Methods For Improving Turbocharger Simulation Accuracy in GT-Power

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Basic Errors

From the definition of volumetric efficiency:

\[
\eta_{\text{vol}} = \frac{\dot{m}}{\left( \frac{D \times N}{NRPC} \right) \times \left( \frac{P_{\text{ref}}}{R \times T_{\text{ref}}} \right)}
\]

\[
T_{\text{ref}} = \text{inlet manifold temperature}
\]
\[
P_{\text{ref}} = \text{inlet manifold pressure}
\]
\[
= \left( (P_{\text{amb}} - \Delta P_{\text{filter}}) \times PR \right) - (\Delta P_{\text{cooler}} + \Delta P_{\text{throttle}})
\]

\[
PR = \left[ \frac{\dot{m} \times R \times NRPC \times IMT}{N \times D \times \eta_{\text{vol}}} \right] + \left[ \Delta P_{\text{cooler}} + \Delta P_{\text{throttle}} \right]
\]

Where:

\[
m = \text{mass flow (g/s)}
\]
\[
D = \text{Engine swept volume (m}^3\text{)}
\]
\[
N = \text{Engine speed in (rev/sec)}
\]
\[
\text{NRPC} = \text{Number of Revs Per Cycle}
\]
\[
P_{\text{ref}} = \text{Reference pressure (Pascals)}
\]
\[
T_{\text{ref}} = \text{Reference temperature (Kelvin)}
\]
\[
R = \text{Gas constant for air (}= 0.287 \text{ J/g.K})
\]
Example Mistakes

- Inlet manifold temperature prediction was incorrect (50K).
- Pressure drop errors after the compressor have a similar effect.
- Pressure drop errors before the compressor move running points up the map.
Back Pressure Effects On Turbine Performance

- Increased exhaust back pressure reduces turbine power, lowering turbo speed and boost pressure.

- Back pressure is frequently a source of turbine specification errors.

![Graph showing turbine size required to maintain lambda with increasing exhaust back pressure.](image)
Bearing loss varies with speed and thrust load, which changes with operating condition.
Turbocharger Shaft Properties

Bearing Losses at 90°C Oil Temperature

- Bearing loss varies with speed and thrust load, which changes with operating condition.
- At 40,000rpm, assuming no frictional losses would give around a 7% error in shaft power to the compressor!
Bearing Losses

- As a minimum, have frictional mechanical efficiency dependent on turbo speed.
- The actual efficiency values will vary with turbo bearing system and particularly oil temperature.
### Turbo Rotor Inertia

- **Fixed Inertia Value**
  - Low inertia reduces time for turbo speed to reach correct value.
  - Excessive reduction may mean unrealistic values read from maps.
  - High inertia slows the approach to the final value.

- **Inertia Profile**
  - Correct inertia and multiplier profile gives fast convergence and correct turbo speed.
  - Use a monitor to observe turbo speed convergence. Adjust multiplier profile to get best results for your particular model.

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![Inertia Multiplier Graph]

- High inertia for initial cycles until model is reasonably stable.
- Low inertia to allow turbo to quickly reach a suitable speed.
- Ramped return so turbo speed converges correctly.

0.05 to 0.1 is an adequate minimum. If too small, unrealistic speeds will result.
Sensitivity to Rotor Inertia

- “Correct” values were derived with convergence to 10rpm turbo speed.
- The following inertia scenarios were simulated: Correct inertia, wrong wheel profiles, next turbo frame size up, inertia ÷1000 and inertia ×1000.

The inertia value should be appropriate for steady state and must be accurate for transient.
Inertia Effects On Maps

- The difference in inertia is noticeable on the compressor map running points.
- Maps to right show running point movement during the simulation.
The parts adjoining the turbo maps have an influence on the points plotted on the maps.

The adjacent pipe diameter is used to calculate the velocity, and thus dynamic head, defining the difference between static and total pressure.

\[ P_{dynamic} = \left[ \frac{8 \times R \times T_s \times \dot{m}^2}{\pi^2 \times P_s \times d^4} \right] \]

<table>
<thead>
<tr>
<th></th>
<th>Inlet dia</th>
<th>Outlet dia</th>
<th>PR (tot-tot)</th>
<th>PR (stat-stat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine data</td>
<td>61</td>
<td>43.5</td>
<td>2.491</td>
<td>2.525</td>
</tr>
<tr>
<td>Simulation (correct)</td>
<td>61</td>
<td>43.5</td>
<td>2.495</td>
<td><strong>2.507</strong></td>
</tr>
<tr>
<td>Simulation (incorrect)</td>
<td>61</td>
<td>75</td>
<td>2.497</td>
<td><strong>2.569</strong></td>
</tr>
</tbody>
</table>

Be aware that engine pressure sensors may not be at the turbo so comparing engine data directly to GT-Power comp maps is not comparing like with like.
Internal volumes of compressor and turbine housings are not usually included.

- Add as loss-less pipes.
- Including these volumes affects steady state simulations by 1%.
- Transient simulations are slowed by 4-5% with volumes included.

- Only transient events and detailed exhaust manifold studies need volumes adding.
- Only compressor outlet and turbine inlet volumes are needed.
- Generic values for each turbo frame size are acceptable.
Turbine Maps

- Cummins Turbo Technologies maps turbines on a dynamometer.
- Reduces need for SAE format file to input for GT-Power. We have test cell data to populate almost the full TRB file with minimal extrapolation.
- SAE format from Cummins Turbo Technologies, use “PRfitted” option.

SAE Turbine Map

Cummins Turbo Technologies turbine dynamometer map.
Compressor Map Issues

Demand
- Accurate low speed map data for both compressors/turbines is increasingly being demanded by OEMs

Problems involved
- Heat transfer between hot turbine end to cold compressor end leads to inconsistency in test data
- Measurement repeatability, accuracy and the cost involved.
- Mathematical extrapolation does not capture the physics of flow losses which is more important at low flows

Experimental figures

<table>
<thead>
<tr>
<th>Speed</th>
<th>Approx dT</th>
<th>Effect of +/- 1 K temp error (inlet / outlet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60k rpm</td>
<td>60 K</td>
<td>+/- 1.5% pts efficiency</td>
</tr>
<tr>
<td>40k rpm</td>
<td>25 K</td>
<td>+/- 3.5% pts efficiency</td>
</tr>
<tr>
<td>20k rpm</td>
<td>7 K</td>
<td>+/- 10% pts efficiency</td>
</tr>
</tbody>
</table>
- Flow, PR repeat reasonably well.
- TIT has certainly an effect on compressor efficiency measurement.
Low Speed Extrapolation

- A method based on flow similarity is developed at CTT and being investigated for low flow predictions of compressor/turbine maps.
- Initial results are encouraging. Simulation results clearly show the importance low speed data accuracy.

![Graph showing efficiency vs. flow rate for different speeds and conditions.](image)
Flow and PR Prediction

Red : Run hot
Black : Run cold
Blue : Prediction

- Flow/PR predictions are reasonably good.
Three different map variants were provided for engine performance study:

- Map – 1, which uses **standard mathematical extrapolation**.
- Map – 2, which contains **flow/PR from test data** and assumes **same efficiency levels** as those at high speeds (60,000 rpm)
- Map – 3 is predicted based on similarity approach.

Engine running conditions are chosen to be within the extrapolated region of the map. Details are as below.

<table>
<thead>
<tr>
<th>Engine model</th>
<th>6 Cylinder, 12L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine speed (rpm)</td>
<td>1100 and 1300</td>
</tr>
<tr>
<td>Load</td>
<td>20%, 10%</td>
</tr>
<tr>
<td>EGR fraction</td>
<td>0%</td>
</tr>
</tbody>
</table>
Engine Performance

1100 rpm, 10% load

- Standard extrapolation predicts low PR and low efficiency than other map variants.
- The map predictions by similarity is close to test data within 1-2% accuracy.
Compressor maps are now being generated at CTT using raw test data from gas stand in order to avoid intermediate manipulations and subsequent errors.

At low speed/flow regions similarity approach is applied instead of a linear extrapolation method.

After validation, maps will be available directly in GT-Power format (.cmp and .trb).
The End

Thank you for your attention!

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