SAE 2018 High Efficiency IC Engine Symposium

ASSESSING THE EFFICIENCY POTENTIAL OF FUTURE GASOLINE ENGINES

April 8, 2018

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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 INTERNATIONAL

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

NVFEL's National Center for Advanced Technology
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

NVFEL is proud to be an ISO certified and ISO accredited lab

ISO 14001:2004 and ISO 17025:2005

NVFEL is a state of the art test facility that provides a wide array of dynamometer and analytical testing and engineering services for EPA's motor vehicle, heavy-duty engine, and nonroad engine programs

- 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 modeling, advanced technology testing and demonstrations)**

National Center for Advanced Technology (NCAT)

EPA's program to Study the Efficiency Potential of Future Gasoline Engines

TOPICS

1. **Assessing Current Production Engines**
   a) Develop benchmarking methods that yield good understanding of engine operation.
   b) Generate consistent fuel maps to appropriately compare engines.
   c) Use vehicle simulation (ALPHA) to assess vehicle fuel consumption.

2. **Assessing Potential Future Engines**
   a) What engine technologies are still on the table?
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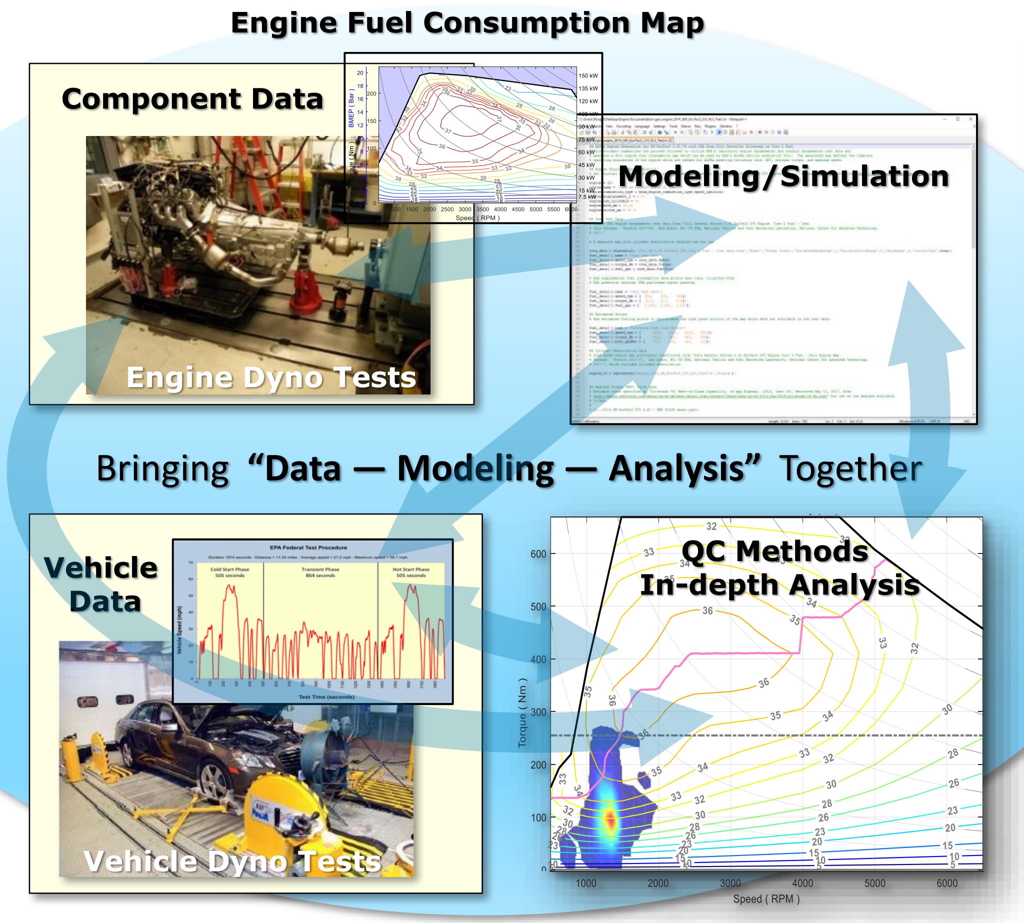
Overall Technology Assessment Program
Relationships between Benchmarking, Modeling and Quality Control Methods

Inter-dependent data sets are used to cross-validate each other in an iterative process, such as:

a) **Vehicle** and **component** data informs development of the **model** vehicle control strategies

b) The **model** informs benchmarking methods and understanding of **vehicle** and **component** technology



EPA's Quality Control Tools

- **Engine, Transmission, and Vehicle Test Data Package** review and publication process
- **Share results with stakeholders** including the supplier / manufacturer
- **Energy flow audit** to ensure that the model agrees with proper physics.
- **Data visualization tool** to compare and contrast simulation modeling results
- **Systematic comparison of simulation results against test data** to verify understanding of the technology combinations
- **Publish technical papers** in peer-reviewed journals / conferences
- **Conduct formal peer-reviews** of major modeling and analysis methodologies

Additional Details are Available from EPA's SAE Technical Papers

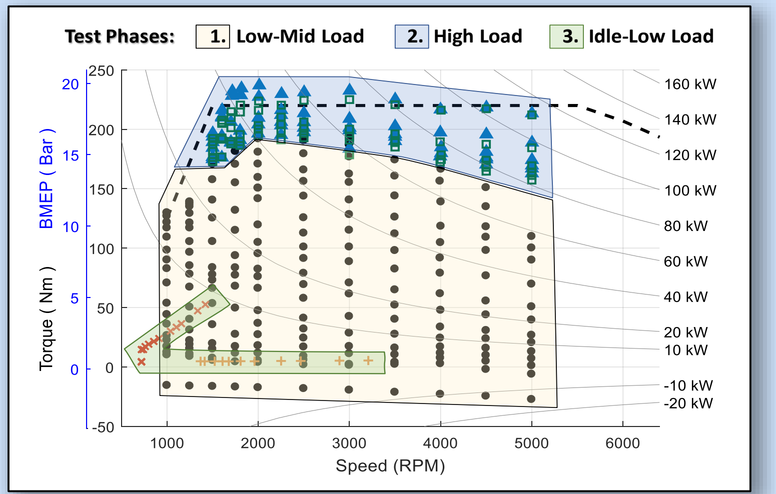
SAE 2018-01-0319 *Benchmarking a 2016 Honda Civic 1.5-liter L15B7 Turbocharged Engine and Evaluating the Future Efficiency Potential of Turbocharged Engines*

SAE 2018-01-1412 *Constructing Engine Maps for Full Vehicle Simulation Modeling*

EPA's Latest Benchmarking Methods Described in SAE Paper 2018-01-0319

The design and performance of the 1.5-liter Honda L15B7 turbocharged engine are benchmarked and then compared to several other past, present, and future downsized-boosted engines.

Benchmarking Test Data Points



Contents

A. Engine tethering setup

B. Engine test phases

1. Steady-State operation during **Low-Mid** torque loading
2. Initial and Final intervals identified during **High** torque loading
3. **Idle-Low** torque loading

C. Engine benchmarking test data points

D. Suite of benchmarking data maps

E. Complete ALPHA Input Map made from benchmarking data (SAE 2018-01-1412)

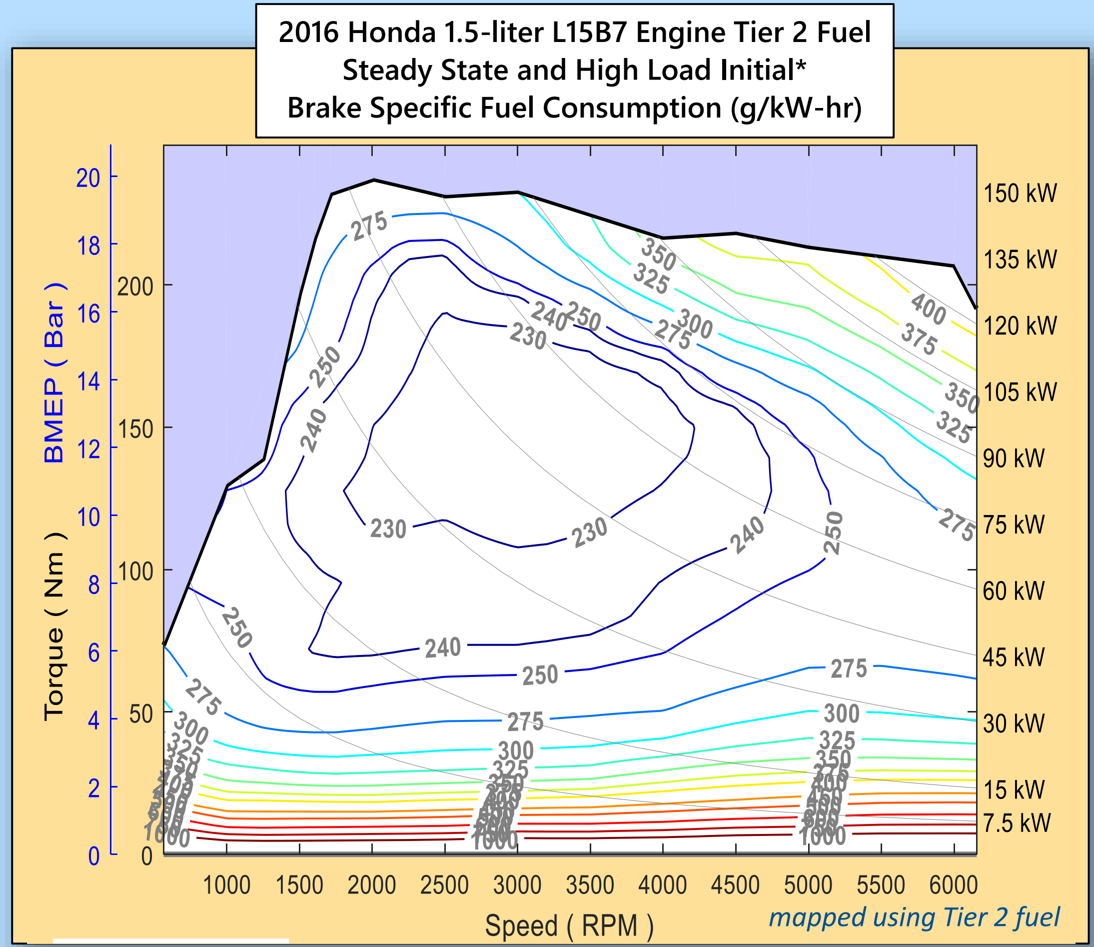
F. ALPHA full vehicle simulation using fuel map

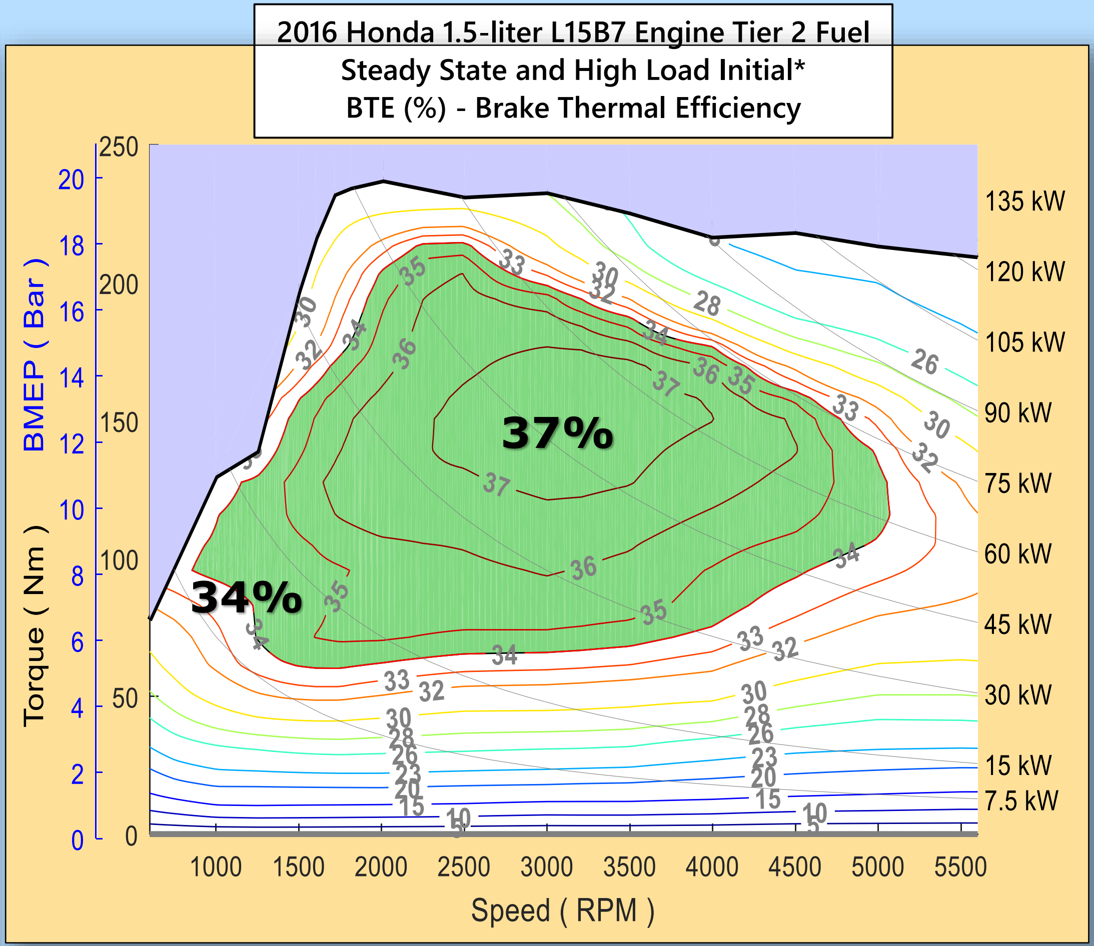
G. Compare to BTE map published by Honda

CITATION: Mark Stuhldreher, John Kargul, Daniel Barba, Joseph McDonald, Stanislav Bohac, Paul Dekraker, Andrew Moskalik, "Benchmarking a 2016 Honda Civic 1.5-liter L15B7 Turbocharged Engine and Evaluating the Future Efficiency Potential of Turbocharged Engines," SAE Technical Paper 2018-01-0319, 2018, doi:10.4271/2018-01-0319.

Generate Complete ALPHA Input Maps

Fuel Consumption Map from Benchmarking Data (2016 Honda 1.5L Turbo Tier 2 fuel)





*refer to SAE paper **2018-01-0319**

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Generate Consistent Fuel Maps to Appropriately Compare Engines

NCAT has developed a process* to generate well documented engine maps to:

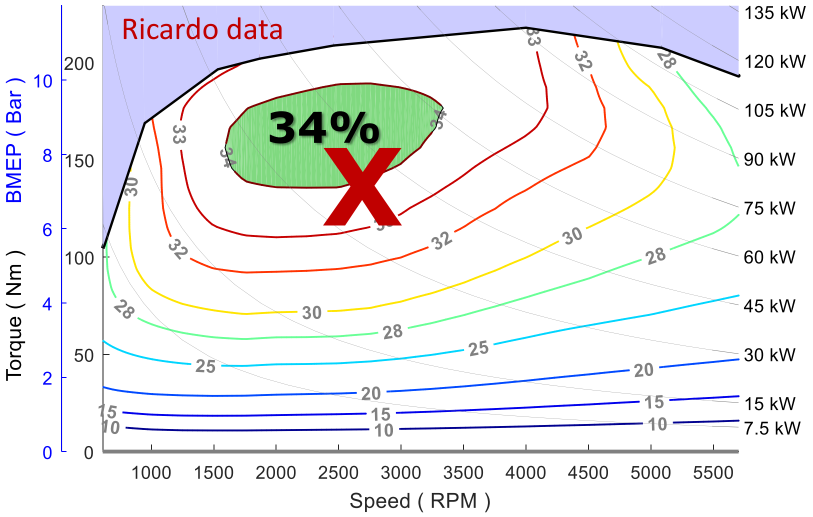
- Translate component data consistently into engine maps and vehicle model inputs
- Ensure engine technologies are evaluated equitably in engine map comparisons, and in vehicle simulation modeling
- Predict engine operation and behavior in real world operation
- Consistently scale engine size when estimating the effectiveness of technologies across the vehicle fleet (small cars to large trucks)
- Assess the potential effectiveness of new engine technologies
- Enable modeling for assessments of current and future standards
- Publish data and engine maps from EPA's benchmarking efforts

  Published data can be found at https://www.epa.gov/regulations-emissions-vehicles-and-engines/midterm-evaluation-light-duty-vehicle-greenhouse-gas#technical-projects

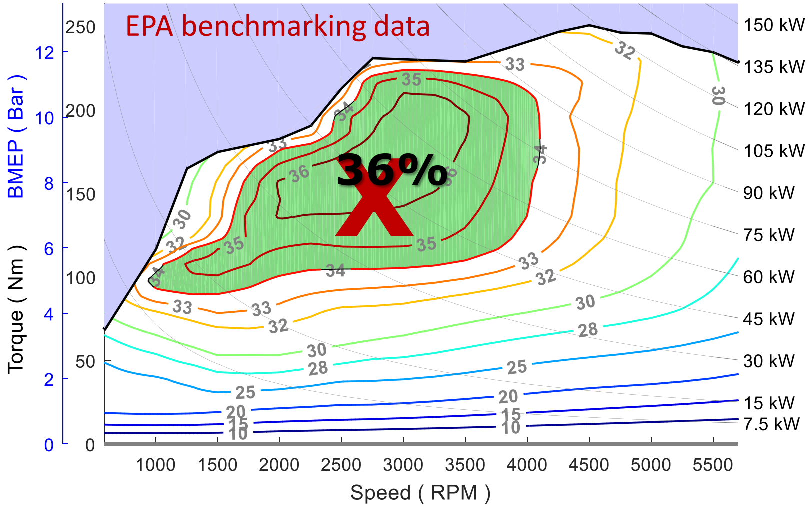
* ***Described in SAE paper:*** *Paul Dekraker, Daniel Barba, Andrew Moskalik, Karla Butters, "Constructing Engine Maps for Full Vehicle Simulation Modeling," SAE Technical Paper 2018-01-1412, 2018, doi:10.4271/2018-01-1412.*

Progression of Engine Brake Thermal Efficiency (BTE)
Naturally Aspirated Engines

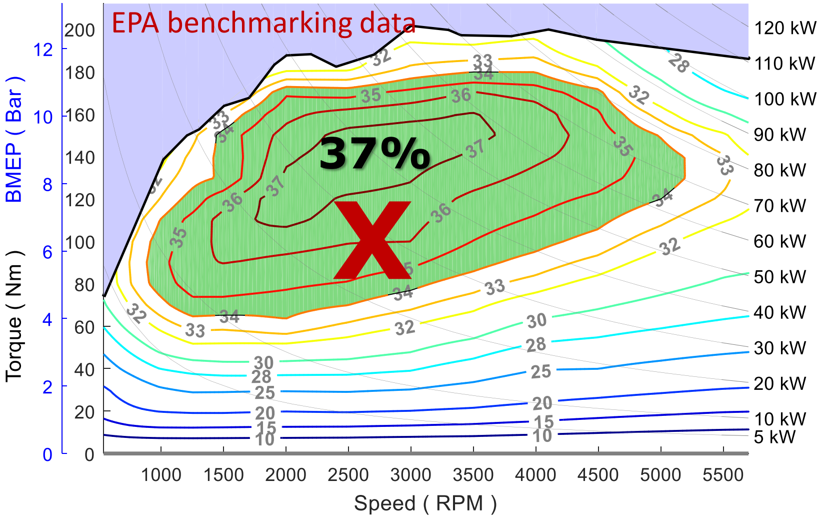
2007 Toyota Camry 2.4-liter Engine



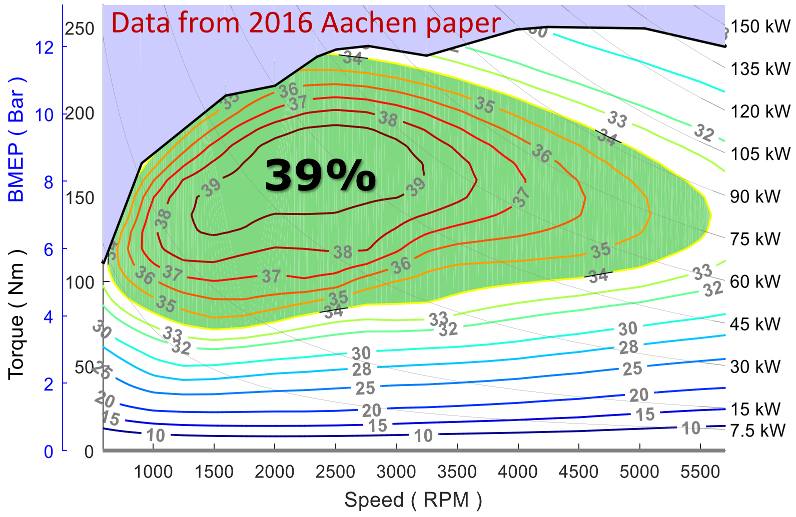
2013 GM EcoTec LCV 2.5-liter Engine Reg E10 Fuel



2014 Mazda Skyactiv-G 2.0-liter Engine Tier 2 Fuel



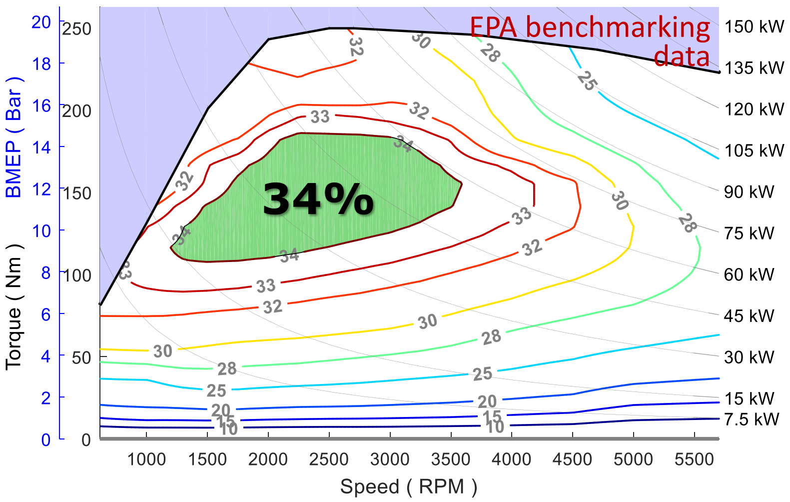
<u>Prototype</u> Toyota TNGA 2.5-liter Engine



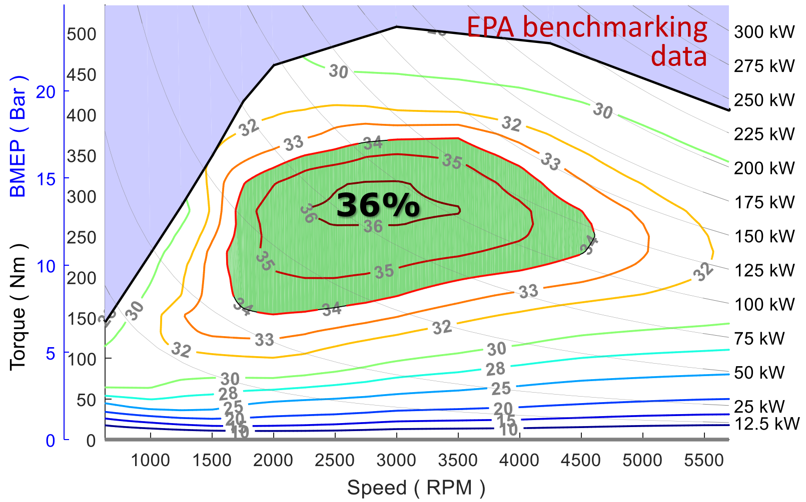
Progression of Engine Brake Thermal Efficiency (BTE)

Turbocharged Engines

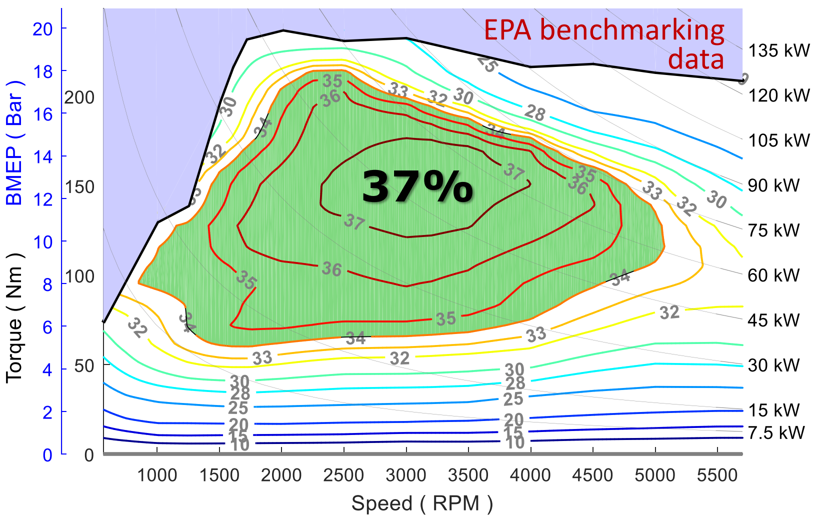
2013 Ford EcoBoost 1.6-liter Turbo Tier 2 Fuel



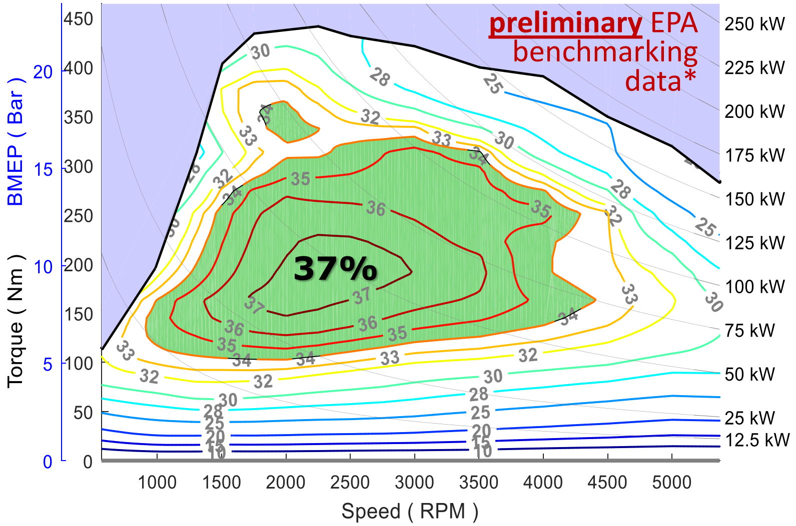
2015 Ford EcoBoost 2.7-liter Turbo Tier 2 Fuel



2016 Honda L15B7 1.5-liter Turbo Tier 2 Fuel



2016 Mazda Skyactiv-G 2.5-liter Turbo Tier 2 Fuel



** EPA's final data set will be published on EPA's website.*

EPA's program to Study the Efficiency Potential of Future Gasoline Engines

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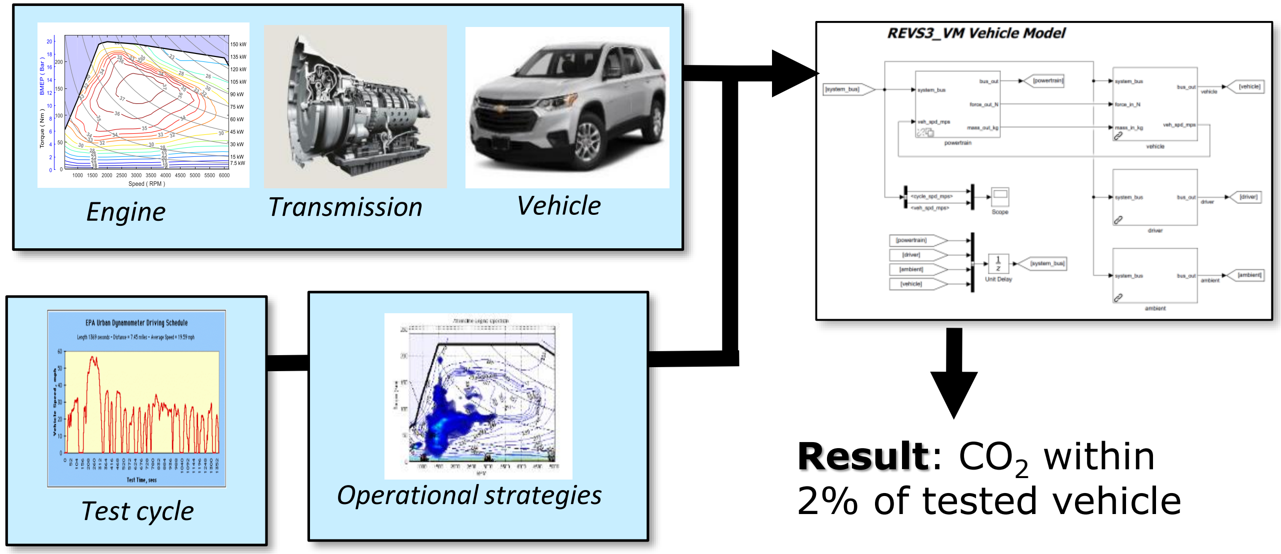
EPA's Vehicle Simulation Modeling Tool

- **ALPHA** is EPA's tool for understanding vehicle behavior, effectiveness of various powertrain technologies and their greenhouse gas emissions.
- **ALPHA** is an Advanced Light-Duty Powertrain and Hybrid Analysis tool created by EPA to estimate greenhouse gas (GHG) emissions from current and future light-duty vehicles.

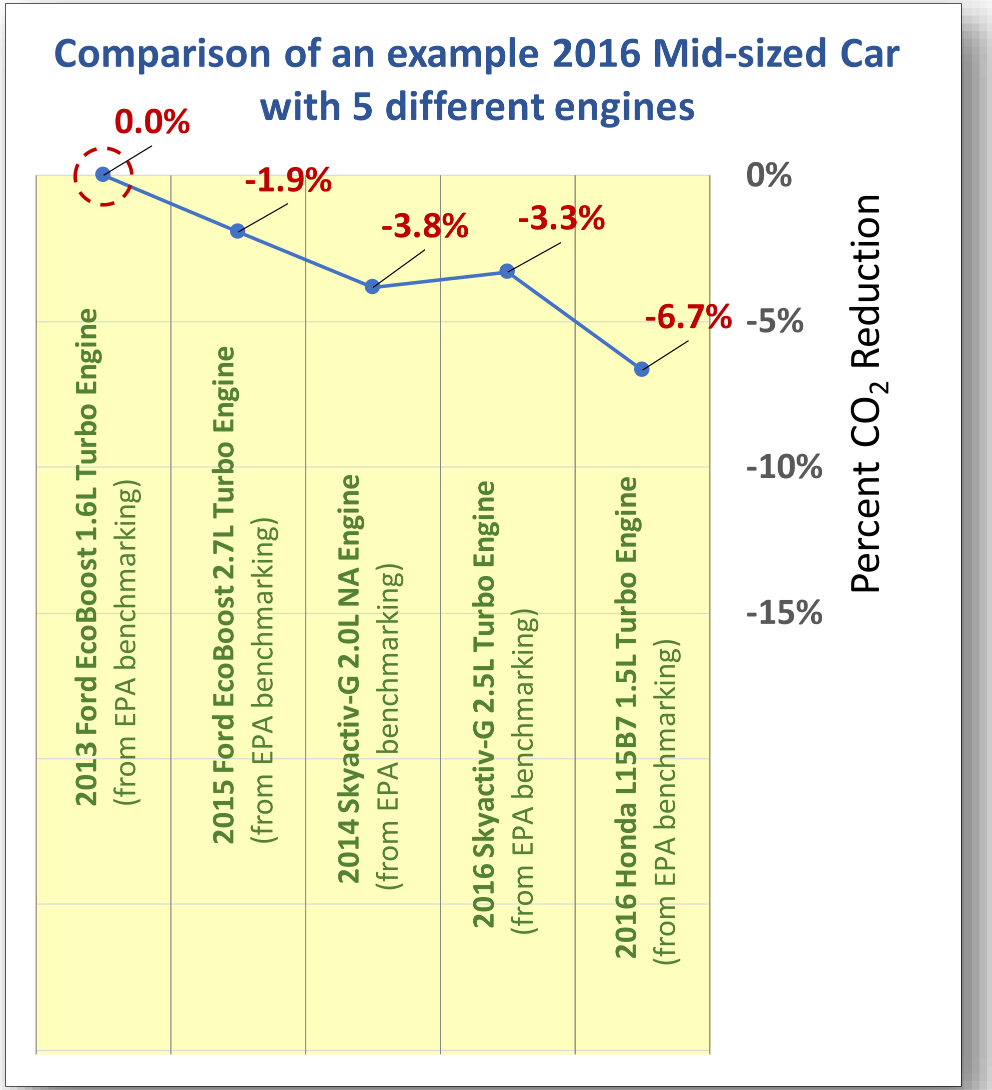


- **ALPHA** is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types combined with different powertrain technologies.
- **ALPHA** is not a commercial product - e.g. there are no user manuals, tech support hotlines, graphical user interfaces, full libraries of components, etc.
  - **ALPHA** is freely available on EPA's web-site, and open for use by interested stakeholders.

Efficiency Comparison of 5 Production Engines Using ALPHA

Comparison of ALPHA vehicle simulations with 5 different engines

Engine	Perf Neutral Sized Displacement (liters)	Combined Cycle Engine Efficiency (%)	Combined Cycle CO_2 (gCO_2/mi)	Improved Efficiency [CO_2 Reduction] (%)
	2016			
2013 Ford EcoBoost 1.6L Turbo Engine	1.7	19.8	246.6	0.0%
2015 Ford EcoBoost 2.7L Turbo Engine	1.5	20.2	241.9	-1.9%
2014 Mazda Skyactiv-G 2.0L NA Engine	2.5	20.7	237.1	-3.8%
2016 Skyactiv-G 2.5L Turbo Engine	1.7	20.5	238.4	-3.3%
2016 Honda L15B7 1.5L Turbo Engine	1.7	21.3	230.1	-6.7%



Notes:

- Refer to SAE paper 2018-01-0319 for road load values for this simulation.
- Each of the engines in the table has 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 baseline vehicle (as described in SAE paper 2017-01-0899).

What Engine Technologies are Still on the Table?

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What Engine Technology Combinations Remain Available for the Future?

EPA regularly conducts technology assessments to better understand the status of the industry's engine development

- Attend conferences, review papers and journal articles, meet with manufacturers and suppliers.
- Determine technology content of recently introduced or announced engines.
- Determine the technology frontier and possible future technology combinations.

See 2018 SAE paper* for an example assessment performed by EPA to evaluate the degree of implementation of turbocharged engine technologies.

**CITATION: Mark Stuhldreher, John Kargul, Daniel Barba, Joseph McDonald, Stanislav Bohac, Paul Dekraker, Andrew Moskalik, "Benchmarking a 2016 Honda Civic 1.5-liter L15B7 Turbocharged Engine and Evaluating the Future Efficiency Potential of Turbocharged Engines," SAE Technical Paper 2018-01-0319, 2018, doi:10.4271/2018-01-0319. he color coding designations were determined for each technology in the table.*

Selecting Technologies for Assessment

Example: Technology Frontier for Turbocharged Engines

Selection Criteria for Benchmarking Programs

1. Recent model year vehicles with emerging advanced fuel and emissions technologies (US-market strongly preferred)
2. High potential for cost-effectiveness
3. Heavy focus on advanced engine technology like those shown in the table.
4. Little or no publically available data describing its operation or effectiveness

- Chart is taken from EPA's technical paper* describing the current "technology frontier" for turbo-charged engines in the US-market.
- Features of each engine are compared against EPA's projection of 2025 engine technology (Ricardo EGRB 24) for the 2012 LD GHG FRM.

Boosted Engines	Intro Year	Variable Valve Timing (VVT)	Integrated Exhaust Manifold	High Geometric CR	Friction Reduction	Higher Stroke/Bore Ratio	Boosting Technology	cooled EGR	Variable Valve Lift (VVL)	Miller Cycle	VNT/VGT Turbo	Partial Discreet Cylinder Deac.	Full Authority Cylinder Deac.	Variable Compression Ratio	Gasoline SPCCI / Lean Modes
Ford EcoBoost 1.6L	2010														
Ford EcoBoost 2.7L	2015														
Honda L15B7 1.5L	2016														
Mazda SKYACTIV-G 2.5L	2016						4				4				
VW EA888-3B 2.0L	2018														
VW EA211 EVO 1.5L	2019							?[3]							
VW/Audi EA839 3.0L V6	2018				?[3]										
Nissan MR20 DDT VCR 2.1L	2018			+	?[3]		?[3]	?[3]							?[3]
Mazda SKYACTIV-X SPCCI 2.0L SC[1]	2019			+	?[3]						NA				
EPA/Ricardo EGRB24 1.2L[2]	N/A														

yellow = early implementation *light & dark green* = nearing maturity *red* = technology not present

1- Supercharged **2**- EPA Draft TAR **3**- Not known at time of writing
4- Mazda accomplishes equivalent of VNT/VGT using novel valving system

*SAE paper 2018-01-0319

Technology Comparison with Other Turbo Engines

Takeaways*

- **Engine parameters and technologies have been steadily advancing since 2010** – including:
  a) compression ratio (CR), b) stroke/bore ratio, c) intake cam phase authority, d) integrated exhaust manifolds, e) friction reduction, f) faster camshaft phasing control, g) advanced boosting technology, h) cooled EGR, and i) Miller Cycle.

- **No engine incorporates all potential improvements –**
  significant untapped efficiency improvement potential is still available with application of:
  a) cylinder deactivation
  b) variable valve lift [VVL]
  c) variable compression ratio [VCR]
  d) variations of dilute combustion/spark assisted gasoline compression ignition

refer to SAE** *paper* ***2018-01-0319

What Might Future Engine Maps Look Like?

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What Might Future Engine Maps Look Like?

EPA previous engine map projections and recent work

Previous Engine Map Projections:

1. Honda 1.5L turbo engine
2. EPA GT-Power model of future Atkinson engine with cooled EGR (based on Skyactiv-G 2.0L)
3. Toyota Prototype 2.5L TNGA engine (Atkinson w/cooled EGR)

Recent Evaluations of Emerging Engine Technologies:

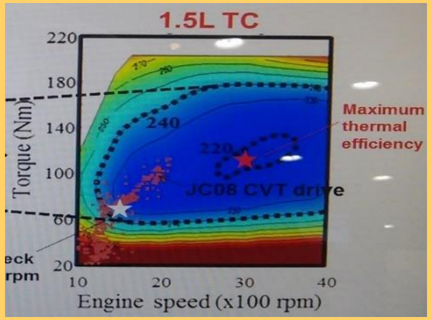
4. Mazda Skyactiv-X 2.0L engine (gasoline compression ignition)
5. Addition of Cylinder Deactivation to engine maps

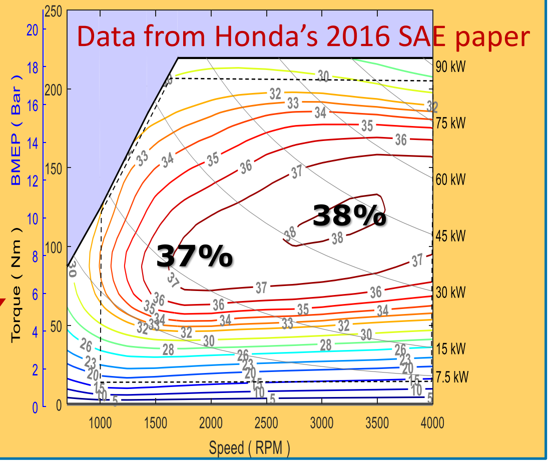
Example 1: Projection of Honda 1.5L Turbo Engine

based on Honda Published Data (and later verified with benchmarking data)

EPA's BTE map made from Honda's BSFC map <u>image of the Prototype Engine*</u>

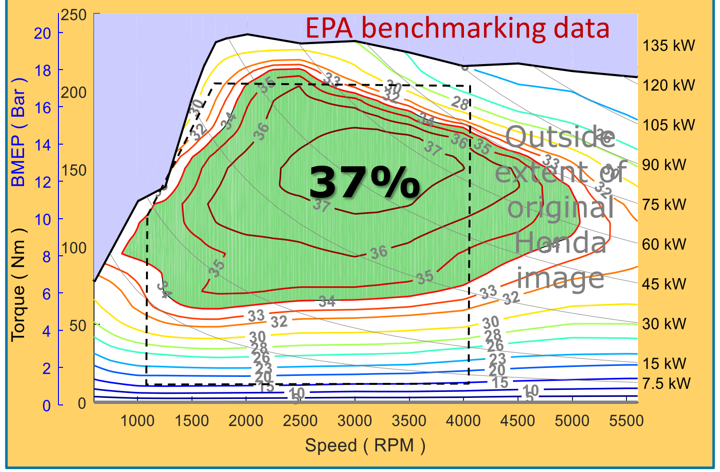
from SAE World Congress:





The dotted black line reflects the extent of the original Honda image.

EPA's BTE map made from <u>test data</u>



For ALPHA engine input maps, go to:

https://www.epa.gov/regulations-emissions-vehicles-and-engines/midterm-evaluation-light-duty-vehicle-greenhouse-gas#technical-projects

And click link to:

Test Data for Light-duty Greenhouse Gas (GHG) Technology

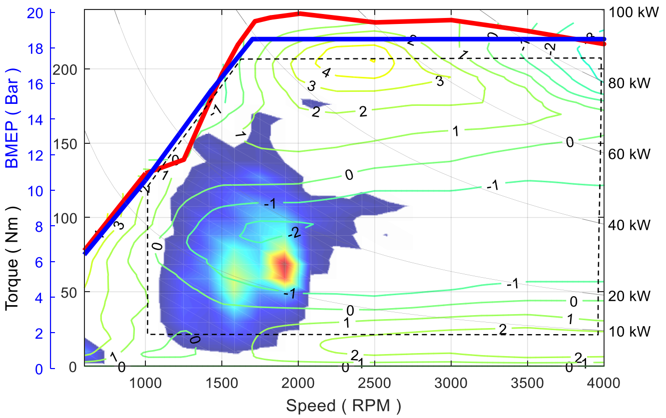
Veh. Tech.	Engine	Sized Displ. (liters)	Combined Cycle Fuel Economy (MPG)	Combined Cycle CO_2 (gCO_2/mi)	Map: % CO_2 Delta (EPA/Honda - 1)	Year: % CO_2 Delta (2025/2016 - 1)
	Baseline 2016 mid-sized car	2.437 (I4)	36.8	241.4	--	--
2016	Honda L15B7 Earth Dreams Turbo (map from Honda published image)	1.653 (I4)	39.0	227.8	1.1%	--
2016	2016 Honda L15B7 Turbo (map from EPA test data)	1.654 (I4)	38.6	230.4		--
2025	Honda L15B7 Earth Dreams Turbo (map from Honda published image)	1.427 (I4)	52.6	168.9	0.9%	-26%
2025	2016 Honda L15B7 Turbo (map from EPA test data)	1.420 (I4)	52.2	170.4		-26%

See paper for vehicle and road load definitions.

Efficiency (BTE) Difference Plot

EPA map from test data <u>minus</u> EPA map from Honda image

- ✓ **ALPHA runs only predict about a 1% difference in CO_2 over the regulatory cycles for both 2016 and 2025 mid-sized vehicles.**
- ✓ **CO2 is higher using the map from EPA's test data.**

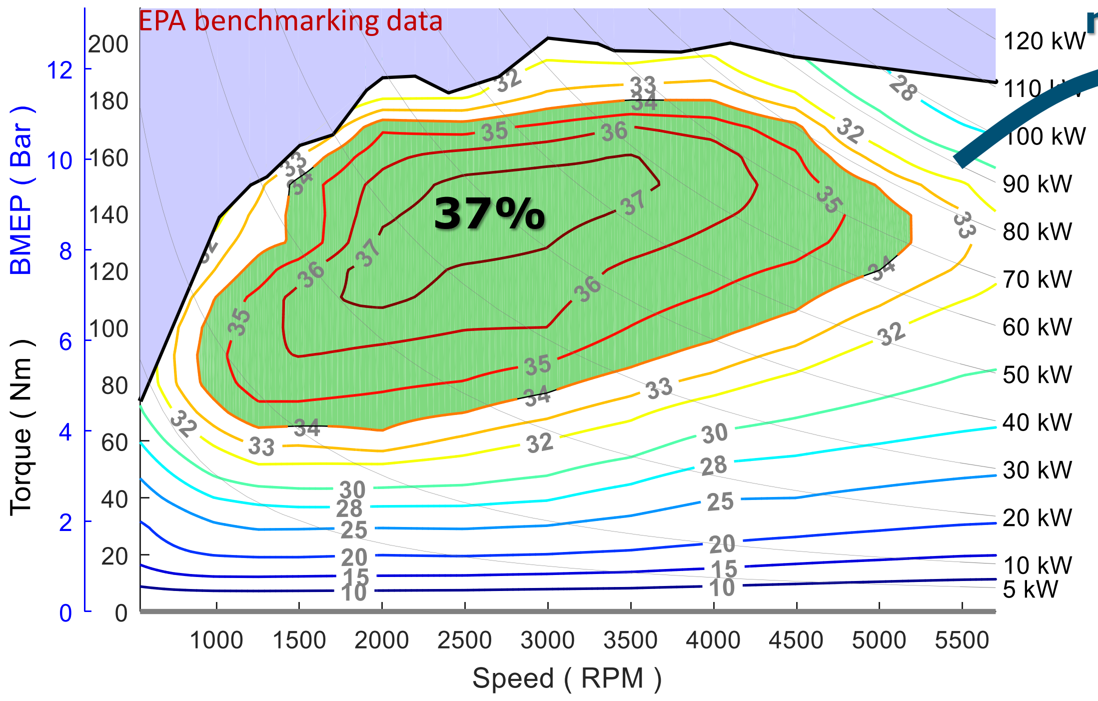


***refer to SAE paper 2018-01-0319**

Example 2: Projection of Future Atkinson w/ Cooled EGR
based on EPA GT-Power model of a Skyactiv-G 2.0L

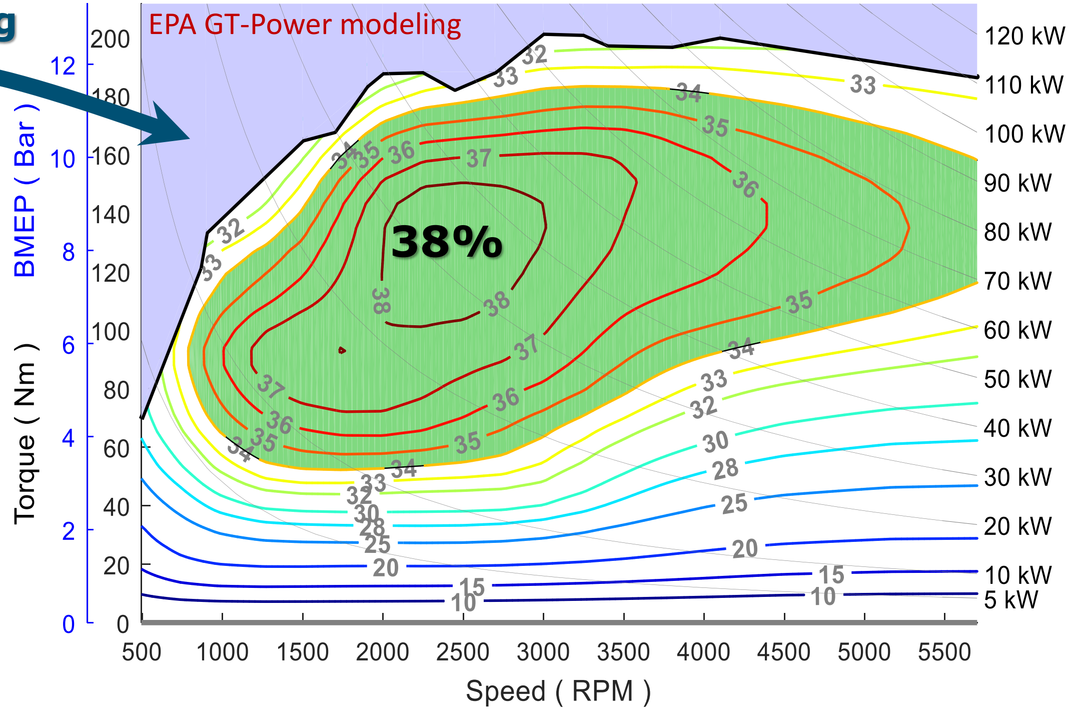
- EPA used GT-Power modeling used to add cooled EGR technology to the Skyactiv-G 2.0L engine.

2014 Mazda Skyactiv-G 2.0L Engine Tier 2 Fuel



GT-Power modeling

Future Atkinson Concept Engine with cEGR [1,2]



1 *CITATION:* ***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.***

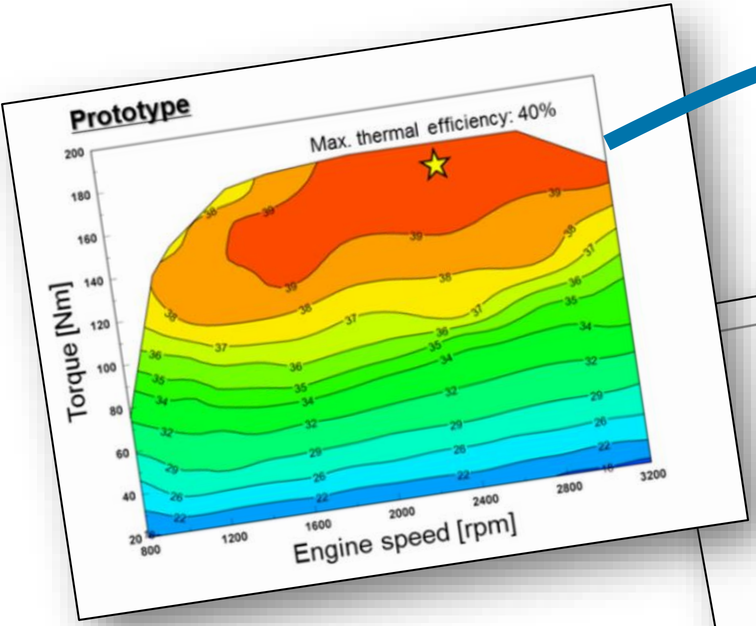
2 EPA's engine map process document is at: https://www.epa.gov/regulations-emissions-vehicles-and-engines/midterm-evaluation-light-duty-vehicle-greenhouse-gas#technical-projects, and then click link to *Test Data for Light-duty Greenhouse Gas (GHG) Technology*

Example 3: Projection of Toyota's 2.5L TNGA Engine (Atkinson w/cooled EGR)

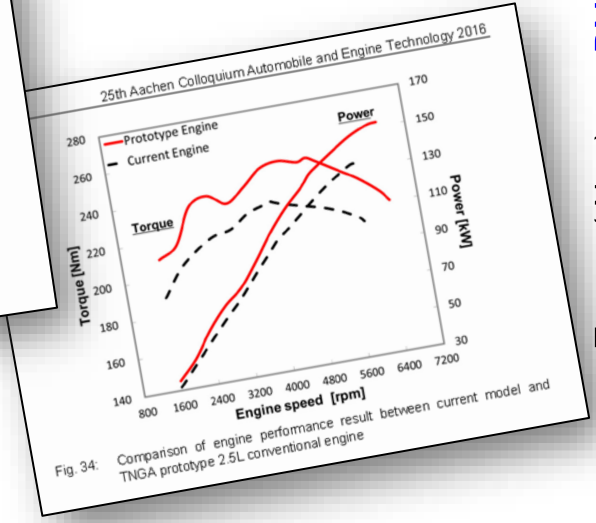
based on Toyota published data

Prototype TNGA 2.5L conventional engine

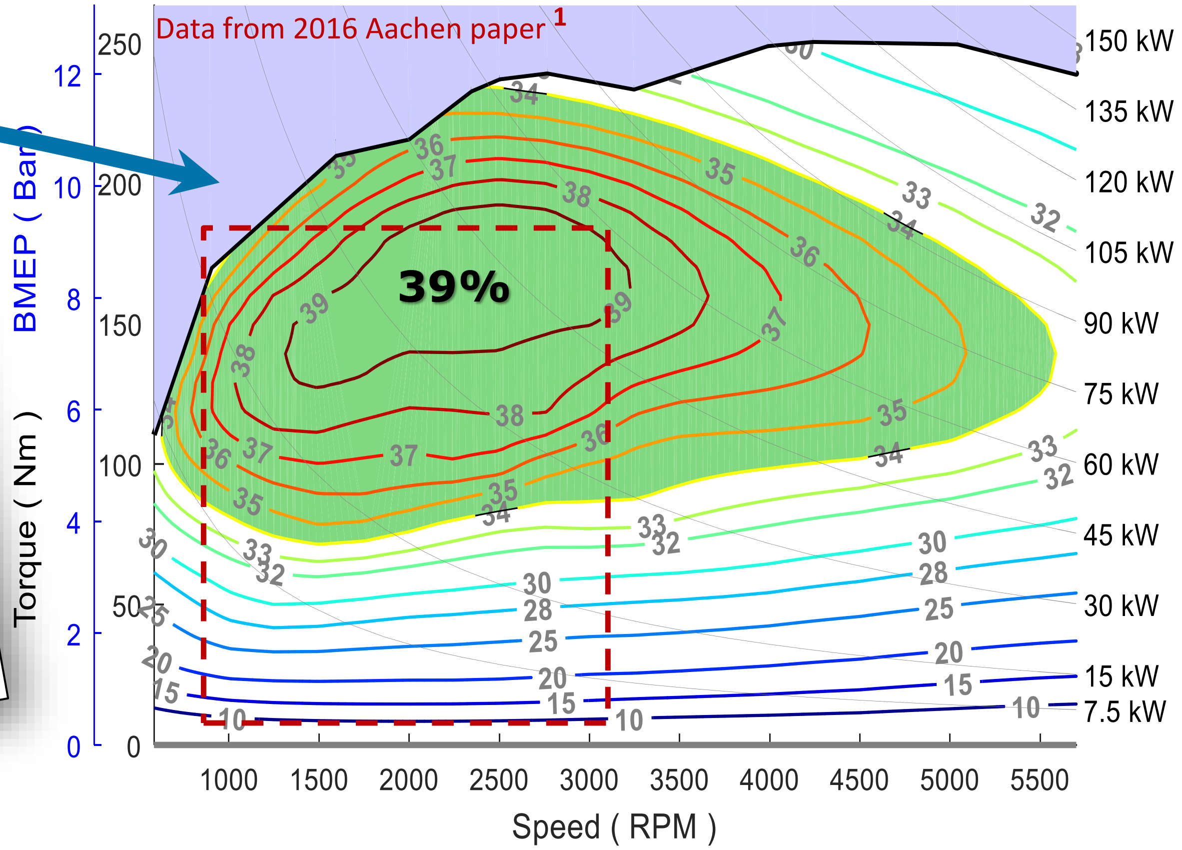
Toyota's data from 2016 Aachen paper[1]



Converted using techniques described in SAE 2018-01-1412 [2,3]



Prototype Toyota 2.5L TNGA Engine



1 Data from Toyota's 2016 Aachen paper:

Innovative Gasoline Combustion Concepts for Toyota New Global Architecture, Eiji Murase, Rio Shimizu, Toyota Motor Corporation.

2 *CITATION:* ***Paul Dekraker, Daniel Barba, Andrew Moskalik, Karla Butters, "Constructing Engine Maps for Full Vehicle Simulation Modeling ," SAE Technical Paper 2018-01-1412, 2018, doi:10.4271/2018-01-1412.***

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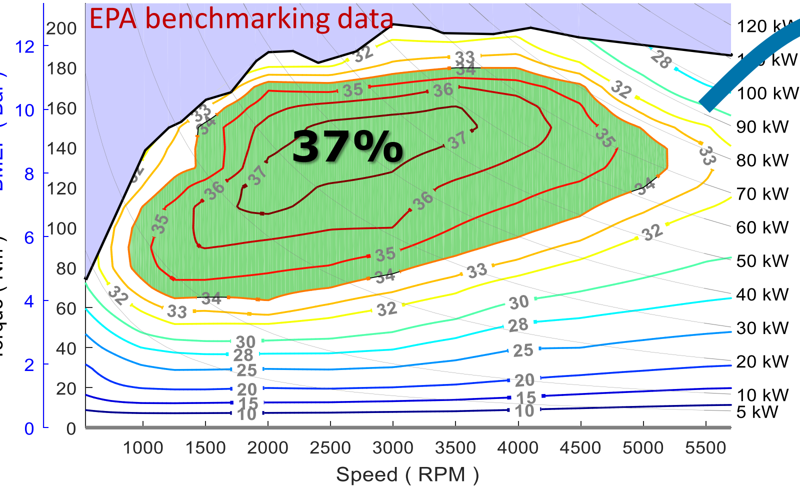
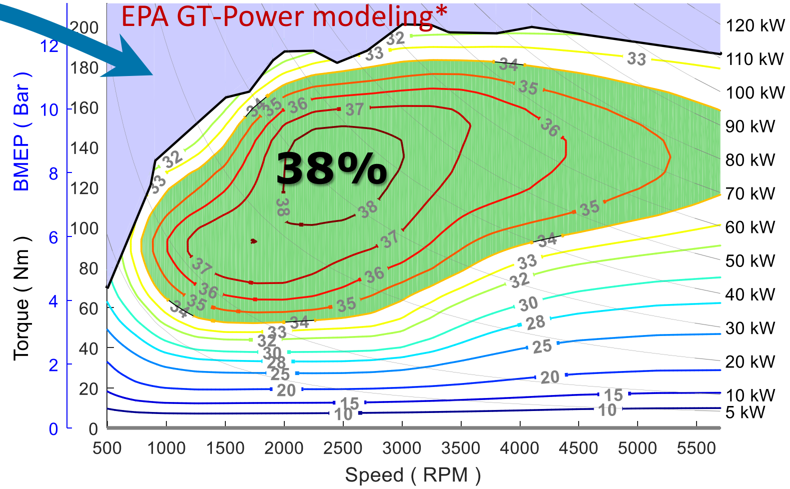
EPA's GT Power Future Atkinson Engine (Atkinson w/cooled EGR) VS. Toyota's Prototype TNGA 2.5L Future Atkinson Engine (Atkinson w/cooled EGR)

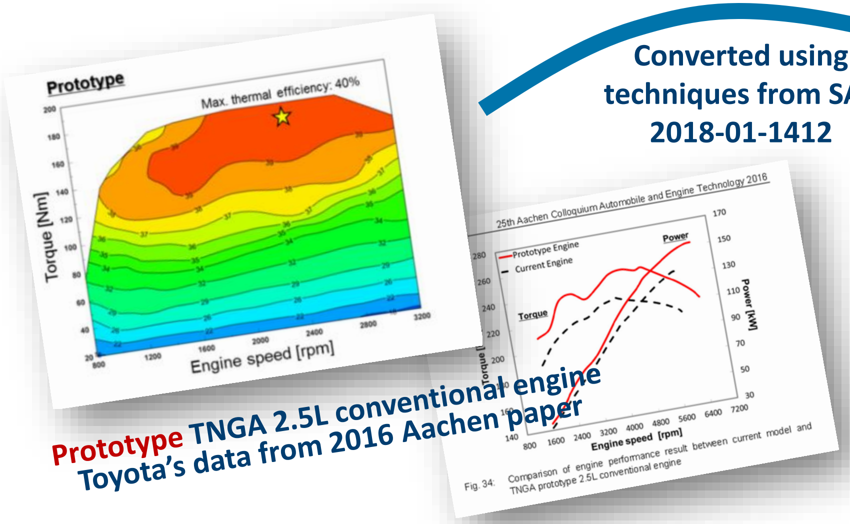
2014 Mazda Skyactiv-G 2.0L Engine Tier 2 Fuel



Future Atkinson Concept Engine with cEGR

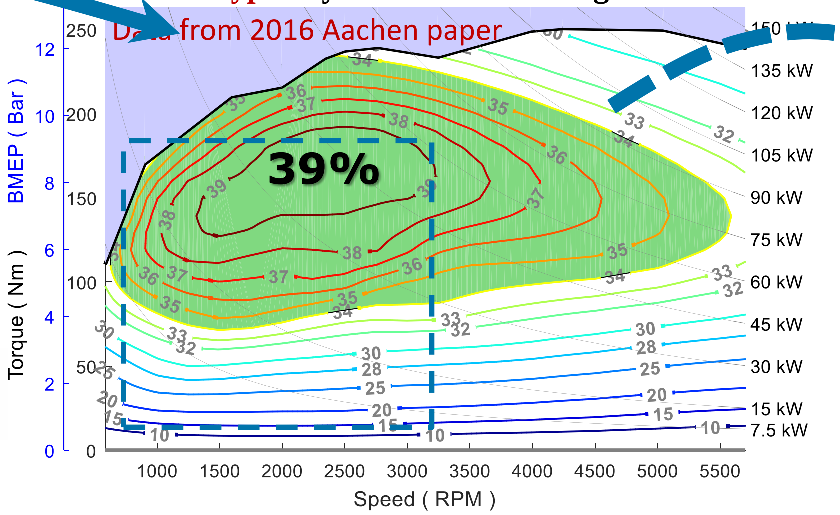


* *CITATION: Lee, S., Schenk, C., and McDonald, J., "Air Flow Optimization and Calibration in High-Compression-Ratio Naturally Aspirated SI Engines with Cooled-EGR," SAE Technical Paper 2016-01-0565, 2016, doi:10.4271/2016-01-0565.*



Converted using techniques from SAE 2018-01-1412

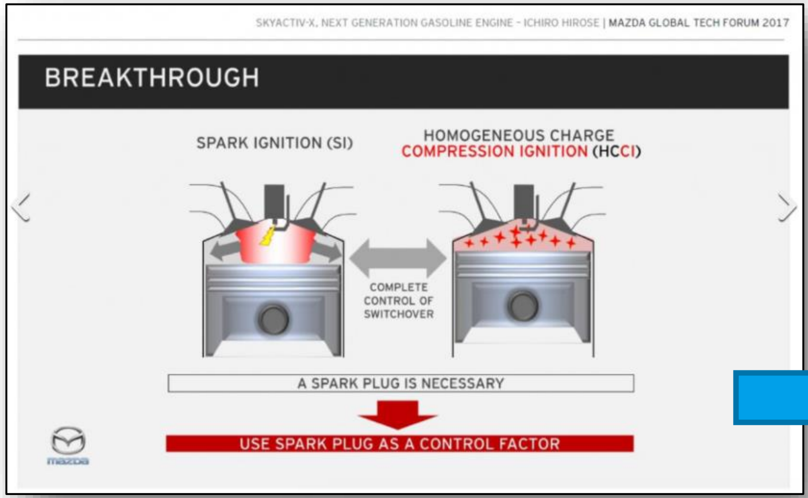
Prototype Toyota 2.5L TNGA Engine



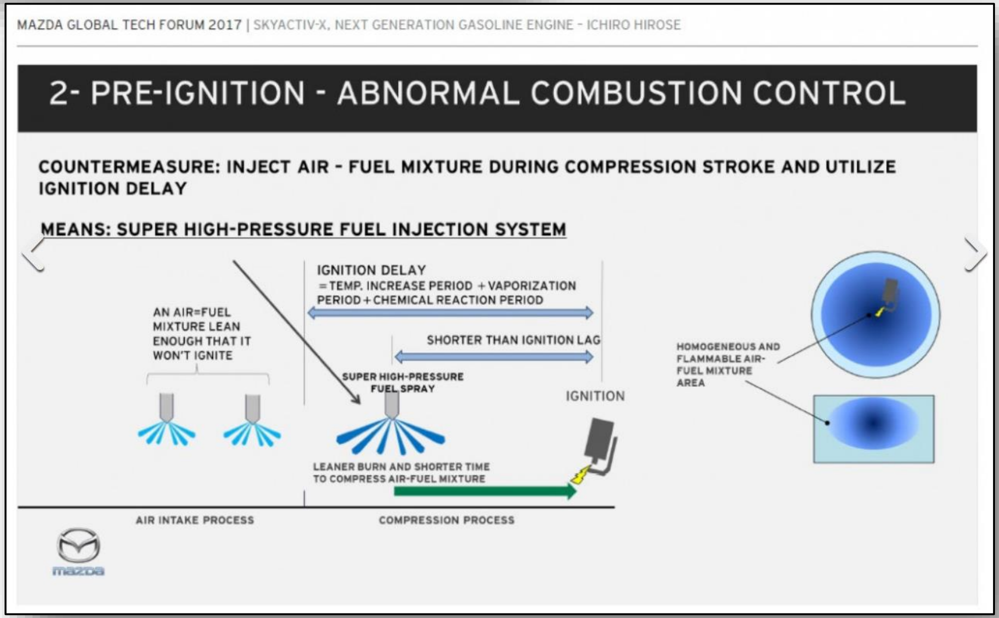
EPA Benchmarking is Underway!

Example 4: Projection of Skyactiv-X 2.0L Engine

Summary of New Mazda SPCCI - Spark Controlled Compression Ignition



As Mazda explained at their 2017 Global Tech Forum*, a breakthrough was needed to enable compression ignition gasoline engines

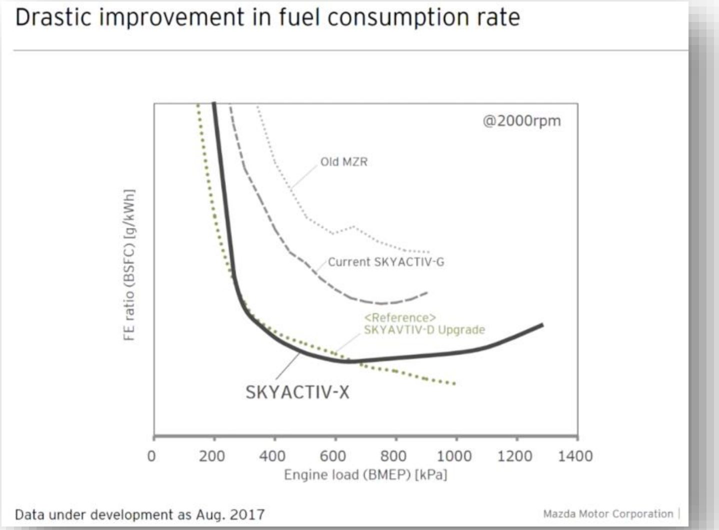


How it Works:

- Lean premixture injected during intake stroke that won't ignite
- 2nd high pressure injection during compression stroke to create a combustible mixture near spark plug
- Spark initiates combustion
- Expanding fireball creates final push to cause the whole mixture to combust

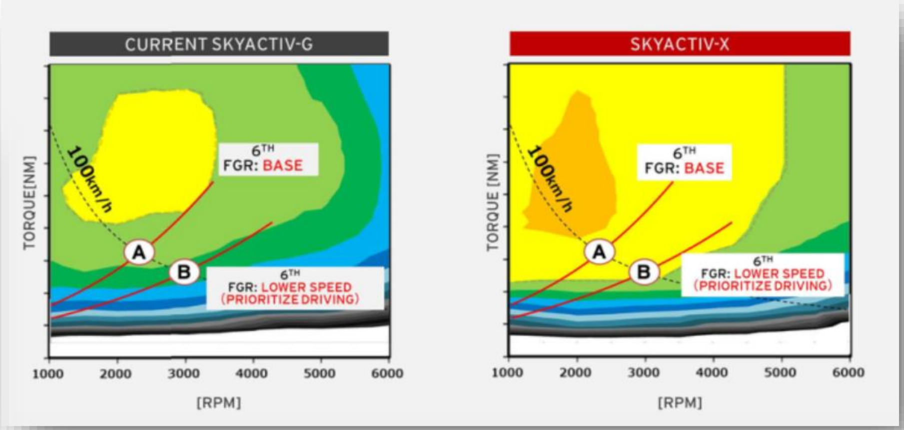
*https://www.greencarreports.com/news/1112524_mazdas-skyactiv-x-diesel-fuel-economy-from-gasoline-engine/page-2

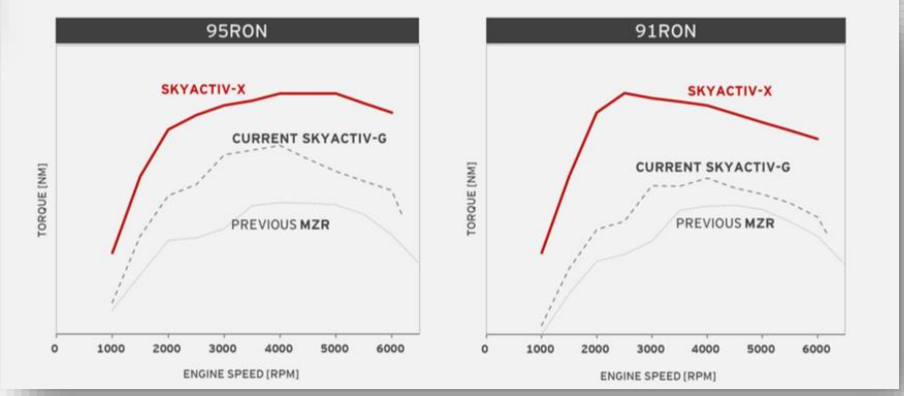
Example 4: Projection of Skyactiv-X 2.0L Engine based on Mazda published Information (gasoline spark controlled compression ignition)



Mazda images published in:
MAZDA Next-generation Technology – PRESS INFORMATION, October 2017

Mazda announced new Skyactiv-X engine
(SPCCI -Spark Control Combustion Ignition)

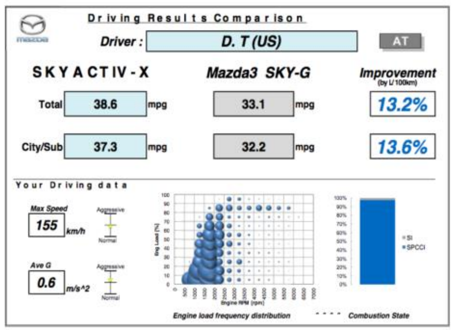


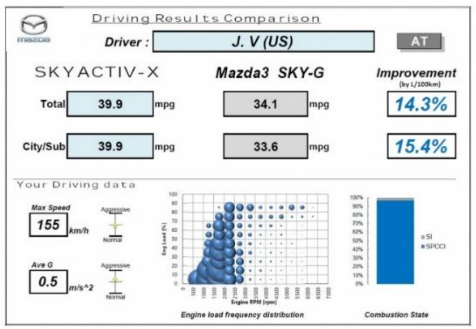


Mazda's press release: *"SKYACTIV-X delivers a 20 percent improvement in fuel economy compared to the SKYACTIV-G"*

https://jalopnik.com/i-drove-mazda-s-holy-grail-of-gasoline-engines-and-it-w-1800874806

https://www.greencarreports.com/news/1112524_mazdas-skyactiv-x-diesel-fuel-economy-from-gasoline-engine/page-2





Real-world driving done by automotive press using Mazda's dataloggers on their demo vehicle.

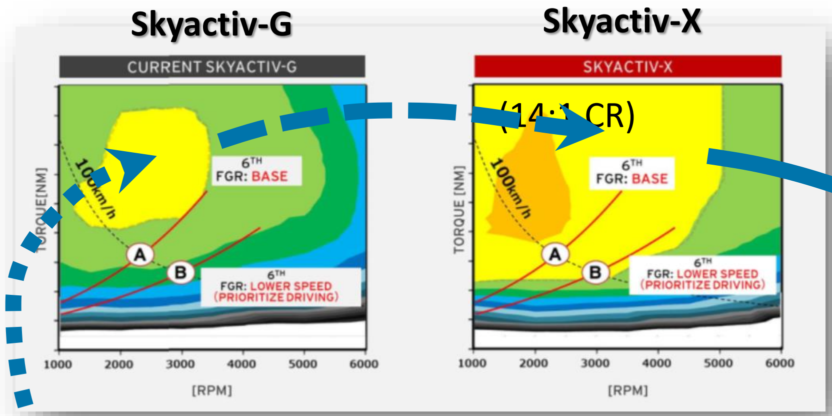
Mazda's press release: *"With an engine displacement of 2.0L, the SKYACTIV-X delivers at least 10 percent more torque than the current SKYACTIV-G, and up to 30 percent more at certain rpms"*

Suggested Reading / Sources

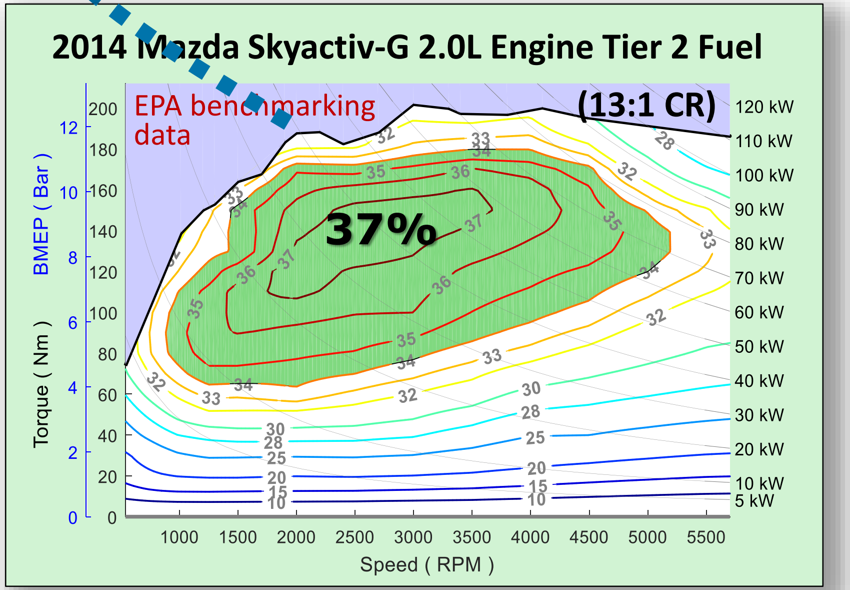
1. **MAZDA Next-generation Technology - PRESS INFORMATION**, October 2017, https://1ijylmozio83m2nkr2v293mp-wpengine.netdna-ssl.com/wp-content/uploads/2017/10/02_ENG_Mazda_Next_Generation_Technology_Press_Information.pdf
2. **Briefing on Mazda's Long-Term Vision for Technology Development -Technical Overview of SKYACTIV-X**, Kiyoshi Fujiwara, https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=3&cad=rja&uact=8&ved=0ahUKEwjRk9jqu6HaAhUuTd8KHc4gCOIQFgg4MAI&url=http%3A%2F%2Fwww.autopareri.com%2Fapplications%2Fcore%2Finterface%2Ffile%2Fattachment.php%3Fid%3D17652&usg=AOvVaw26JAUTbUZBDs_lP8NW0vZw
3. **Mazda Global Tech Forum 2017,** https://www.mazda-press.com/ch-de/news/mazda-global-tech-forum-2017/
4. **Mazda's Skyactiv-X: diesel fuel economy from gasoline engine - Page 2, Green Car Reports**, https://www.greencarreports.com/news/1112524_mazdas-skyactiv-x-diesel-fuel-economy-from-gasoline-engine/page-2
5. **Mazda's 'Holy Grail' Of Gasoline Engines Is Completely Fascinating**, David Tracy, 9/07/17, https://jalopnik.com/mazda-s-holy-grail-of-gasoline-engines-is-completely-1801820285
6. **I Drove Mazda's Holy Grail Of Gasoline Engines And It Was Incredibly Impressive**, David Tracy, 9/07/17, https://jalopnik.com/i-drove-mazda-s-holy-grail-of-gasoline-engines-and-it-w-1800874806

Example 4: Projection of Skyactiv-X 2.0L engine

Apply the Skyactiv-G Contour Values to Mazda's Skyactiv-X Contours



Mazda images published in: *MAZDA Next-generation Technology – PRESS INFORMATION, October 2017*

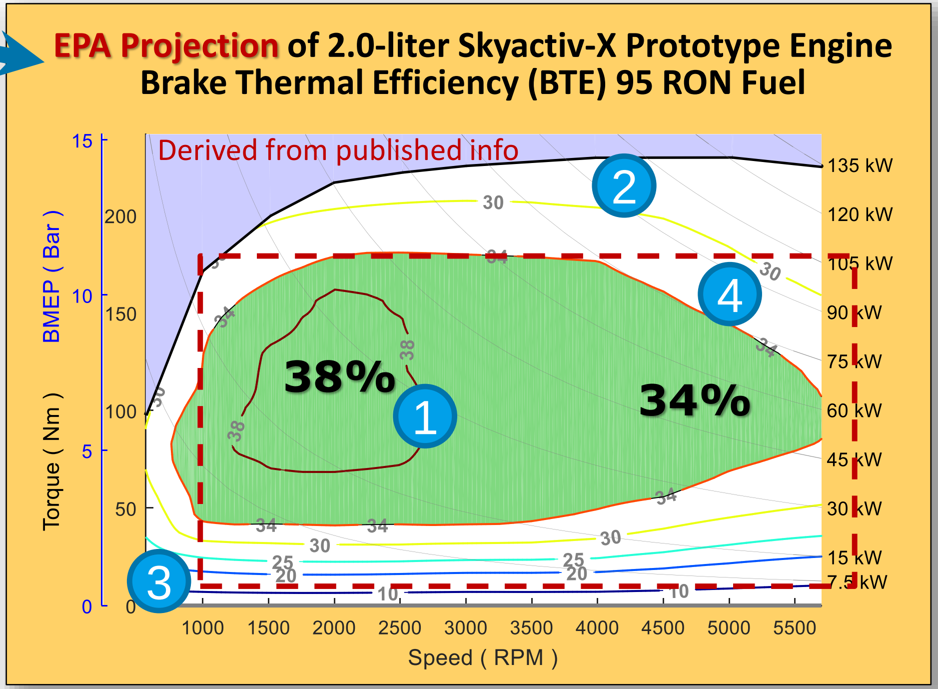


EPA Projection of Mazda's newly announced Skyactiv-X engine

(SPCCI -Spark Controlled Compression Ignition)

Assumptions

1. Contours based on Mazda's contour resolution and EPA's benchmarking data on the Skyactiv-G engine.
2. WOT curve based on Mazda's shape of its 95 RON torque curve and stated goal of 230 Nm peak torque and 139 kW peak power.
3. Engine idle assumed to be the same as Skyactiv-G engine.
4. Added fuel consumption for enrichment.



Example 4: Initial Projection of Skyactiv-X 2.0L Engine

Comparison of Reduced Fuel Consumption from Test Drives v. Initial ALPHA Estimate

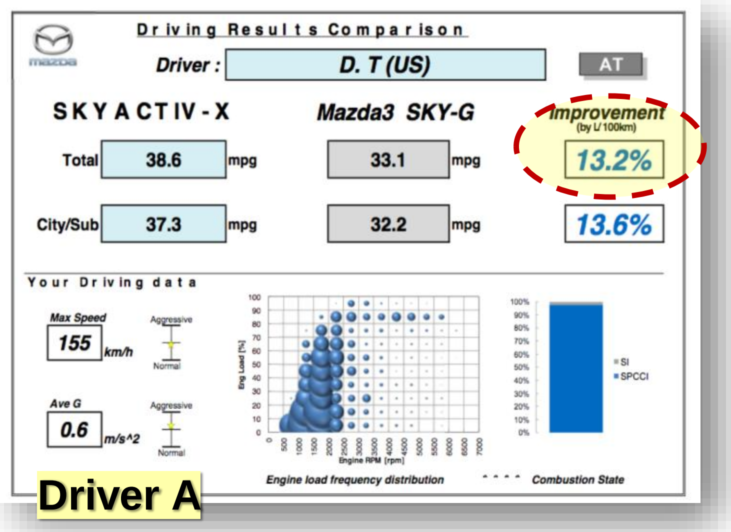
Initial ALPHA Estimate

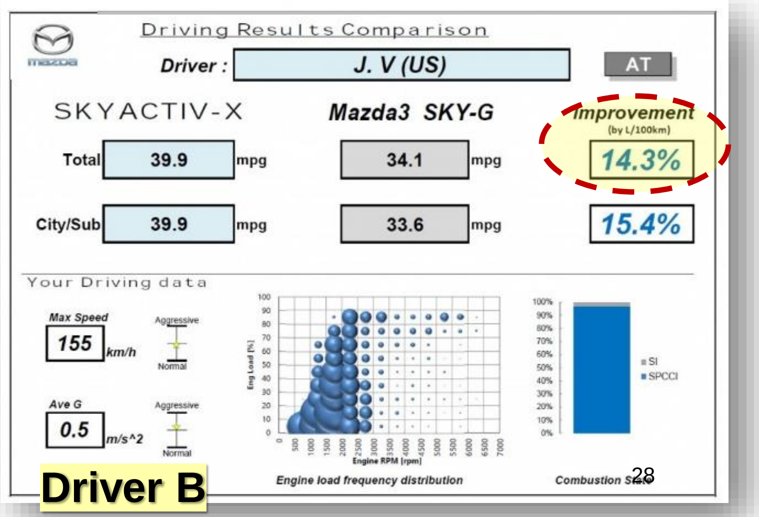
Engine	Perf Neutral Sized Displacement (liters)	Combined Cycle Engine Efficiency (%)	Combined Cycle CO_2 (gCO_2/mi)	Improved Efficiency [CO_2 Reduction] (%)
	2016 Mid-sized Car			
2014 Mazda Skyactiv-G 2.0L Engine	2.5	20.7	237.1	0.0%
2019 Skyactiv-X 2.0L SPCCI Engine[5]	2.1	23.6	207.6	12.5%

**using data from ALPHA using Mazda's published information*

The 12.5% efficiency improvement in ALPHA results compare reasonably with real-world driving results in the automotive press test drives (13%-14%).

- This is just an initial estimate to gain a sense of the potential impact of this technology. *Since the technology is not yet in the market place, it is too early to project if Skyactiv-X technology could be widely used in the industry and in what time frame.*
- EPA plans to confirm this estimate with vehicle and engine benchmarking data as soon as the vehicle becomes available.





Test Drive Notes:

- It appears that the test drive involved a comparison to a European Skyactiv-G (14:1 CR), probably operating on European premium fuel.
- Some of the drive cycle was standard traffic around suburban Frankfurt, Germany, including low-speed residential and town stop-and-go, but they also spent a few miles at up to 160 km/h (100 mph) during two short Autobahn stints.*

**Mazda's Skyactiv-X: diesel fuel economy from gasoline engine - Page 2, Green Car Reports*

Example 5: Projection of Adding Cylinder Deactivation to Current and Future Engines

Adding Full Continuous Cylinder Deactivation (deacFC)

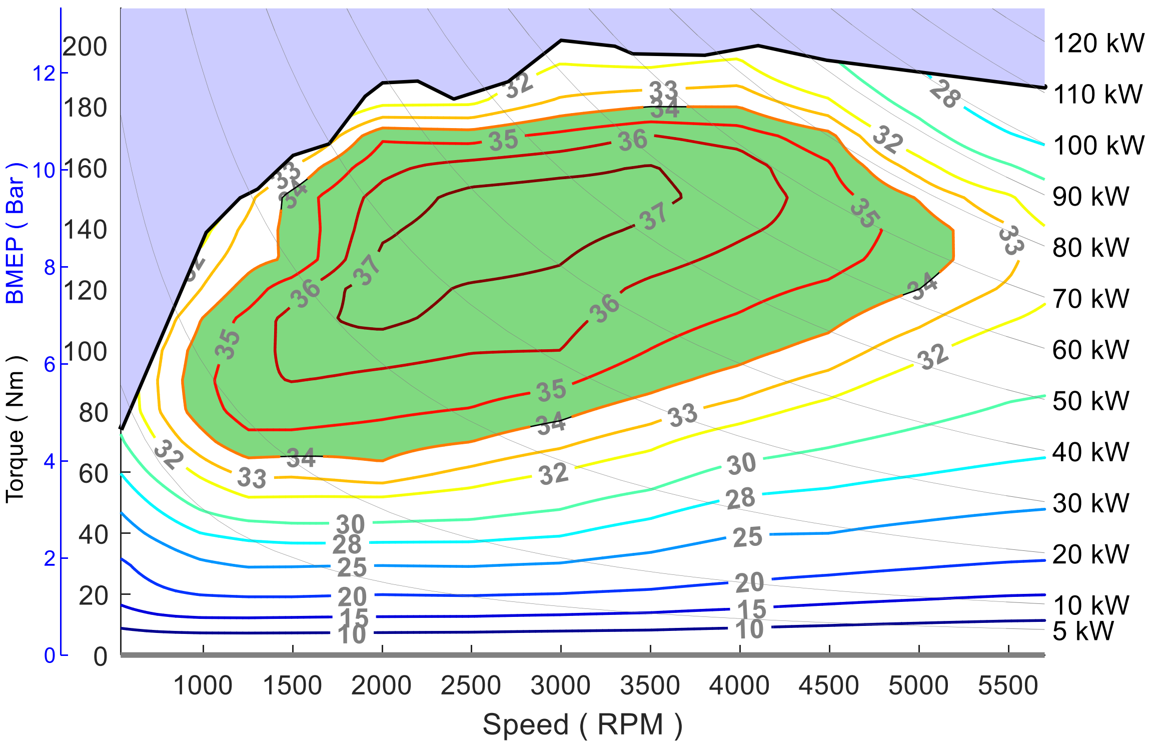
- Full Continuous Cylinder Deactivation (**deacFC***) allows any of the cylinders to be deactivated, and the number of deactivated cylinders can be varied in a continuous fashion.
  This is an advanced form of cylinder deactivation that involves all cylinders (e.g, all 8 cylinders in V8) rather than a fixed subset (e.g., only 4 specific cylinders in a V8).
- **deacFC** engine can be run on a non-integer number of cylinders (e.g., 2.5 cylinders) by varying number and pattern of firing cylinders from cycle to cycle.
- **deacFC** can command complete cylinder cutout during decelerations, cutting both fuel and air to the engine, reducing aftertreatment cooling and vehicle deceleration.
- ***Tula Technology*** developed an implementation of **deacFC** called *Dynamic Skip Fire (DSF)* and applied it to V8 and I4 engines.

*Bohac, S. V., 2018 "Benchmarking and Characterization of a Full Continuous Cylinder Deactivation System," Oral Only, SAE World Congress, Detroit, MI, April 10-12, 2018. Presentation to be made available following SAE World Congress at: *https://www.epa.gov/regulations-emissions-vehicles-and-engines/midterm-evaluation-light-duty-vehicle-greenhouse-gas*

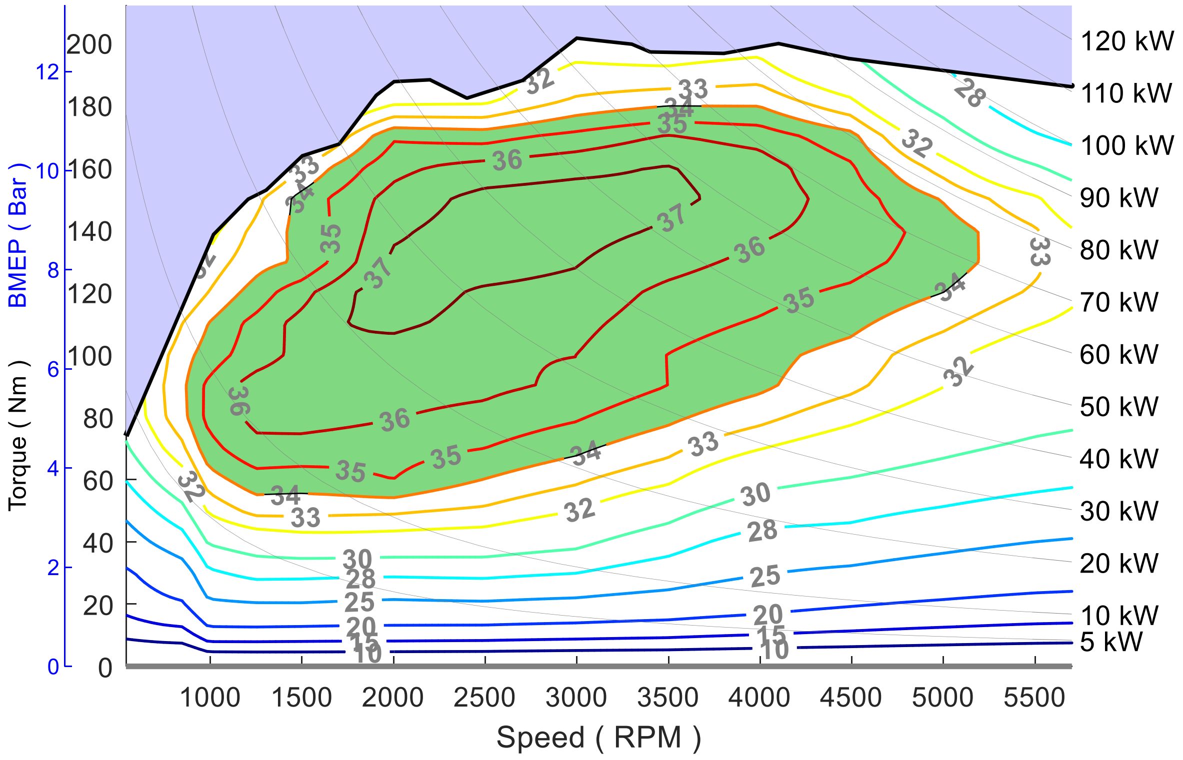
Example 5: Projection of Adding Cylinder Deactivation to Current and Future Engines

Adding deacFC to Skyactiv-G 2.0L Engine

2014 Mazda Skyactiv-G 2.0L Engine Tier 2 Fuel



2014 Mazda Skyactiv-G 2.0L Engine with deacFC Tier 2 Fuel



EPA's program to Study the Efficiency Potential of Future Gasoline Engines

TOPICS

1. **Assessing Current Production Engines**
   a) Develop benchmarking methods that yield good understanding of engine operation.
   b) Generate consistent fuel maps to appropriately compare engines.
   c) Use vehicle simulation (ALPHA) to assess vehicle fuel consumption.

2. **Assessing Potential Future Engines**
   a) What engine technologies are still on the table?
   b) What might future engine maps look like?
   c) Use vehicle simulation (ALPHA) to assess vehicle fuel consumption.

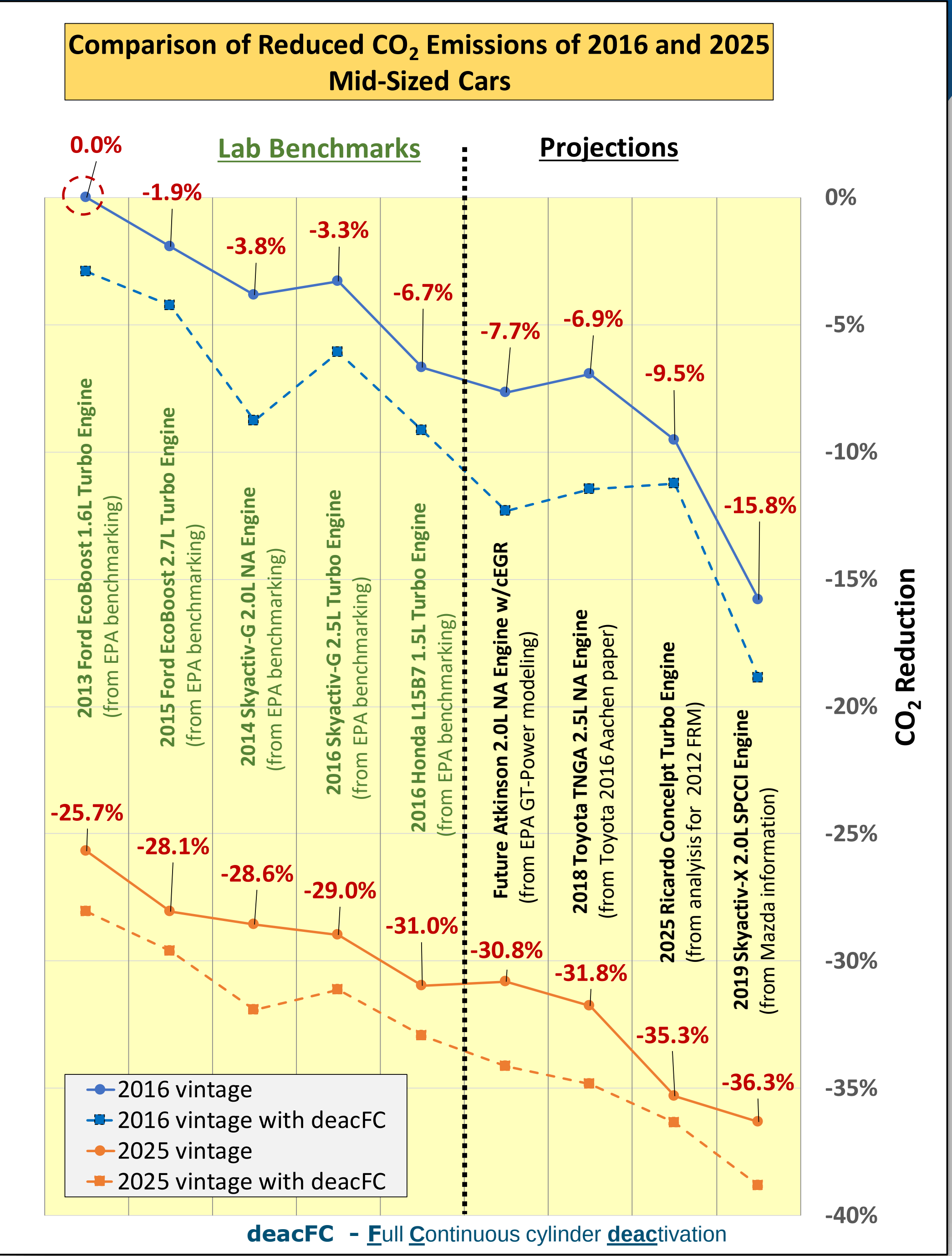
Using ALPHA to Compare Engine Maps in a Mid-sized Car

ALPHA vehicle simulations of current and potential future engines*

Mid-Sized Car Engine	Perf Neutral Sized Displacement (liters)	Combined Cycle Engine Efficiency (%)	Combined Cycle CO_2 (gCO_2/mi)	Improved Efficiency [CO_2 Reduction] (%)	Perf Neutral Sized Displacement (liters)	Combined Cycle Engine Efficiency (%)	Combined Cycle CO_2 (gCO_2/mi)	Improved Efficiency [CO_2 Reduction] (%)
	2016				2025			
2013 Ford EcoBoost 1.6L Turbo Engine[1]	1.7	19.8	246.6	0.0%	1.5	23.8	183.2	-25.7%
2015 Ford EcoBoost 2.7L Turbo Engine	1.5	20.2	241.9	-1.9%	1.3	24.5	177.4	-28.1%
2014 Mazda Skyactiv-G 2.0L NA Engine	2.5	20.7	237.1	-3.8%	2.1	24.7	176.2	-28.6%
2016 Skyactiv-G 2.5L Turbo Engine	1.7	20.5	238.4	-3.3%	1.5	24.8	175.1	-29.0%
2016 Honda L15B7 1.5L Turbo Engine	1.7	21.3	230.1	-6.7%	1.4	25.6	170.2	-31.0%
Future Atkinson Engine w/cEGR[2]	2.5	21.5	227.7	-7.7%	2.1	25.5	170.6	-30.8%
2018 Toyota TNGA 2.5L N/A Engine[3]	2.4	21.4	229.5	-6.9%	2.0	25.9	168.2	-31.8%
2025 Ricardo Concept Turbo Engine[4]	1.5	21.9	223.0	-9.5%	1.2	27.3	159.5	-35.3%
2019 Skyactiv-X 2.0L SPCCI Engine[5]	2.1	23.6	207.6	-15.8%	1.8	27.8	157.0	-36.3%

1- baseline 2- from EPA GT-Power model 3- from Toyota 2016 Aachen paper
4- from Ricardo for EPA's 2012 FRM 5- from Mazda published information

*refer to SAE paper 2018-01-0319 for roadload values.



Using ALPHA to Compare Engine Maps in Sport Utility Vehicles (SUVs)

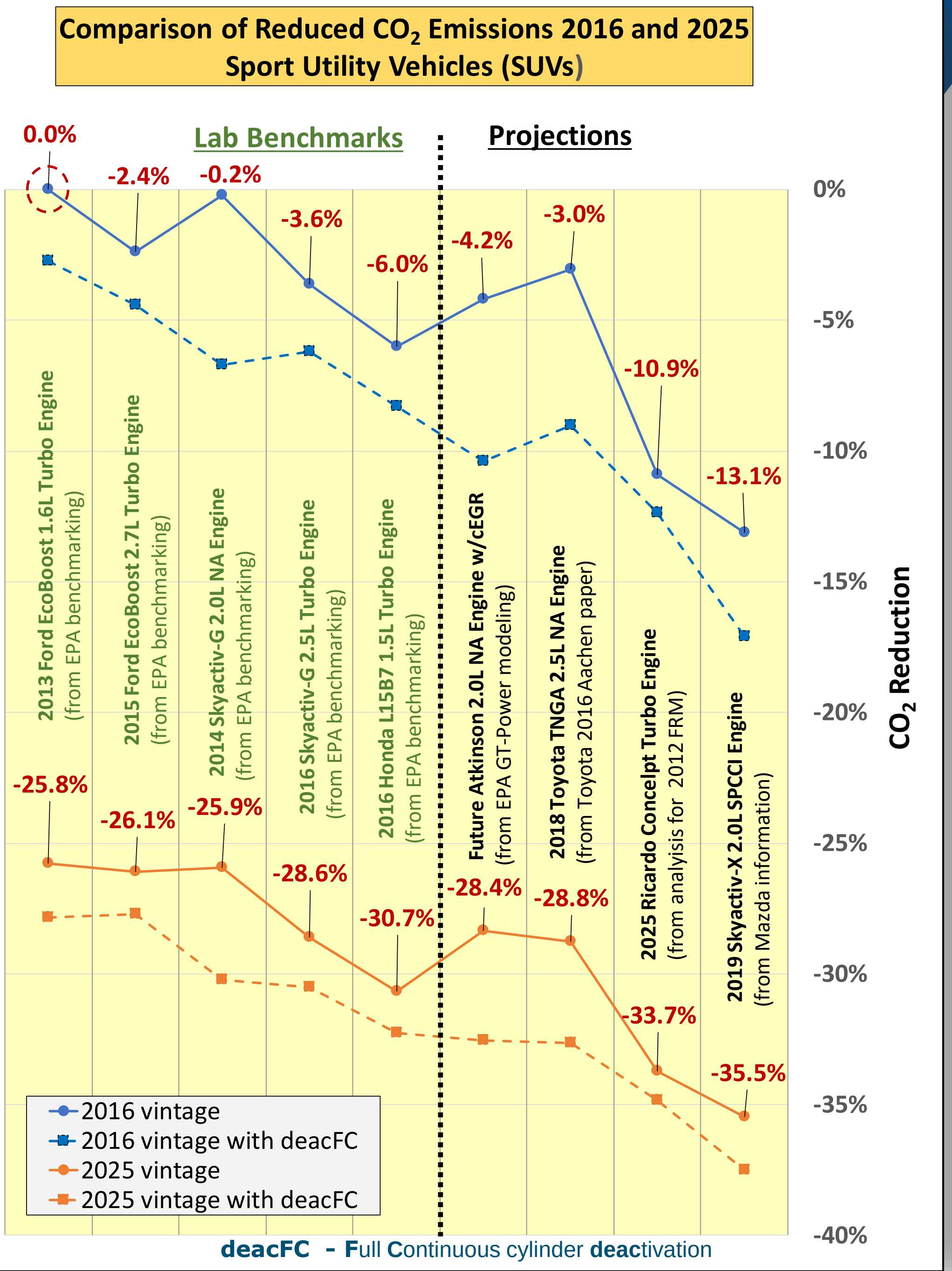
ALPHA vehicle simulations of current and potential future engines*

Sport Utility Vehicle

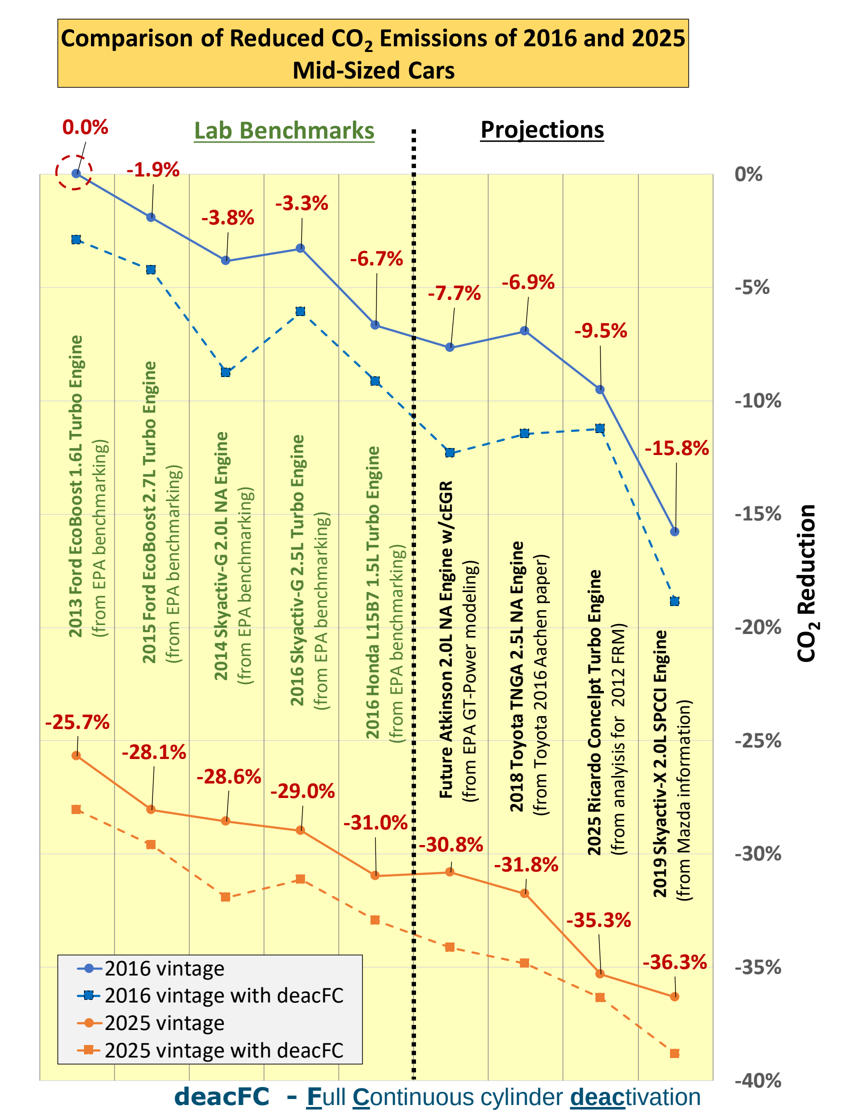
Engine	2016 Perf Neutral Sized Displacement (liters)	2016 Combined Cycle Engine Efficiency (%)	2016 Combined Cycle CO_2 (gCO_2/mi)	2016 Improved Efficiency [CO_2 Reduction] (%)	2025 Perf Neutral Sized Displacement (liters)	2025 Combined Cycle Engine Efficiency (%)	2025 Combined Cycle CO_2 (gCO_2/mi)	2025 Improved Efficiency [CO_2 Reduction] (%)
2013 Ford EcoBoost 1.6L Turbo Engine[1]	2.3	20.8	318.4	0.0%	2.0	25.1	236.3	-25.8%
2015 Ford EcoBoost 2.7L Turbo Engine	2.0	21.3	310.9	-2.4%	1.7	25.2	235.4	-26.1%
2014 Mazda Skyactiv-G 2.0L NA Engine	3.4	20.9	317.7	-0.2%	2.8	25.1	235.9	-25.9%
2016 Skyactiv-G 2.5L Turbo Engine	2.4	21.6	306.9	-3.6%	2.0	26.1	227.3	-28.6%
2016 Honda L15B7 1.5L Turbo Engine	2.3	22.1	299.3	-6.0%	1.9	26.8	220.8	-30.7%
Future Atkinson Engine w/cEGR[2]	3.4	21.7	305.1	-4.2%	2.8	26.0	228.2	-28.4%
2018 Toyota TNGA 2.5L N/A Engine[3]	3.3	21.5	308.8	-3.0%	2.7	26.1	226.8	-28.8%
2025 Ricardo Concept Turbo Engine[4]	1.9	23.3	283.8	-10.9%	1.6	28.1	211.1	-33.7%
2019 Skyactiv-X 2.0L SPCCI Engine[5]	2.8	24.0	276.7	-13.1%	2.3	28.9	205.5	-35.5%

1- baseline 2- from EPA GT-Power model 3- from Toyota 2016 Aachen paper
4- from Ricardo for EPA's 2012 FRM 5- from Mazda published information

*refer to SAE paper 2018-01-0319 for roadload values.



Using ALPHA to compare engine maps



Engine
2013 Ford EcoBoost 1.6L Turbo Engine[1]
2015 Ford EcoBoost 2.7L Turbo Engine
2014 Mazda Skyactiv-G 2.0L NA Engine
2016 Skyactiv-G 2.5L Turbo Engine
2016 Honda L15B7 1.5L Turbo Engine
Future Atkinson Engine w/cEGR[2]
2018 Toyota TNGA 2.5L N/A Engine[3]
2025 Ricardo Concept Turbo Engine[4]
2019 Skyactiv-X 2.0L SPCCI Engine[5]

Effect on CO_2 Depends on Factors

- Engine size v. vehicle loading
- Implementation & architecture (e.g., I4, V6 etc.)
- Implementation of strategies (e.g., cylinder deacFC fly zone)
- Other elements in powertrain (e.g., where transmission allows engine to operate)