transient test. It should be emphasized that this test was used to calibrate steady-state behavior, and thus the transient differences between the model and the data should be ignored.

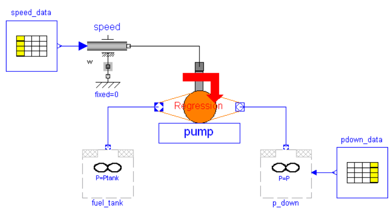


Figure 10. Pump flow calibration model

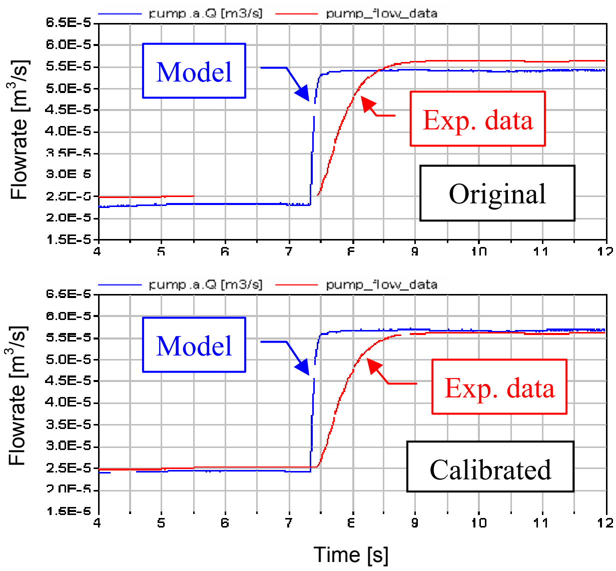


Figure 11. Pump flow calibration (steady-state) results

Figure 12 shows a model used for steady-state calibration of the flow in a valve as shown in Figure 7. In this case, the valve flowrate is not directly measured so the flow characteristics of the valve are calibrated such that the steady-state pressure upstream of the valve matches the experimental data given the flowrate upstream of the volume and the pressure downstream of the valve. Again, slight tweaks to the valve parameters, namely the pre-load force and the flow area, yield significant improvements in the steady-state behavior shown in Figure 13.

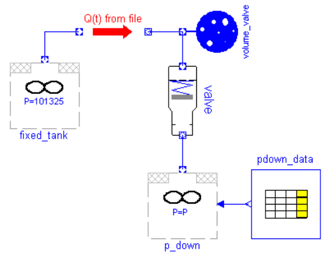


Figure 12. Valve calibration model

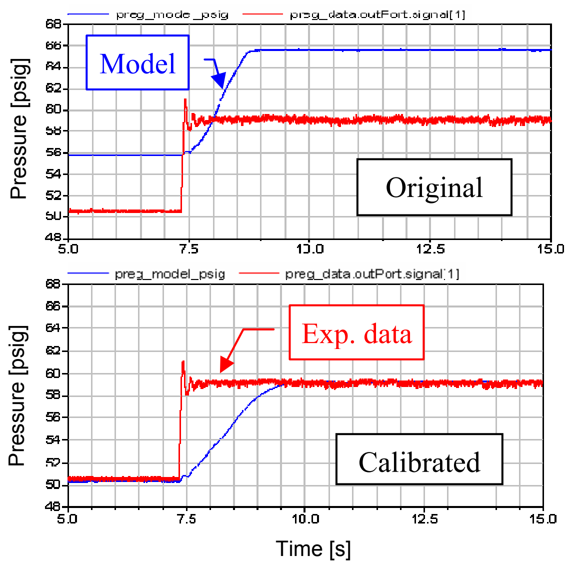


Figure 13. Valve flow calibration (steady-state) results

3.2 Model Sensitivity

Given the initial calibration of the components, the system in Figure 9 was simulated to understand the fuel system model sensitivities to estimated parameters. One key parameter in hydraulics modeling is the effective compressibility β in Eq. (7). This parameter accounts for the compressibility of the fluid, lines, and gas dissolved in the liquid. Figure 14 shows the effect of changing the system compressibility via the amount of air dissolved in the fuel. Decreasing the amount of air dissolved in the fuel results in a faster pressure response in the volume. It is not surprising that this value, which is difficult to estimate and often used as a model calibration factor, has a profound impact on the system stiffness as shown in the rate of pressure rise upstream of the injector.

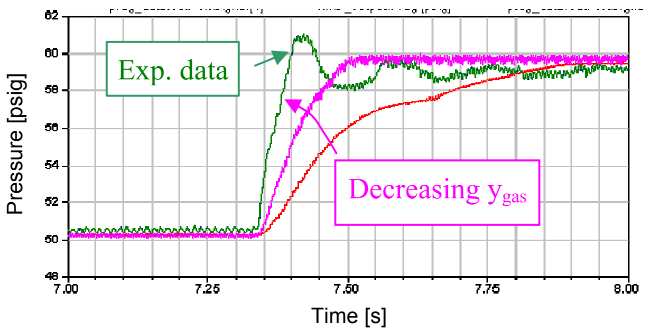


Figure 14. Sensitivity to effective compressibility

Figure 15 shows the effect of changing the size of the lumped volume upstream of the injector. As expected, reducing the size of the volume also increases the rate of pressure rise but, in this simulation, does not affect the response as significantly as changing the amount of dissolved gas in the liquid. It should be noted that system volumes are not typically considered adjustable parameters as the values are available from system/component design specifications. However, the sensitivity was explored here as there was considerable uncertainty in the differences between the experimental setup and the vehicle configuration from which the system data was obtained.

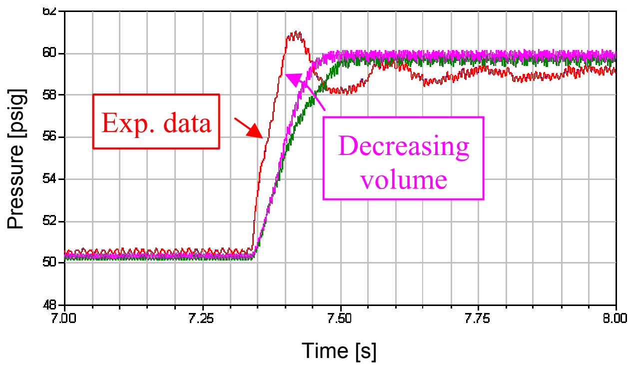


Figure 15. Sensitivity to volume size

3.3 Revised Model and Simulations

Following the sub-model calibration adjustments, the calibrated model was used in transient simulations. Figure 16 shows an overall comparison between the experimental data and the simulation for the pressure upstream of the injector. While the model captures the steady-state behavior reasonably well, there are certainly some differences in the transient details, namely the rate of pressure rise and the oscillatory response following the transient.

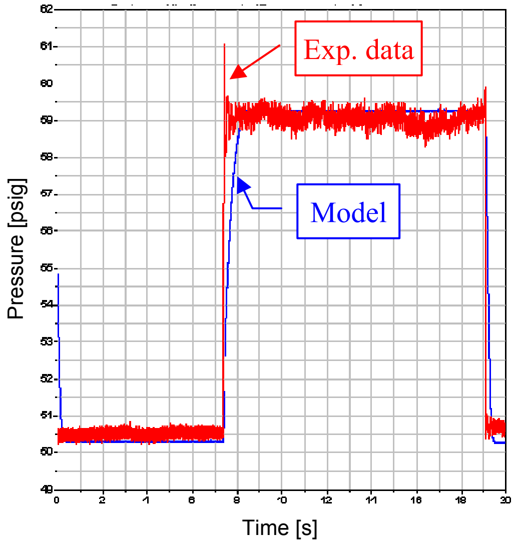


Figure 16. Transient simulations

Given the results from the model sensitivity study and these initial transient tests, the vehicle fuel system model was modified slightly to more accurately represent the dynamic response exhibited in the experimental data. Figure 17 shows the modified model as compared to the original in Figure 9. Note the region highlighted in the box. The initial model formulation considered a single, lumped volume in front of the injector. Since this volume represents the portion of the fuel system from the pump to the injector, it was rather large. Thus, the simulated response represented a filtered value of the actual dynamic response. The revised model shown in Figure 17 replaces the single large volume with two smaller volumes and models the fluid inertia between the volumes to account for the underbody fuel lines. Figure 18 shows the improved model results. Though further improvement is possible, the revised model clearly does a better job of capturing the detailed dynamic response of the fuel system.

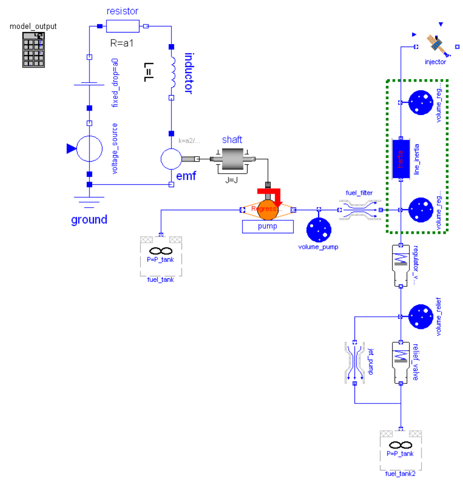


Figure 17. Fuel system model with inertia

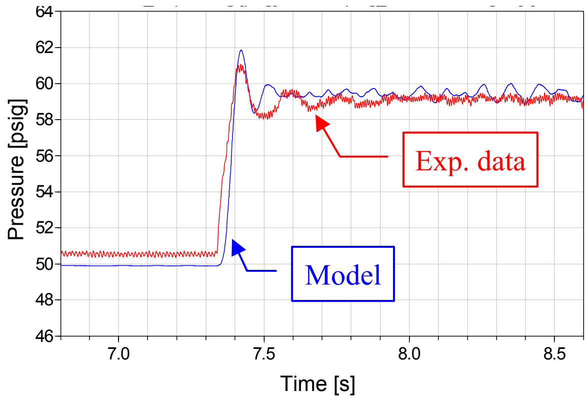


Figure 18. Improved model results

3.4 Drive Cycle Simulations

Having established that the model does a reasonable job of simulating the dynamic response of the vehicle fuel system subject to simple transient inputs, the model in Figure 17 was used to simulate drive cycle dynamics over a common US emissions cycle. Figure 19 shows the vehicle speed during the drive cycle (the first 1400s of the cycle shown in Figure 1a). The dynamic inputs to the fuel system model were provided by VPACS, a Ford-proprietary tool that models the vehicle and control system ([9],[10]). The simulations ran faster than real time though real time simulation was not a stated requirement for the system model.

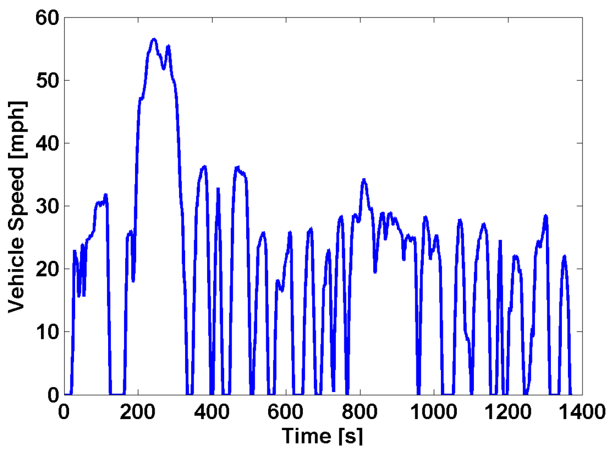


Figure 19. Vehicle speed during drive cycle

Figure 20 shows the pressure upstream of the injector and the engine fuel flowrate during the simulation. The dynamics are a result of the transient operating conditions (*i.e.* vehicle speed, engine operating conditions, desired fueling from the engine controller, *etc.*) combined with the dynamics of the fuel system. In these sample simulations, the pressure upstream of the injector is nominally maintained at a constant value, but some excursions can be seen. Depending on the implementation of the fuel control system, these excursions can lead to differences between the desired and actual fueling to the engine and potentially degraded fuel economy, drivability, and emissions.

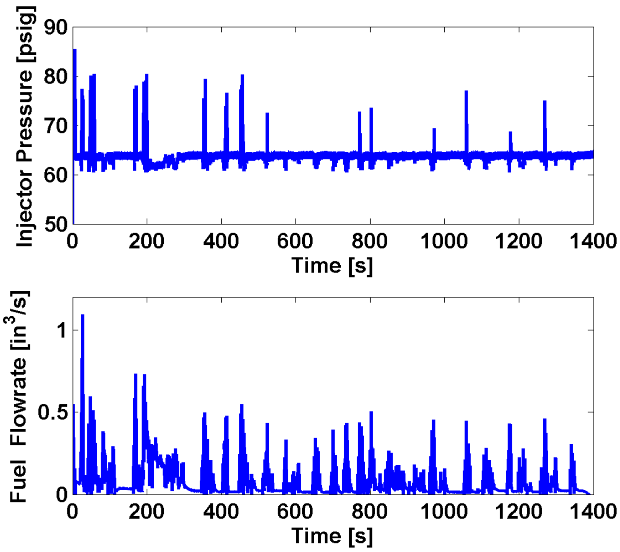


Figure 20. Drive cycle simulation results

3.5 Model Usage Scenarios

While this paper describes the initial model development for a multi-domain physical model of the vehicle fuel system, this model capability can be used in various applications. As an extension of the model sensitivity analysis described previously, the model can be used in conjunction with the NestedAnalysisToolkit [11] or the "Design Optimization" feature in Dymola [8] for structured system robustness analyses. In addition, the model can be combined with detailed models of the liquid fuel behavior ([12],[13]) and cycle simulation dynamics ([14]-[16]) in the engine to understand the impact of the injection dynamics on engine operation, drivability, and emissions. While the complex dynamics considered in such comprehensive engine models may not be suitable for simulation of entire drive cycles, the combined fuel system and engine model can be useful for in detailed analysis of selected transient events. In particular, the engine cranking and cold start behaviors which are extremely important for emissions compliance can be simulated while including the dynamics of the fuel system.

4 Conclusions

This paper details the formulation, development, calibration, and simulation of a multi-domain physical model for a vehicle fuel system. Simulation of the calibrated model shows good agreement with experimental data. A sample simulation of the model over a vehicle drive cycle is included to illustrate possible application usage. Several potential applications of this model are discussed including integration with other detailed models of the power-train system. In addition to the modeling details, this work provides additional anecdotal evidence of the benefits of component-based physical modeling as compared to equation-based system modeling approaches.

Acknowledgements

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