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Benchmarking a 2018 Toyota Camry 2.5-liter Atkinson Cycle Engine with Cooled-EGR

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National Center for Advanced Technology
Office of Transportation and Air Quality
Office of Air and Radiation
U.S. Environmental Protection Agency

SAE 2019-01-0249

EPA's Advanced Technology Testing and Demonstration

EPA's National Vehicle and Fuel Emissions Laboratory   Part of EPA's Office of Transportation and Air Quality in Ann Arbor, MI

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- Certify that vehicles and engines meet federal emissions and fuel economy standards
- Test in-use vehicles and engines to assure continued compliance and process enforcement
- Analyze fuels, fuel additives, and exhaust compounds
- Develop future emission and fuel economy regulations
- Develop laboratory test procedures
- Research future advanced engine and drivetrain technologies (involving 20+ engineers – modeling, advanced technology testing and demonstrations)

National Center for Advanced Technology (NCAT)

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Topics

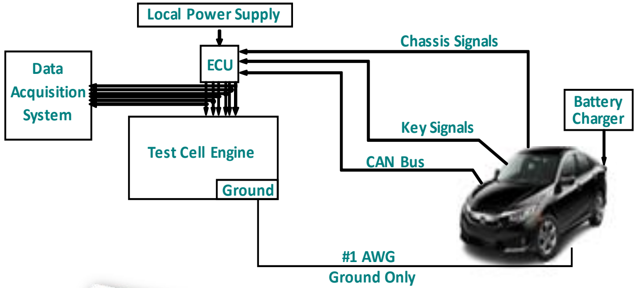
1. **Overview of EPA's Engine Benchmarking Method**
2. **Key Points of Interest for the Toyota A25A-FKS**
   - A25A-FKS - PFI and GDI Fuel Injector Systems
   - Percent Volume of EGR
   - Effective Expansion and Compression Ratios, Atkinson Ratios
   - Efficiency (BTE)
   - Comparison of Toyota's 2018 Production & 2016 TNGA Development Engines
3. **EPA's Technical Analyses for Future Engines**
   - Efforts to Validate EPA Concept Modeling
   - Toyota's 2018 Production Engine versus EPA's 2016 Future Concept Engine
   - Effects of Adding Partial and Full Cylinder Deactivation to 2018 Toyota A25A-FKS Engine

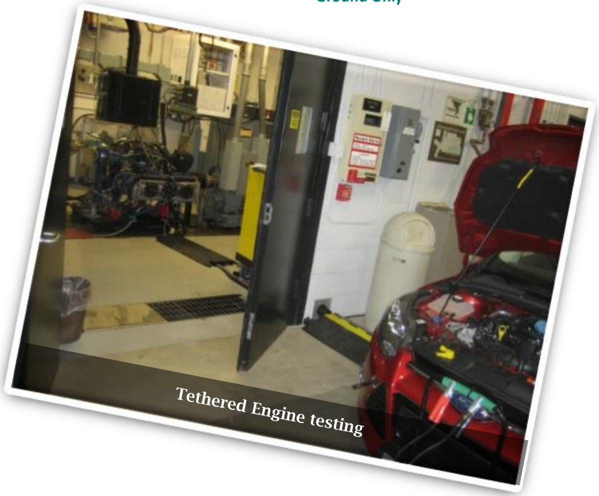
EPA's Benchmarking Method

Engine Setup

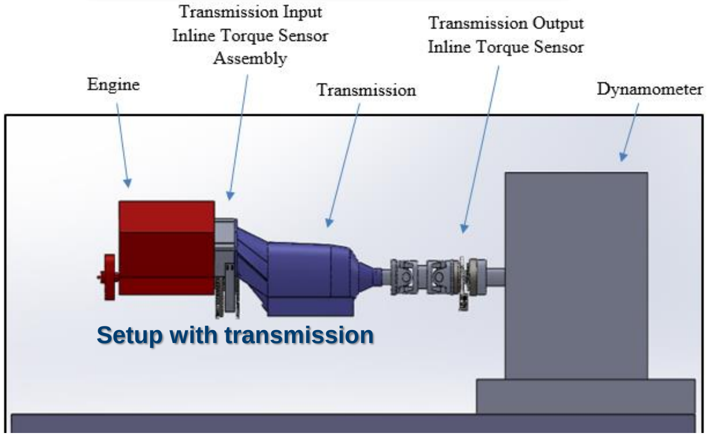
- The engine and its ECU were installed in an engine dynamometer test cell while the engine's wiring harness was tethered to the complete vehicle parked outside the test cell.
- A second engine is used in the test cell to keep vehicle intact for reference.
- Wiring connections/disconnects are made using vehicle connectors at ECU and other major harness junctions.
- Control engine load with pedal command.
- Some signals have to be simulated such as transmission OSS, ABS wheel speed, etc.
- Verifying proper operation
  - No check engine light
  - Makes rated load and power
  - Correct air fuel ratio
  - Verify combustion phasing with in cylinder pressure sensor

Engine Tethering





Engine Connected to Dyno via a Transmission



To gather data for this benchmarking program, the engine was connected to the dynamometer via a GM 6L80 6-speed rear drive automatic transmission and torque converter, and drive shaft.

There are several reasons an automatic transmission was used.

1. Minimize torsional vibrations. The transmission and torque converter have built in torsional damping. This allows low speed and high torque testing that could not be done with just a driveshaft connection.
2. The transmission is easily adapted to any engine.
3. The transmission gears selection and torque converter clutch are manually controlled. The gear ratios in overdrive allow a higher torque engine to be tested.
4. The transmission can be placed in neutral to allow idling and unloaded operation.
5. The transmission enables starting the engine with a production starter, which is important when doing cold start testing.

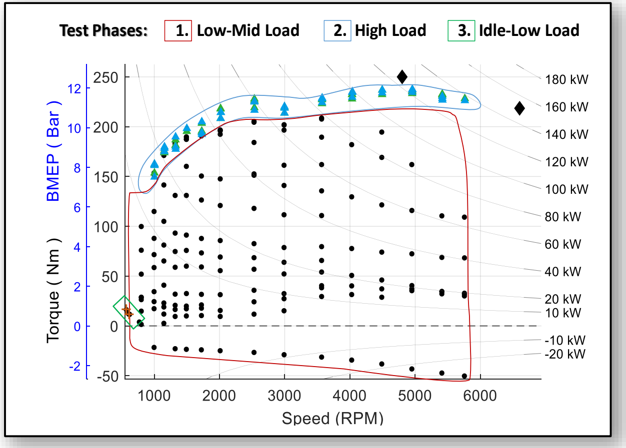
Test Data Collection and Analysis

Engine Test Phases

1) **Low-Mid loading** — Tested in steady-state operation at **low to mid torque loads** where the air-to-fuel ratio remains stoichiometric at speeds from 1000 to 5000 rpm.

2) **High loading** — Tested in transient operation at **high torque loads** where the air-to-fuel ratio will transition to enriched to protect the engine at speeds of 1000 to 5000 rpm.

3) **Idle-Low loading** — Tested in steady-state operation at **low torque loads** where the air-to-fuel ratio remains stoichiometric at speeds from idle to approximately 3000 rpm.



Test Phase	Engine Operation	Data Collection	Data Processing
1 Low-Mid loading	Approx. 30 sec. (stoichiometric)	Steady-state	Steady-state avg. (using iTest)
2 High loading	Stab test (stoich.→enriched)	Transient	Transient Intervals (using MATLAB)
3 Idle-Low loading	Approx. 30 sec. (stoichiometric)	Steady-state	Stead-state avg. (using iTest)

Topics

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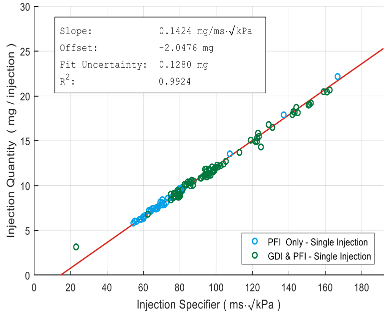
Test Data Collection and Analysis

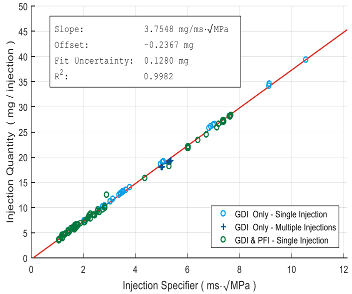
A25A-FKS - PFI and GDI Fuel Injector Systems

- Toyota refers to the system as **"D-4S"** and states that it uses both direct injection (DI) and port fuel injection (PFI) methods together, and interchangeably, to optimize engine performance and emissions.
- Both PFI and GDI fuel injectors systems are used at low loads, while only GDI is used at high load.
- For this test program, both the PFI and GDI fuel injectors were calibrated to determine the relationship between injection pulse width, injection pressure and fuel flow.

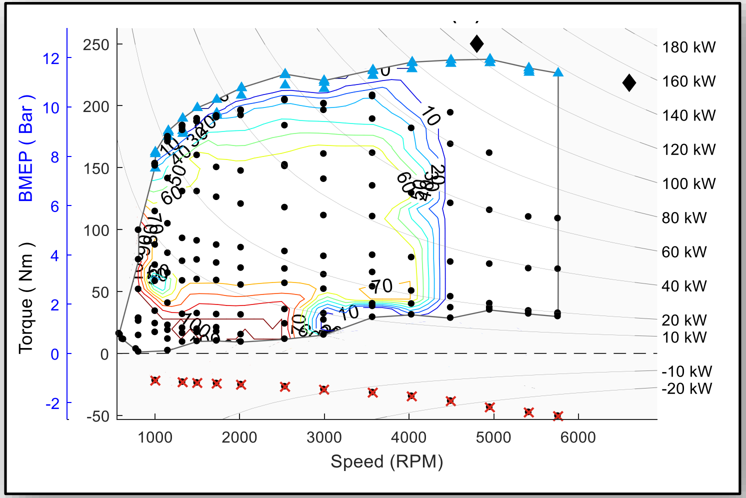
PFI injector calibration data



GDI injector calibration data



Percent portion of fuel supplied by PFI on Tier 2 Fuel



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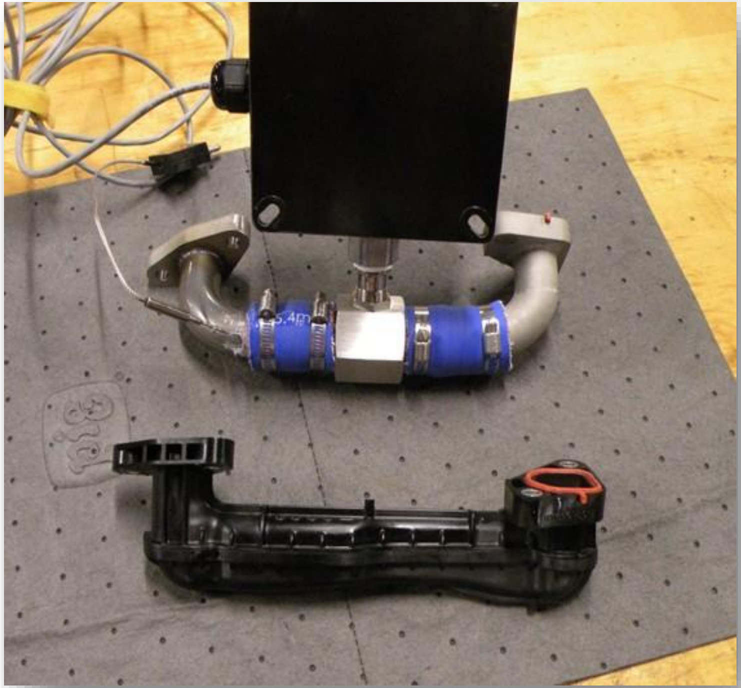
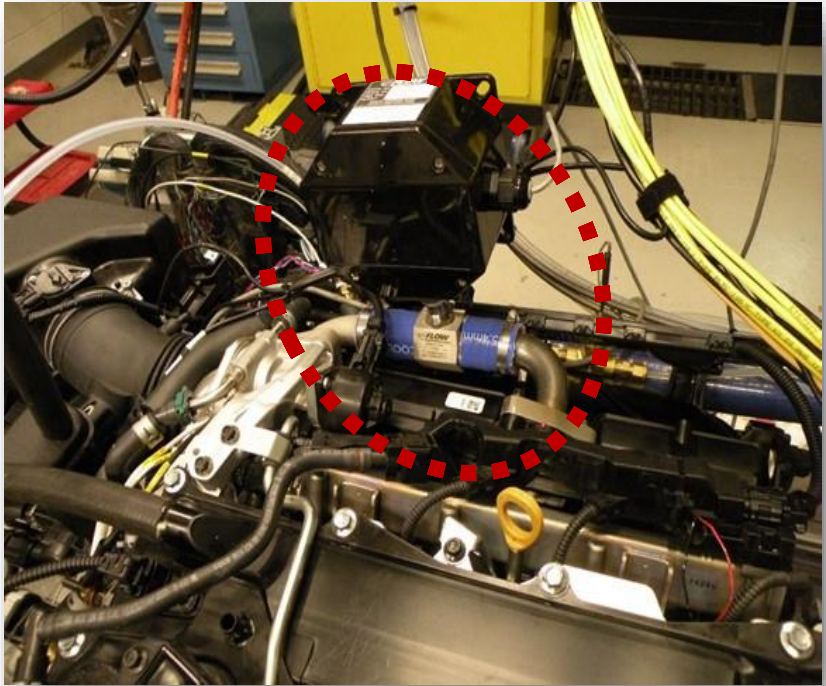
Test Data Collection and Analysis
cEGR Measurement Hardware



Original equipment EGR manifold (bottom) versus **fabricated and instrumented EGR manifold (top).**



Fabricated EGR manifold, instrumented with **flow meter** mounted on engine.

Test Data Collection and Analysis

Targeted Percent Opening of EGR Valve & Percent Volume of EGR

2018 Toyota 2.5-liter A25A-FKS Engine on Tier 2 Fuel

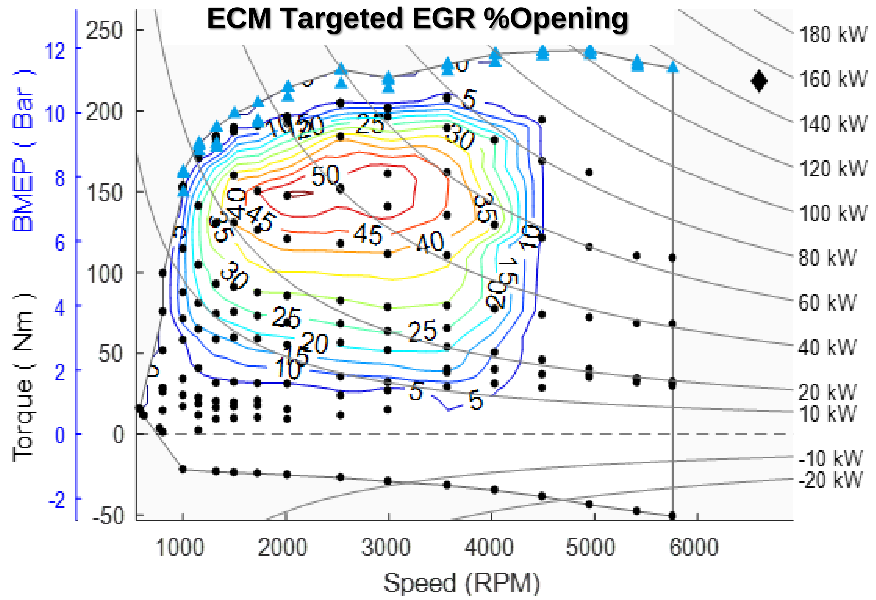


Figure 17. ECM's targeted percent opening of the EGR valve in the A25A-FKS engine, on Tier 2 fuel, (initial interval).

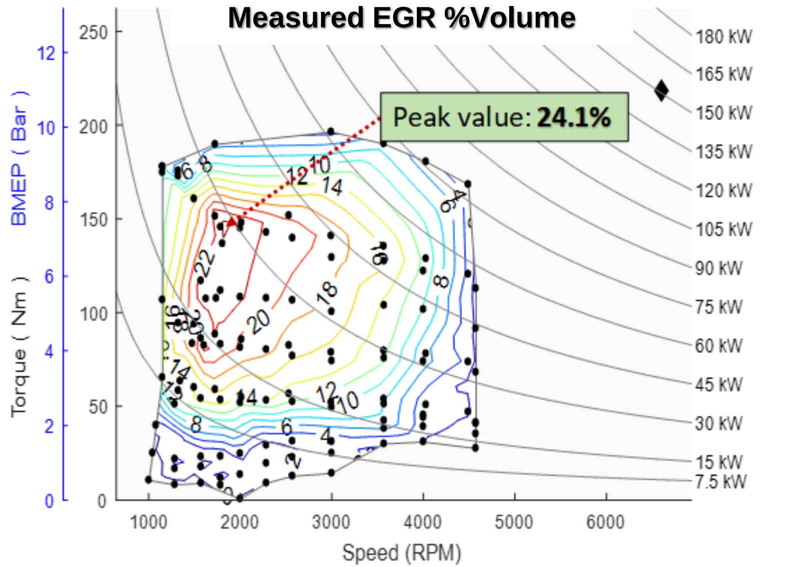


Figure 18. Percent volume of EGR as reported by EPA test cell measurements of the A25A-FKS engine using the fabricated cEGR manifold shown in Figure 8, on Tier 2 fuel.

Measured peak value of 24.1% compares well with the 25% maximum EGR described by Toyota in SAE 2017-01-1021

Test Data Collection and Analysis

Effective Expansion and Compression Ratios, Atkinson Ratios

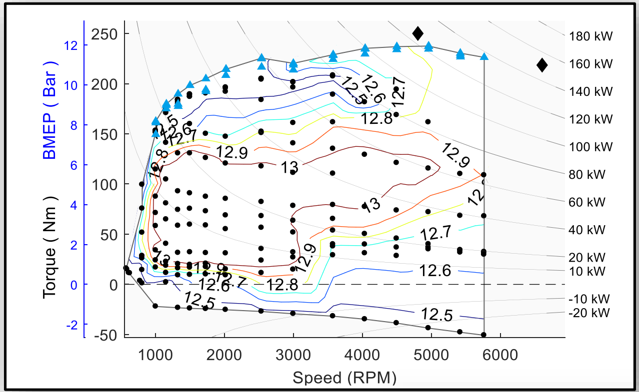


Figure 19. Effective Expansion Ratio in the **A25A-FKS engine**, on Tier 2 fuel, 1 mm reference lift, (initial interval).

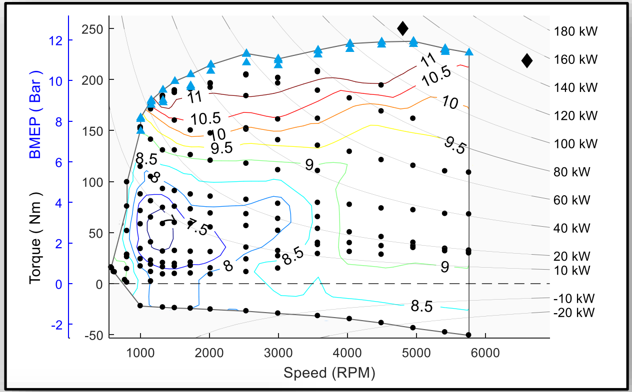


Figure 20. Effective Compression Ratio in the **A25A-FKS engine**, on Tier 2 fuel, 1 mm reference lift, (initial interval).

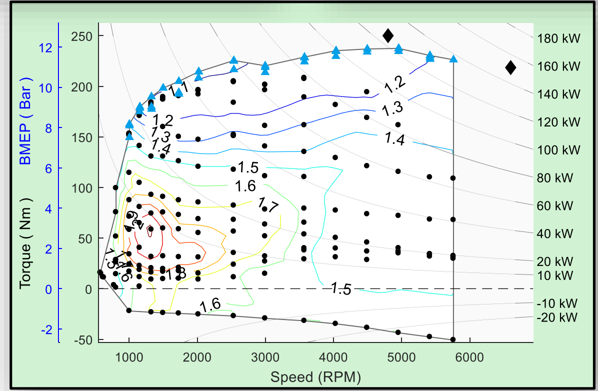


Figure 22. Atkinson Ratio of the **A25A-FKS engine** (defined as the effective expansion stroke divided by the effective compression stroke), on Tier 2 fuel, 1 mm reference lift, (initial interval)

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Test Data Collection and Analysis
Atkinson Ratios

Atkinson Ratio of Toyota 2.5L 13:1 CR

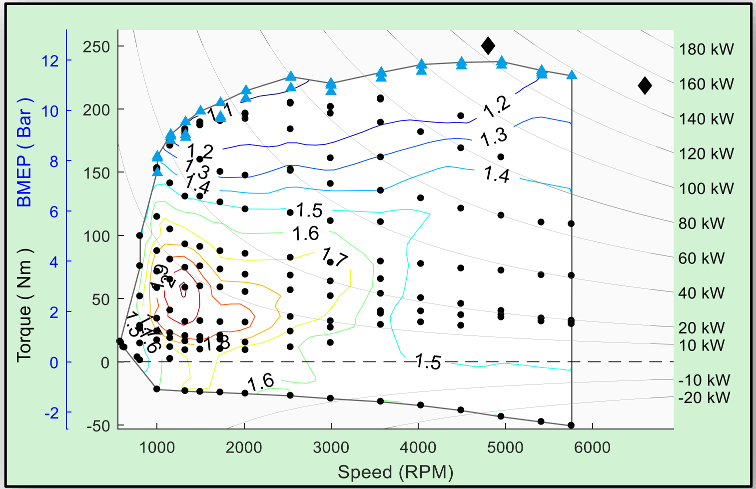

Figure 22. **<u>Atkinson Ratio</u>**
of the **A25A-FKS engine** (defined as the effective expansion stroke divided by the effective compression stroke), on Tier 2 fuel, 1 mm reference lift, (initial interval)

Atkinson Ratio of Mazda 2.0L 13:1 CR

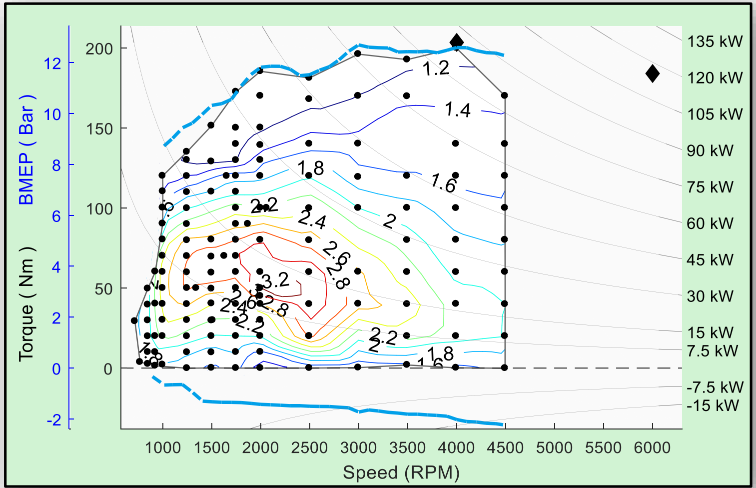

Figure 23. **<u>Atkinson Ratio</u>**
of the base **OE Mazda 2.0L 13:1 geometric CR SKYACTIV-G** engine (defined as the effective expansion stroke divided by the effective compression stroke), on Tier 2 fuel, 1 mm reference lift.

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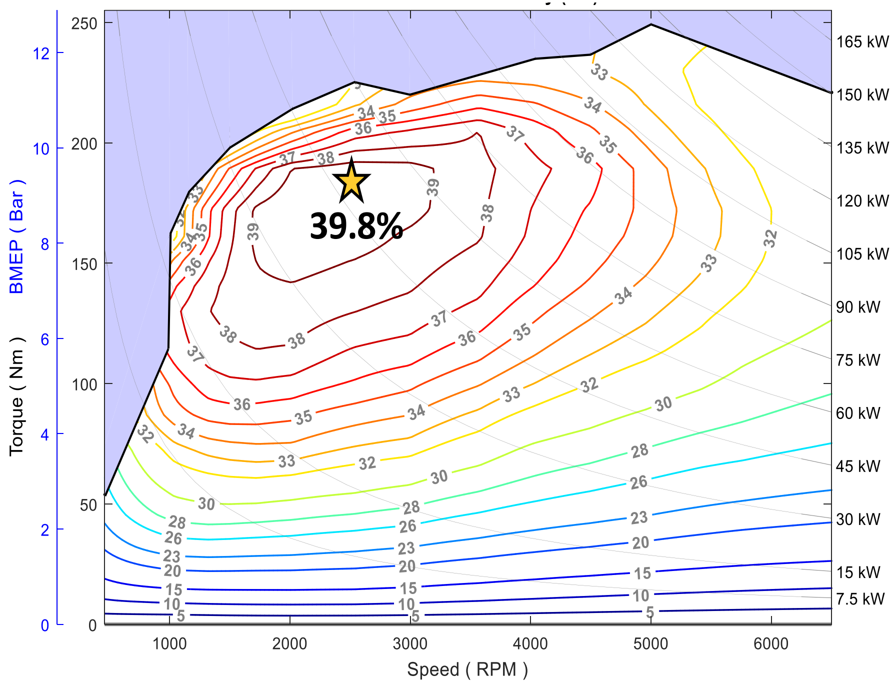
EPA's Complete BTE Map on Tier 2 Fuel

2018 Toyota 2.5-liter A25A-FKS engine with cEGR



Engine BTE map used as inputs for ALPHA model.

Note: See SAE 2018-01-1412 for information about how we construct ALPHA input maps suitable for Full Vehicle Simulation Modeling.

The complete EPA engine maps for this engine can also be found along with other EPA engine maps data at:

https://www.epa.gov/vehicle-and-fuel-emissions-testing/combining-data-complete-engine-alpha-maps

EPA benchmarking data for this engine can also be found along with EPA benchmarking data for other engines at:

https://www.epa.gov/vehicle-and-fuel-emissions-testing/benchmarking-advanced-low-emission-light-duty-vehicle-technology

Comparison of EPA Benchmarking Map & Toyota Published Map Image

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BTE Map from EPA Benchmarking

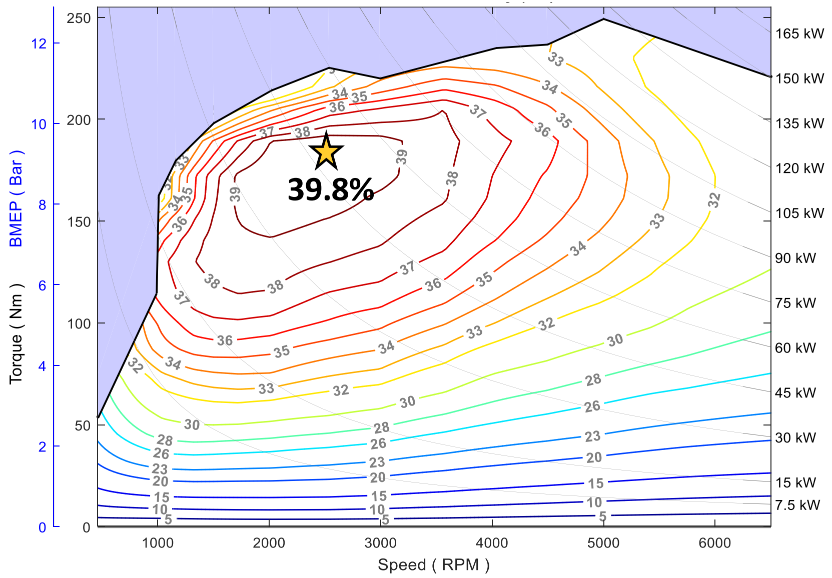


Figure 29. Complete BTE map generated from EPA benchmarking test data of Toyota 2.5L A25A-FKS engine, on Tier 2 fuel. Peak efficiency is 39.8 percent.

BTE Map from Toyota Published Map Images*

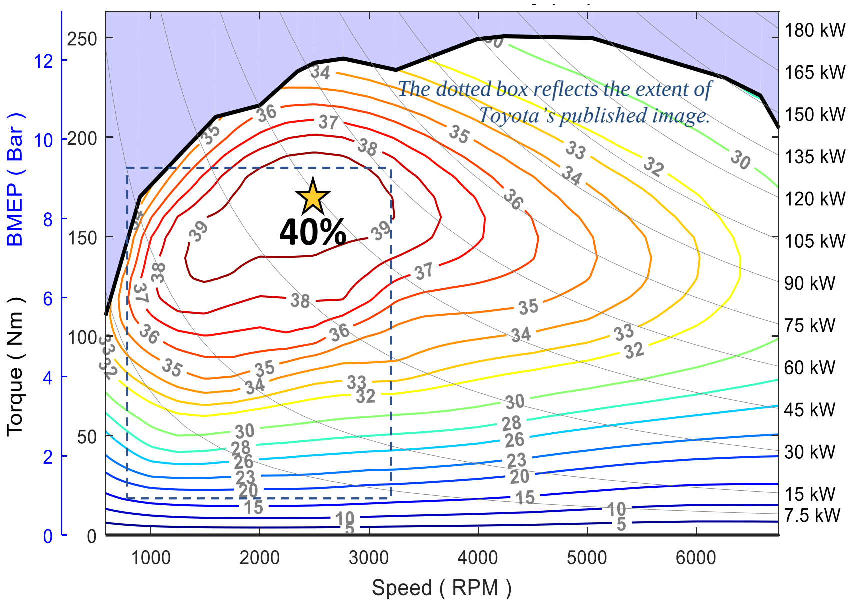


Figure 30. Complete BTE map generated from Toyota's publicly released map images of its 2016 2.5L developmental engine, on Tier 2 fuel. Peak efficiency is 40 percent.

***Map was derived from Toyota's data in this paper:** *Murase, E., Shimizu, R. "innovative Gasoline Combustion Concepts for Toyota New Global Architecture." 25th Aachen Colloquium – Automobile and Engine Technology, 2016.*

Efficiency (BTE) Difference Map

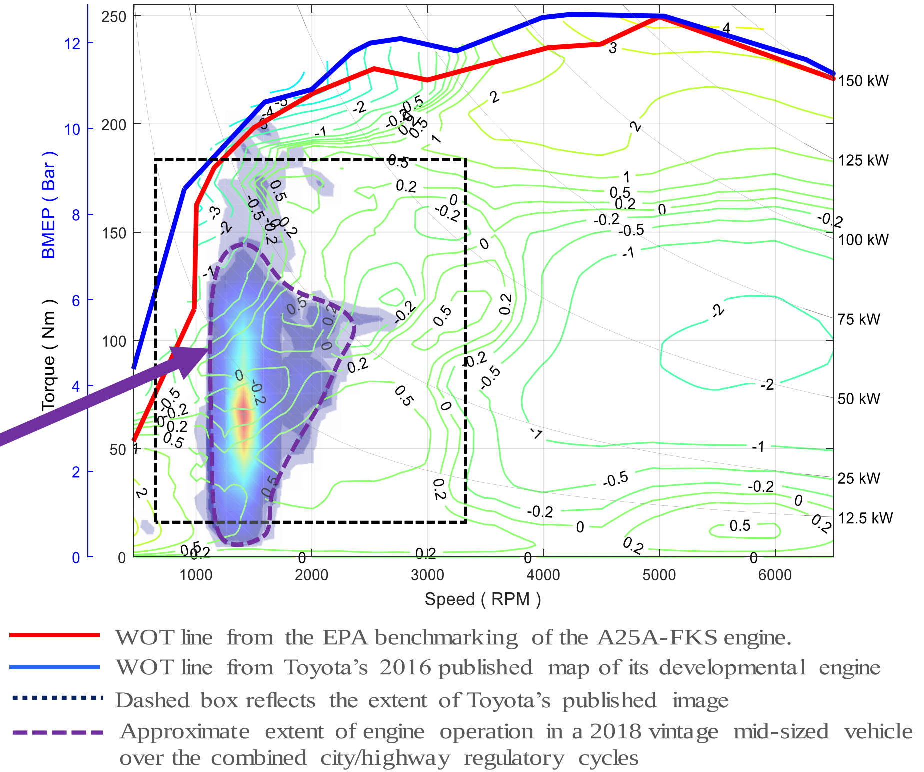
Figure 31.

BTE map from EPA benchmarking of the production 2018 Toyota A25A-FKS engine (Figure 29)

minus

BTE Map generated from Toyota published map images of its 2016 Developmental Engine (Figure 30)

The heatmap for the approximate extent of EPA's benchmarking map of the A25A-FKS engine's operation in a 2018 vintage mid-sized vehicle over the combined city/highway regulatory cycles using Tier 2 fuel.



ALPHA CO2 Results from a Mid-sized CAR

Table 6. Comparison of CO_2 results using EPA's benchmark-based map of the A25A-FKS engine versus results using EPA's map of Toyota's published image of its developmental version of this engine.

Engine	Sized Engine Displacement (liters)	Combined FE (mpg)	Combined GHG gCO2/mi	Combined GHG % Diff %
2016 Performance Neutral Baseline Vehicle				
2013 Chevrolet 2.5L Ecotec LCV	2.44 I4	36.9	240.5	
2018 mid-size Exemplar Vehicle				
2016 Developmental Toyota 2.5L 13:1 w/cEGR (2016 Aachen paper)	2.24 I4	44.6	199.1	0.0%
2018 Toyota 2.5L A25A-FKS 13:1 w/cEGR (EPA Benchmark)	2.26 I4	44.7	198.9	-0.1%
2025 mid-size Exemplar Vehicle				
2016 Developmental Toyota 2.5L 13:1 w/cEGR (2016 Aachen paper)	1.99 I4	52.8	168.2	0.0%
2018 Toyota 2.5L A25A-FKS 13:1 w/cEGR (EPA Benchmark)	2.00 I4	52.8	168.4	0.1%

Comparison:

- ✓ **2016 Toyota Developmental**
  TNGA 2.5L 13:1 CR engine with cEGR (2016 Aachan paper)
- ✓ **2018 Toyota Production**
  A25A-FKS 2.5L 13:1 CR engine with cEGR (EPA benchmark)

Note: *Each of the engines have a slightly different displacement since when adapting an engine to a specific vehicle's technology package and roadload mix ALPHA resizes the engine displacement so that the vehicle's acceleration performance remains within 2% of the baseline vehicle as described in a previous SAE paper (2017-01-0899).*

Topics

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EPA's Technical Analyses for Future Engines

	Publicly Available Data	EPA Benchmarking	EPA Concept Modeling
2012 Target Engine (EPA LD GHG Rule)			**Ricardo Future Turbo** EGRB 24-bar *(EPA-420-R-11-020, 2011)*
2016 EPA Draft TAR Midterm Evaluation		**2014 Mazda** SKYACTIV 2.0L 13:1 CR *(docket # EPA-HQ-OAR-2015-0827-0533)*	**EPA Future Atkinson** 14:1 CR w/cEGR (*SAE 2016-01-0565*)
2017 EPA Final Determination for Midterm Evaluation	**2016 Toyota** Developmental TNGA 2.5L 13:1 CR w/cEGR (2016 Aachen Colloquium)		**2016 Toyota** Developmental TNGA 2.5L 13:1 CR w/cEGR (EPA-420-R-17-002, 2017)
2018/2019 EPA Ongoing Technology Assessments		**2017 Tula Concept** vehicle w/deacFC (2018 SAE oral-only*)	Add **deacFC** to ALPHA *(2018 SAE oral-only*)*
		2018 Toyota A25A-FKS 2.5L 13:1 CR w/cEGR (SAE 2019-01-0249)	**EPA Future Atkinson** Toyota A25A-FKS w/Cylinder Deac. *(SAE 2019-01-0249)*

*Citation: Bohac, S., "Benchmarking and Characterization of Two Cylinder Deactivation Systems – Full Continuous and Partial Discrete," SAE Oral-Only Presentation, SAE World Congress, 2018, https://www.epa.gov/vehicle-and-fuel-emissions-testing/benchmarking-advanced-low-emission-light-duty-vehicle-technology

Efforts to Validate EPA Concept Modeling

EPA Concept Modeling (engine maps and vehicle simulations)	**EPA Concept Validation Data**
Ricardo Future Turbo EGRB 24-bar	• **2016 Honda 1.5L L15B7** - benchmarking *(SAE 2018-01-0319)* • **PSA EP6CDTx** - Predictive GT-Power Simulation for VNT Matching on a 1.6 L Turbocharged GDI Engine *(SAE 2018-01-0161 – SwRI/EPA)* • **PSA EP6CDTx** - Evaluation of Emerging Technologies on a 1.6 L Turbocharged GDI Engine *(SAE 2018-01-1423 - SwRI/EPA)* • **2016 Honda 1.5L L15B7 -** Active EPA program to demonstrate the effect of adding cooled-EGR on a turbocharged engine
EPA Future Atkinson 14:1 CR w/cEGR	• **2016 EPA Future Atkinson Concept –** demonstrated effect of adding cEGR *(SAE 2016-01-0565, SAE 2017-01-1016)* • **2018 Toyota 2.5L A25A-FKS** - benchmarking *(SAE 2019-01-0249)*
EPA Future Atkinson Toyota A25A-FKS w/Cylinder Deactivation	• **2019 Mazda 6 w/deacPD -** Active EPA benchmarking • **2019 GM Silverado w/deacFC -** Active EPA benchmarking

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Comparison of Toyota's 2018 Production Engine & EPA's 2016 Future Concept Engine*

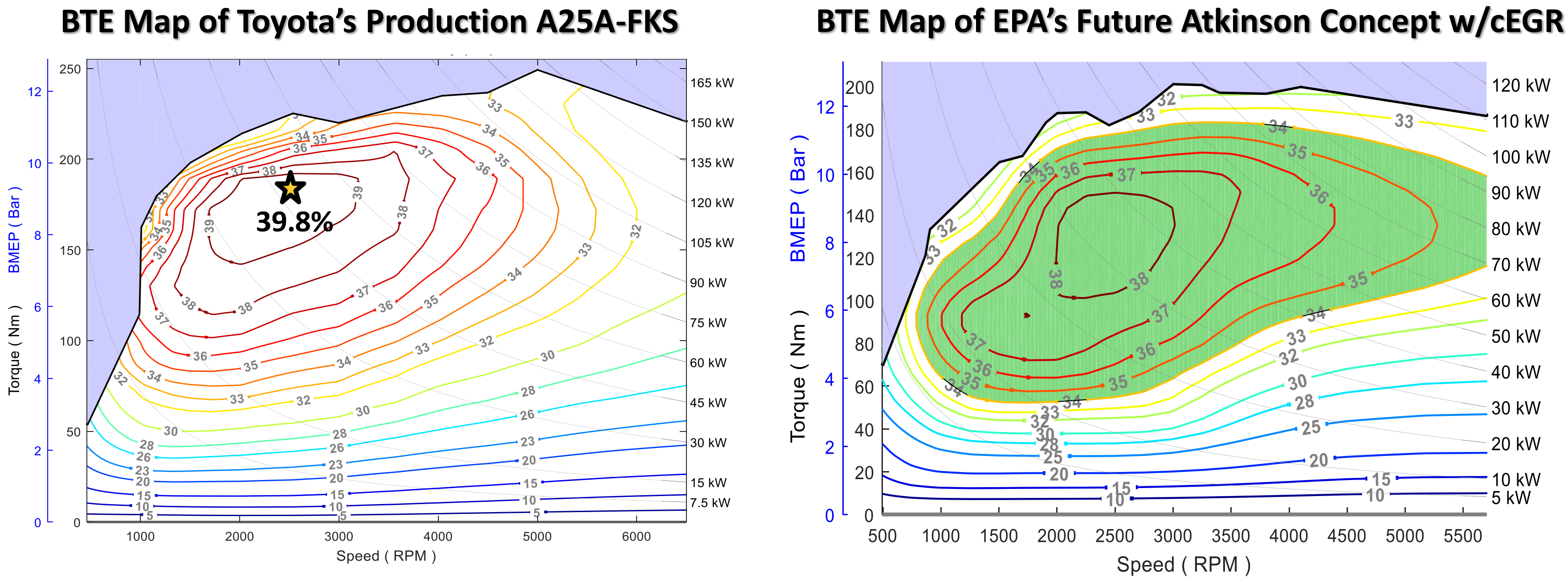


Figure 29. Complete BTE map generated from EPA benchmarking test data of Toyota 2.5L A25A-FKS engine, Tier 2 fuel. Peak efficiency is 39.8 percent.

Figure 32. EPA concept of a Future Atkinson 2.0L engine 14:1 geometric CR with cEGR on Tier 2 Fuel [15].

*Lee, S., Schenk, C., and McDonald, J., "Air Flow Optimization and Calibration in High-Compression-Ratio Naturally Aspirated SI Engines with Cooled-EGR," SAE Technical Paper 2016-01-0565, 2016, doi:10.4271/2016-01-0565.

Efficiency Difference Plot (on Tier 2 fuel)

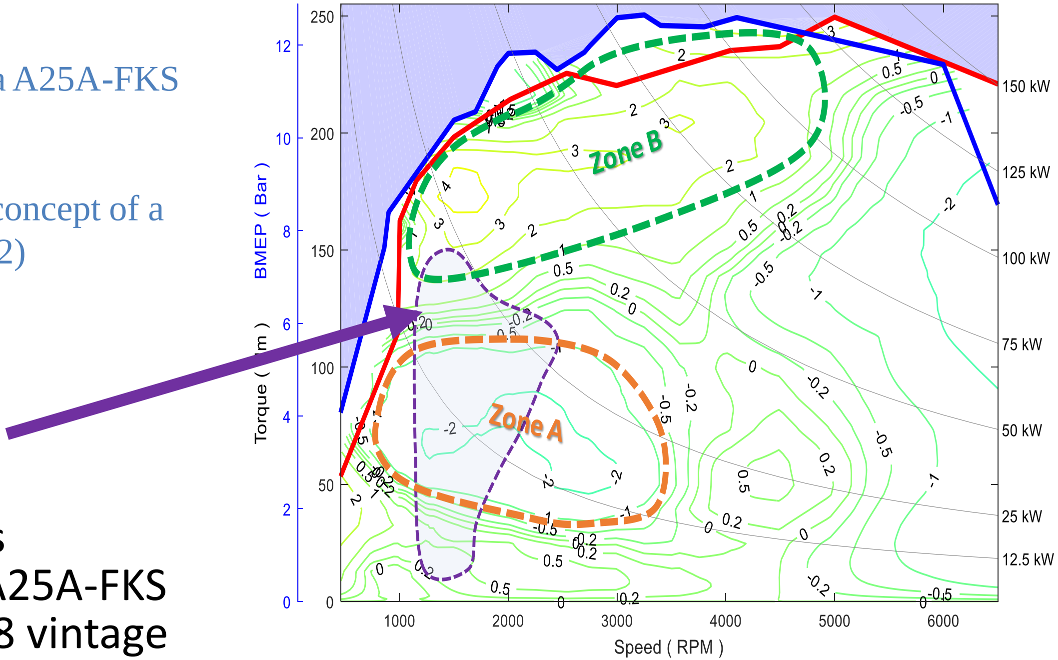
Figure 33.

EPA BTE map from benchmarked Toyota A25A-FKS (Figure 29)

minus

a scaled EPA BTE map of the modeled concept of a future ATK w/cEGR (Figure 32)

The heatmap zone for the approximate extent of EPA's benchmarking map of the A25A-FKS engine's operation in a 2018 vintage mid-sized vehicle over the combined city/highway regulatory cycles.



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Comparison of ALPHA CO2 Results

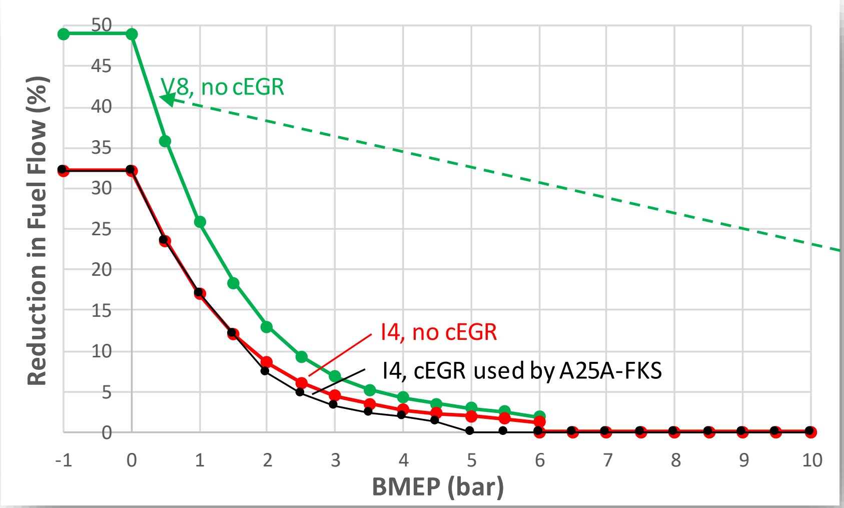
- ✓ **2016 EPA <u>Future Atkinson</u>** engine concept with cEGR
- ✓ **2018 Toyota <u>Production</u> engine** A25A-FKS 2.5L 13:1 CR engine with cEGR

Note: *Each of the engines have a slightly different displacement since when adapting an engine to a specific vehicle's technology package and roadload mix <u>ALPHA resizes the engine displacement so that the vehicle's acceleration performance remains within 2% of the baseline vehicle</u> as described in a previous SAE paper (2017-01-0899).*

Engine	Sized Engine Displacement (liters)	Combined FE (mpg)	Combined GHG 188.9	Combined GHG % Diff %
2016 Performance Neutral Baseline Vehicle				
2013 Chevrolet 2.5L Ecotec LCV	2.44 I4	36.9	240.5	
2018 mid-size Exemplar Vehicle				
2014 Mazda SKYACTIV 2.0L 13:1	2.30 I4	43.2	205.8	**0.0%**
Future Atkinson w/14:1 + cEGR (EPA GT-Power model)	2.30 I4	44.9	198.0	**-3.8%**
2018 Toyota 2.5L A25A-FKS 13:1 w/cEGR (EPA Benchmark)	2.26 I4	44.7	198.9	**-3.4%**
2025 mid-size Exemplar Vehicle				
2014 Mazda SKYACTIV 2.0L 13:1	2.09 I4	50.4	176.2	**0.0%**
Future Atkinson w/14:1 + cEGR (EPA GT-Power model)	2.08 I4	52.1	170.6	**-3.2%**
2018 Toyota 2.5L A25A-FKS 13:1 w/cEGR (EPA Benchmark)	2.00 I4	52.8	168.4	**-4.4%**

Full Continuous Cylinder Deactivation

Figure 38. EPA estimate of deacFC effectiveness (% reduction of BSFC)



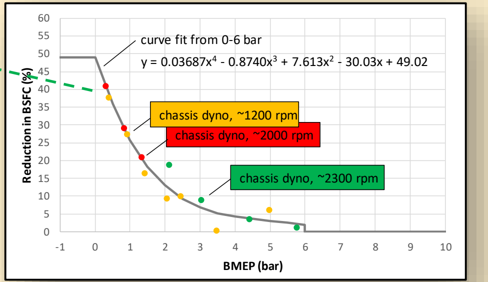
green curve – the L94 V8 engine as measured by EPA

red curve – an I4 engine without cEGR (an I4 engine that is the equivalent of the deacFC effectiveness of the L94 engine)

black curve – an I4 engine with cEGR (further adjusted for the mass flow and temperature of cEGR of the A25A-FKS engine)

- **Full continuous cylinder deactivation (deacFC)** enables any number of cylinders to be deactivated
- **Partial discrete cylinder deactivation (deacPD)** enables only certain cylinders to be deactivated.
- Both systems reduce pumping work and cylinder heat loss at low and medium engine loads but deacFC is more effective because of its greater flexibility.

From EPA's 2018 Benchmarking of Tula's Full Continuous Cylinder Deactivation



Data from Tula's Demonstration Vehicle*
MY2011 Yukon Denali with Tula deacFC
GM 6.2L L94 V8 PFI engine
Tier 2, 93 AKI test fuel

*Citation: Bohac, S., "Benchmarking and Characterization of Two Cylinder Deactivation Systems – Full Continuous and Partial Discrete," SAE Oral-Only Presentation, SAE World Congress, 2018, https://www.epa.gov/vehicle-and-fuel-emissions-testing/benchmarking-advanced-low-emission-light-duty-vehicle-technology

Effects of Adding Partial and Full* Cylinder Deactivation to 2018 Toyota A25A-FKS Engine

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EPA Estimates for Cylinder Deactivation

Table 9. Effect of deacFC and deacPD on vehicle fuel economy and CO_2 (2025 exemplar vehicle) using data from prior EPA benchmarking of supplier demonstration vehicles with cylinder deactivation.

Engine	Type of cylinder Deac	Sized Engine Displacement (liters)	Combined FE (mpg)	Combined GHG gCO2/mi	Delta from Mazda %	Effect of Adding Cylinder Deac. %
2014 Mazda SKYACTIV 2.0L 13:1	none	2.09 I4	50.4	176.2	0.0%	
2018 Toyota 2.5L A25A-FKS 13:1 w/cEGR (EPA Benchmark)	none	2.00 I4	52.8	168.4	-4.4%	0.0%
	deacPD	2.00 I4	53.5	166.0	-5.8%	-1.4%
	deacFC	2.00 I4	54.6	162.8	-7.6%	-3.3%
Future EGRB-24 + cEGR (EPA model)	none	1.22 I4	54.6	162.7	-7.7%	

Tula Estimates for Cylinder Deactivation

Table 10. Effect of deacFC and deacPD on vehicle fuel economy and CO_2 (2025 exemplar vehicle) using data from cylinder deactivation supplier.

Engine	Type of cylinder Deac	Sized Engine Displacement (liters)	Combined FE (mpg)	Combined GHG gCO2/mi	Delta from Mazda %	Effect of Adding Cylinder Deac. %
2014 Mazda SKYACTIV 2.0L 13:1	none	2.09 I4	50.4	176.2	0.0%	
2018 Toyota 2.5L A25A-FKS 13:1 w/cEGR (EPA Benchmark)	none	2.00 I4	52.8	168.4	-4.4%	0.0%
	deacPD	2.00 I4	54.0	164.6	-6.6%	-2.3%
	deacFC	2.11 I4	57.3	155.1	-11.9%	-7.9%
Future EGRB-24 + cEGR (EPA model)	none	1.22 I4	54.6	162.7	-7.7%	

ALPHA simulations show that the addition of **Full Continuous** cylinder deactivation enables the Toyota A25A-FKS engine to nearly meet or exceed the CO2 emission target of the EGRB24 engine from the 2012 GHG rulemaking.

Thank you

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EPA benchmarking data for the Toyota engine, along with this presentation, can be found at:

https://www.epa.gov/vehicle-and-fuel-emissions-testing/benchmarking-advanced-low-emission-light-duty-vehicle-technology