Detailed Simulation of Turbocharged Engines with Modelica

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Abstract

This paper describes the development and application of detailed models for the simulation of turbocharged spark-ignited engines in Modelica. Following a brief overview of previously-published modeling capabilities, a new engine architecture that provides the flexibility required for simulating boosted systems is detailed. Techniques for turbocharger modeling are discussed followed by sample steady state and transient simulations that illustrate potential model usage in design and control applications.

Keywords: cycle simulation; turbocharging; engine; thermodynamics

1 Introduction

The convergence of increasingly-stringent fuel economy and CO_2 emissions standards and an overall increase in the awareness and impact of global warming trends have led to increased focus on advanced vehicle concepts for improved fuel economy. Given the historical growth in market share of large trucks and sport utility vehicles in the US shown in Figure 1 [1], the focus on improved fuel economy is especially acute. Vehicle fuel economy is clearly a system attribute that is affected by a myriad of different factors, including powertrain system configuration, vehicle weight, aerodynamic drag, rolling resistance, controls and calibration features, and various component efficiencies in the system. While OEMs are exploring opportunities in all aspects of the fuel economy picture, one area of continued focus is on the fuel consumption of the primary powerplant.

A potential opportunity for increasing fuel economy of spark-ignited engines is by turbocharging in combination with engine downsizing. The first patent [2] for a turbocharger on an internal combustion engine was filed in 1905 by Alfred Buchi, a Swiss engineer. Figure 2 shows a sample schematic of a turbocharged engine [3]. The exhaust from the engine is routed through a turbine where exhaust energy is extracted to drive the compressor. The compressed air is typically fed through an intercooler before being routed to the engine. When compared with naturally-aspirated engines, turbocharged engines have increased volumetric efficiency and specific power output thereby enabling engine downsizing. Benefits from engine downsizing include reduced pumping (throttling) losses for part load operation, potential friction reductions, and also potential reductions in powertrain system weight. It should be noted that turbocharging does not come without cost. A few commonly-cited disadvantages of turbocharged engines are increased backpressure to the engine, hardware and controls complexity and cost, and the potential for "turbo lag", broadly defined as the time required from the initial driver throttle demand to spin up the turbo, increase the boost, and deliver the requested torque.

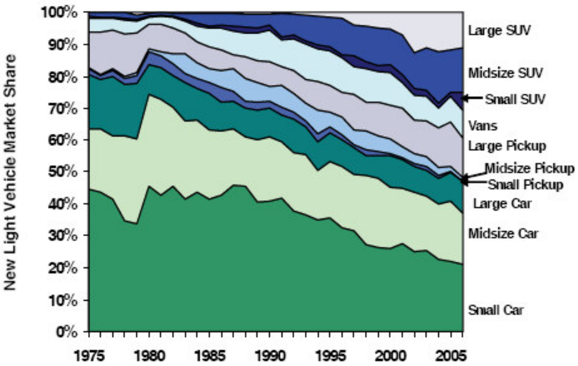


Figure 1. US light vehicle market share, 1975-2006 [1]

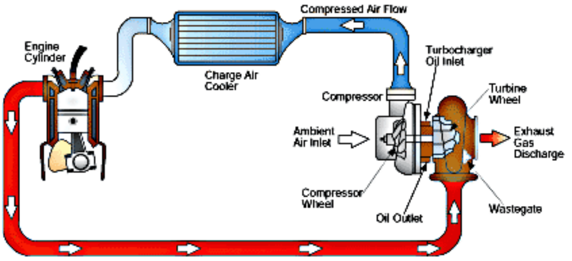


Figure 2. Turbocharged engine schematic [3]

The turbocharger introduces strong feedback between the exhaust and intake systems. Coupled with the different time scales in the engine system, robust design and control of turbocharged engine systems is challenging, even more so with an intense scrutiny on fuel economy benefits. Thus analytic capability for detailed simulation of turbocharged engines is a key enabler for upfront powertrain system design. Potential simulation applications include analytic turbocharger matching and optimization, advanced engine concept assessment, and assessment of transient turbocharger performance.

This paper describes the development and application of detailed models for simulation of turbocharged spark-ignited engines in Modelica [4]. Following a brief overview of previously-published engine cycle simulation capability, new architecture changes are detailed that allow for configurable, efficient modeling of turbocharged engines. Modeling of the turbochargers is also discussed, and some sample steady state and transient results are shown.

2 Engine Model Architecture

Detailed cycle simulation modeling and applications have been discussed in depth in previous publications [5]-[7]. These publications describe an engine model architecture for flexible modeling of the intake, mixture preparation, combustion, and exhaust processes for spark-ignited engines. The crankangle-resolved model includes submodels for breathing past the intake and exhaust valves based on discharge coefficients as a function of valve lift, flow-based turbulence generation and dissipation, mixture preparation and injection dynamics, predictive combustion with laminar and turbulent flame propagation, and heat transfer and thermal warm-up. These models have been used in both steady-state and transient applications for design optimization and robustness, performance, fuel economy, and cold start.

2.1 Restructuring

Previous applications of the engine model were focused on naturally aspirated applications. The existing engine architecture divided the engine into cylinders with each individual cylinder model containing the intake, exhaust, and combustion chamber submodels. The architecture supported both single and multi cylinder applications via engine templates with `replaceable` cylinder models. Inside a given engine template, the instantiated cylinders were wired to the external connectors for the crankshaft, engine block, and intake and exhaust ambient reservoirs.

The existing architecture provided highly flexible for naturally aspirated engines but did not provide the necessary configurability for boosted applications. Figure 3 shows the new, restructured engine model architecture. The new structure divides the engine along the head (`intake_exhaust_system` component) and block (`bottom` component). The connection between the head and block is an array based on the number of modeled cylinders. The head contains the model of the intake and exhaust system such as the throttle, plenum, and individual cylinder heads, which contain the fuel injectors and intake/exhaust ports and valves. The block component consists of the individual combustion chambers which primarily contain the respective cylinder volumes and combustion models. One addition to the engine structure is a `replaceable` boost device model situated between the intake and exhaust reservoir connectors and the head component. The constraining class for this component is of sufficient generality that it can be replaced by a class which can simulate naturally aspirated, supercharged, turbocharged, or turbocompounded behavior.

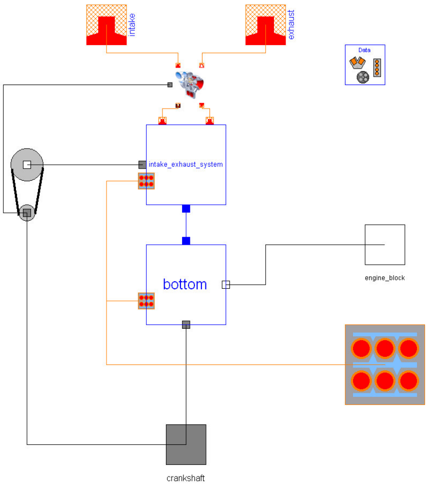


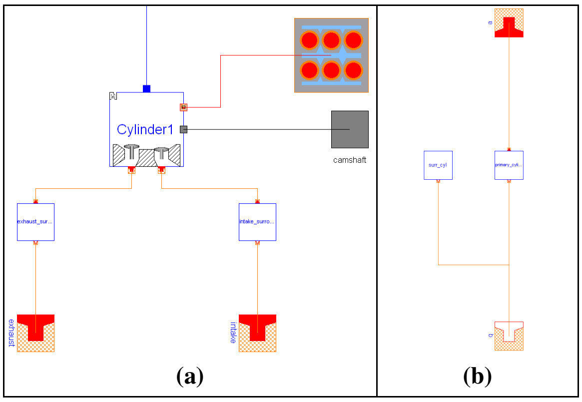
Figure 3. New engine model structure

2.2 Surrogate Modeling

Single cylinder models are often used to represent multi-cylinder engines due to their computational efficiency. While this representation is more appropriate for steady-state applications and some transient applications with prescribed intake and exhaust conditions, it is typically not appropriate for turbocharged applications where the transient blowdown pulses from the cylinders provide the exhaust energy that drives the turbocharger. Crankangle-resolved representation of turbocharged engines requires the modeling of the filling and emptying dynamics of the intake and exhaust manifolds to accurately represent the downstream compressor and upstream turbine conditions respectively.

In an effort to retain the computational efficiency of single cylinder modeling for turbocharged engines, a new structure is introduced consisting of both primary and surrogate cylinder-head representations. The detailed breathing calculations are performed in the primary cylinder head, which is connected to the detailed combustion model. The resulting flows of chemical species and energy from the breathing calculations in the primary cylinder are then replicated in the surrogate cylinder head representations at the appropriate phasing as surrogates for the contributions of the missing cylinders. The implicit assumption is that the manifold conditions are quasi-steady on the time scale of a single, complete firing cycle of the engine.

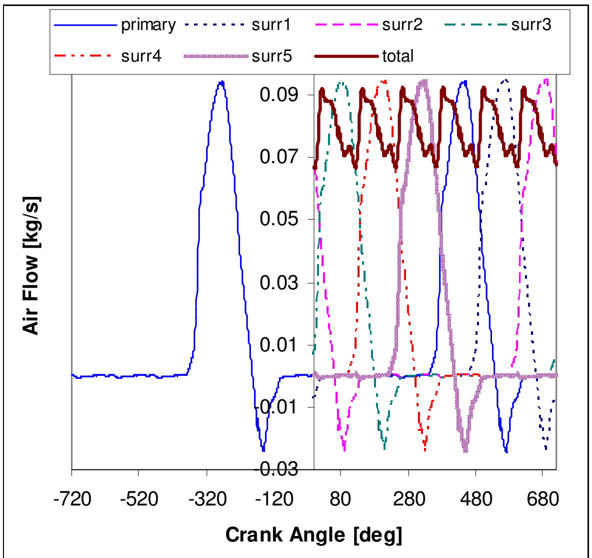
Figure 4 shows the surrogate flow structure. Figure 4a shows an engine head model with a single cylinder intake system mimicking a multicylinder engine. The intake and exhaust surrogate models are positioned between the manifolds and the head model for the primary cylinder. Figure 4b shows a single instance of the surrogate model. The primary flow path is broken by a flow sensor that is used by the surrogate flow source that is instantiated in parallel.



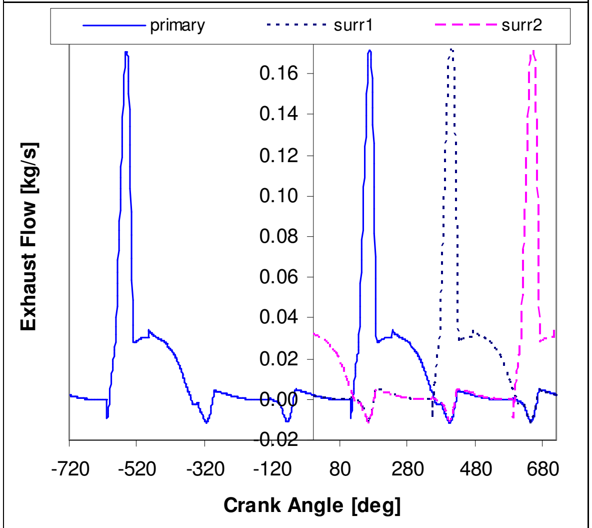
(a) (b)

Figure 4. Surrogate flow structure

Figure 5 illustrates the surrogate flow concept. Figure 5a depicts a surrogate flow representation for the intake of an I6 engine. There is a single primary flow with five replicated and phased surrogate flows. For clarity, only the primary flow is shown from the first cycle followed by all the flows in the second cycle. The total flow is the superposition of all the flows. Figure 5b shows a surrogate exhaust flow representation for a single bank of a V6 engine. The total exhaust flow is not pictured as it obscured the ability to see clearly the individual surrogate flows. The dynamic exhaust events from the individual cylinders that are used to drive the turbine are clearly captured. Note that the phasing changes appropriately based on the number of replicated cylinders.



(a) Intake flow (I6)



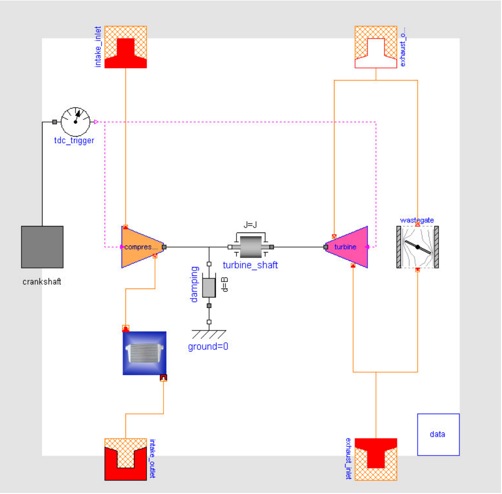
(b) Exhaust flow (single bank V6)

Figure 5. Sample intake (a) and exhaust (b) flows

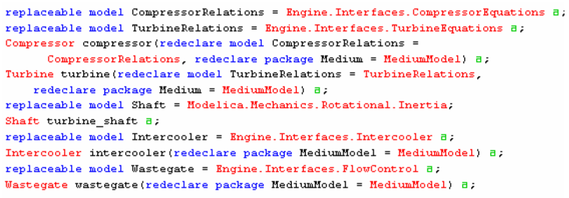
Several alternatives for the surrogate flow calculations were implemented in Modelica. The alternatives differ in the way in which the surrogate flows are calculated and provide slightly different numerical results. The traces shown in Figure 5 are from the `DelayedSurrogateFlow` model. This model uses the built-in `delay` operator to phase the mass flow rates for the surrogate cylinders based on the primary cylinder calculation. It is worth noting that this implementation yields numerical Jacobians in Dymola (and in the authors' opinion should not).

3 Turbocharger Modeling

In addition to the engine restructuring to support inclusion of boost device models, various boost device models were implemented in Modelica. Figure 6 shows a model for an exhaust-driven turbocharger. The `ConfigurableTurboCompressor` model provides a template for turbocharger modeling. It consists of a `turbine` component connected to the `compressor` component by the `turbine_shaft`. There is also a `wastegate` component on the turbine side and an `intercooler` component on the compressor side. Extensive use of `replaceable` models allow for flexibility in configuring the template to simulate specific hardware.



(a) Diagram



```
replaceable model CompressorRelations = Engine.Interfaces.CompressorEquations a;
replaceable model TurbineRelations = Engine.Interfaces.TurbineEquations a;
Compressor compressor(redeclare model CompressorRelations =
      CompressorRelations, redeclare package Medium = MediumModel) a;
Turbine turbine(redeclare model TurbineRelations = TurbineRelations,
    redeclare package Medium = MediumModel) a;
replaceable model Shaft = Modelica.Mechanics.Rotational.Inertia;
Shaft turbine_shaft a;
replaceable model Intercooler = Engine.Interfaces.Intercooler a;
Intercooler intercooler(redeclare package MediumModel = MediumModel) a;
replaceable model Wastegate = Engine.Interfaces.FlowControl a;
Wastegate wastegate(redeclare package MediumModel = MediumModel) a;
```

(b) Code excerpt

Figure 6. Turbo model

Detailed modeling of turbocharger behavior based on geometric information typically requires CFD-type simulations. For lumped systems models, steady-state mapped data, typically provided by the component supplier from gas stand testing, is often used to simulate component model behavior. The mapped data for the turbine and compressor consists of mass flow rate and efficiency data over a range of shaft speeds and pressure ratios [8]. Figure 7 shows a sample compressor efficiency map with annotations showing the various features of the map (*i.e.*surge line, choke line, efficiency islands, speed lines, *etc.*) [9].

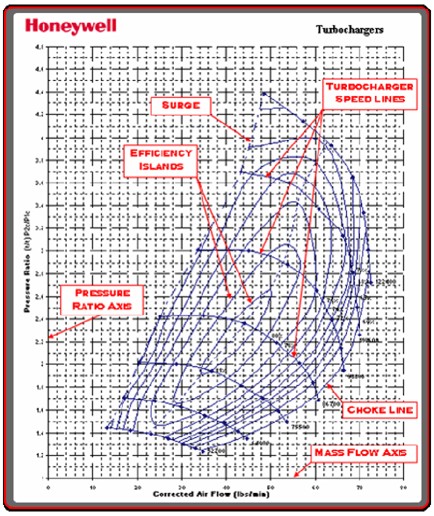


Figure 7. Sample compressor efficiency map [9]

Typically the mapped data exists for a rather limited range of speeds and pressure ratios and must be extended analytically to ensure model robustness. There are a variety of ways to implement and/or fit the map data for component modeling [10]. The following discussion and figures provide some sample results from the fitting procedure used by the authors.

To account for differences in inlet conditions, turbine map data is often provided in reduced form. The map data gives reduced mass flow and efficiency as a function of reduced speed and pressure ratio as defined in the following equations:

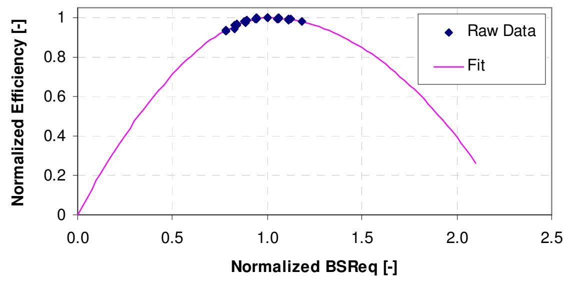
$$N_r = \frac{N}{\sqrt{T_{inlet}}} \qquad (1)$$

$$\dot{m}_r = \frac{\dot{m}\sqrt{T_{inlet}}}{P_{inlet}} \qquad (2)$$

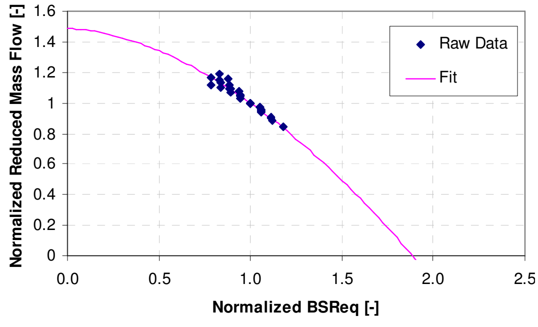
where N is the shaft speed in RPM, $\dot{m}$ is the flow rate through the turbine in kg/s, and the inlet pressure and temperature conditions are denoted by P_{inlet} and T_{inlet}, respectively. Blade speed ratio (BSR) is defined as the blade speed divided by the isentropic enthalpy drop across the turbine and can be computed as follows [11]:

$$BSR = \frac{\frac{2\pi N}{60}\left(\frac{D}{2}\right)}{\left[2h_{in}\left(1-PR^{\frac{1-\gamma}{\gamma}}\right)\right]^{1/2}} \tag{3}$$

where D is turbine diameter, h_{in} is the inlet enthalpy, and PR is the pressure ratio across the turbine. Note that BSR is an independent variable that combines both the pressure ratio and the shaft speed. In an attempt to collapse the data onto a single line to facilitate fitting, efficiencies and reduced mass flow rates are normalized. The normalized variables can then be fit based on a normalized blade speed ratio as shown in Figure 8.



(a) Normalized efficiency



(b) Normalized reduced mass flow

Figure 8. Sample turbine fits for normalized variables

Compressor map data is often corrected to reference conditions to account for differences in inlet conditions.

$$N_c = \frac{N}{\sqrt{\frac{T_{inlet}}{T_{reference}}}} \tag{4}$$

$$\dot{m}_c = \frac{\dot{m}\sqrt{\frac{T_{inlet}}{T_{reference}}}}{\frac{P_{inlet}}{P_{reference}}} \tag{5}$$

where $P_{reference}$ and $T_{reference}$ denote the reference conditions. Similar techniques to those described previously for the turbine can be used to fit the normalized compressor efficiency. A tabular implementation is used for the corrected mass flow data as a function of shaft speed and pressure ratio.

To facilitate the modeling of new turbocharger hardware, an external tool has been developed to generate the fits to the mapped data. Given the raw map data from the supplier, the tool calculates the various required fit coefficients for efficiency and flow rate using least square regression. As shown in the code in Figure 6b, the `replaceable` models for `CompressorRelations` and `TurbineRelations` are used to specify the mapped component behavior. Base classes for various types of raw data (*i.e.* corrected, reduced, mass flow, volume flow) and fitting techniques have been created. By extending from the appropriate base class and providing the fit coefficients, the component map for a given piece of hardware can be defined and selected for use in the `ConfigurableTurboCompressor`.

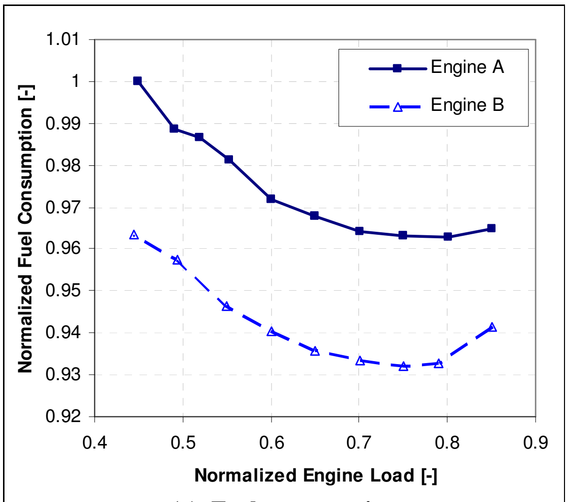
4 Simulation Results

The new engine architecture and turbocharger modeling capability in conjunction with predictive combustion cycle simulation provide a tool for upfront assessment of advanced engine concepts. Simulation results from a few sample applications are provided. The simulations were performed using Dymola [12].

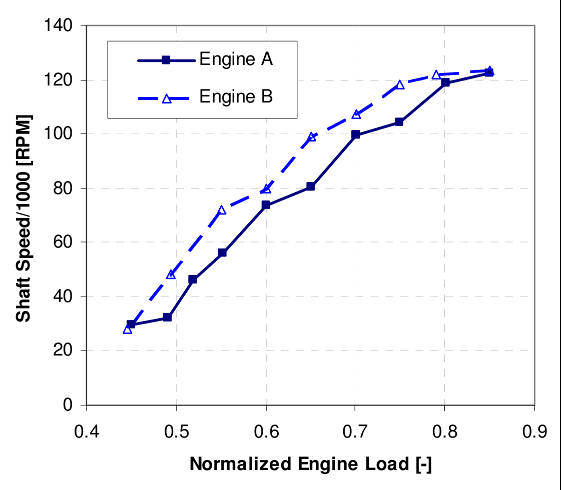
4.1 Steady State

Early concept assessment typically occurs on an engine dynamometer long before vehicle work begins. These assessments are usually steady state for performance, fuel economy, and calibration. Surrogate hardware is often used prior to vehicle hardware availability thereby necessitating a configurable modeling environment for maximum flexibility.

Figure 9 compares the results from a simulated load sweep at a fixed engine speed for two different turbocharged engine concepts. The model was initially calibrated based on experimental data from an early hardware iteration of Engine A. Following a major hardware update, the model was updated to the latest hardware level, and the original calibration was validated via prediction at a different engine operating condition. The percent difference between the model prediction and the experimental data is shown in Table 1 for various pressure, temperature, flow, and combustion statistics. The model agrees well with the experimental data. The model predictions in Figure 9 are purely analytic based on virtual hardware changes for Engine A and concept Engine B over operating conditions which were only simulated. The predicted fuel consumption for Engine B is roughly 3-4% less than that of Engine A. Figure 9b shows the steady state shaft speeds for the two engine concepts.



(a) Fuel consumption



(b) Shaft Speed

Figure 9. Load sweep at a fixed speed

Table 1. Model validation (depicted as percent difference between model prediction and experimental data)

[redacted]		%err
airflow	kg/s/cyl	0.078212
BMEP	bar	-0.051359
gIMEP	bar	-0.241572
PMEP	bar	[redacted]
ISFC	g/kW.h	0.430916
BSFC	g/kW.h	0.240178
burn010	deg	-0.662252
ca50	degATDC	1.421053
caPmax	degATDC	2.137423
MAP	kPa	-0.676617
CompoutP	kPa	-0.620951
CompoutT	K	-0.393695
ICoutletT	K	-0.099168
TurbinP	kPa	3.410164
TurbinT	K	0.095168

4.2 Transient

In addition to steady state characterization, transient performance metrics play a crucial role in concept assessment. The ability to provide analytic assessments of transient response is a key enabler for upfront powertrain system design and optimization. In particular, transient response metrics are especially important in turbocharged engine applications to ensure robust hardware and control system design to mitigate the impact of any potential turbo lag issues.

Figure 10 shows the results for a simulated throttle transient with Engine A. The simulations were run at a fixed engine speed. As the throttle opens, the engine load quickly increases as the manifold pressure approaches compressor outlet pressure. The resulting rise in exhaust mass flow drives the turbine shaft to higher speeds, producing additional boost and increasing the load even further. The transient behavior results from the inertia of the turbocharger shaft, filling and emptying of the intake and exhaust manifolds, turbocharger performance dynamics, intercooler dynamics, and combustion phasing dynamics. Given the highly-coupled nature of turbocharged systems, a transient, physical model is an extremely valuable tool for understanding the various feedback mechanisms and key parameters for robust design and system control.

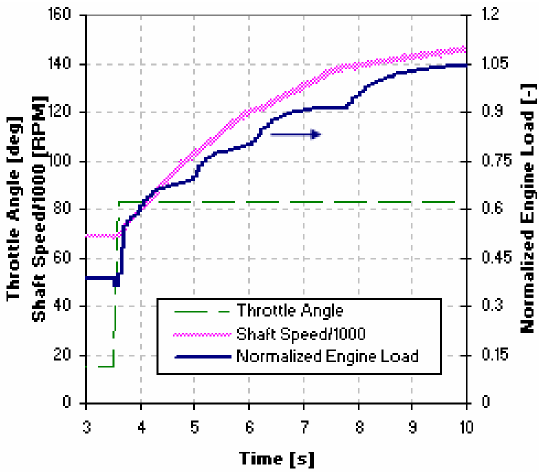


Figure 10. Throttle transient, Engine A

5 Conclusions

Development and implementation of a new engine architecture in Modelica for the detailed simulation of turbocharged, spark-ignited engines has been presented. In conjunction with previously-developed capability for predictive engine cycle simulation, the models provide a highly-capable platform for analytic, upfront design assessment and optimization for turbocharged engines. The model predictions have been validated with experimental data, and the results from several sample applications provide some insight into potential model usage.

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