Using GT-POWER to Simulate Fuel Economy Drive Cycles on High Specific Output Small Gasoline Engines

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Objectives, Methodology

• Assess engine fuel consumption and vehicle drive cycle fuel economy utilizing various boosting system arrangements
  – Engine calibration parameters (e.g. valve timing, combustion phasing) adjusted for each boosting configuration

• Gain better understanding of relationship between supercharger efficiency (SC and drive system) and fuel economy in comparison to turbocharger
  - Configure models using different boosting system arrangements
  - Application and verification of SwRI developed knock model
  - Optimization of engine model calibrations
  - Drive cycle simulation using optimized engine models
Engine Models

- 5 different engine and boosting system configurations
  - 1.6 liter 4-cylinder configurations:
    - Turbocharger (TC)
    - Clutched Supercharger R570 (SC)
  - 1.2 liter 3-cylinder configurations:
    - TC-TC (HP and LP stage)
    - TC-SC (clutched V250 SC)
    - SC-TC (clutched V250 SC)
  - Implementation of controls logic for load control
    - Different models for different operating regimes

PID Controller

Low pressure turbine waste gate lookup table of engine speed vrs accelerator position
Engine Testing

- Generate engine test results to assist in tuning and validating SwRI knock model
- Generate background engine test data to validate simulation results
- Steady-state engine testing at various speed and load points
  - Spark timing sweep to explore knock characteristics
  - Re-creation of operating conditions in GT-Power model incl. cylinder pressure
  - Comparison of predicted knock characteristics to engine data
- Generation of data to explore impacts of valve phasing, CA50 timing, compression ratio and boost system configuration on BSFC

Optimum valve phasing for best BSFC varies for different boosting system configuration
Knock Prediction Tool

• A stand-alone tool to predict end-gas knock based on a prescribed pressure trace
  – Usable for parametric studies on combustion systems
  – Implemented as a GT-Power user model for knock prediction during simulations
Task 2: Calculation Method

Indirectly represents the flame speed

Pressure

CAD/ Time

End gas at point 1

Constant pressure process
Chemical reactions are applied for \( \Delta t = t_2 - t_1 \)

End gas at point 2

Gas may expand due to combustion process
An adiabatic process is applied to restore the gas volume to point 1

End gas at point 3

Reaction mechanism:
Jia hybrid mechanism
(43 species, 78 reactions)
Knock Model

- In case of knock (end-gas auto-ignition) a sudden spike in calculated endgas temperature occurs.
- Location of temperature spike with respect to location of peak cylinder pressure or mass fraction burned curve (MFB) indicates severity of knock:
  - No auto-ignition: No knock
  - Late auto-ignition: Light knock
  - Early auto-ignition: Heavy knock
The knock model is very sensitive to the initial temperature calculated by GT-Power.

Important Factors:
- Trapped residuals, scavenging flow during valve overlap periods
- In-cylinder fuel evaporation characteristics
- Heat transfer settings for intake system (ports), combustion chamber components (e.g. piston, cylinder head)
Scavenging Object

- Influence on in-cylinder temp. calculation
- Impact on calculated mixture composition

→ Strong impact on knock predictions
Model optimization

- Calibration of five engine models, optimizations to yield best fuel economy

1. Low speed, high load optimization (full factorial DOEs)
   - Optimization parameters for best BSFC, optimum CR:
     - Intake Valve Timing
     - Exhaust Valve Timing
     - Combustion Phasing (CA50 Timing)
     - Compression Ratio

2. Part load optimization (full factorial DOEs)
   - 28 and 30 part load points (dependent on model)
   - Optimization parameters for best BSFC:
     - Intake Valve Timing
     - Exhaust Valve Timing
     - Combustion Phasing (CA50 Timing)

3. Full load optimization (full factorial DOEs)
   - 8 point along lug curve
   - Optimization parameters for best BSFC:
     - Intake Valve Timing
     - Exhaust Valve Timing
     - Combustion Phasing (CA50 Timing)
     - A/F Ratio (over-fueling)

2000 rpm – 19.0 bar; IVO = 10 deg bTDC; Trapped Residuals: ~2.0 %
Model Optimization

- Engine calibration/ performance maps
  - BSFC
  - A/F ratio
  - CA50 timing
  - Valve phasing, intake & exhaust
  - etc...

4-cyl TC Engine

4-cyl SC Engine

<table>
<thead>
<tr>
<th>Engine Configuration</th>
<th>Geometric CR</th>
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<tr>
<td>4-cylinder turbocharger</td>
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<tr>
<td>4-cylinder supercharger</td>
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<td>3-cylinder series-sequential turbocharger</td>
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<tr>
<td>3-cylinder super-turbo combination</td>
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<tr>
<td>3-cylinder turbo-super combination</td>
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Avg. Δ BSFC = 1.4%

Reduced fuel efficiency at high loads due to higher parasitic losses and more over-fueling

Improved fuel efficiency at low loads due to higher CR and reduced BP (SC clutched out)
Vehicle Drive Cycle Simulation

Run engine model to generate detailed look-up tables of BSFC & engine performance parameters

Driver Model:
Contains gear shift strategy and controllers for accelerator and brake pedal to follow drivecycle

Engine + Driver + Vehicle Model

Detailed vehicle model containing transmission and car model
### Comparison – Vehicle Drive Cycle

| Source: [www.fueleconomy.gov](http://www.fueleconomy.gov) |

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<th>Test Cycle</th>
<th>Fuel [g]</th>
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### Impacts of transient response of engine and boosting system not captured:
- Energy required to generate boost during transient condition can differ from steady-state maps
  - Inertia effects
  - Boost response (particularly for TC)
  - Desired flow and PR during transients
- Transmission shift schedule would need to be adapted for differences in transient response behavior
  - Effects of transmission shift schedule can impact fuel economy significantly
  - Potential benefit with SC configuration due to faster transient response of supercharger
Summary, Conclusions

• When modifying engine hardware components such as the boosting system, re-tuning of engine calibration settings is necessary.

• SC configuration using clutched SC allows increase in geometric compression ratio and alternative valve phaser settings and combustion phasing, resulting in improved fuel economy at low and mid engine loads.

• Fuel economy at full load limited by increased parasitic losses associated with driving SC as well as increased enrichment due to reduced exhaust gas temperature limits.

• Downsized 3-cylinder configuration offers greatest fuel economy benefits at low and part loads (when compared on the basis of torque – “downsizing effect”).

• Vehicle drive cycle fuel economy impacted by selected drive cycle:
  – For low load drive cycles (e.g. NEDC), down-sized 3-cylinder engine models using supercharger-turbocharger combination offer greatest FE.
  – For higher load drive cycles (e.g. US06), 4-cylinder supercharged configuration is a good option.
  – Vehicle drive cycle simulation not accounting for FE impacts related to transient response/behavior:
    ▪ Largest impact expected with turbo-turbo arrangement.
    ▪ Further characterization of engine transient behavior as well as transmission shift schedules would be necessary.