Downspeeding a Heavy-Duty Pickup Truck with a Combined Supercharger and Turbocharger Boosting System to Improve Drive Cycle Fuel Economy

Presenter: Philip Wetzel – Eaton Corporation
Agenda

- Introduction
- Engine Modeling
- Vehicle Modeling
  - Steady State Results
  - Transient Results
- Conclusions
Introduction – Engine Definition

- Historical trend for HD diesel pickup truck segment to increase peak torque and increase rated power
- Created “Next Generation” torque curve based on projected MY 2014
- Engine targets for “next generation” vehicle

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>V-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>6.6 L</td>
</tr>
<tr>
<td>Fuel</td>
<td>Diesel</td>
</tr>
<tr>
<td>Rated Power</td>
<td>420 hp @ 3000 rpm</td>
</tr>
<tr>
<td>Rated Torque</td>
<td>800 ft-lbs @ 2000 rpm</td>
</tr>
<tr>
<td>Comp Ratio</td>
<td>15.1:1</td>
</tr>
<tr>
<td>PCP</td>
<td>165 bar</td>
</tr>
<tr>
<td>Fuel Injection</td>
<td>up to 3000 bar</td>
</tr>
<tr>
<td>EGR</td>
<td>&gt;50 % at part load</td>
</tr>
<tr>
<td>Aftertreatment</td>
<td>DOC, DPF, SCR</td>
</tr>
<tr>
<td>Emission Level</td>
<td>US EPA 2010</td>
</tr>
</tbody>
</table>

Legend:
DOC Diesel Oxidation Catalyst
DPF Diesel Particulate Filter
EGR Exhaust Gas Recirculation
SCR Selective Catalytic Reduction
Introduction – Boosting Systems

- GT-Power model represents non-manufacturer specific engine
- Combination of high torque & high power not possible with a single production TC
- Boost system for “next generation” requires multi-stage boosting

- Configurations
  - Series Twin-Turbocharger → TC/TC
  - Series Turbocharger-Supercharger → TC/SC
  - Series Supercharger-Turbocharger → SC/TC

- What is the best boosting system for this vehicle – engine combination?
Series Twin-Turbocharger Schematic → TC/TC

- Air Filter
- Interstage CAC
- Primary CAC
- Intake Throttle
- EGR Valve
- EGR Cooler
- VGT
- FTG w/out Wastegate
Series Turbocharger-Supercharger Schematic \(\rightarrow\) TC/SC

- Air Filter
- Interstage CAC
- Eaton TVS® Supercharger w/ Integrated CAC and Bypass Valve
- FTG w/ Wastegate
- EGR Valve
- EGR cooler
**Series Supercharger-Turbocharger Schematic → SC/TC**

- **Air Filter**
- **Primary CAC**

Eaton TVS® Supercharger w/ integrated CAC & Bypass valve

- **FGT w/ Wastegate**
- **EGRv**
- **EGR Cooler**

[Diagram of Series Supercharger-Turbocharger System]
Steady State Full Load Comparison

- SC size and pulley ratio selected for low speed operation only
- SC pulley clutch is engaged at speeds below 2500 rpm and when target manifold pressure cannot be achieved with TC alone

Steady state BSFC of TC/SC is similar to TC/TC
Steady State Full Load Map Operation

HP Stage
TVS® R900
5.9 Drive Ratio

LP Stage
TVS® R1320
7.2 Drive Ratio

Corrected Mass Flow (kg/s)

TC/SC Maps

SC/TC Maps
Vehicle Modeling

- Vehicle model created in GT-Drive & GT-Power and correlated to performance test data
- ¼ mile pull used for vehicle acceleration comparison of different boost configurations
- Supercharged configurations allow for improved transient performance
  - Guides the way to downspeed engine to reduce fuel consumption
  - Retain original vehicle performance

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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td><strong>Vehicle Type</strong></td>
<td>¾ ton HD Pickup Truck</td>
</tr>
<tr>
<td><strong>Engine</strong></td>
<td>Diesel, 6.6L – V8</td>
</tr>
<tr>
<td><strong>Transmission</strong></td>
<td>6 speed TC automatic</td>
</tr>
<tr>
<td><strong>Final Drive Ratio</strong></td>
<td>3.29</td>
</tr>
<tr>
<td><strong>Vehicle Weight</strong></td>
<td>8500 lbs</td>
</tr>
<tr>
<td><strong>Frontal Area</strong></td>
<td>2.05 m²</td>
</tr>
<tr>
<td><strong>Aero Coefficient</strong></td>
<td>0.32</td>
</tr>
<tr>
<td><strong>Tire Diameter</strong></td>
<td>0.585</td>
</tr>
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</table>

**Engine Downsrieeding**
- Shift strategy manipulation (short shifting)
- Final drive ratio change → effects grade performance and additional hardware change
Vehicle Modeling – Acceleration Performance – ¼ Mile Pull

- Detailed engine model and vehicle model combined to run in “forward” dynamic mode
- Captures the transient boost effect on vehicle acceleration performance

- Quicker time with supercharged system … allows reduction in upshift point for similar performance

- 300 RPM upshift point downspeeding
  - Similar performance for TC/SC and SC/TC lead to same downsped shift strategy for both systems
  - Scaled with engine load
    - Full load 300 RPM lower
    - Linear scaling with load to maintain accepted vehicle creep speeds
Steady State Model Operating Points

- Drive cycle “point consolidation” was used to assess the engine models at standard and downsped shift points for steady state fuel economy simulation.

Baseline Shift Calibration – FTP Phase 3

Downsped Shift Calibration – FTP Phase 3

Steady state model - transient boost effects not captured but method used as quick guidance for future direction.
Steady State Model Fuel Consumption

- Stead state “Point Consolidation” modeling applied to FTP-75 Phase 2, FTP-75 Phase 3
- Downsped SC/TC and TC/SC both showed significant fuel economy gains

Positive steady state results is a “green light” for more detailed transient drive cycle simulations.
Transient Model Fuel Economy – FTP 75

- Forward looking “real world” control strategy (not cycle beater calibration)
- Supercharger clutch strategy was used to enable SC only when required
- Aggressive torque converter lock up schedule used

Large fuel economy improvements with supercharging and downspeeding
Transient Model Fuel Economy – US06

- Highly loaded US06 cycle still shows up to 6.4% fuel mileage benefit with downsped TC/SC system

- SC/TC vs. TC/SC do show differences depending on cycle
  - Highly transient, light loaded cycles such as FTP-75 show little difference between SC/TC and TC/SC because both are driven by transient performance
  - Less transient cycles such as US06 rely more on steady state BSFC to differentiate between technologies – TC/SC has better BSFC than SC/TC
  - Better transient capabilities plus lower low-speed BSFC of TC/SC compared to TC/TC allows reduced fuel usage over US06 style driving
Transient Model Analysis: Where is the Fuel Economy Coming From?

- Reduced accelerator pedal aggressiveness
  - Driver overcompensates for turbo lag with pedal request
  - Supercharged versions require less aggressive pedal request

- Increase in average gear number
  - Lower average engine speed
  - Operate engine in better BSFC region
  - Higher transmission ratios decrease gearbox parasitics

<table>
<thead>
<tr>
<th>Average Gear Ratio</th>
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<tbody>
<tr>
<td>T-T</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>FTP Phase 2</td>
</tr>
<tr>
<td>FTP Phase 3</td>
</tr>
<tr>
<td>US06</td>
</tr>
</tbody>
</table>
Conclusions

- A boosting system featuring a mechanical SC and exhaust driven TC was shown to have significant advantages over a TC/TC system.

- The TC/SC configuration shows a moderate fuel consumption advantage over the SC/TC.

- A downsped shift schedule was compiled to trade the vehicle acceleration time of the SC configurations for lower average engine speeds.

- A fuel economy improvement up to 17.1% for steady state models for a downsped TC/SC configuration was demonstrated.

- Improvements in real world transient fuel consumption up to 30.1% was demonstrated when driver behavior was considered with respect to transient boost response.
THANK YOU
Vehicle Modeling – Tip-In Response during ¼ Mile Acceleration

- The Turbocharger-Supercharger and Supercharger-Turbocharger configurations significantly improved “tip-in” response.

- ¼ mile launch includes significant loading of the engine before launch – faster boost rise than typical real world driving with tip-in starting at a low idle condition.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>1-2 Upshift</th>
<th>TC/TC Boost</th>
<th>Reduced Average RPM</th>
<th>Higher Boost</th>
<th>Fuel Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC/TC</td>
<td>0.54 s faster</td>
<td>Higher from 1.5 s to end</td>
<td>Lowering A/F ratio</td>
<td>Higher</td>
<td>9% less fuel</td>
</tr>
<tr>
<td>SC/TC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.5% lower BSFC</td>
</tr>
</tbody>
</table>

- Supercharged configurations reached 1-2 upshift 0.54 seconds faster.
- TC/TC boost remains higher from 1.5 seconds to end of the run to overcome initial lag.
- Reduced average RPM and boost for supercharged vehicles.
- Higher boost without lowering A/F ratio targets results in higher fuel flow rates.
- SC/TC and SC/TC used approximately 9% less fuel than TC/TC over ¼ mile.
- SC/TC and SC/TC ~1.5% lower BSFC than TC/TC over ¼ mile.
Transient Model With Driver Behavior

- Transient analysis was conducted in an attempt to capture the application of real driver behavior rather than a pre-programmed certification run
  - To accomplish this, it is assumed that the accelerator would be depressed by the driver until the desired torque response is achieved
  - For a sequential turbocharged model, this means that the accelerator will initially be depressed further than the supercharged combinations until the desired torque is achieved and then returned as the torque build-up continues

**Accelerator Positions**

**Sequential Turbo System** – Throttle moves from position “A” at idle to position “B_{INITIAL}” until demanded torque is felt by the driver and then reduced to “B_{FINAL}”

**Supercharged Systems** – Throttle moves from position “A” at idle to position “B_{FINAL}” as torque is acquired in direct proportion with throttle position