An Energy-Based Proper Model of an Automotive Fuel Delivery System

Greg Browne, Nicholas Krouglicof, and Geoff Rideout
Memorial University of Newfoundland

Copyright © 2010 SAE International

ABSTRACT

Mathematical modeling is widely used throughout any scientific industry when trying to predict the behavior of dynamic systems. Oftentimes it is desirable that these models be simple and efficient, while still delivering accurate data.

This paper builds and examines an energy-based (bond graph) model of an automotive fuel delivery system and suggests which elements are required to produce a Proper Model. The Model Order Reduction Algorithm (MORA) provides a mechanism to quantitatively rank each element in the model and determine its contribution to the system dynamics.

Utilizing this approach, a model is developed that retains 98% of the complete system energy from 12 of the most active of 25 elements. This model requires 46.6% less simulation time while continuing to provide an adequate prediction of the system response.

INTRODUCTION

Any design expert in the automotive industry will most likely use some form of mathematical modeling when analyzing a product or procedure. An accurate mathematical model is essential in determining the response of a system and reviewing its characteristics.

Bond graphs are an efficient way of describing multiport systems, in that the connections (bonds) between system elements have both an effort and a flow whose product is the power of the bond [1]. Moreover, bond graphs allow for the seamless interconnection of systems across energy domains (hydraulics, rotational mechanics, translational mechanics, electrodynamics, etc). Therefore, bond graphs are used as the preferred means of modeling presented in this paper.

The main subsystems of an automotive fuel delivery system are shown as a block diagram in Fig. 1.

![Fig. 1 Fuel Delivery System Block Diagram](image1)

MODEL CONSTRUCTION

To better understand the characteristics of the fuel delivery system, the subsystems can be generalized by their basic elements – shown as a schematic in Fig. 2.

![Fig. 2 Fuel Delivery System Schematic](image2)
The variables illustrated in Fig. 2 are used in the equations and derivations to follow.

Each subsystem can then be modeled individually based on the schematic. These subsystems are described in the following sections.

For quick reference, a table of bond graph elements can be found in Appendix A. For a more detailed description of bond graph formalism, the reader is referred to [1].

**FUEL TANK**

The simple function of the fuel tank is to store the fuel to be used by the system. Fuel is stored under slightly pressurized conditions, $P_T$, until it is drawn by the fuel pump. Unused fuel is returned to the tank via the return pipe.

The bond graph model for the fuel tank is shown in Fig. 3.

![Fuel Tank Submodel](image)

**FUEL PUMP**

The fuel pump (either in-tank or in-line) draws fuel from the fuel tank to be delivered to the system via the fuel pipe. Classically, a pump is modeled as an ideal flow source, $Q_{PT}$, with some internal leakage proportional to the pressure across the pump, $P_P$ [2]. This relationship is shown in Eq. (2).

$$Q_P = Q_{PT} - C_P P_P \quad (2)$$

Where, $Q_P$ is the actual fuel flow delivered by the pump and $C_P$ is the inherent leakage coefficient of the fuel pump (indicative of its volumetric efficiency).

This relationship is represented in bond graph form as illustrated in Fig. 4.

![Fuel Pump Submodel](image)

**FUEL PIPE**

The fuel pipe delivers fuel from the fuel pump to the fuel rail. As fuel enters the fuel pipe, there will be an apparent loss in fluid flow due to its compressibility (bulk modulus, $\beta$), which is given by Eq. (3) [2].

$$\beta = -V_P(0) \frac{\partial P_P}{\partial V_P} \quad (3)$$

Where, $V_P$ is the volume of fuel in the fuel pipe.

The resulting fuel flow undergoes a pressure drop associated with the inertia, $I$, and resistance, $R$, of the fuel pipe, before being delivered to the fuel rail. The pressure drop due to pipe inertia is given by Eq. (4).

$$\Delta P = I \dot{Q} = \frac{\rho l}{A} \dot{Q} = \frac{4 \rho l}{\pi D^2} \dot{Q} \quad (4)$$

Where, $\rho$ is the density of gasoline, $l$ and $D$ are the length and diameter of the fuel pipe, respectively.

The pressure drop due to the resistance of a pipe is non-linear, given by Eq. (5).

$$\Delta P = R Q^2 \quad (5)$$

Furthermore, the resistance of a pipe varies based on the nature of the fluid flow that passes through it (determined by its Reynolds Number,
Re). This piece-wise relationship is given by Eq. (6).

\[
R = \begin{cases} 
\frac{32\nu \rho}{AD^2} & \text{Re} \leq Re_L \\
\frac{64}{Re} + \left(\frac{0.3164}{Re}\right)\left(\frac{Re}{Re_T-\text{Re}}\right)\frac{\alpha a^2}{2D} & Re_L < Re < Re_T \\
\frac{0.3164}{Re} a^2 & \text{Re} \geq Re_T
\end{cases}
\]

Where, \(\nu\) is the viscosity of gasoline, \(A\) is the cross-sectional area of the fuel pipe, \(Re_L\) is the maximum Reynolds number for laminar fluid flow, and \(Re_T\) is the minimum Reynolds number for turbulent flow. The first part of the expression is the relationship for pipe flow with laminar flow, the last part is for turbulent flow [2], and the middle part is a linear interpolation function [3].

The Reynolds Number is calculated using Eq. (7).

\[
Re = \frac{QD}{\nu A} \quad (7)
\]

By combining Eq. (3)-(7), a relationship can be derived for output pressure, \(P_{out}\), given by Eq. (8).

\[
P_{out} = \frac{B}{v_{P(0)}} \int Q \, dt - \frac{4\rho l}{\pi D^2} \dot{Q} - RQ^2
\]

This relationship is represented in bond graph form as illustrated in Fig. 5.

A bolt is attached to a diaphragm that moves with changes in fuel pressure, \(P_{R,\text{in}}\). This relationship is shown as Eq. (9).

\[
P_{R,\text{in}} - P_{atm} = \frac{k_A}{A_A} \int Q_A \, dt
\]

Where, \(P_{atm}\) is atmospheric pressure (101.325 kPa), \(k_A\) is the stiffness of the bolt/diaphragm assembly (the inverse of the compliance, \(C_A\)), \(A_A\) is the cross-sectional area of the pulsation damper, and \(Q_A\) is the fuel flow into the pulsation damper.

This relationship is represented in bond graph form as illustrated in Fig. 6.

The fuel rail is a pipe that delivers fuel to each of the fuel injectors \((Q_{\text{inj1}}\) through \(Q_{\text{inj4}}\)). Unused fuel is returned to the fuel tank via the return pipe.

The piping between each injector will have restrictive effects similar to that discussed in the Fuel Pipe section – a change in fluid flow due to its compressibility (bulk modulus) and a pressure drop due to the inertia and resistance of the pipe segment.

The bond graph for the fuel rail is given in Fig. 7.
FUEL INJECTORS

The fuel injectors take fuel from the fuel rail, atomize it, and spray it directly into the intake manifold of their respective cylinder.

A fuel injector consists of a solenoid-actuated pintle or needle valve [5] that is controlled by the vehicle ECU (Electronic Control Unit). The injected fuel flow, $Q_{\text{inj}}$, from the injector is given by Eq. (10).

$$Q_{\text{inj}} = \begin{cases} C_d A_v \sqrt{\frac{2}{\rho} (P_R - P_{\text{man}})}, & \text{ON} \\ 0, & \text{OFF} \end{cases}$$

Where, $C_d$ is the internal discharge coefficient of the injector valve, $A_v$ is the cross-sectional area of the injector valve, $P_R$ is the rail pressure at the given injector, and $P_{\text{man}}$ is the manifold pressure (MAP).

The $\text{ON}$ condition in Eq. (10) deals with the two main factors that control the fuel injection – timing and quantity.

Some vehicles utilize "simultaneous fuel injection" whereby, at a given series of crank angles, all fuel injectors fire at the same time and for the same duration. This is a less interesting injection pattern and, hence, will not be discussed.

The most common type of electronic fuel injection (EFI) is "sequential fuel injection" (SFI). This is a more robust scheme, illustrated by example in Fig. 8, whereby at four different crank angles a single injector fires. This allows the system to make adjustments to fuel metering more quickly [4].

The assumption is that each injector has a baseband crank angle, $\theta_B$, at which, for all multiples of this angle, the given injector will fire. For simulation, these are assumed to be 180° for injector 1, 720° for injector 2, 360° for injector 3, and 540° for injector 4 (based loosely on Fig. 8).

It is also assumed that, at each particular triggering crank angle, the fuel injected will be half completed (i.e. the pulsed fuel will be centered about this trigger point).

The crank angle, $\theta_C$, in degrees, can easily be derived from the engine RPM, as given by Eq. (11).

$$\theta_C = \frac{360}{2\pi} \int \left(\frac{2\pi}{60}\right) \text{RPM} \, dt = 6 \int \text{RPM} \, dt$$

The quantity of fuel to be injected is converted to a pulse width, $t_{\text{ON}}$, during which the given injector is to fire. For a given load and negligible fuel trim, $t_{\text{ON}}$ can be determined using Eq. (12).

$$t_{\text{ON}} = \frac{60(MAF)}{n_S R_{AF} m_I(RPM)}$$

Where, MAF is the mass air flow rate (g/s), $n_S$ is the number of strokes per revolution, $R_{AF}$ is the air-fuel ratio, and $m_I$ is the maximum fuel mass flow rate of the fuel injector (g/s).

However, the injection pattern is time-independent; therefore, it is more appropriate to express the fuel injection in terms of crank position. Therefore, the number of degrees the injector should fire per piston stroke, $\theta_{\text{ON}}$, can be calculated using Eq. (13) (by multiplying the pulse width, given in Eq. (12), by the engine speed in deg/s).

$$\theta_{\text{ON}} = \frac{360(MAF)}{n_S R_{AF} m_I}$$
For vehicles that do not have direct access to MAF (i.e. no MAF sensor is present), it is calculated by the ECU using Eq. (14) [6].

\[
MAF = \frac{(MAP)(RPM)}{60 R_{air} T_{IA}} \left( \frac{V_{eng}}{2} \right)
\]  

(14)

Where, \( R_{air} \) is the specific gas constant for dry air, \( T_{IA} \) is the intake air temperature, and \( V_{eng} \) is the engine displacement (halved due to half the volume being swept during each revolution).

Considering Eq. (11) and Eq. (13), Eq. (10) can be re-written as Eq. (15).

\[
Q_{inj} = \begin{cases} C_d A_v \sqrt{\frac{\rho}{2}} (P_{in} - P_{man}), & \frac{Q_{out}}{2} \leq (\theta_c \mod 900) - \theta_B \\ 0, & \text{otherwise} \end{cases}
\]  

(15)

A fuel injector is represented in bond graph form as illustrated in Fig. 9.

![Fig. 9 Fuel Injector Submodel](image)

FUEL PRESSURE REGULATOR

The fuel pressure regulator is a diaphragm-operated pressure relief valve that maintains a constant pressure differential across the fuel injectors [5]. This is accomplished by means of a ball valve, which is held in place by a preloaded spring against a diaphragm [4]. The regulated fuel rail pressure, \( P_{R, out} \), is given by Eq. (16).

\[
P_{R, out} = P_{R, in} - P_{man} - \frac{\rho}{2} \left( \frac{Q_{out}}{2 \pi r_{out} x_R c_B} \right)^2
\]  

(16)

Where, \( P_{R, in} \) is the pressure of the fuel as it enters the pressure regulator, \( Q_{out} \) is the fuel out of the pressure regulator (given by Eq. (17)), \( r_{out} \) is the output radius of the pressure regulator, \( x_R \) is the displacement of the spring (the solution to the ODE given by Eq. (18)), and \( c_B \) is the discharge coefficient of the ball valve.

\[
Q_{out} = Q_R - A_R \dot{x}_R
\]  

(17)

Where, \( Q_R \) is the fuel flow into the pressure regulator and \( A_R \) is the effective area of the pressure regulator that can be filled with fuel.

\[
k_R x_R + B_R \dot{x}_R + M_R \ddot{x}_R = A_{RP}(P_{R, in} - P_{man}) - F_0
\]  

(18)

Where, \( k_R \) is the pressure regulator spring stiffness, \( B_R \) is the viscous damping resulting from the volume of fuel present in the regulator, \( M_R \) is the mass of the regulator, \( A_{RP} \) is the effective area upon which pressure is exerted, and \( F_0 \) is the preload on the spring.

The bond graph representation of the fuel pressure regulator is given in Fig. 10.

![Fig. 10 Fuel Pressure Regulator Submodel](image)

RETURN PIPE

The return pipe delivers the fuel from the pressure regulator back to the fuel tank to be recirculated by the system. The return pipe has the same submodel as previously discussed in the Fuel Pipe section.

SUBMODEL INTERCONNECTION

Due to the nature of bond graphs, the submodels can be easily interconnected to form the complete model previously outlined in the fuel delivery system schematic (Fig. 2). This complete model is shown in Fig. 11.
MODEL SIMULATION

Model construction and simulation is implemented in the software package 20-Sim.

All system parameters used for simulation are given in Appendix B.

The required inputs to the model in order to produce a representative system response are manifold air pressure (MAP), engine RPM, and mass air flow (MAF). As previously discussed, MAF is either available directly or calculated using the previous two inputs in conjunction with intake air temperature (IAT).

In order to achieve the most accurate results, data was logged directly from a vehicle (2004 Chevrolet Optra) using a previously developed OBD-II hardware and software interface [7].
Logged sensor inputs were emulated as shown in Fig. 12. In this case, the Optra did not have a MAF sensor; therefore MAF was calculated as described in Eq (14).

The resulting pressure responses of interest are shown in Fig. 13.

One can see the pulsation damper accumulator displacement, $x_A$, acting in response to fluctuations in rail pressure, $P_R$.

The resulting flow responses of interest are shown in Fig. 14.
One can see the pressure regulator displacement, $x_R$, acting to maintain a constant differential between rail and manifold pressure (shown in Fig. 13). Also, it is shown that the fuel volume in the tank decreases, as expected, from an (arbitrary) initial volume of 30 L.

The initial transients are present for approximately the first second of simulation, and are better illustrated in Fig. 15 (transient pressure responses) and Fig. 16 (transient flow responses).

Any model used to describe a similar fuel injection system should aim to accurately reproduce the transients and steady-state responses, depending on the application.

Therefore, any elements that do not have an effect on these responses can effectively be removed without adversely changing the behavior of the system.
MODEL REDUCTION

By utilizing a method that quantizes the contribution of each element, one can make an informed decision regarding which elements to retain and which to eliminate from a proper model. A proper model has minimal complexity, physically meaningful parameters, and accurately predicts dynamic system responses [8].

The Model Order Reduction Algorithm (MORA) uses activity, $A_i$, to quantize the contribution of a given element. Activity is "absolute energy" and, for a given element $i$, is calculated by Eq. (19) [8].

$$A_i = \int |P_i(t)| \, dt \quad (19)$$

Where, $P_i$ is the instantaneous power of element $i$.

Each element is assigned a non-dimensional activity index, $A_{I_i}$, which is its fraction of the total system activity. For a given element $i$ of $k$ elements, its activity index is calculated using Eq (20) [8].

$$A_{I_i} = \frac{A_i}{A_{Total}} = \frac{\int |P_i(t)| \, dt}{\sum_{i=1}^{k} (\int |P_i(t)| \, dt)} \quad (20)$$

Activity indices are then sorted and elements eliminated from the lower end until the minimum number of elements required to satisfactorily reproduce the responses of the complete model is achieved.

ELEMENT ELIMINATION

Element activities and activity indices resulting from the simulations are given in Appendix C.

99% Model

By following the MORA algorithm to achieve a 99% model (a model that still retains at least 99% of the activity of the complete model), the following elements were eliminated:

- Needle Valves for Injectors 1 through 4
- Fuel Pipe Resistance
- Pressure Regulator Fuel Damping
- Return Pipe Resistance
- Fuel Pipe Fuel Incompressibility
- Fuel Pipe Inertia
- Fuel Rail Resistance 1 and 3

However, by strictly following the algorithm, one can see in the transient plots, Fig. 17 and Fig. 18 that the system responses acquire a high frequency infection and become less damped than the complete model.
High frequency infection is particularly noticeable in the pressure differential maintained by the pressure regulator (Fig. 17) as well as the fuel back to tank (Fig. 18).

The decrease in system damping is prevalent in each response shown.

However, if the fuel damping in the pressure regulator, $B_R$, is reinstated, the system responses can be returned to an adequate representation of the responses of the complete model.

This decision also has a physically intuitive basis – there must be some damping present in the mass-spring subsystem of the pressure regulator to prevent it from continuing to oscillate beyond a reasonable time constant.
98% Model

While maintaining $B_R$, the model can be further reduced to 98% by removing the following elements:

- Fuel Rail Resistance 2
- Pressure Regulator Mass, $M_R$

The transient responses of this 98% model are shown in Fig. 19 and Fig. 20.

By comparing the transient pressure responses of the 98% model (Fig. 19) to that of the complete model (Fig. 15) one can see that the rail pressure, $P_R$, and the pulsation damper displacement $x_A$, are certainly replicated. The differential between $P_R$ and MAP is fairly well replicated; however, the initial 4.7 kHz harmonic is missing from the 98% model. The suitability of this model will be based on the given application.

By comparing the transient flow responses of the 98% model (Fig. 20) to that of the complete model (Fig. 16) one can again see that the 98% model is still a relatively accurate representation of the complete system. Yet again the suitability would have to be determined by the given application.
97% Model

To further reduce the model to 97% of the original system activity would require the elimination of the following element:

- **Pressure Regulator Spring Stiffness, \( k_R \)**

Eliminating \( k_R \) effectively adds infinite stiffness to an already massless diaphragm assembly in the pressure regulator. When considering the rail pressure differential transient, the system is now incapable of effectively responding with the proper overshoot, as shown in Fig. 21 (compared to Fig. 19).

![Fig. 21 97% Model Rail Pressure Differential Transient Response](image)

Furthermore, the output fuel flow from the pressure regulator, given by Eq. (17), was originally constrained by Eq. (18). For the 97% model, Eq. (18) becomes Eq. (21).

\[
B_{PR} \dot{x}_R = A_{RP} \left( P_{R,in} - P_{man} \right) - F_0 \quad (21)
\]

This implies that any fluctuation in rail pressure, \( P_R \), will cause an instantaneous change in the output flow from the pressure regulator. This is illustrated in Fig. 22.

![Fig. 22 97% Model Pressure Regulator Output Fuel Flow Transient Response](image)

**MODEL SELECTION**

In many cases the 98% model will be a good choice for modeling a typical fuel injection system. The pressure and flow transients (Fig. 19 and Fig. 20) match reasonably well those of the complete model (Fig. 15 and Fig. 16).

The benefits to using the 98% model over the complete model include:

- Less complexity (less elements)
- Improved computational efficiency
  - 19.4% less computations required for simulation
  - 46.6% less computation/simulation time

The 98% model is shown in Fig. 23.
CONCLUSION

The reduced model presented in this paper was intended to provide an accurate representation of the complete system in terms of both transient and steady state responses.

However, the best selection of model to use will be based on the intended application for which it is to be applied. For example, if the intention is to study, in detail, the transient response, perhaps the complete model would be necessary in order to maintain the initial 4.7 kHz harmonic that was lost in the reduction process. Alternatively, if the study is focused on the steady state response of the system, the model could most likely undergo even further reduction than that presented in this paper.

Beyond the consideration of model activity, other elements may be retained if they are of particular interest. For example, the fuel injector needle valves could be retained if the fuel injection pattern was part of the intended study.

Regardless, this paper outlines the means by which one can reduce the complexity of a fuel delivery model, while still retaining the desired characteristics. Beyond reducing the computational complexity, the submodels of the system could also be imploded into iconic sections for easier analysis, as illustrated in Appendix D. A model with the proper degree of abstraction can be extremely useful as a design tool since it allows the engineer to focus on the elements of the system that have the greatest influence on performance.
REFERENCES


CONTACT INFORMATION

g.browne@mun.ca
### APPENDIX A: BOND GRAPH ELEMENTS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Constitutive Law (Linear)</th>
<th>Causality Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOURCE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow</td>
<td>( f(t) )</td>
<td>fixed flow out</td>
</tr>
<tr>
<td>Effort</td>
<td>( e(t) )</td>
<td>fixed effort out</td>
</tr>
</tbody>
</table>

#### ENERGY ELEMENTS

<table>
<thead>
<tr>
<th>Submodel</th>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>( \beta )</td>
<td>760</td>
<td>MPa</td>
</tr>
<tr>
<td></td>
<td>( \rho )</td>
<td>737.22</td>
<td>kg/m³</td>
</tr>
<tr>
<td></td>
<td>( \nu )</td>
<td>( 6.4 \times 10^{-7} )</td>
<td>m²/s</td>
</tr>
<tr>
<td></td>
<td>( Re_L )</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( Re_T )</td>
<td>4000</td>
<td></td>
</tr>
<tr>
<td>Fuel Tank</td>
<td>( P_T )</td>
<td>( 1.1 \times P_{atm} )</td>
<td>Pa</td>
</tr>
<tr>
<td>Fuel Pump</td>
<td>( Q_{PT} )</td>
<td>( 5.28 \times 10^{-5} )</td>
<td>m³/s</td>
</tr>
<tr>
<td></td>
<td>( C_P )</td>
<td>( 4.11 \times 10^{-11} )</td>
<td>m³/s/Pa</td>
</tr>
<tr>
<td>Fuel/Return Pipe</td>
<td>D</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>3.375</td>
<td>m</td>
</tr>
<tr>
<td>Pulsation Damper</td>
<td>( A_A )</td>
<td>0.001257</td>
<td>m²</td>
</tr>
<tr>
<td></td>
<td>( k_A )</td>
<td>15.63</td>
<td>kN/m</td>
</tr>
<tr>
<td>Fuel Rail</td>
<td>D</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>0.5</td>
<td>m</td>
</tr>
<tr>
<td>Fuel Injectors</td>
<td>( C_d A_v )</td>
<td>( 1.25 \times 10^{-7} )</td>
<td>m²</td>
</tr>
<tr>
<td>Pressure Regulator</td>
<td>( A_{RP} )</td>
<td>0.00085</td>
<td>m²</td>
</tr>
<tr>
<td></td>
<td>( A_R )</td>
<td>0.000275</td>
<td>m²</td>
</tr>
<tr>
<td></td>
<td>( B_R )</td>
<td>2</td>
<td>Ns/m</td>
</tr>
<tr>
<td></td>
<td>( C_d )</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r</td>
<td>3.1</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>( F_0 )</td>
<td>200</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>( M_R )</td>
<td>21.7</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>( k_R )</td>
<td>31.5</td>
<td>kN/m</td>
</tr>
</tbody>
</table>

1. Value typical to the industry
2. Estimated value
3. Value used from [5]
4. Value determined through calculation
APPENDIX C: ELEMENT ACTIVITIES

<table>
<thead>
<tr>
<th>Submodel</th>
<th>Element</th>
<th>Activity</th>
<th>Activity Index</th>
<th>Cumulative Activity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsation Damper</td>
<td>Spring Compliance</td>
<td>38.239</td>
<td>19.433%</td>
<td>19.433%</td>
<td></td>
</tr>
<tr>
<td>Fuel Rail</td>
<td>Rail Inertia2</td>
<td>33.839</td>
<td>17.197%</td>
<td>36.630%</td>
<td></td>
</tr>
<tr>
<td>Fuel Rail</td>
<td>Rail Inertia1</td>
<td>23.014</td>
<td>11.696%</td>
<td>48.325%</td>
<td></td>
</tr>
<tr>
<td>Fuel Rail</td>
<td>Rail Inertia3</td>
<td>22.862</td>
<td>11.618%</td>
<td>59.943%</td>
<td></td>
</tr>
<tr>
<td>Fuel Rail</td>
<td>Fuel Incompressibility1</td>
<td>14.981</td>
<td>7.613%</td>
<td>67.557%</td>
<td>Required elements to maintain 98% integrity.</td>
</tr>
<tr>
<td>Fuel Rail</td>
<td>Fuel Incompressibility2</td>
<td>14.853</td>
<td>7.548%</td>
<td>75.105%</td>
<td></td>
</tr>
<tr>
<td>Return Pipe</td>
<td>Return Pipe Inertia</td>
<td>14.153</td>
<td>7.192%</td>
<td>82.297%</td>
<td></td>
</tr>
<tr>
<td>Pressure Regulator</td>
<td>Orifice Restriction</td>
<td>8.085</td>
<td>4.109%</td>
<td>92.629%</td>
<td></td>
</tr>
<tr>
<td>Fuel Pump</td>
<td>Cₚ</td>
<td>7.200</td>
<td>3.659%</td>
<td>96.288%</td>
<td></td>
</tr>
<tr>
<td>Fuel Rail</td>
<td>Fuel Incompressibility3</td>
<td>2.017</td>
<td>1.025%</td>
<td>97.313%</td>
<td></td>
</tr>
<tr>
<td>Pressure Regulator</td>
<td>Spring Compliance kₚ</td>
<td>1.595</td>
<td>0.811%</td>
<td>98.124%</td>
<td>Required to maintain 99% integrity.</td>
</tr>
<tr>
<td>Pressure Regulator</td>
<td>Regulator Mass Mₚ</td>
<td>1.388</td>
<td>0.705%</td>
<td>98.829%</td>
<td></td>
</tr>
<tr>
<td>Fuel Rail</td>
<td>Rail Resistance2</td>
<td>0.366</td>
<td>0.186%</td>
<td>99.015%</td>
<td></td>
</tr>
<tr>
<td>Fuel Rail</td>
<td>Rail Resistance1</td>
<td>0.364</td>
<td>0.185%</td>
<td>99.200%</td>
<td></td>
</tr>
<tr>
<td>Fuel Pipe</td>
<td>Fuel Pipe Inertia</td>
<td>0.364</td>
<td>0.157%</td>
<td>99.543%</td>
<td></td>
</tr>
<tr>
<td>Fuel Pipe</td>
<td>Fuel Incompressibility</td>
<td>0.309</td>
<td>0.153%</td>
<td>99.696%</td>
<td></td>
</tr>
<tr>
<td>Return Pipe</td>
<td>Return Pipe Resistance</td>
<td>0.190</td>
<td>0.097%</td>
<td>99.793%</td>
<td></td>
</tr>
<tr>
<td>Pressure Regulator</td>
<td>Fuel Damping Bₚ</td>
<td>0.134</td>
<td>0.068%</td>
<td>99.861%</td>
<td>Retained to prevent high freq.</td>
</tr>
<tr>
<td>Fuel Pipe</td>
<td>Fuel Pipe Resistance</td>
<td>0.092</td>
<td>0.047%</td>
<td>99.907%</td>
<td></td>
</tr>
<tr>
<td>Inj1</td>
<td>Needle Valve</td>
<td>0.049</td>
<td>0.025%</td>
<td>99.932%</td>
<td>May be retained due to interest.</td>
</tr>
<tr>
<td>Inj4</td>
<td>Needle Valve</td>
<td>0.049</td>
<td>0.025%</td>
<td>99.957%</td>
<td></td>
</tr>
<tr>
<td>Inj2</td>
<td>Needle Valve</td>
<td>0.044</td>
<td>0.022%</td>
<td>99.979%</td>
<td></td>
</tr>
<tr>
<td>Inj3</td>
<td>Needle Valve</td>
<td>0.041</td>
<td>0.021%</td>
<td>100.000%</td>
<td></td>
</tr>
</tbody>
</table>

TOTAL ACTIVITY: 196.774

APPENDIX D: ICONIC BOND GRAPH MODEL

![Bond Graph Model Diagram]