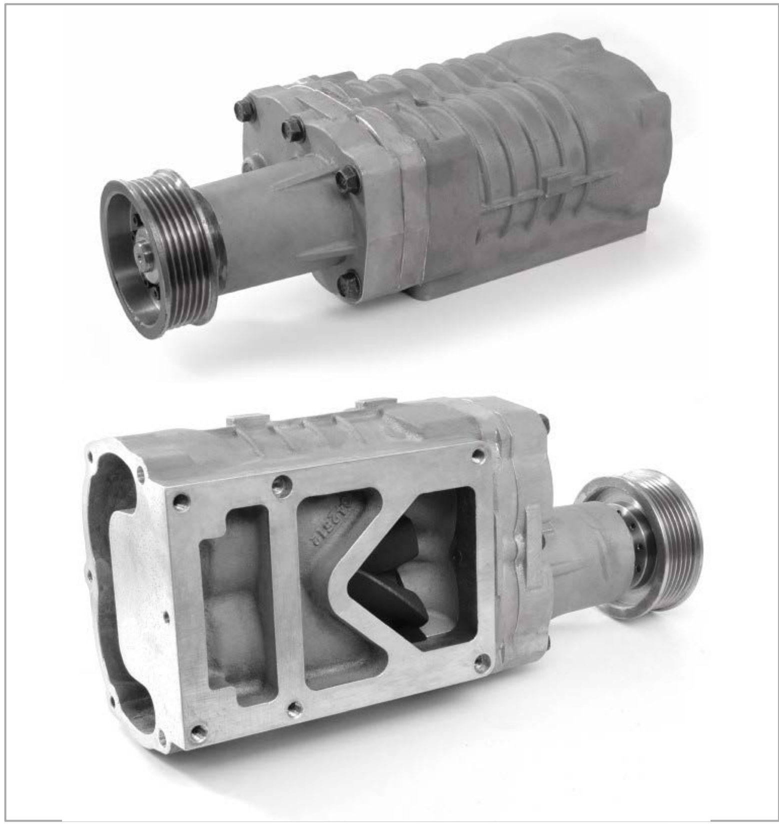
2012 DOE DEER Conference – Dearborn, Michigan

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

Eaton Corp. - Philip Wetzel, Sean Keidel
FEV, Inc. - Aaron Birckett

October 18th, 2012

Powering Business Worldwide

Agenda

- **Introduction**
- **Engine Modeling**
- **Vehicle Modeling**
  - Steady State Results
  - Transient Results
- **Conclusions**

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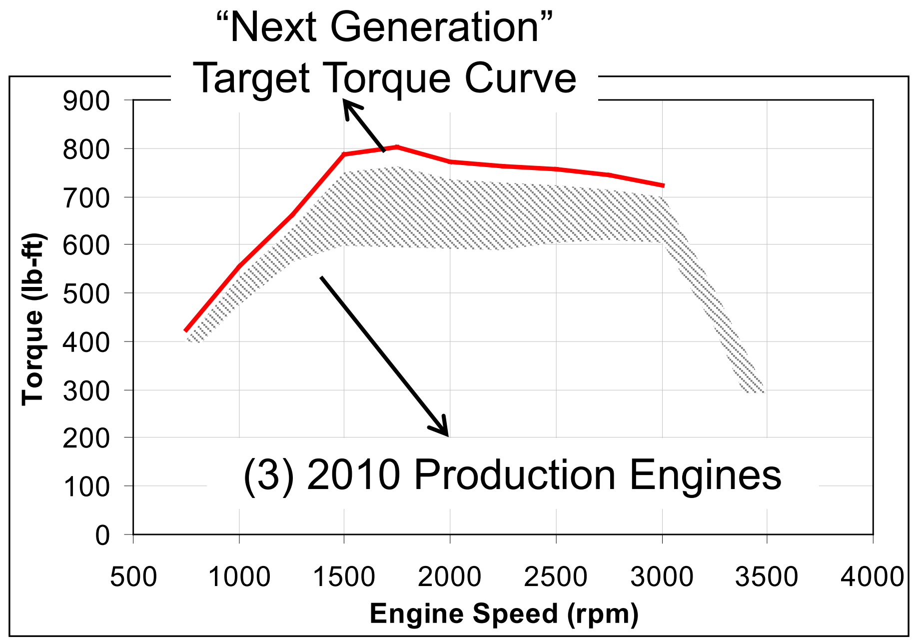
Introduction – Engine Definition

- 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

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



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

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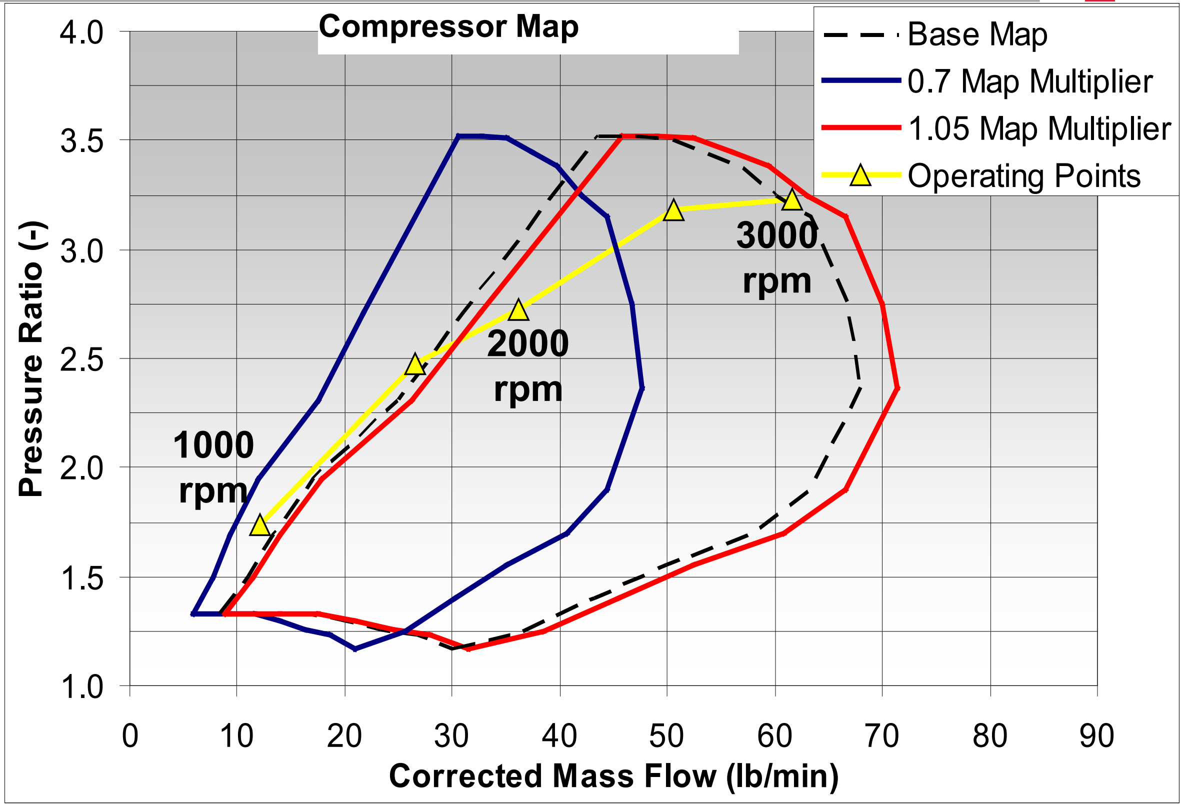
Introduction – Boosting Systems

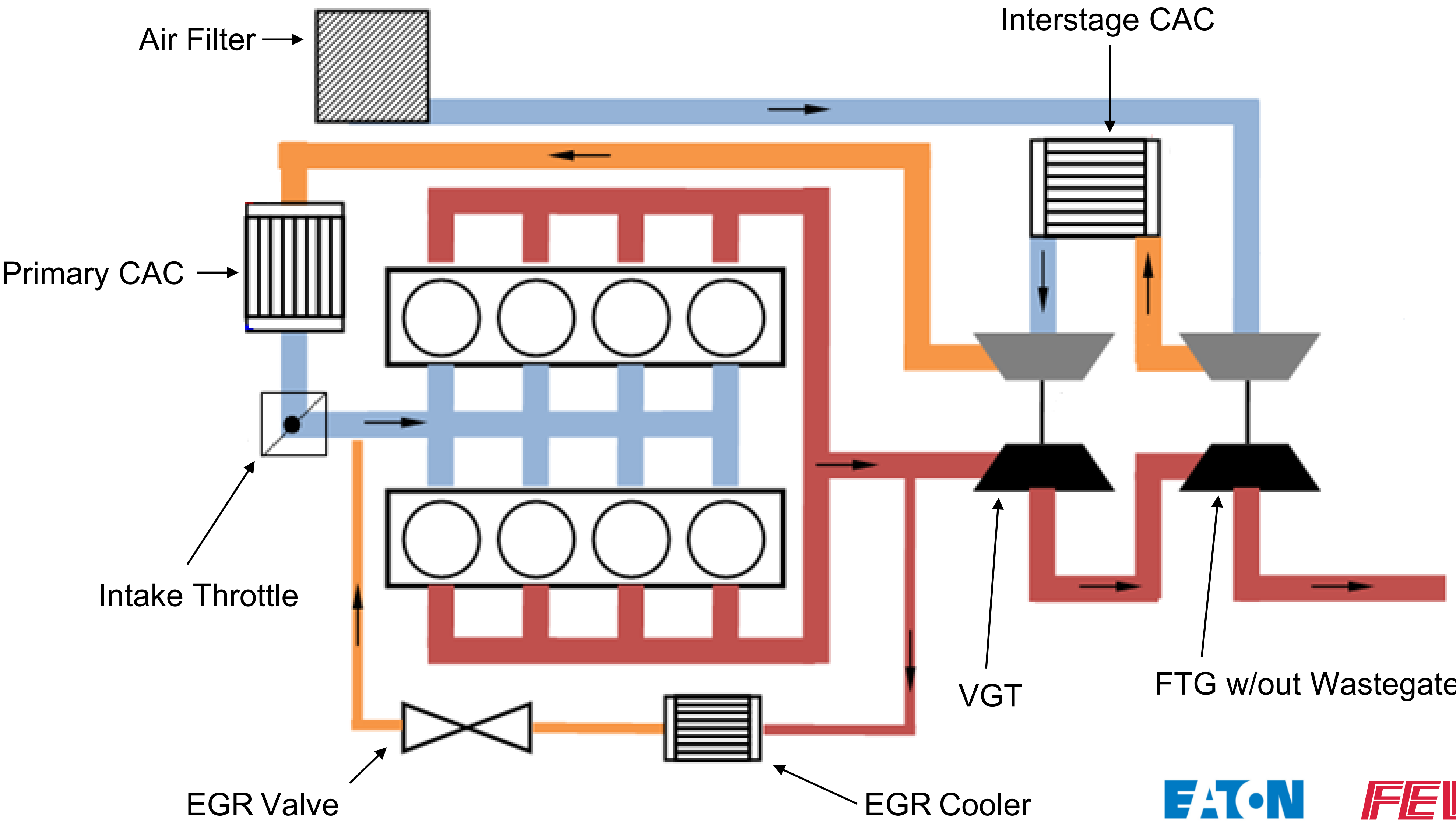
- GT-Power model represent non-manufacturer specific engine
- Combination of high torque & high power not possible with a single production TC
- Boost system for “next generation” requires multi-stage boosting
- **Configurations**
  - Series Twin-Turbocharger → TC/TC
  - Series Turbocharger-Supercharger → TC/SC
  - Series Supercharger-Turbocharger → SC/TC



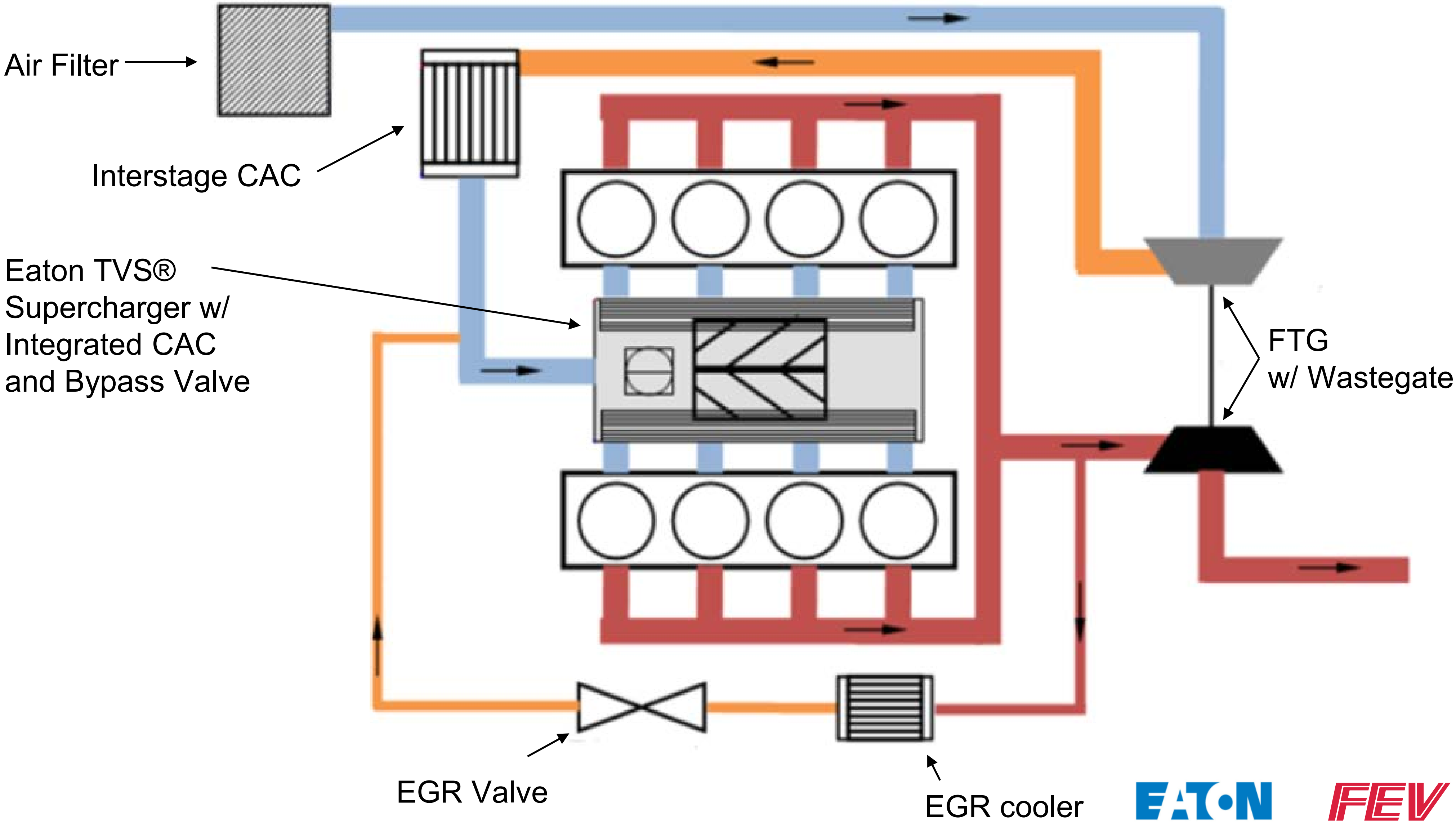
Two Stage Boosting Required

- **What is the best boosting system for this vehicle – engine combination?**

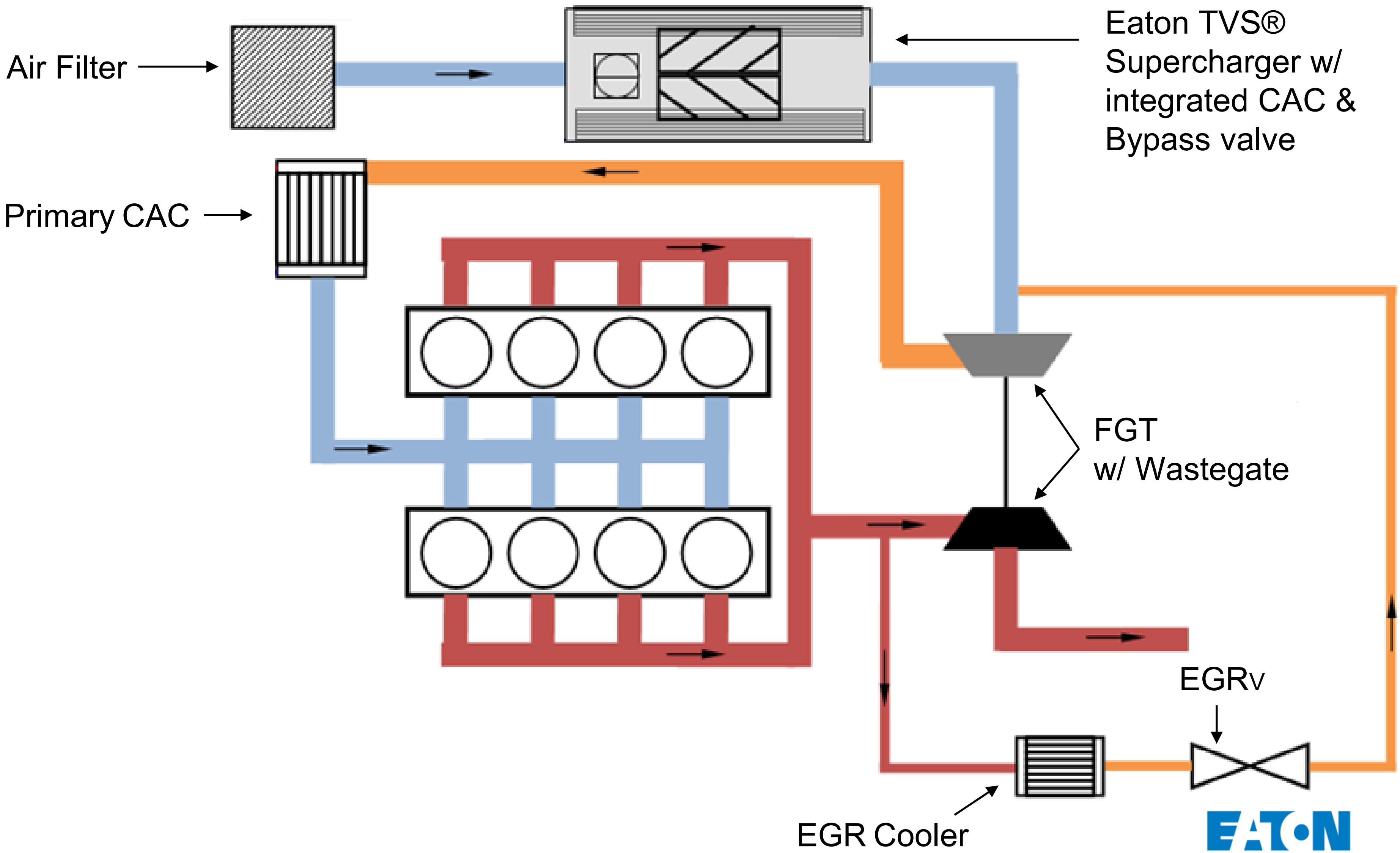
Series Twin-Turbocharger Schematic → TC/TC



Series Turbocharger-Supercharger Schematic → TC/SC

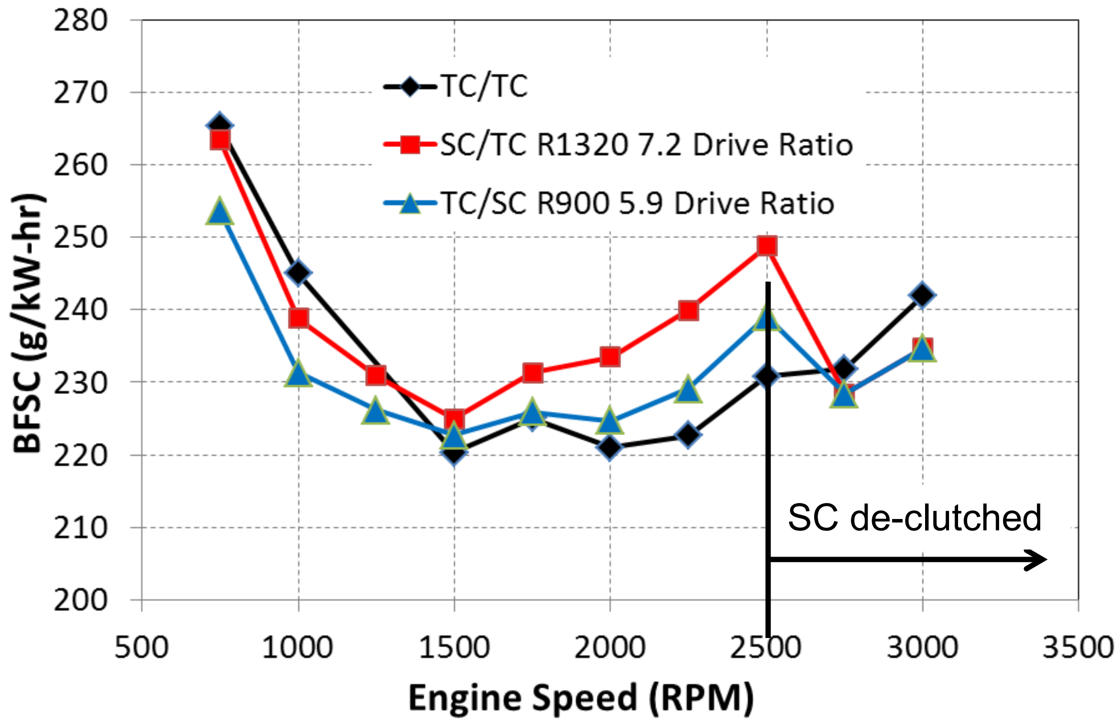


Series Supercharger-Turbocharger Schematic → SC/TC

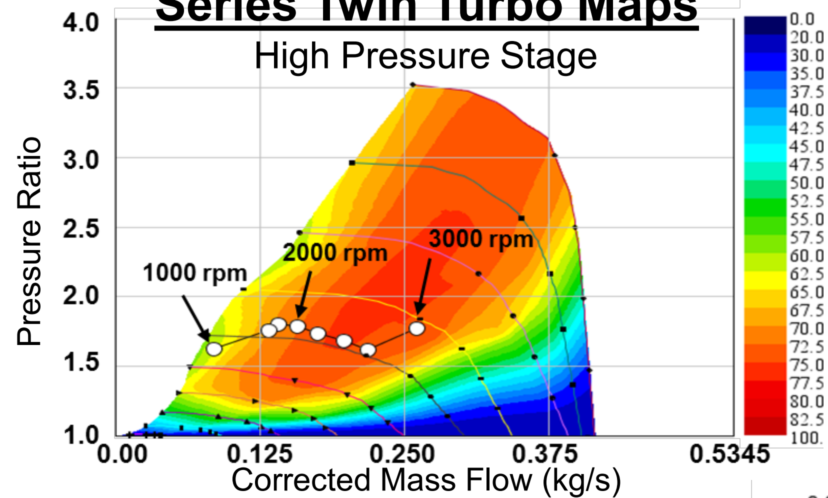


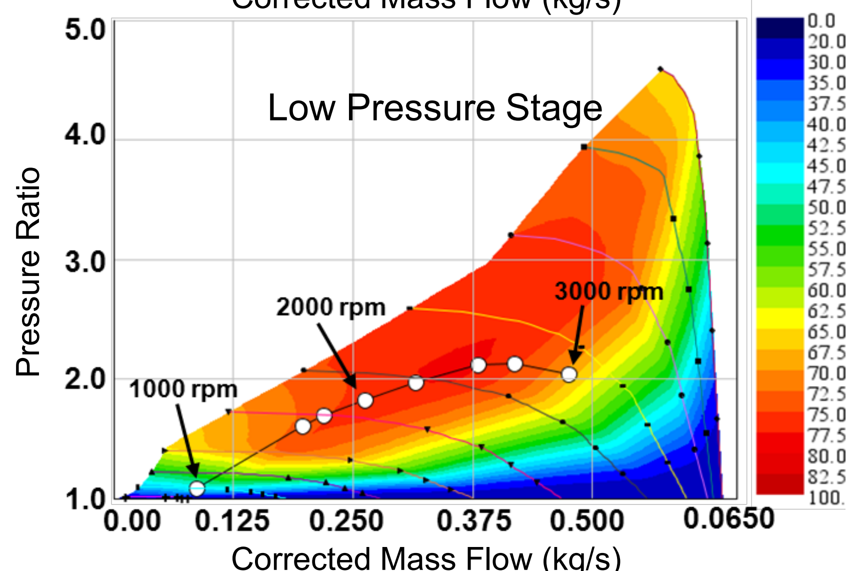
Steady State Full Load Comparison

- 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



Series Twin Turbo Maps





Steady state BSFC of TC/SC is similar to TC/TC

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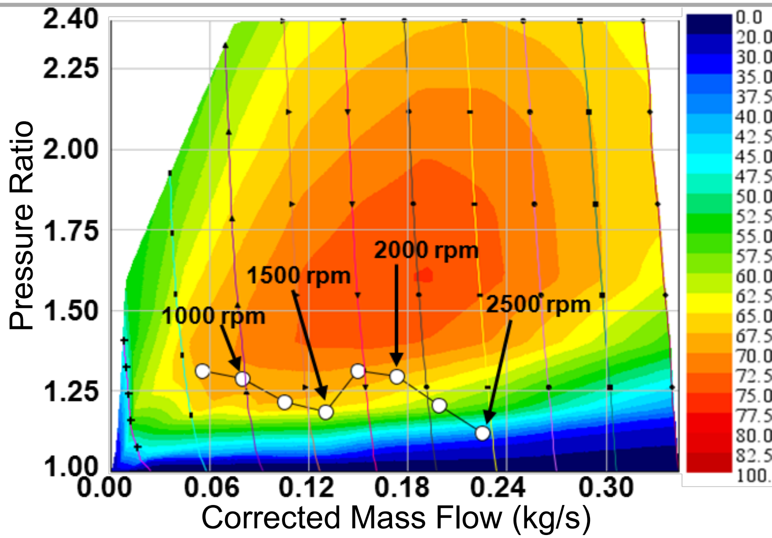
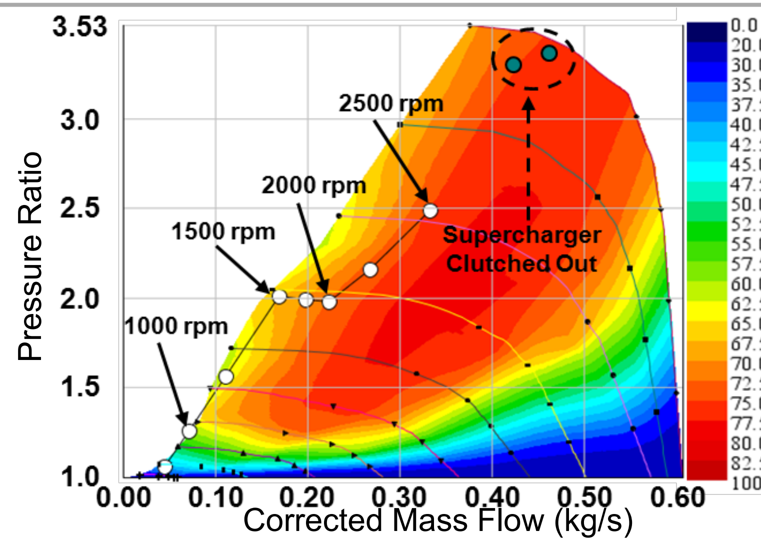
Steady State Full Load Map Operation

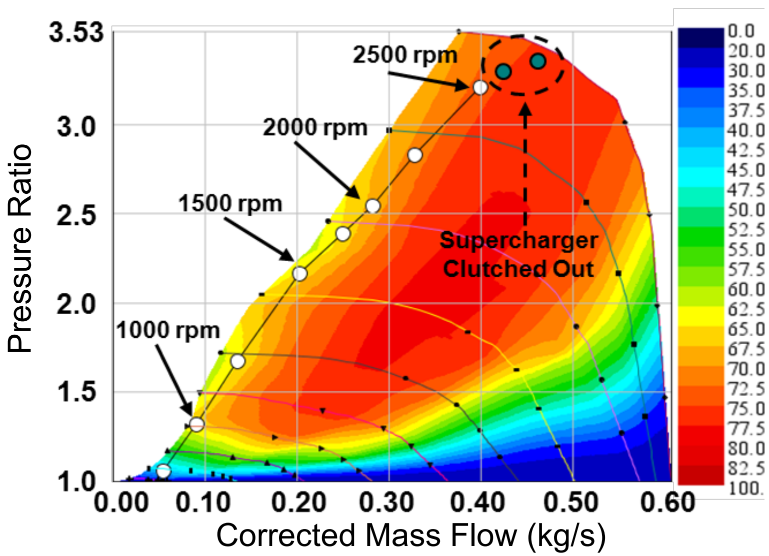
HP Stage TVS® R900 5.9 Drive Ratio

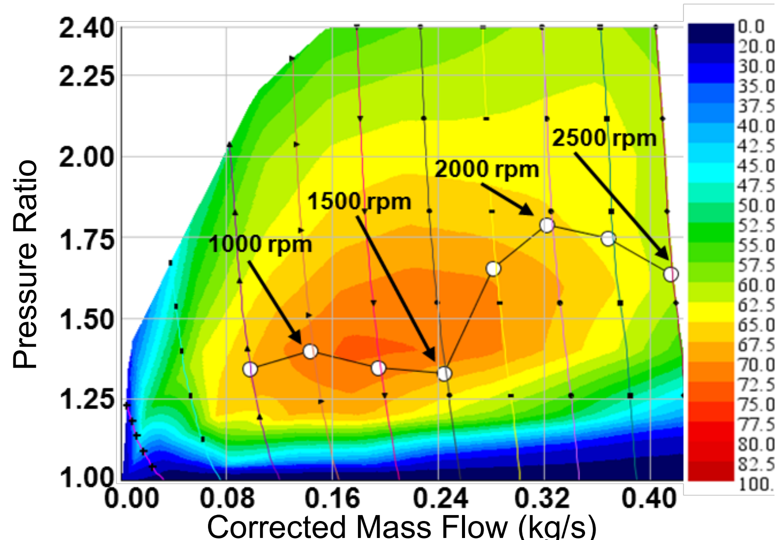




HP Stage FGT w/ Wastegate

LP Stage FGT w/ Wastegate





LP Stage TVS® R1320 7.2 Drive Ratio

TC/SC Maps

SC/TC Maps

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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

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

Engine Downspeeding

- Shift strategy manipulation (short shifting)
- ~~Final drive ratio change~~ → effects grade performance and additional hardware change

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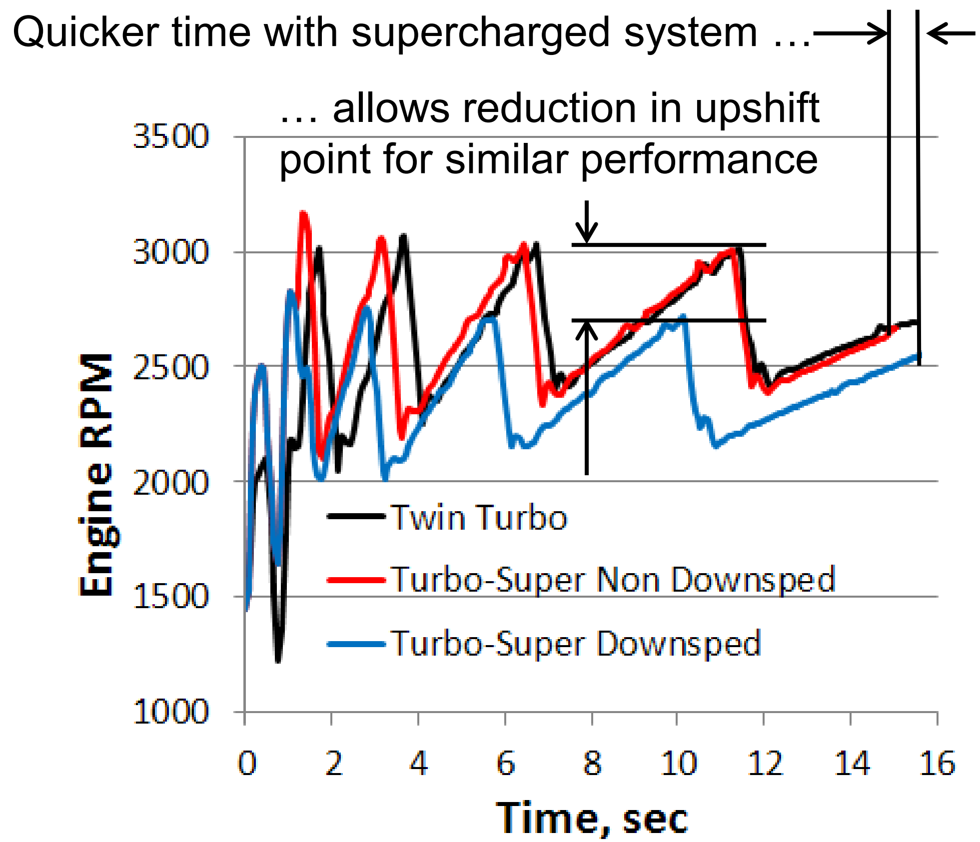
Vehicle Modeling – Acceleration Performance – ¼ Mile Pull

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

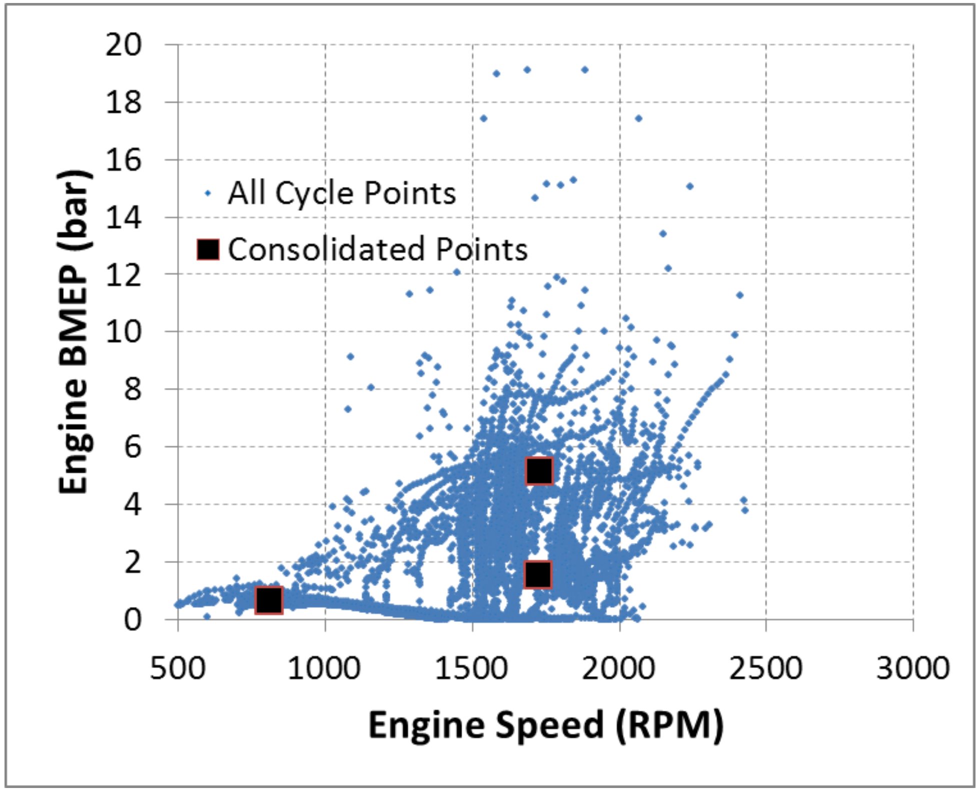


- 300 RPM upshift point downspeeding
  - Similar performance for TC/SC and SC/TC lead to same downsped shift strategy for both systems
  - Scaled with engine load
    - Full load 300 RPM lower
    - Linear scaling with load to maintain accepted vehicle creep speeds

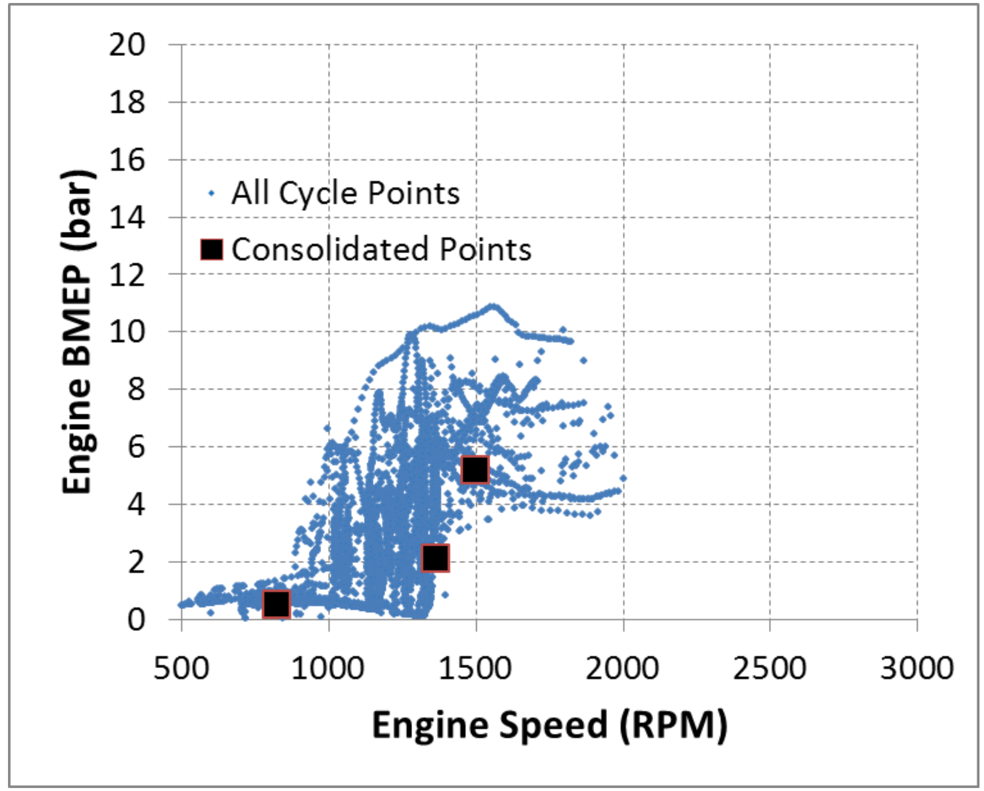
Steady State Model Operating Points

- 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

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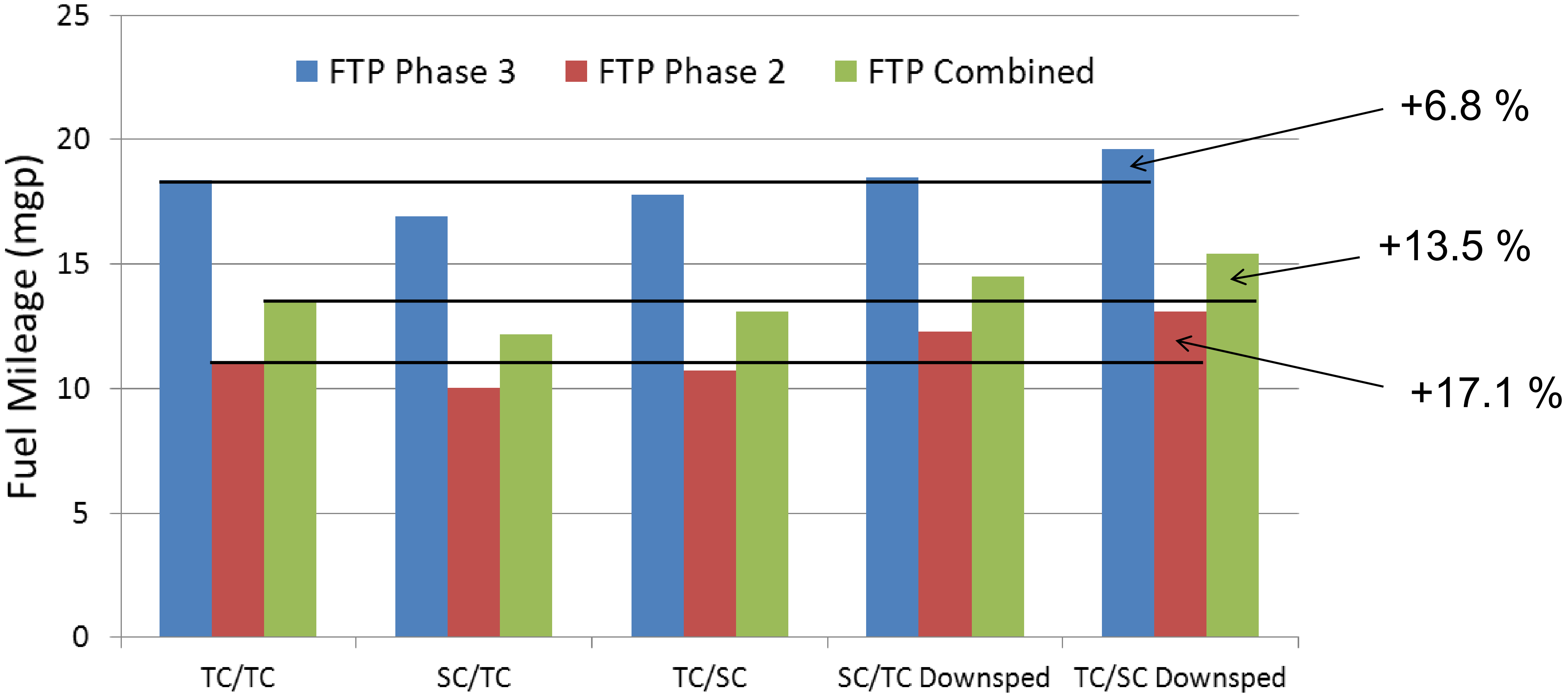
Steady State Model Fuel Consumption

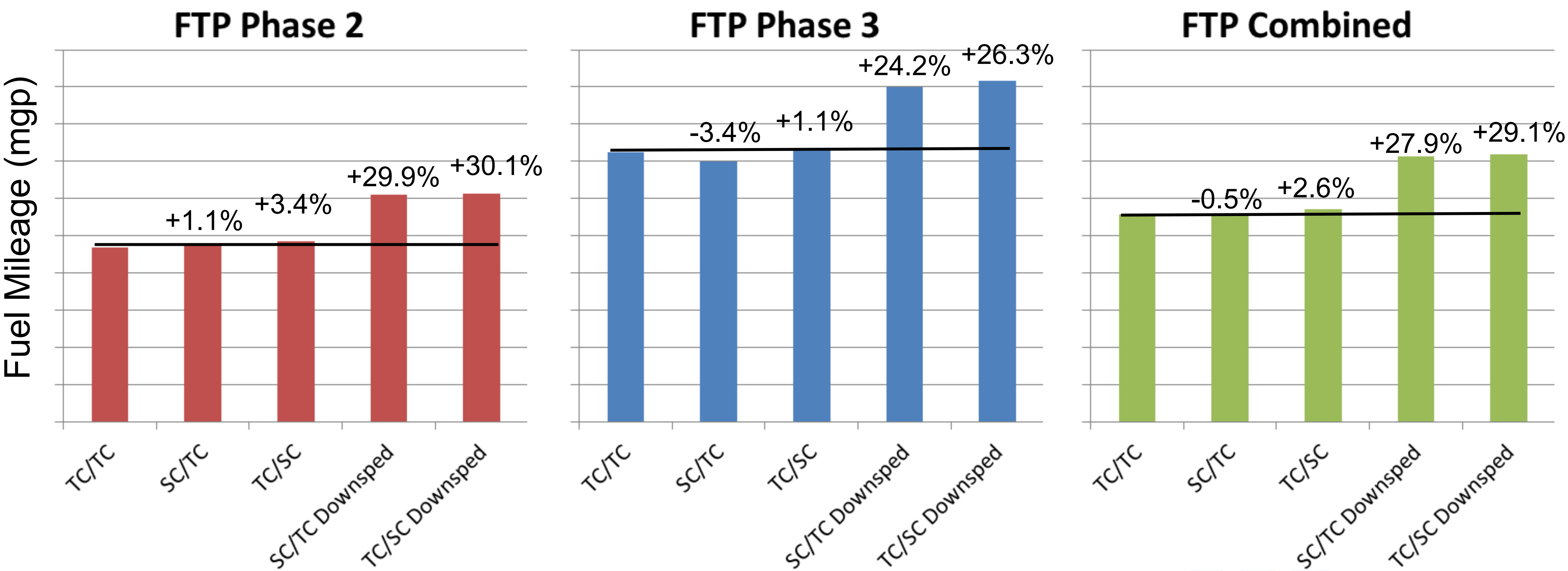
- Stead state "Point Consolidation" modeling applied to FTP-75 Phase 2, FTP-75 Phase 3
- Downsped SC/TC and TC/SC both showed significant fuel economy gains



Positive steady state results is a "green light" for more detailed transient drive cycle simulations

Transient Model Fuel Economy – FTP 75

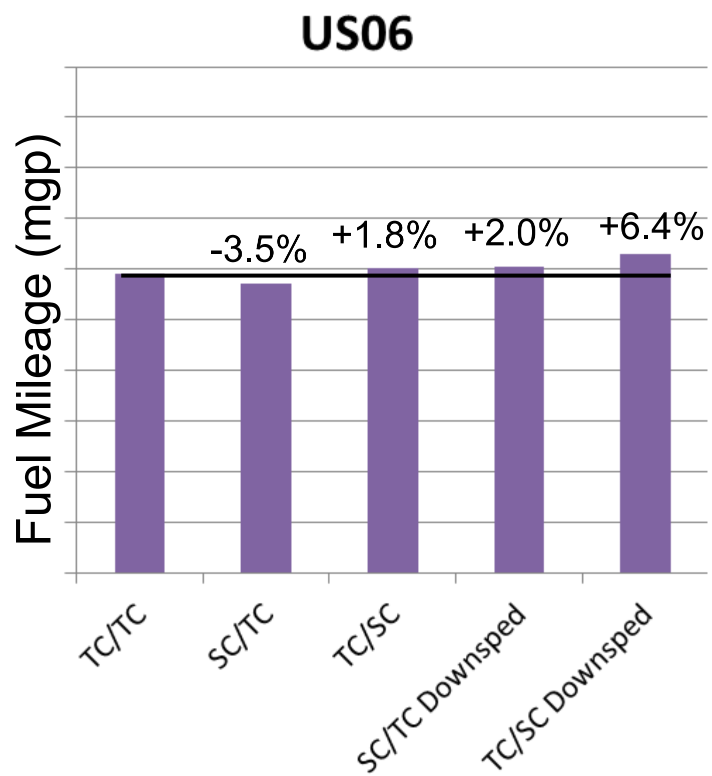
- Forward looking "real world" control strategy (not cycle beater calibration)
- Supercharger clutch strategy was used to enable SC only when required
- Aggressive torque converter lock up schedule used



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

Average Gear Ratio			
	T-T	S-T Dsp	T-S Dsp
FTP Phase 2	1.91	2.49	2.48
FTP Phase 3	2.68	3.52	3.49
US06	4.49	4.82	4.82

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

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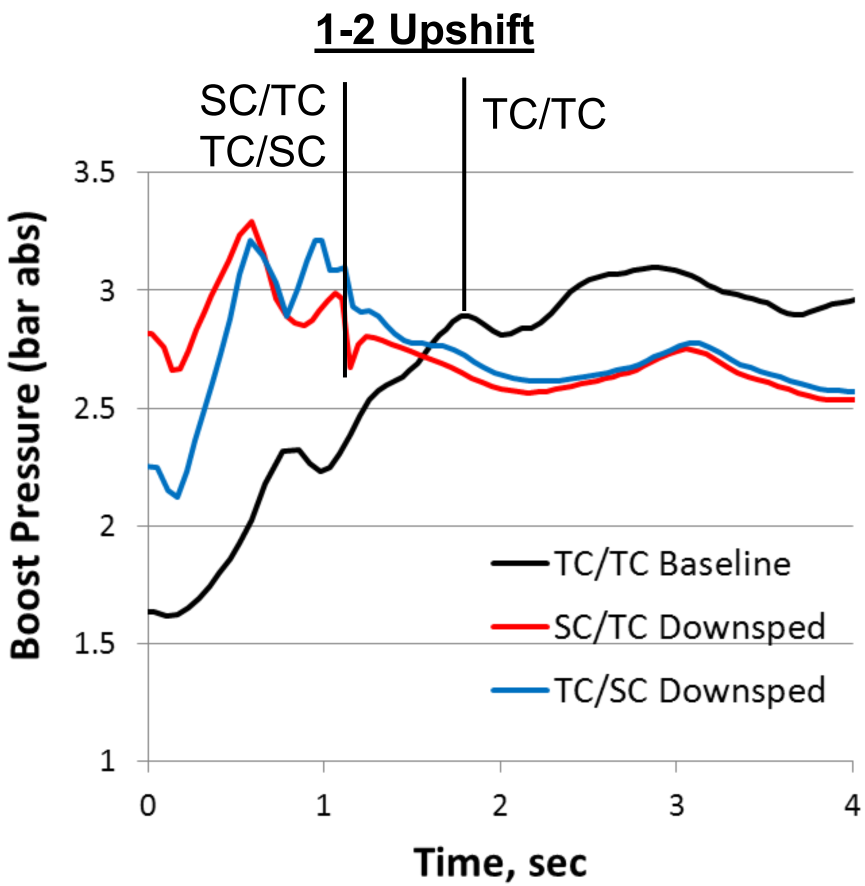
Vehicle Modeling – Tip-In Response during ¼ Mile Acceleration

- 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



- 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

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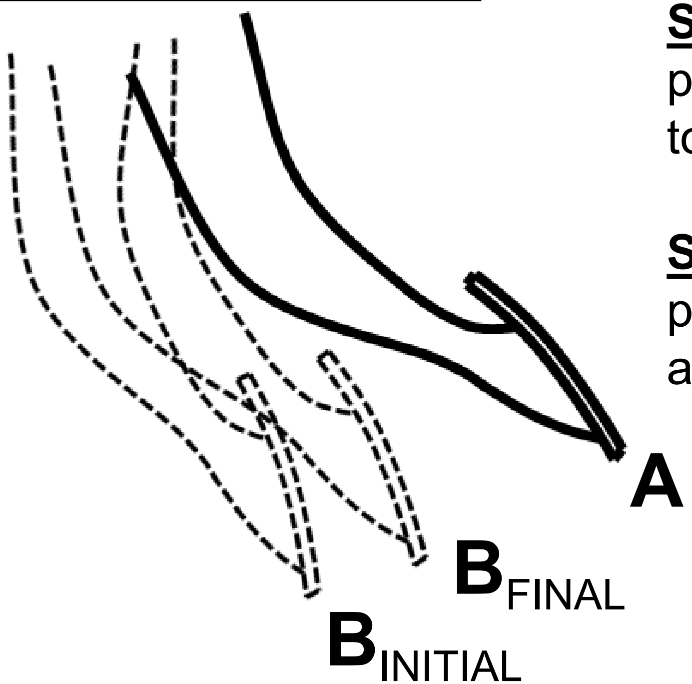
Transient Model With Driver Behavior

- 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

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