Light-Duty Vehicle
Powertrain Benchmarking and Technology Effectiveness Assessments

National Vehicle and Fuel Emissions Lab
Office of Transportation and Air Quality – Ann Arbor, MI

Dan Barba, Director
National Center of Advanced Technology (NCAT)

Presented to NAS-NRC
on June 16, 2020

Topics

1. **NVFEL Background**
2. **Benchmarking & Technology Assessments**
   - **A. Conventional technology benchmarking**
     - Overview of Conventional Powertrain Benchmarking
     - Review of EPA's ICE benchmarking and analysis
     - Current benchmarking of cylinder deactivation engines
     - Highlights of new ICE's announced at Vienna Motor Symposium
     - Transmissions
     - Acceleration Performance, Fuel Consumption, and Engine Scaling
     - Key take-aways
   - **B. Electrified technology benchmarking**
     - 2017 Chevy Bolt vehicle & e-motor/battery components
     - Effect of temperature on EV range
     - 2018 Jeep Wrangler 48-volt BISG hybrid component
     - Key take-aways
3. **Other Emerging Work**
   - Development of test methods for Connected Automated Vehicles
   - Expansion of In-Use Testing and Data Analysis
4. **Responses to Specific NAS Questions**

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EPA's Advanced Technology Testing and Demonstration

NVFEL's National Center for Advanced Technology

NVFEL Background

EPA's National Vehicle and Fuel Emissions Laboratory
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)**

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Publicly Available Data Packets Released on EPA Website*

Available Benchmarking Data

Engine Test Data Packets

2018 Toyota 2.5L A25A-FKS Engine Tier 2 & Tier 3 Fuels
2016 Mazda 2.5L Turbo Skyactiv-G Tier 2 & Tier 3 Fuels
2016 Honda 1.5L L15B7 Engine Tier 2 & Tier 3 Fuels
2013 Ford 1.6L EcoBoost Engine Tier 2 & LEV III Fuels
2014 Chev. 4.3L EcoTec LV3 Engine Tier 2 & LEV III Fuels
2015 BMW 3.0L N57 Engine Diesel Fuel
2013 Chevrolet 2.5L Ecotec LCV Engine Reg E10 Fuel
2014 Mazda 2.0L Skyactiv Engine Tier 2 & LEV III Fuels
2015 Ford F150 2.7L Tier 2 Fuel

Transmission Test Data Packets

2018 Toyota Camry 8-speed Transmission (in process)
2014 GM 6L80 Transmission
2013 Chevrolet Malibu 6T40 Transmission
2014 Ram 1500 HFE 845RE Transmission
2013 Nissan Jatco CVT8 Transmission

Vehicle Test Data Packets

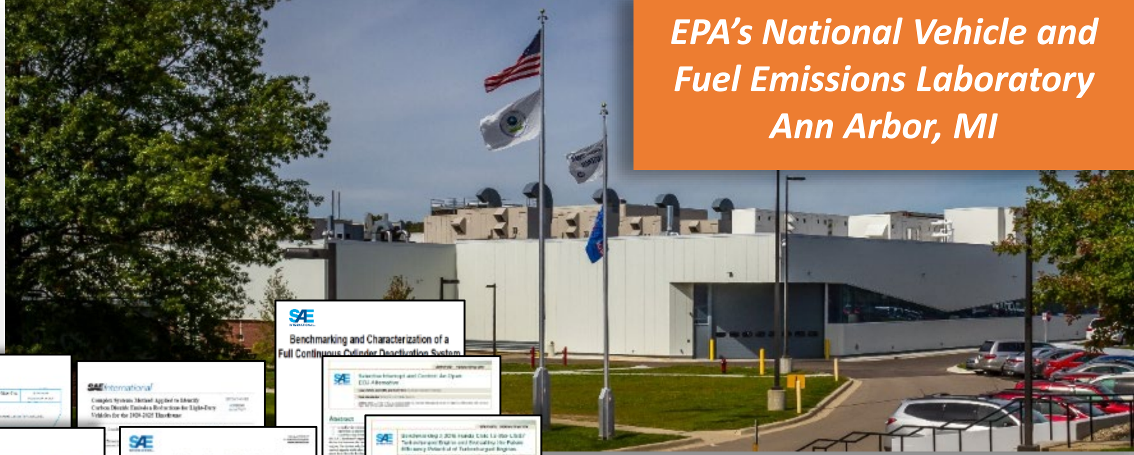
2018 Toyota Camry 2.5L Engine Tier 2 & 3 Fuels
2014 Dodge Charger 3.6L Tier 2 Fuel
2013 Chevrolet Malibu 1LS Tier 2 & 3 Fuels
2013 Mercedes E350 BlueTEC Diesel Fuel

***Note:** Additional data packets for a 2016 Honda Civic, 2016 Mazda 6, 2018 Jeep Wrangler, 2015 F-150 and 2014 Silverado with fixed cylinder deactivation are planned, as time permits.*

***Data packets are available at:**

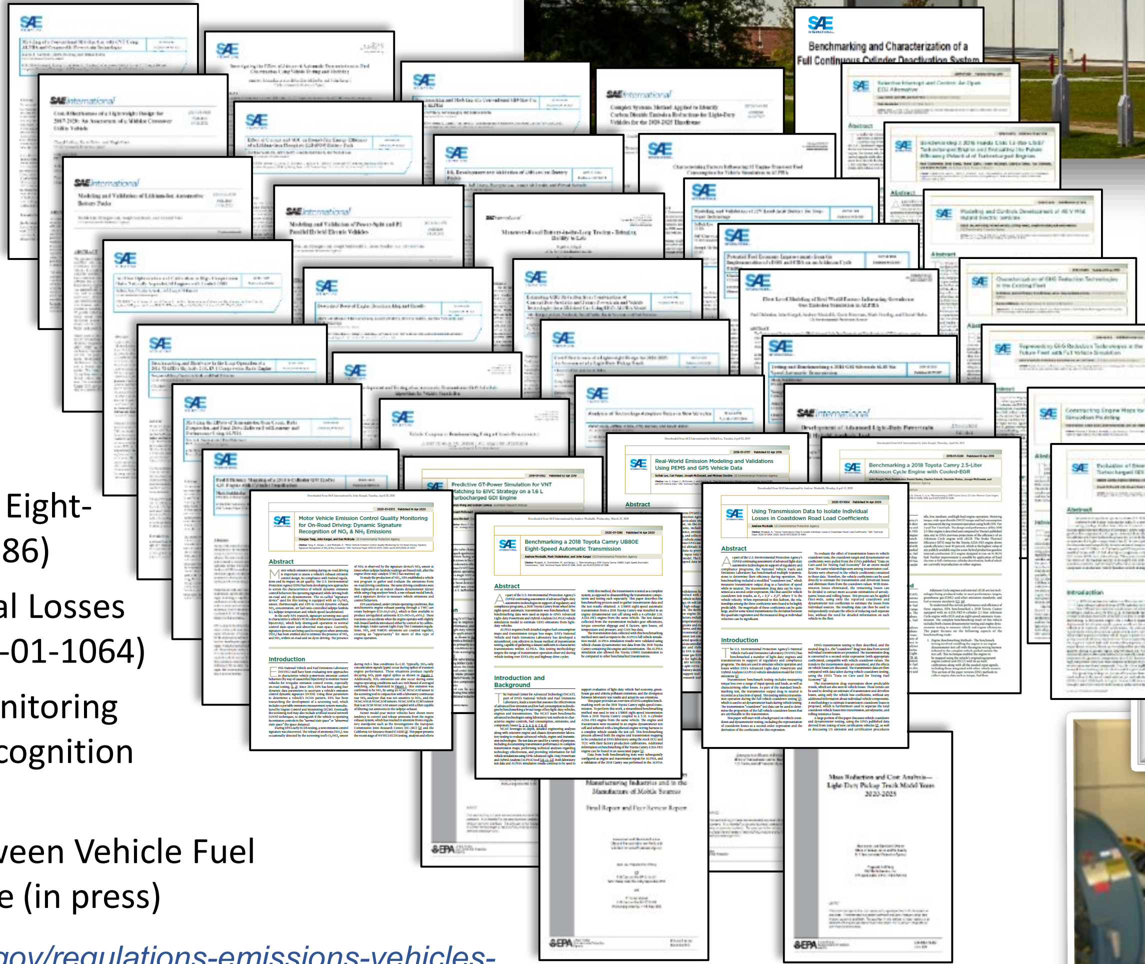
- https://www.epa.gov/vehicle-and-fuel-emissions-testing/benchmarking-advanced-low-emission-light-duty-vehicle-technology
- https://www.epa.gov/vehicle-and-fuel-emissions-testing/combining-data-complete-engine-alpha-maps

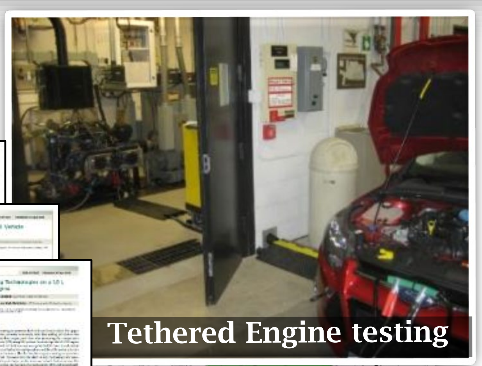
EPA Technical Information Available to All Stakeholders and the Public

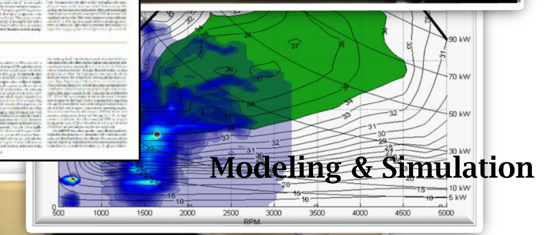


Wide range of presentations & peer-reviewed publications:

- Conference presentations
- Modeling workshop
- Technical papers*, including SAE papers (38) and reports
- 4 more new papers in 2020
  - ✓ Benchmarking a 2018 Toyota Camry UB80E Eight-Speed Automatic Transmission (2020-01-1286)
  - ✓ Using Transmission Data to Isolate Individual Losses in Coastdown Road Load Coefficients (2020-01-1064)
  - ✓ Motor Vehicle Emission Control Quality Monitoring for On-Road Driving: Dynamic Signature Recognition of NOx & NH_3 Emissions (2020-01-0372)
  - ✓ Assessment of Changing Relationships Between Vehicle Fuel Consumption and Acceleration Performance (in press)







****Available at:** https://www.epa.gov/regulations-emissions-vehicles-and-engines/midterm-evaluation-light-duty-vehicle-greenhouse-gas*

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Overview of Conventional Powertrain Benchmarking

Conventional Powertrain Benchmarking

- Over the past seven years EPA has undertaken a very thorough technical assessment of conventional vehicle powertrain technologies.
- This assessment included a deep technical dive into **turbocharged engine technology** (culminating with testing of a 2016 Honda Civic L15B7 1.5-liter turbo engine technology) and **naturally aspirated engine technology** (culminating with testing of a 2018 Toyota Camry 2.5-liter A25A-FKS Atkinson-cycle engine with cooled-EGR).
- Transmission benchmarking included **continuously variable transmissions** and **automatic transmissions** (5, 6, 8 and 10 speed transmissions).
- Our benchmarking data is still largely representative of the current state-of-the-art in conventional powertrain technology, with the exception of cylinder deactivation technology.
- With the recent U.S. market launches of products with **advanced cylinder deactivation** technology (like skip-fire), we have started a couple of benchmarking programs to gather data to validate our previous ALPHA modeling assessment of the amount of additional GHG reduction benefit that could be gained with the addition of cylinder deactivation technology.
- Given our solid understanding of conventional vehicle technologies and looking ahead to coming trends in the light-duty market, EPA has shifted its primary benchmarking focus to **electrified** technologies.

Key EPA Conventional Powertrain Benchmarking and Assessments

1. Boosted Engine Technology: *Benchmarked* – 2016 Honda Civic 1.5-liter L15B7 turbocharged engine, includes estimated effect of adding full continuous cylinder deactivation (SAE 2018-01-0319)

   EPA Advanced Boosted Engine Demonstration (ongoing)

2. Atkinson Cycle Engine Technology: *Benchmarked* – 2018 Toyota Camry 2.5L A25A-FKS Atkinson engine with cooled-EGR, includes estimated effect of adding full continuous cylinder deactivation (SAE 2019-01-0249)

3. Cylinder Deactivation Benchmarking (ongoing):
   - *Current Benchmarking* – 2018 Mazda 6 2.5L engine with partial cylinder deactivation
   - *Current Benchmarking* – 2019 Chevy Silverado 5.3L engine with Dynamic Fuel Management *(Tula's Dynamic Skip Fire – full continuous cylinder deactivation)*

4. Spark Controlled Compression Ignition (SPCCI): *Analysis only* – Mazda's 2.0L SPCCI Skyactiv-X Engine with supercharger

5. European ICE Developments

Boosted Engine Technology Frontier

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

Key Takeaways

- Engine parameters and technologies have been steadily advancing since 2010
- No engine incorporates all potential technology improvements.
- Significant untapped efficiency improvement potential is still available

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														

Technology Frontier

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

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EPA Advanced Boosted Engine Demonstration

Project Plan

- Base engine is 2016 Honda L15B7 1.5L
- Add cool EGR system on hand
- Add VGT turbo purchased
- Built GT power model

Status

- Paused due to focus on EPA's Cleaner Trucks Initiative (CTI)
- Plan to resume in FY21 or FY22

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
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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				
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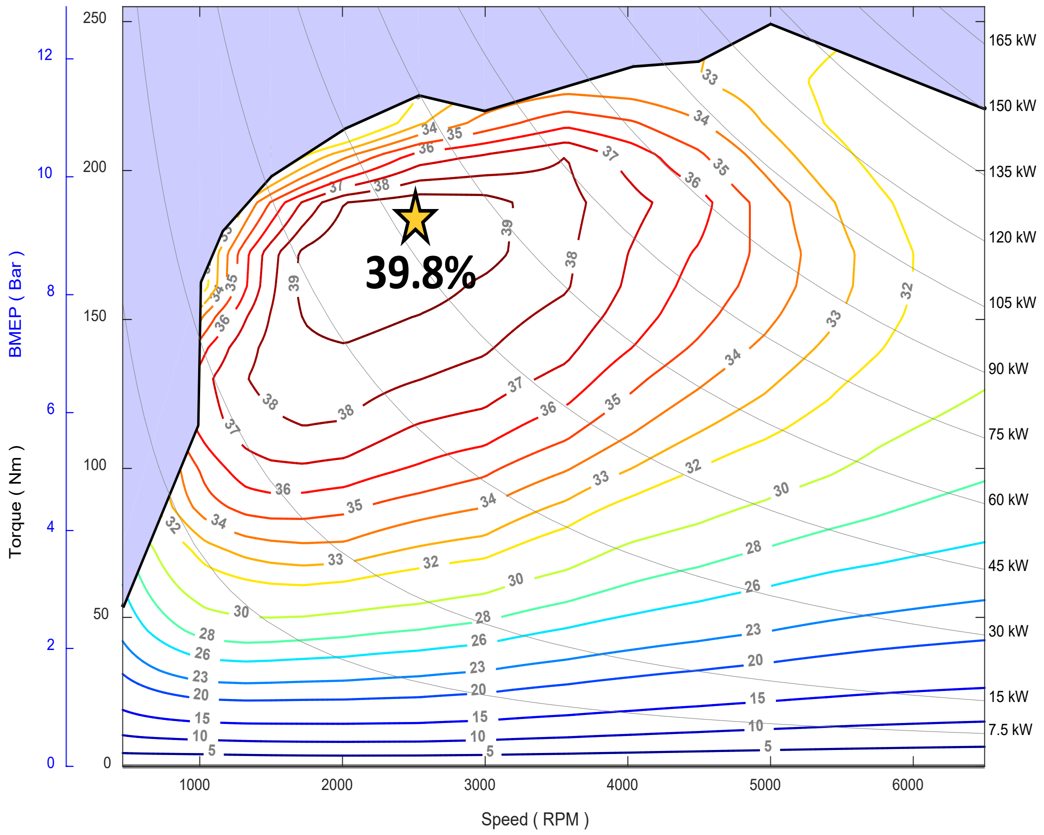
EPA Benchmarking of Toyota Atkinson-Cycle Engine with Cooled EGR

- *Benchmarked* – 2018 Toyota Camry 2.5L A25A-FKS Atkinson engine with cooled-EGR
- EPA's 2016 modeling estimate of an Atkinson cooled-EGR concept engine with was within 0.4% of Toyota's eventual 2018 production engine in a 2018 mid-sized exemplar vehicle.

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%**

2018 Toyota 2.5-liter A25A-FKS engine with cEGR



See SAE paper 2019-01-0249, "Benchmarking a 2018 Toyota Camry 2.5-Liter Atkinson Cycle Engine with Cooled-EGR")

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ALPHA Estimate of Future Mid-size Vehicle with Toyota Atkinson-Cycle Engine with Cooled EGR plus Cylinder Deactivation

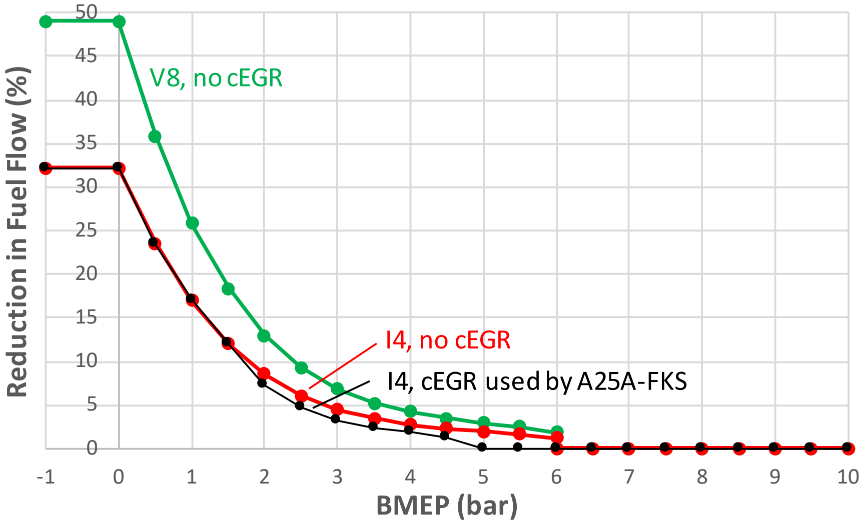
- Estimated the effect of adding full continuous cylinder deactivation technology
- ALPHA simulations of future mid-size exemplar vehicle show that the addition of cylinder deactivation would significantly improve efficiency.

Future mid-size Exemplar Vehicle (as defined in SAE paper)

Engine	Type of cylinder Deac	Sized Engine Displacement		Combined FE	Combined GHG	Delta from Mazda	Effect of Adding Cylinder Deac.
		(liters)		(mpg)	gCO2/mi	%	%
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%	

EPA's estimate of effectiveness of full continuous cylinder deactivation

(% 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)

See SAE paper 2019-01-0249, "Benchmarking a 2018 Toyota Camry 2.5-Liter Atkinson Cycle Engine with Cooled-EGR"

Benchmarking Mazda 6 2.5L Engine with Cylinder Deactivation

Progress with Chassis Testing

- Vehicle chassis testing has been completed (includes forcing “no deactivation” operation).
- Spare engine is mounted in test cell, ready for benchmarking
- SWRI to tether car to test cell engine
- Complete engine benchmarking with and without cylinder deactivation

Test Cell Configuration

- Engine’s control strategy is fixed 4-cylinder to 2-cylinder cylinder deactivation (CDA)
- We will map the speed/load map in the area where CDA is operational
- We will use valve position sensors to detect valve motion

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Benchmarking 2019 Chevy Silverado with Cylinder Deactivation

Progress with Chassis Testing

- Factory scan tool authority over Dynamic Fuel Management system (Tula "Skip fire") is more limited than that with the AFM system (fixed cylinder deactivation)
- Break-out-box will be added to monitor critical signals & possibly gain authority over the AFM system.
- Test plan includes 40 tests for Alpha model validation
  - Repeats of 6 different cycles
  - Steady states
  - Mild accel and decel tests
  - Torque converter stall test

5.3L V-8 DFM VVT DI (L84)

- ✓ Cast aluminum block and head
- ✓ CR 11.0:1
- ✓ 355 hp at 5600 rpm
- ✓ 383 ft-lb at 4100 rpm
- ✓ Direct high-pressure fuel injection with Dynamic Fuel Management

Spark-Controlled Compression Ignition (SPCCI) Technology

- EPA's initial modeling analysis* estimated a potential for a 12.5% efficiency improvement with SPCCI alone, based on Mazda's publicly available data.
- Mazda has not yet disclosed their plans for any US-based design.
- Tier 3 emission standards present a significant challenge for lean burn technology.
- EPA is still considering benchmarking the European version to better understand the technology and its applicability to the US-market.

* https://www.epa.gov/vehicle-and-fuel-emissions-testing/daniel-barba-assessing-efficiency-potential-future-gasoline

Displacement	1,998	cm^3
Compression ratio	16.3: 1	
Max. power	132 (180)/6,000	kW (PS)/rpm
Max. torque	224/3,000	Nm/rpm
Recommended fuel type	95 RON	

European Production Version

- ✓ Marketed in Europe – fall 2019
- ✓ Spark Controlled Compression Ignition (SPCCI)
- ✓ 24-volt mild-hybrid system
- ✓ Extended engine off periods when stopped in traffic
- ✓ 6-speed manual or automatic transmission
- ✓ 10-30% more torque than current SKYACTIV-G 2.0
- ✓ 10% power increase than current SKYACTIV-G 2.0
- ✓ Better fuel efficiency than current SKYACTIV-D

Mazda's Fuel Consumption and CO_2 Emission values

Body type		Hatchback				Sedan		
Transmission		6MT	6AT	6MT	6AT	6MT	6AT	
Powertrain		FWD	FWD	AWD	AWD	FWD	FWD	
WLTP:	wheels							units
Combined fuel consumption	16 inch	5.5	6.2	6	6.6	5.4	6	l/100
Combined fuel economy	16 inch	42.8	37.9	39.2	35.6	43.6	39.2	mpg
CO_2 emissions (combined)	16 inch	125	140	137	149	122	136	g/km
NEDC:								
Combined fuel consumption	16 inch	4.4	5.3	4.7	5.5	4.3	5.2	l/100
Combined fuel economy	16 inch	53.5	44.4	50.0	42.8	54.7	45.2	mpg
CO_2 emissions (combined)	16 inch	100	119	107	123	96	117	g/km

https://www.mazda-press.com/eu/news/2019/revolutionary-mazda-skyactiv-x-engine-details-confirmed-as-sales-start/

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Highlights of the 41ST International Vienna Motor Symposium

(for information about key features on these engines see Appendix)

1. Toyota 1.5L I3 M15A-FKS and M15A-FXE Atkinson-cycle engines
   "The new 1.5 L gasoline engine from the TNGA series", H. Kitadani et al. (2020)

2. Ford EcoBoost 500 - 1.5L I3 GDI turbo engine
   "EcoBoost 500: Taking Award-Winning Technology to the Next Level", C. Weber et al. (2020)

3. Hyundai-Kia Smartstream 1.0L GDI turbo engine
   "The New Hyundai-Kia's Smartstream 1.0L Turbo GDi Engine", K. Hwang et al. (2020)

4. Mercedes M254 GDI turbo engine
   "M254 – the Mercedes-Benz 4-Cylinder Gasoline Engine of the Future", T. Schell et al. (2020)

5. Mercedes-AMG M139 GDI turbo engine
   - Super Sports Cars in the Compact Class; the world's most powerful four-cylinder engine in series production, made in Affalterbach, R. Illenberger et al. (2020)

6. Light-duty diesel engines with dual-SCR dosing system
   (VW 2.0L EA288 and BMW 3.0)
   - *"Volkswagen's TDI-Engines for Euro 6d – Clean Efficiency for Modern Mobility", C. Helbing et al. (2020)*
   - *"The technical concept of the new BMW 6-cylinder 2nd generation modular Diesel engines", F. Steinparzer et al. (2020)*

EPA Benchmarking of Toyota UB80E Eight-Speed Transmission

Test Process

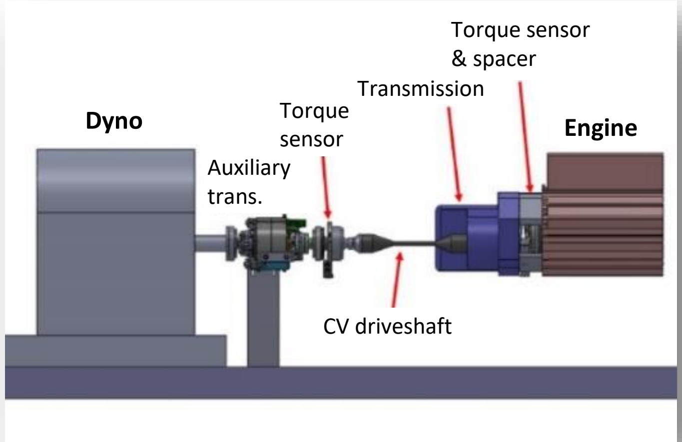
- Transmission tested in engine test cell, connected to the engine and tethered to vehicle.
- Process is relatively inexpensive.
- Uses stock ECU and TCU, so transmission operates as intended and calibrated.

Test data from UB80E

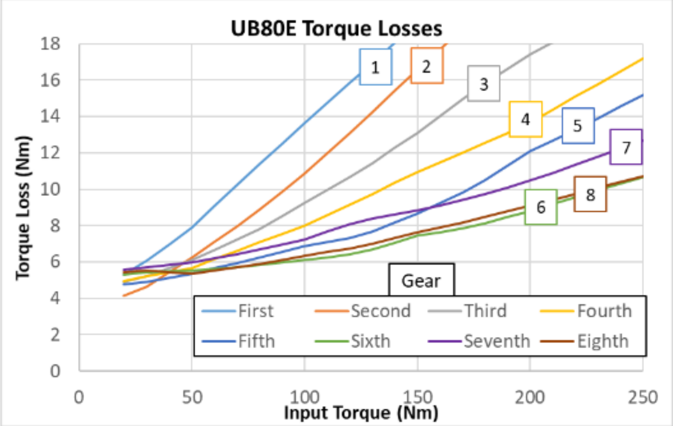
- FWD transmission includes differential losses.
- Tests measured torque losses in each gear, as a function of input speed and torque.
- Other testing including effect of temperature on loss, idle torque, torque converter K factor.

See SAE paper 2020-01-1286, "Benchmarking a 2018 Toyota Camry UB80E Eight-Speed Automatic Transmission."

Test cell schematic



Speed-averaged losses



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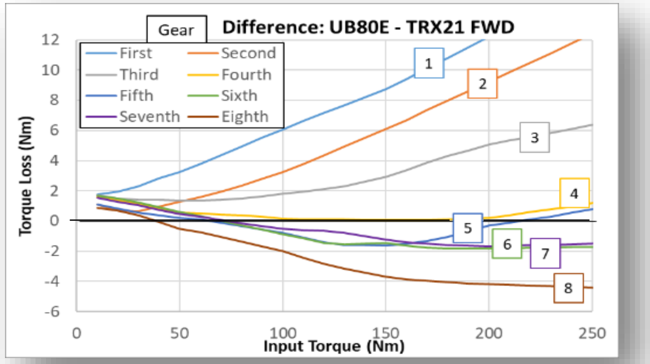
Comparison of Present Benchmarked to Future Transmissions

- Used earlier benchmark data from Chrysler 845RE RWD eight-speed transmission to create an equivalent ALPHA model FWD transmission called **TRX21** by (a) scaling torque losses and (b) accounting for differential loss.
- The future advanced ALPHA transmission called **TRX22** incorporates advanced technology:
  - Wider gear spread
  - Reduced drag torque
  - Earlier torque converter lockup
  - Reduced creep torque
  - Reduced oil pump losses
  - Early warm-up

Comparison: UB80E to scaled 845RE



Simulate transmissions in ALPHA for future CO_2 reduction

- Using Toyota Camry vehicle parameters and Toyota engine map…
  - Toyota UB80E performs very similarly to TRX21 transmission (modified 845RE 8-spd)
  - TRX22 transmission (future 8-spd) shows potential for up to 7% CO_2 reduction in this application *(however, transmission effectiveness depends on engine and vehicle parameters).*
- Earlier work outlined in the 2016 Proposed Determination suggests ~4.5% is closer to center of range of potential effectiveness with the additional cost of a TRX22 transmission over a TRX21 transmission estimated at about $250.

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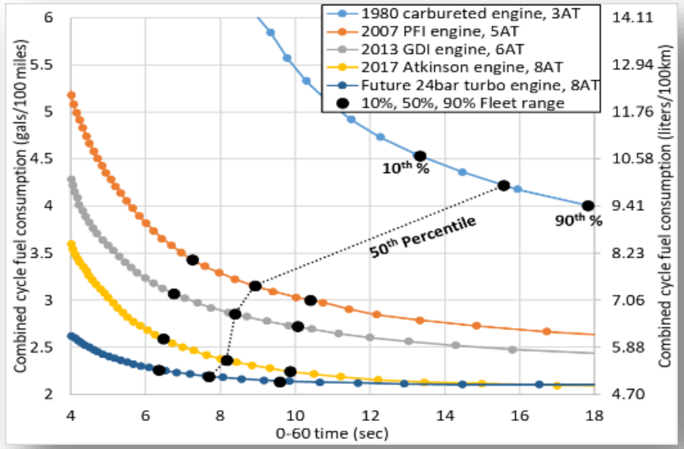
Acceleration Performance, Fuel Consumption, and Engine Scaling

Modeling study with multiple generations of powertrains

- Powertrains become more efficient over time.
  - High-efficiency areas become broader.
  - Efficiency does not fall off as sharply at lower power.
  - Acceleration – fuel consumption tradeoff “flattens.”
- Meanwhile, average acceleration has increased.
  - Nominal performance shifts down the tradeoff curve.
  - Tradeoff slope (elasticity) has remained roughly the same.
- However, future powertrains produce much flatter curves.
  - Acceleration increase is unlikely to increase to keep up.
  - In the future, it is likely that increasing or reducing performance will have a reduced effect on CO_2.
- The effect is accentuated in more aggressive driving, so it may already be occurring in real-world cycles.

See in-press SAE paper, "Assessment of Changing Relationships Between Vehicle Fuel Consumption and Acceleration Performance."

Combined FTP-HW



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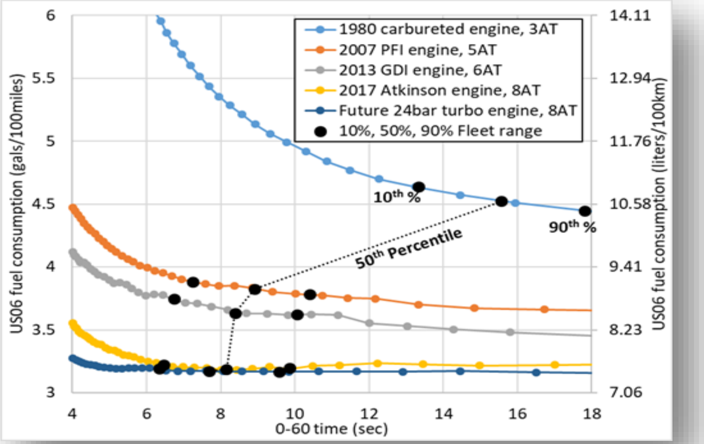

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Key Take-Aways for Conventional Technologies

Conclusions

- All the individual technologies EPA is evaluating are already in production, though some are at an earlier stage of implementation (e.g., advanced turbos, spark controlled compression ignition).
- Large emissions reductions could be achieved by implementing available technologies throughout the fleet (e.g., full implementations of Atkinson cycle, cylinder deactivation, cooled EGR, etc.)
- No engine currently incorporates all potential technology improvements <u>in combination</u> (e.g., Miller cycle + advanced turbo + cylinder deactivation and Atkinson cycle + cylinder deactivation).
- There are also promising advanced engine technologies that have not yet been introduced into the U.S. market, including spark controlled compression ignition.
- Transmissions also have potential to incorporate packages with multiple technology improvements.
- As future powertrains become more efficient, the effect of changing engine power (and acceleration performance) on CO_2 production decreases.

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2017 Chevy Bolt Vehicle & e-Motor/Battery Components

Electric Vehicle (EV) Benchmarking

Investigate how to benchmark an EV

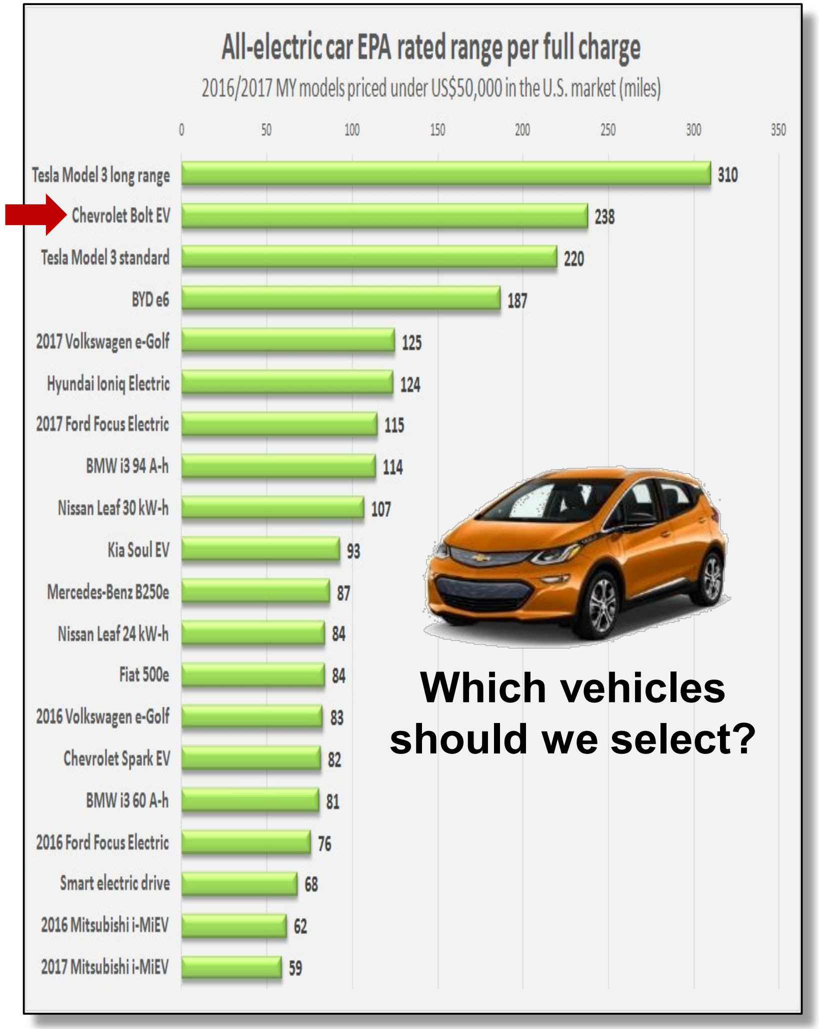
a) What components are involved?
b) How to instrument components?
c) Where to test (chassis, engine dyno cell, etc.?)

What information is useful?

a) Mechanical efficiency of gears & electric motor
b) Electrical efficiency of inverter and battery (including charging eff. of battery and charger)
c) Battery durability (reduction in range) and temperature management
d) Parasitic losses from other vehicle systems (HVAC, controls and lighting)
e) Other?

What are data used for?

a) Full validation modeling of EV submodel for future versions of ALPHA and OMEGA
b) Institutional knowledge and inform EPA policy
c) Informing the public (SAE papers)



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Testing/Safety

Types of Testing	Safety Concerns
<u>Chassis</u> a) Full signal interrogation by RPECS b) Some instrumentation c) Cycle testing ("City/Hwy/US06 test – 60mph cruise", repeat at mid SOC, repeat at end SOC)	**<u>Chassis</u>** a) Normal vehicle testing safety
<u>Engine dyno</u> a) Tether <u>powertrain</u> to <u>car and battery</u> b) Tether <u>powertrain and battery</u> to <u>car</u> c) Full instrumentation d) Steady-state and transient?	**<u>Engine dyno & Component</u>** a) High voltage wiring and connections b) Battery containment for testing (best practices) c) Substitute AVL emulator for battery?
<u>Component testing</u> a) Battery b) E-motor c) Transmission	

Electric Vehicle (EV) Benchmarking

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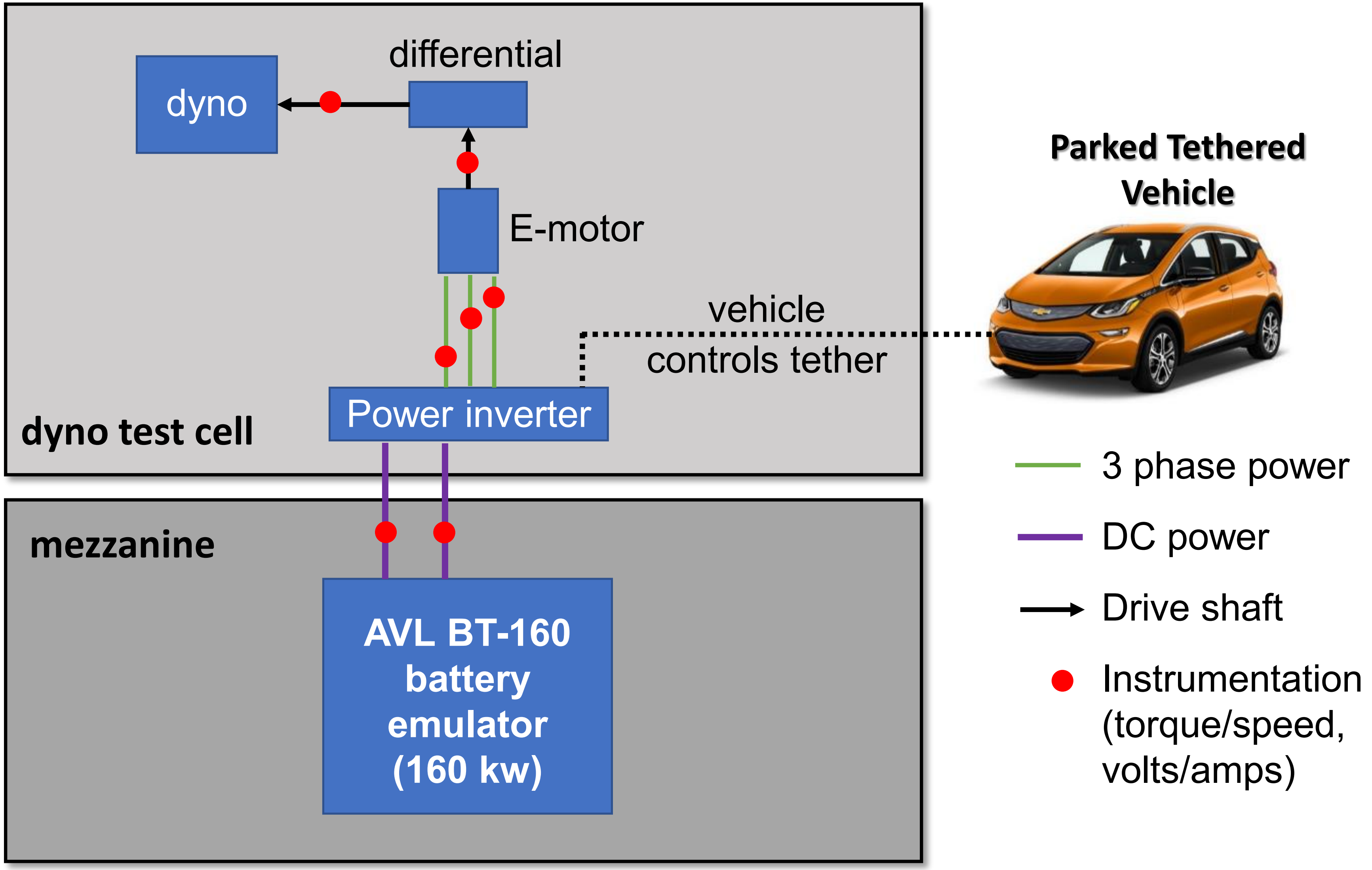
Engine Test Cell Configuration

Bolt e-Motor Drivetrain Testing

(without battery)



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Configuration within Battery Test Facility (no dyno needed)

Stationary Battery Testing

- Add capability to mimic a J1634 Multi Cycle Test (MCT) in the Battery Test Facility (see next slide)
- Evaluate using the AV-900 as a fast DC charger
- Explore battery durability testing methods

J1634 Multi Cycle Test (vehicle dyno based) will be run to gather battery power profiles for MCT and other BTF AV-900 simulations.

Battery Test Facility (BTF) SHED

battery remains in vehicle

battery cooling is needed

Some vehicle controls tethering may be needed

DC power flow

Battery Emulator - AeroVironment AV-900

1) Simulate vehicle drive cycles (starting with J1634 test*) using data from vehicle dyno testing
2) Use as a fast DC charger for battery charging studies

DC power
Instrumentation (volts/amps)

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SAE J1634 – Battery Electric Vehicle Energy Consumption & Range Test Procedure

Draft EV Test Procedure

Defines test procedures and equipment to be used to accurately measure vehicle energy consumption and range for standard drive cycles (e.g., UDDS & HWY).

- First issued in 1993, the procedure has undergone multiple revisions:
  - ✓ Improve test procedures to reduce dynamometer time
  - ✓ Addition of 5-cycle testing & calculations

Single Cycle Test (SCT) is the legacy procedure.

- Requires operation of the vehicle over repeated drive cycles until the battery is depleted.
- Extremely time consuming, e.g., UDDS test for a 400 mile range vehicle requires more than 26 hours of dynamometer time.

Multi Cycle Test (MCT) was introduced to allow energy & range consumption for multiple drive cycles (e.g., UDDS & HWY) with one full depletion test.

- Significantly reduced amount of dynamometer time required and eliminated one recharge event.

Short Multi Cycle Test (SMCT) is currently under consideration by SAE committee.

- SMCT includes the use of a battery cycler to further reduce the amount of dynamometer time required to deplete the battery.
- SMCT is included in current draft document and will be voted on by the committee later this year.

There is still an open issue on how to incorporate CAN data acquisition into J1634 (EVs) and **J1711** (PHEVs).

- Investigations continue on incorporating CAN data as part of these test procedures.
- NVFEL has collected both CAN and power analyzer data on multiple vehicles over the past several years as part of these investigations.
- Use of CAN data could eliminate the need for instrumenting vehicles for current and voltage measurement during the discharge portion of the test.

Chevy Bolt Battery

Battery System Components

(1) High Voltage Battery

(2) Heater Coolant Heater

(3) High Voltage Battery Disconnect Control Module Assembly

(4) Accessory DC Power Control Module

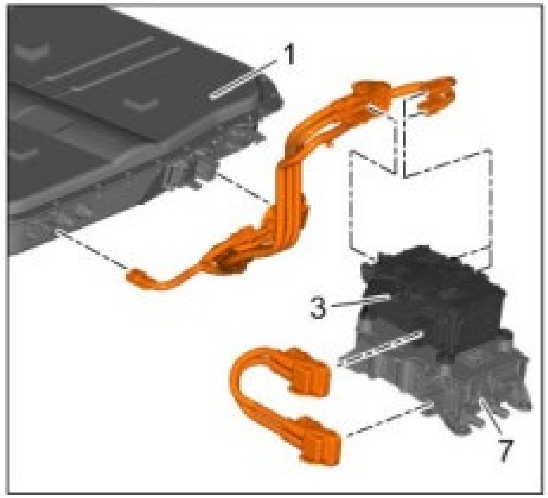
(5) Drive Motor Battery Charger

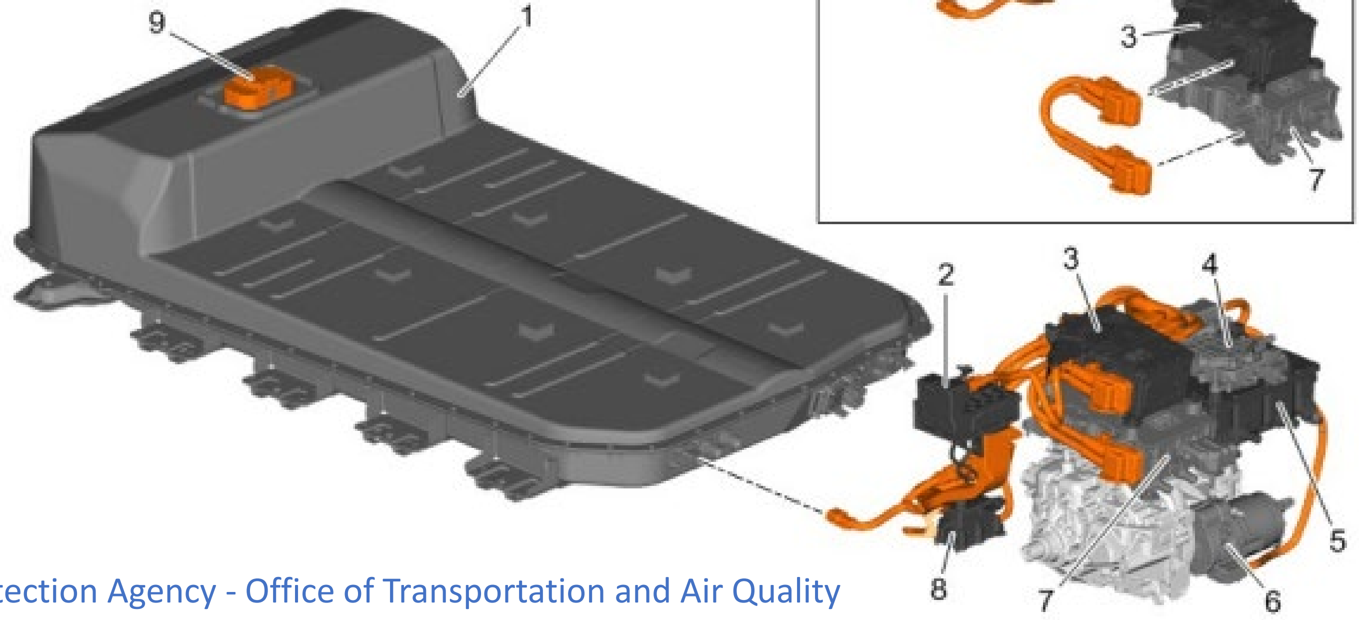
(6) Air Conditioning and Drive Motor Battery Cooling Compressor

(7) Drive Motor Inverter Module

(8) High Voltage Battery Heater

(9) Drive Motor Battery High Voltage Manual Disconnect Lever





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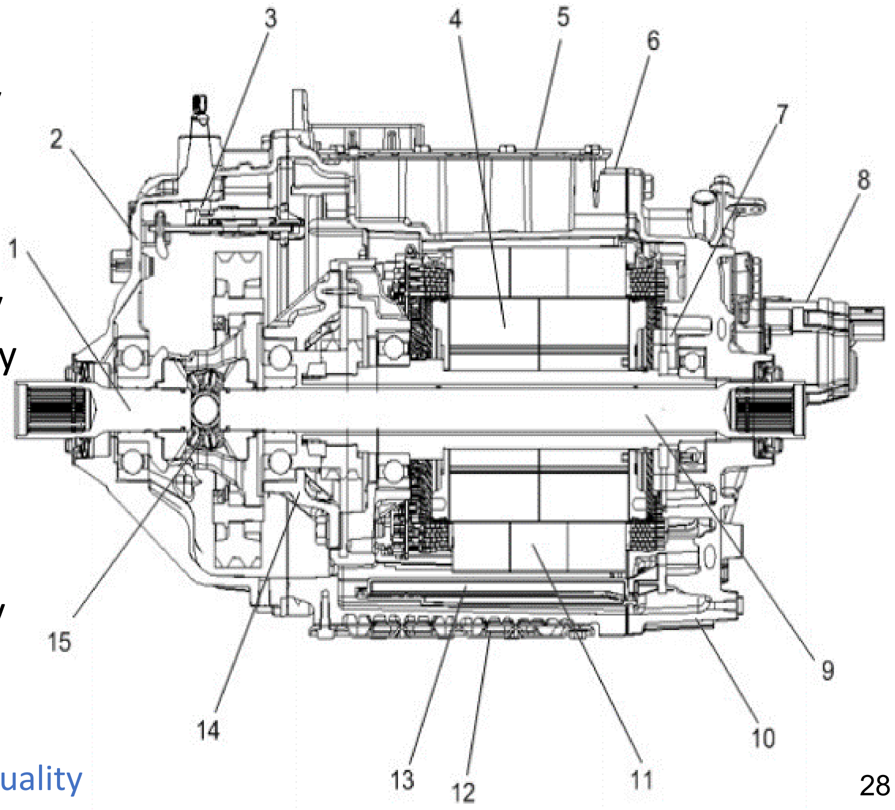
Transmission Components

- Consists of E-motor and single gear reduction
- Investigate how to separate e-Motor from gear drive to install torque sensor
- Purchasing salvage unit for tear down & design concepts
- Will tether the transmission to vehicle

Chevy Bolt Transmission Components

(1) Output Shaft Assembly (RHS)
(2) Automatic Transmission Case
(3) Manual Shift Shaft Position Switch Assembly
(4) Drive Motor Rotor Assembly
(5) Shift Shaft Cover (Oil Sump)
(6) Drive Motor Housing
(7) Drive Motor Position Sensor Stator Assembly
(8) Automatic Transmission Fluid Pump Assembly
(9) Output Shaft Assembly (LHS)
(10) Automatic Transmission Case Cover
(11) Drive Motor Stator Assembly
(12) Shift Shaft Cover (Coolant Sump)
(13) Automatic Transmission Fluid Filter Assembly
(14) Center Support
(15) Front Differential Assembly



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Chassis Testing

- CAN reverse engineering completed by SwRI this past spring
- Includes 140 signals across 10 modules
- Vehicle also equipped with a Yokogawa power analyzer for discrete measurement of high voltage battery currents
- Chassis testing is nearly complete
- Test plan includes 40 tests for Alpha model validation
  - Repeats of 6 different cycles
  - Steady states
  - Mild accel and decel tests
  - Torque converter stall test
  - Testing ~50% complete
- Plan to use mild hybrid validation to complete SPCCI assessment

2018 Jeep Wrangler with 48-volt eTorque

Jeep Wrangler with eTorque

- **2.0 L GME-T4**
  - 270 hp (100 kW/L) @ 5250 RPM
  - 295 ft-lb / 400 Nm @ 4400 RPM
  - 25.1 bar BMEP
  - Cooled EGR
  - Twin-scroll, low-inertia turbocharger
- **48 V BiSG "eTorque"**
  - Start-stop & e-Assist at low vehicle speeds
    - Typical torque assist likely between idle and 1500 RPM and during gear shifting
  - 90 Nm of torque
- **48 V Lithium-Ion Battery Pack**
  - Nickel Manganese Cobalt (NMC)
  - 330 Wh capacity
  - Air cooled
- **Premium Fuel Recommended**

eTorque, not Hurricane...
Jeep photo at allpar.com

SwRI POWERTRAIN ENGINEERING 7
swri.org

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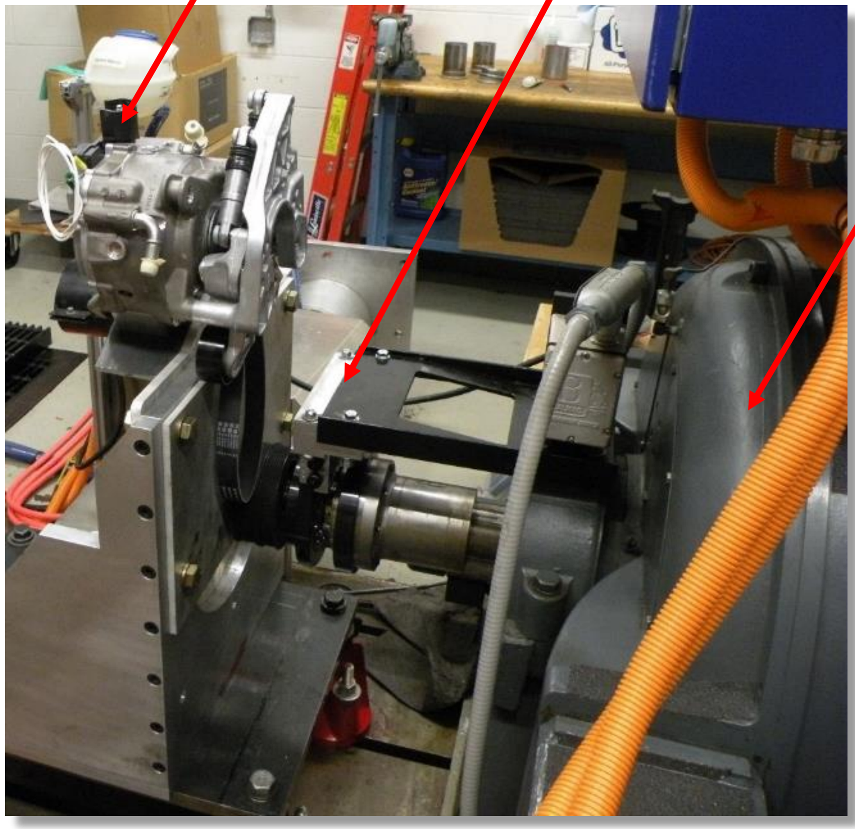
e-Motor Benchmarking Process

2018 Jeep Wrangler with 48-volt eTorque

- Mount e-Motor (starter / generator) to dyno bed plate in cell 12
- Measure speed and torque with HBM torque sensor
- Use AVL battery emulator for load
- Replicate vehicle CAN message controls to operate e-Motor



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Background, Goals & Data

Testing EVs in Hot & Cold Temperatures

Battery electric vehicle driving range decreases in both hot and cold temperatures.

- However, the extent of range loss is not well quantified or understood.
- EPA plans to test light-duty electric vehicles to quantify energy demand in the vehicle.

Primary goal: Quantify the relationship between temperature and energy.

Secondary goal: Quantify trends for extrapolation of energy demand across technologies & vehicles.

Primary data: Discharge energy, range, auxiliary load, recharge energy & time.

Potential additional data and testing:

- Data on HVAC energy consumption (off-cycle credit implications).
- Energy consumption at idle and at various states of charge (affected by thermal management systems).
- Reliability of CAN data compared to measured energy.
- Impact on battery durability, especially at higher mileage.

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EV Benchmarking Study will Quantify Energy Consumption

Testing EVs in Hot & Cold Temperatures

Test Plan: Level 2 charging & range-depletion discharge using the hot and cold chassis dyno sites.

- Across a range of temperatures (20°F-95°F)
- Dedicated to auxiliary loads (cabin cooling, heating, and alternative heating)
- At charging/soak/preconditioning conditions (garage conditions v. outdoor temperatures)

Potential vehicles:

Year	Model	Range (mi)	MPGe (city/hwy)	Battery (kWh)	Power (hp)	Weight (lb)	2019 MSRP
2019	Audi e-tron	204	74/73	95.0	402	5490	$74,800
2019	BMW i3	153	124/102	42.2	170	2965	$44,450
2018	**Chevy Bolt***	**238**	**128/110**	**60.0**	**200**	**3580**	**$36,620**
2019	Hyundai Kona	258	132/108	64.0	201	3715	$36,950
2019/2018	Nissan Leaf	150	124/99	40.0	147	3433	$29,990
2019/2018	Tesla Model 3	240	138/124	59.5	258	3627	$35,400
2018	**Tesla Model S***	**345**	**101/102**	**100.0**	**518**	**4941**	**$99,990**
2019/2018/2017	Tesla Model X	325	91/95	100.0	518	5421	$84,990
2019/2018/2017	Volkswagen eGolf	125	126/111	35.8	134	3455	$31,895

**Vehicles currently on loan from Transport Canada & Environment Canada.*

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Key Take-Aways for Electrified Technologies

Conclusions

- Given global trends in electrification of the light-duty fleet, the EPA Ann Arbor National Vehicle and Fuel Emissions Laboratory (NVFEL) is building up its capabilities to test and analyze electrified technologies.
- Current EPA NVFEL testing efforts include:
  - Collection of test data to validate EV and mild hybrid technologies in ALPHA
  - Evaluation of temperature effects on EV range
  - Building up lab EV test infrastructure including battery cycling, battery charging, and current measurement
  - Collaboration with industry to evaluate and develop a future version of SAE J1634 (EV) and J1711 (PHEV) test procedures

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Topics

1. **NVFEL Background**
2. **Benchmarking & Technology Assessments**
   - A. **Conventional technology benchmarking**
     - Overview of Conventional Powertrain Benchmarking
     - Review of EPA's ICE benchmarking and analysis
     - Current benchmarking of cylinder deactivation engines
     - Highlights of new ICE's announced at Vienna Motor Symposium
     - Transmissions
     - Acceleration Performance, Fuel Consumption, and Engine Scaling
     - Key take-aways
   - B. **Electrified technology benchmarking**
     - 2017 Chevy Bolt vehicle & e-motor/battery components
     - Effect of temperature on EV range
     - 2018 Jeep Wrangler 48-volt BISG hybrid component
     - Key take-aways
3. **Other Emerging Work**
   - Development of test methods for Connected Automated Vehicles
   - Expansion of In-Use Testing and Data Analysis
4. **Responses to Specific NAS Questions**

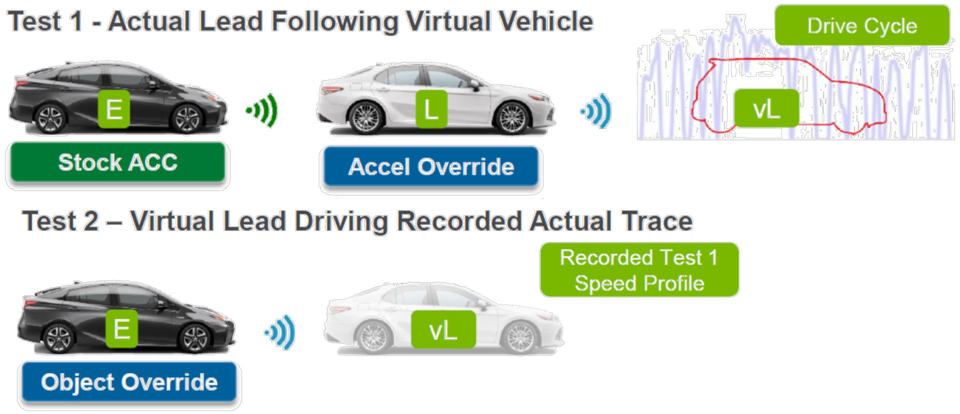
Connected Automated Vehicles (CAV) Testing Methods

Methods for testing CAVs are being developed at the DOE National Labs – NVFEL is doing similar work.

Connected Automated Vehicles

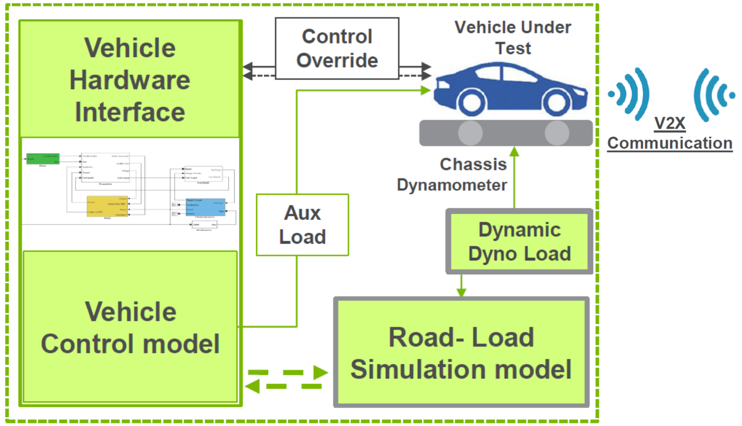
ANL: Vehicle-in the-loop on the track…

Goals: Validate VIL override operation, measure aerodynamic loading.



…& ANL: Vehicle in the test cell

Goals: Explore energy use of varying driver models in safe, controlled variation of test parameters.



ORNL: CAVE Lab: Virtual physical proving ground

Goals: Accurately verify large scale energy benefits and emissions impacts of CAV technologies subjected to virtual traffic conditions. Integrate vehicle/traffic simulation tools with advanced HIL enabled laboratories.

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CAV Test Method Development - Testing on a track

Connected Automated Vehicles

Test Vehicle: "Semi-autonomous" with Adaptive Cruise Control (ACC), controlling forward velocity

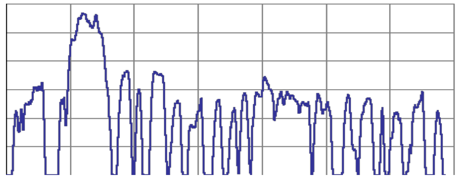
Project Goals - develop test methods to:

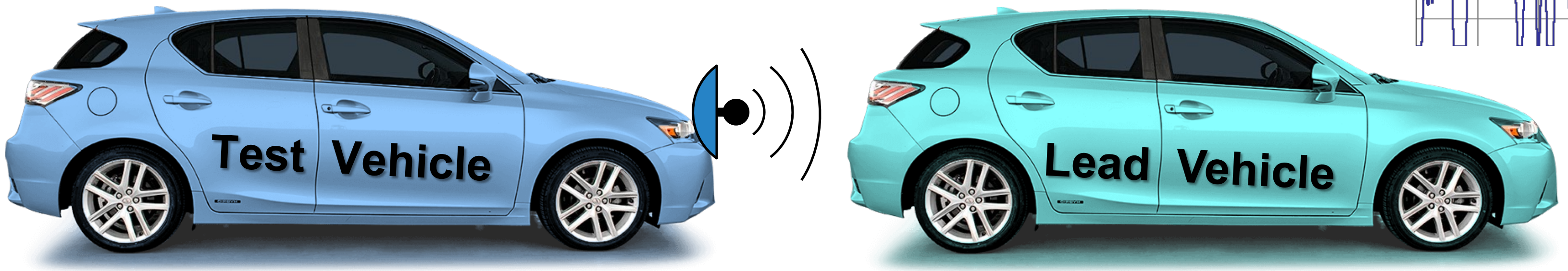
1. Quantify the benefits of ACC in a "real world" setting.
2. Define a lead cycle so the test vehicle mimics a cert cycle.
3. Repeatably drive a lead vehicle for the test vehicle to follow.
4. Determine the repeatability of the test results from the ACC vehicle.
5. Quantify the difference between ACC and a human driver?

Method Development:

- "Leader" vehicle repeats the defined trace.
- Test vehicle follows in ACC mode
(may be repeated with different following distances).
- Test vehicle follows, driven by a human driver
(may be repeated with different drivers).

Track trace follower:
Lead vehicle has equipment installed to repeat trace.
- Could use robot driver.
- Need to address safety.





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CAV Test Method Development - Testing on a vehicle dynamometer

Test Vehicle: "same semi-autonomous" with (ACC), controlling forward velocity

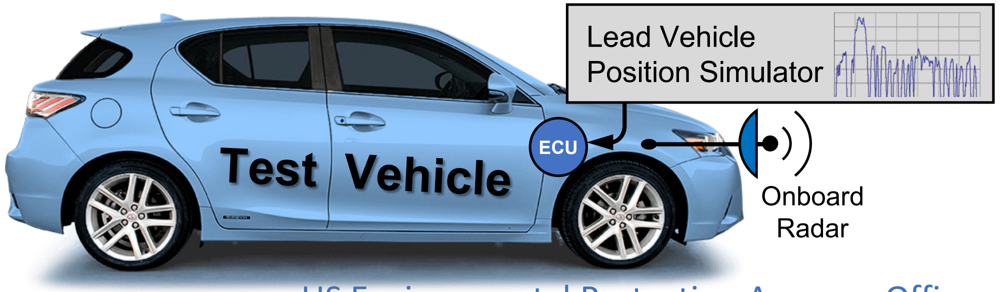
Connected Automated Vehicles

Project Goals - develop test methods to:

1. "Replicate" autonomous behavior and emissions in the lab.
2. "Spoof" vehicle sensors to insert a pre-recorded signal.
3. Quantify how closely a human on-dyno driver can replicate the on-road trace.
4. Compare and contrast results to cert cycle results.

Methods to gather data on vehicle behavior & emissions:

- "Spoof" vehicle sensors to replicate pre-recorded ACC trace.
- Human driver replicates human-driven trace from track.
- Human driver replicates ACC trace.
- Computationally construct and test a "standard human driver" trace.
- Run cert cycle for comparison.



CAN Spoofing:
Radar sensor output is replaced with "spoof" of data recorded earlier.

- Direct wiring into CAN bus.
- Replaces signal from onboard radar.
- Usable with any radar frequency.

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Expansion of In-Use Testing and Data Analysis

In-Use Data Availability

EPA is expanding in-use emission data programs to identify gaps in our understanding of on-road emissions and opportunities for emission reductions.

- The EPA lab has active programs to assess the potential of low cost mini-PEMS devices to expand the number of on-road vehicles tested (advancements in miniature portable emission measurement systems would enable testing on a much broader scale at significantly lower cost.
- NCAT is collaborating with CARB to assess data from their Real Emissions Assessment Logging (REAL) program.
- EPA continues to explore additional collections of OBD-based vehicle and fleet data for light- and heavy-duty.

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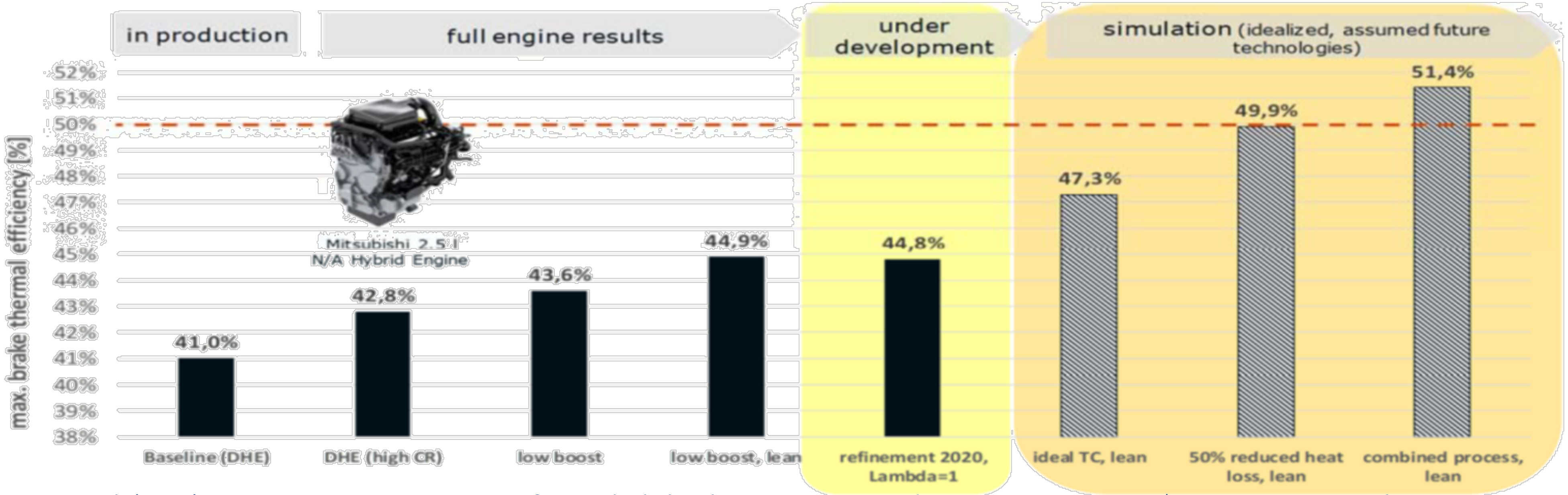
4. **Responses to Specific NAS Questions**

Responses to Specific NAS Questions

7a. **…** it appears that the trend of GTDI engine efficiency developments lean toward higher Miller Cycle potentially with some combination of cooled LP-EGR, VGT to provide expanded boosting requirements, some sort of VVL or cam profile switching to manage pumping losses. … **Does EPA agree with this general direction and is there further quantification of the potential of a similar technology bundle (as proposed follow on in SAE 2018-01-423)?**

EPA response: Yes, we agree that there is additional potential to improve the efficiency of GTDI engines via Miller Cycle (either EIVC or LIVC), VNT or other boosting system improvements, VVL (continuous or discrete), increased charge motion, reduced friction (offset crankshaft, improved bore finishing, etc.), and use of cooled EGR. The engine model developed in SAE 2018-01-0161 was validated with engine dynamometer testing summarized in SAE 2018-01-1423. The developmental engine reached a peak BTE of 38.5% during testing. The modeling was extended to include Miller Cycle (EIVC) using VNT with a developmental goal of 40% BTE on the same engine platform (SAE 2019-01-0192).

Kapus et. al (2020) investigated the potential for using Miller Cycle as a dedicated hybrid engine, with 44.8% peak BTE achievable for λ=1 operation. Considering the use of U.S. vs. EU gasoline (i.e., lower AKI fuels) 42-43% peak BTE appears achievable by 2026 for λ=1 operation with developmental advances applied to current Miller Cycle engine designs (e.g., 48V eCharger or VNT, increased charge motion, reduced engine friction, cooled low-pressure EGR).



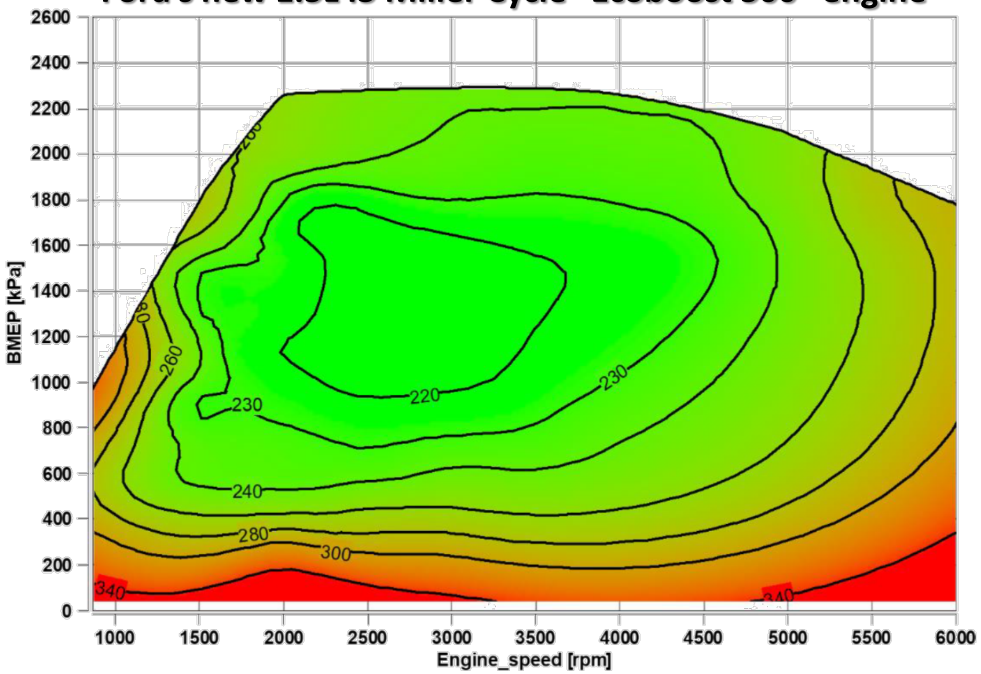
Kapus, P. et al. (2020) Passenger car powertrain 4.x – from vehicle level to a cost optimized powertrain system. 41st Vienna International Motor Symposium

Responses to Specific NAS Questions (continued)

7b. Does EPA agree that Miller Cycle engines will either be performance limited (as in VW 1.5L EVO) or displacement constrained?

EPA response: For a given boosting system approach, Miller Cycle places additional constraints on the achievable peak BMEP. For a given torque requirement, that means either accepting a lower BMEP level (e.g., increased displacement), using a more advanced boosting system (improved turbo match, switching to VNT) or reducing geometric compression ratio and the resulting achievable expansion ratio. We have observed all three approaches used in production and developmental Miller Cycle engines. Using advanced boosting systems, the achievable BMEP is still quite high.

Ford's new 1.5L I3 Miller Cycle "Ecoboost 500" engine



Weber, C. et al. (2020) EcoBoost 500 : Taking Award-Winning Technology to the Next Level. 41st Vienna International Motor Symposium.

We were able to maintain the 21 bar BMEP on the developmental PSA EP6 platform using VNT with EIVC. AVL has demonstrated Miller Cycle Concepts with 24 bar BMEP. Ford's new 1.5L I3 Miller Cycle "Ecoboost 500" engine developed for the EU market has a geometric compression ratio of 12.5:1 and reaches 23-bar BMEP using a VGT (Weber et al. 2020). The BMEP level achieved is comparable to Ford's existing line of light-duty Ecoboost engines.

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Responses to Specific NAS Questions (continued)

8a. Does EPA believe that the technologies included in Table 9 of SAE 2018-01-0319 still represents a comprehensive look ahead for our study timeframe (2025-2035)?

EPA response: Yes. We continue to see new engines with cooled EGR, variable valve lift, Miller Cycle, improved turbos and also more advanced cylinder deactivation technologies being developed and introduced to the market. We expect this to continue as conventional technology engines are still needed to meet fuel economy and emission standards throughout the world market. (see slide 9)

8b. What does EPA believe is the ultimate BTE potential of a practical and cost effective bundle of technologies ("still on the table").

EPA response: We do not yet have a complete answer to this question. Our benchmarking of the Toyota A25A naturally-aspirated Atkinson cycle engine included estimates of effectiveness for both fixed and dynamic cylinder deactivation (SAE 2019-01-0249). Our work on an advanced turbo demonstration engine explored the effectiveness of a cost-effective bundle of technologies, but we have not yet completed the work to determine the bundle's BTE potential. Initial exploratory work (SAE 2019-01-0192) indicated that 40% BTE at peak was achievable but achieving BTE above 40% would have been difficult when considering the age of our developmental engine platform (2012 PSA EP6) and it's hardware limitations (peak cylinder pressure, suboptimal bore-to-stroke ratio, suboptimal port tumble characteristics, lack of IEM, and fuel system limitations).

For EPA to explore this further would require use of a more modern developmental engine platform. Additional developmental work on more advanced Miller Cycle concepts is underway for the EU and other world markets (e.g., Kapus et al. 2020, Weber et al. 2020). Based on published data and when considering the use of U.S. (i.e., lower AKI) fuels, 42% peak BTE appears to be achievable by 2026 with developmental advances applied to current Miller Cycle engine designs for full range operation with λ=1 operation. A peak BTE of 43% appears achievable for dedicated hybrid engines with λ=1 operation. If octane improvements are included that are comparable to fuels available in the EU, this could be expected to increase to 43 – 45% peak BTE for λ=1 operation based on engines currently under development.

Responses to Specific NAS Questions (continued)

9. **Does EPA believe in the future viability of any sort of lean combustion technology against the constraints of Tier 3 emissions?**

EPA response: Mazda is already in production with the Skyactiv-X in the European market, however there are considerable challenges with respect to bringing lean-burn combustion technologies into compliance with the fully phased-in Tier 3 NMOG+NOx standards, which will require NOx reduction efficiency of 99% or greater even when considering engines with relatively low engine-out NOx emissions. EPA is gaining experience with dual-SCR systems capable of achieving this level of NOx control for lean combustion as part of our development of the heavy-duty Cleaner Trucks Initiative program. Such systems are feasible in the 2026-2027 timeframe for commercial applications and perhaps the upper end of the light-duty market in the U.S. (e.g., large light-duty diesel pickups and separate-frame SUVs) but would face considerable cost pressure from competing technologies (electrification, hybridization, advanced gasoline concepts at λ=1) in smaller light-duty vehicle applications (e.g., passenger cars, CUVs, unibody SUVs)

10. Much of ICE development presented at the Aachen powertrain conference focused on the synergies available in a hybridized powertrain system context. **What are EPA's thoughts on engine in a hybrid in terms of incremental potential, relative to a baseline engine of your definition?**

EPA response: Based on Toyota's and Hyundai's published data *(see appendix slides 47-48 and 50-51)* manufacturers have made the effort to make incremental engine improvements to achieve higher BTE for HEV applications. Toyota previously published that they obtained an extra 1% peak efficiency on the hybrid version of their Atkinson engine. Other dedicated hybrid engines also show a 1-2% improvement relative to nonhybrid versions (e.g., Mitsubishi 2.5L, Honda 2.0L). A peak BTE of 45% appears to be achievable for a dedicated hybrid Miller Cycle engine if combined with use of higher octane fuels (Kapus et. 2020).

Responses to Specific NAS Questions (continued)

11a. What are future technical transmission opportunities that could contribute to improved fuel economy in the 2025-2035 timeframe?

EPA response: More thorough implementation of transmission advances such as wider gear spread, reduced drag torque, earlier torque converter lockup, reduced creep torque, reduced oil pump losses, early warm-up could still contribute to future fuel economy improvements. *(see slide 21)*

11b. What are the costs and effectiveness of those technologies, relative to an appropriate transmission baseline?

EPA response: Earlier work outlined in the 2016 Proposed Determination indicates the additional cost of a TRX22 transmission (future 8-spd) over a TRX21 transmission (modified 845RE 8-spd) is about $250. Earlier estimates for EPA's future TRX22 transmission shows potential for up to 7% CO_2 reduction depending on specific engine and vehicle parameters. Earlier work suggests ~4.5% is closer to center of range of potential effectiveness. *(see slide 21)*

Questions?

Highlights of the 41ST International Vienna Motor Symposium

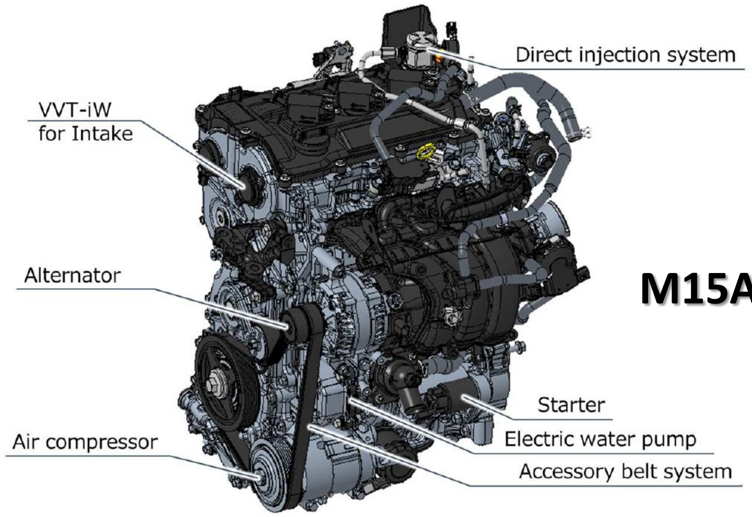
Appendix

1. Toyota 1.5L I3 M15A-FKS and M15A-FXE Atkinson-cycle engines
   "The new 1.5 L gasoline engine from the TNGA series", H. Kitadani et al. (2020)
2. Ford EcoBoost 500 - 1.5L I3 GDI turbo engine
   "EcoBoost 500: Taking Award-Winning Technology to the Next Level", C. Weber et al. (2020)
3. Hyundai-Kia Smartstream 1.0L GDI turbo engine
   "The New Hyundai-Kia's Smartstream 1.0L Turbo GDi Engine", K. Hwang et al. (2020)
4. Mercedes M254 GDI turbo engine
   "M254 – the Mercedes-Benz 4-Cylinder Gasoline Engine of the Future", T. Schell et al. (2020)
5. Mercedes-AMG M139 GDI turbo engine
   - Super Sports Cars in the Compact Class; the world's most powerful four-cylinder engine in series production, made in Affalterbach, R. Illenberger et al. (2020)
6. Light-duty diesel engines with dual-SCR dosing system
   (VW 2.0L EA288 and BMW 3.0)
   - *"Volkswagen's TDI-Engines for Euro 6d – Clean Efficiency for Modern Mobility", C. Helbing et al. (2020)*
   - *"The technical concept of the new BMW 6-cylinder 2nd generation modular Diesel engines", F. Steinparzer et al. (2020)*

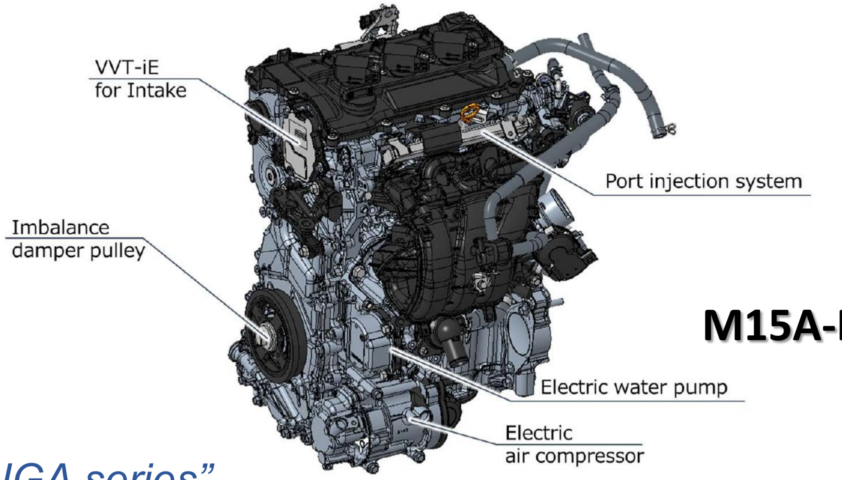
Presented to NAS-NRC
on June 16, 2020

NEW ENGINES: Toyota 1.5L I3 M15A-FKS and M15A-FXE Atkinson Cycle Engines

- 2021 Toyota Yaris and Yaris Hybrid, respectively.
- Lower cost, smaller displacement version of Toyota A20A and A25A Atkinson Cycle engines.
  - I3 maintains 500cc per cylinder of A20A engine
- Introduced in 2020 Yaris and Yaris Hybrid.
- 0W-16 (FKS) and 0W-8 (FXE) lubricants
- 14:1 geometric CR (1-pt higher than A20A)
- Does not use dual injection
  - Cost saving measure
  - FKS is GDI Atkinson
  - FXE is PFI Atkinson and HEV-only
- GPF on both versions



M15A-FKS

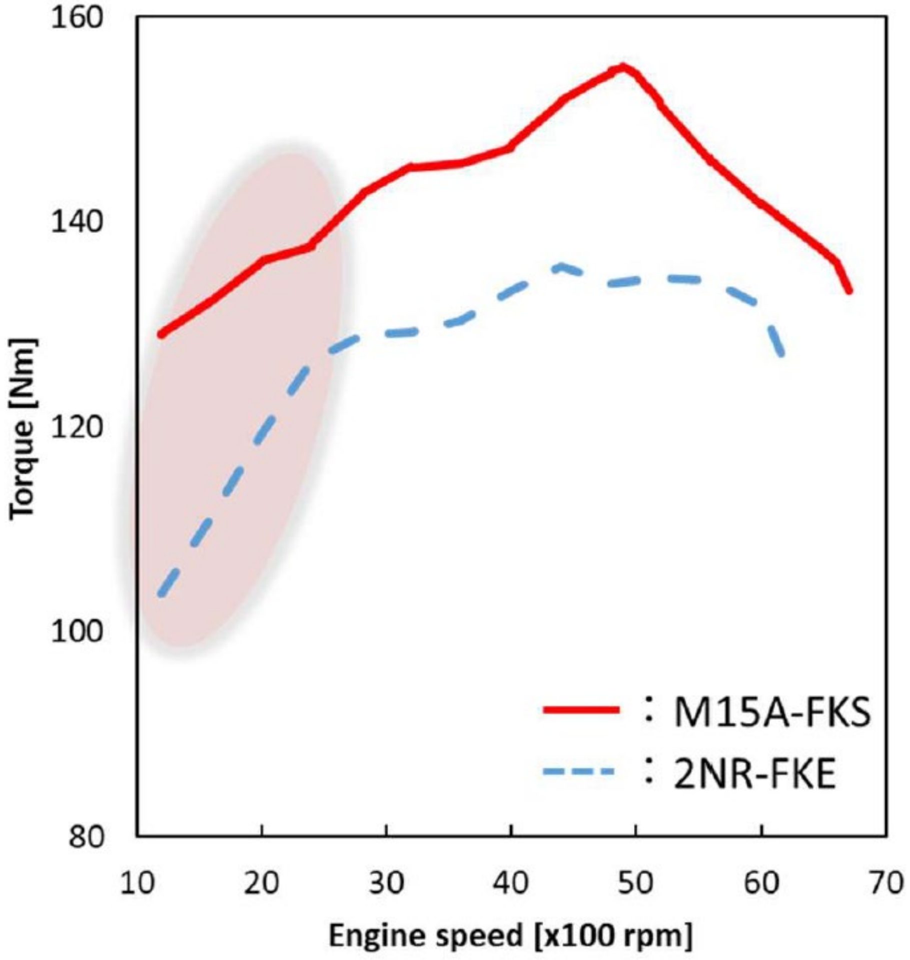


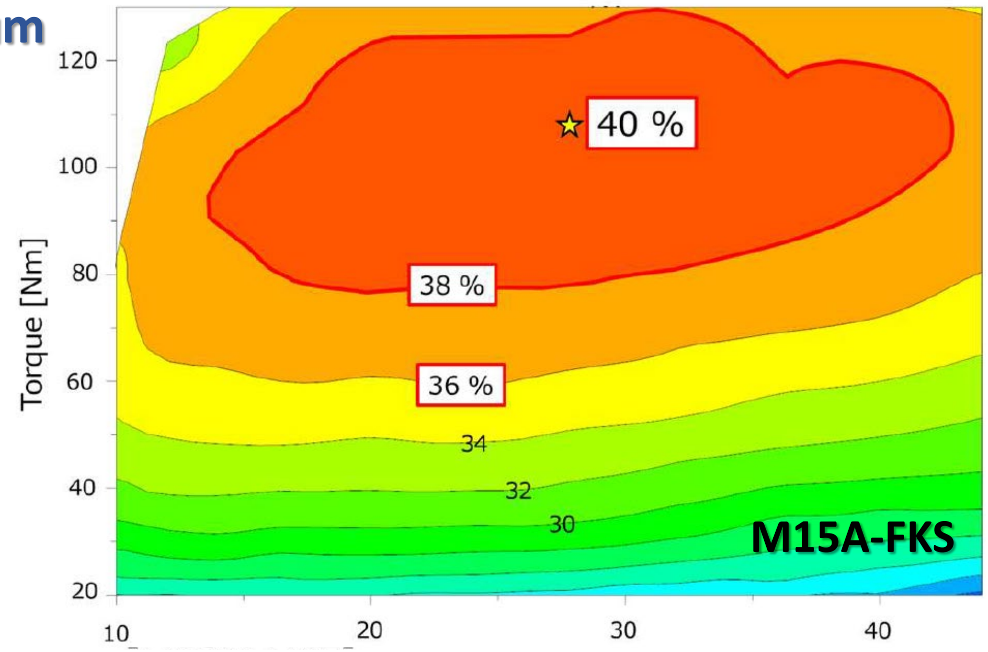
M15A-FXE

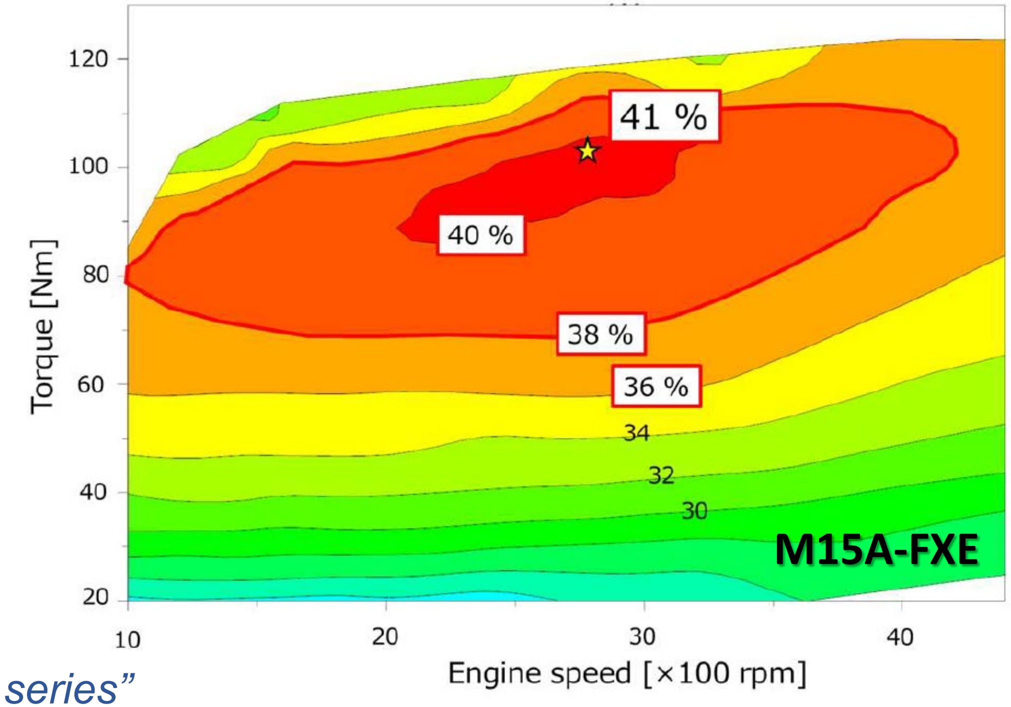
H. Kitadani et al. (2020) "The new 1.5 L gasoline engine from the TNGA series"

Toyota 1.5L I3 M15A-FKS and M15A-FXE

Note: Abbreviated torque map



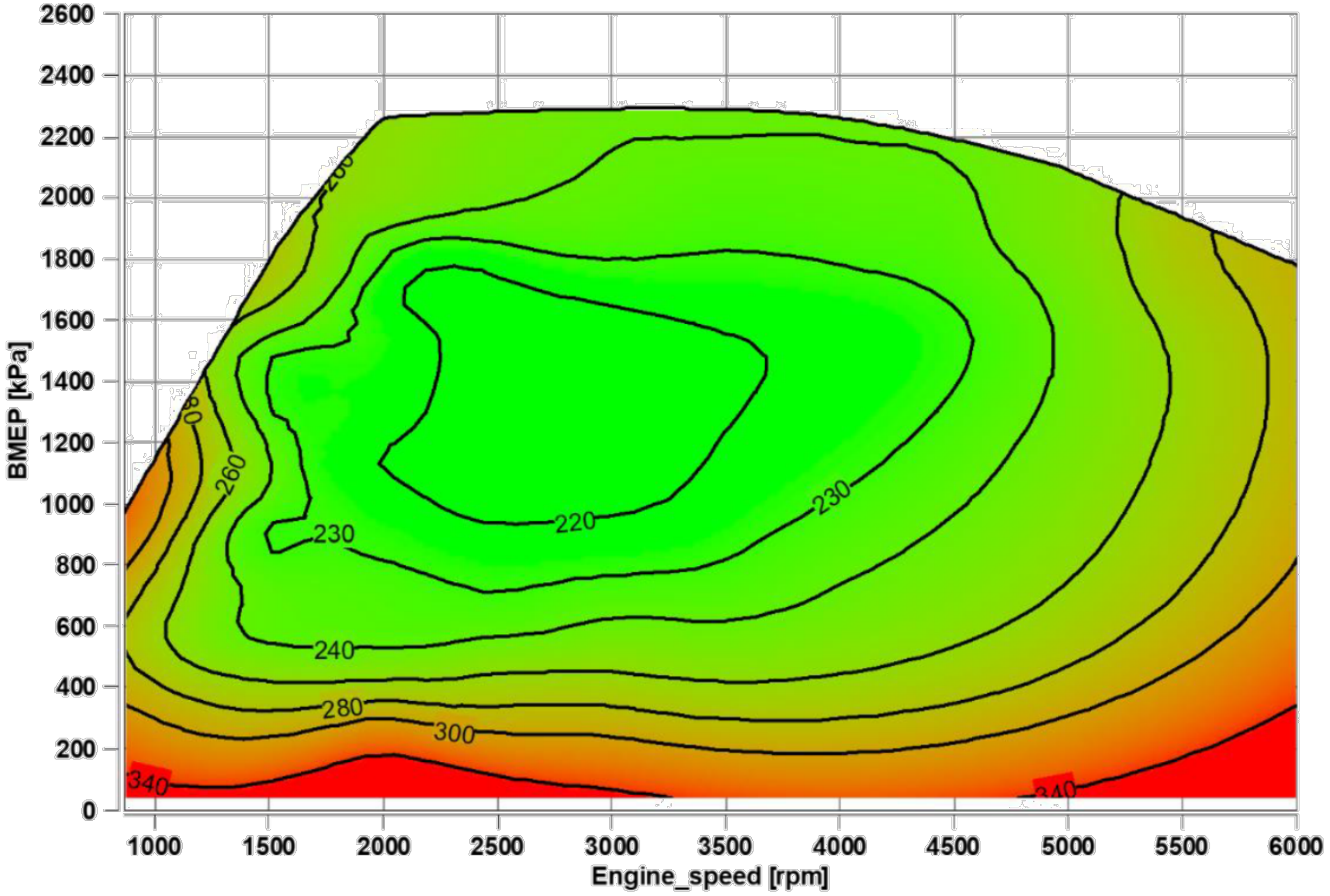




H. Kitadani et al. (2020) "The new 1.5 L gasoline engine from the TNGA series"

NEW ENGINE: Ford EcoBoost 500 1.5L I3 GDI Turbo

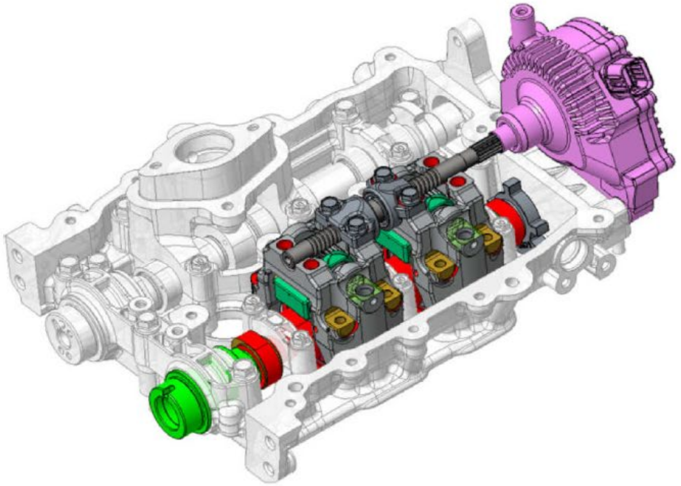
- Central injector
- Miller Cycle engine
- Schaeffler "UniAir" hydromechanical CVVL
- VGT turbocharger
- 12.5:1 geometric compression ratio
- 23 bar BMEP
  - Up to 30 bar BMEP @ 9.5:1 CR
- Large area at < 230 g/bhp-hr (~37% BTE)

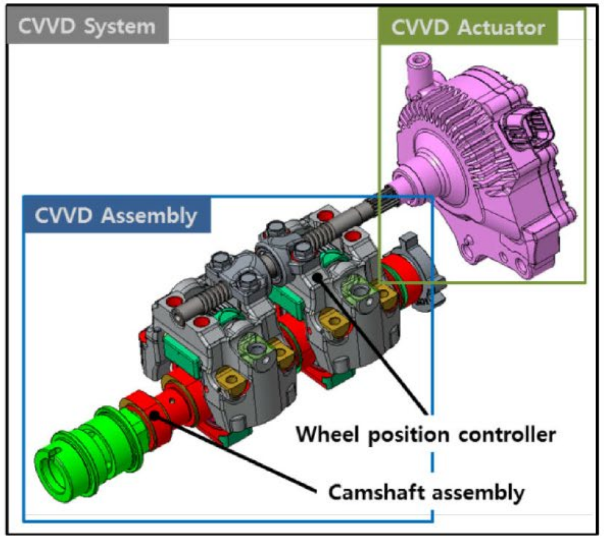


C. Weber et al. (2020) "EcoBoost 500: Taking Award-Winning Technology to the Next Level"

NEW ENGINE: Hyundai-Kia Smartstream 1.0L GDI Turbo

- Continuously variable valve duration (CVVD)
  - Intake valve duration can vary from 195 to 360 CAD
  - Can transition into and out of Atkinson/Miller operation
- 350 bar (max) direct injection
- Low-pressure cooled EGR
- Active coolant management
- Both 12V and 48V (P0) variants
- 25-bar BMEP
- Also a 1.5L I4 version

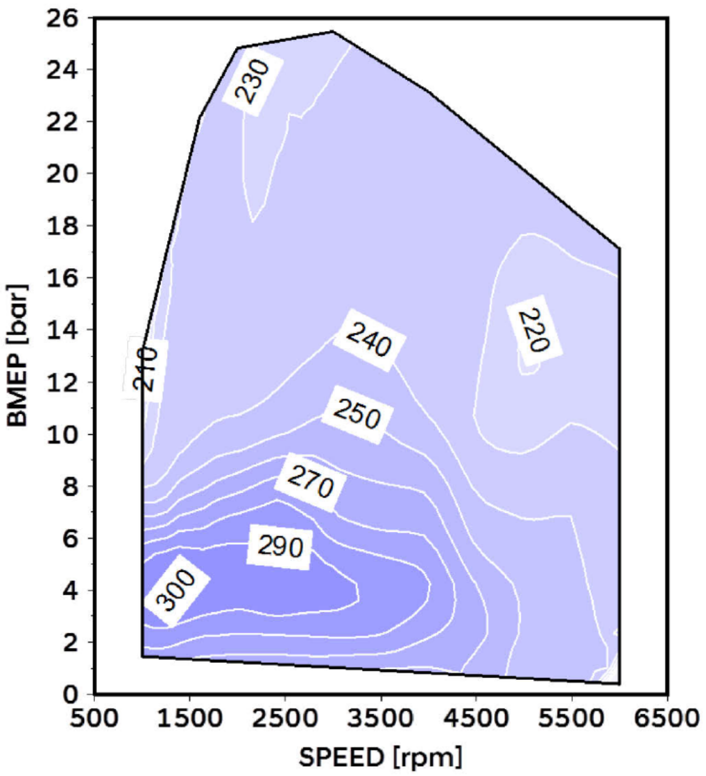




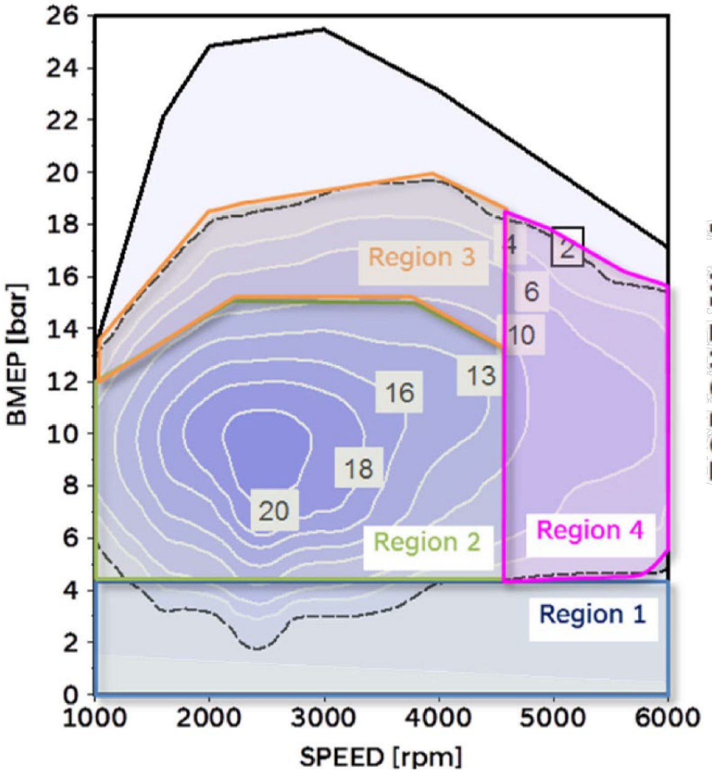
K. Hwang et al. (2020) "The New Hyundai-Kia's Smartstream 1.0L Turbo GDi Engine"

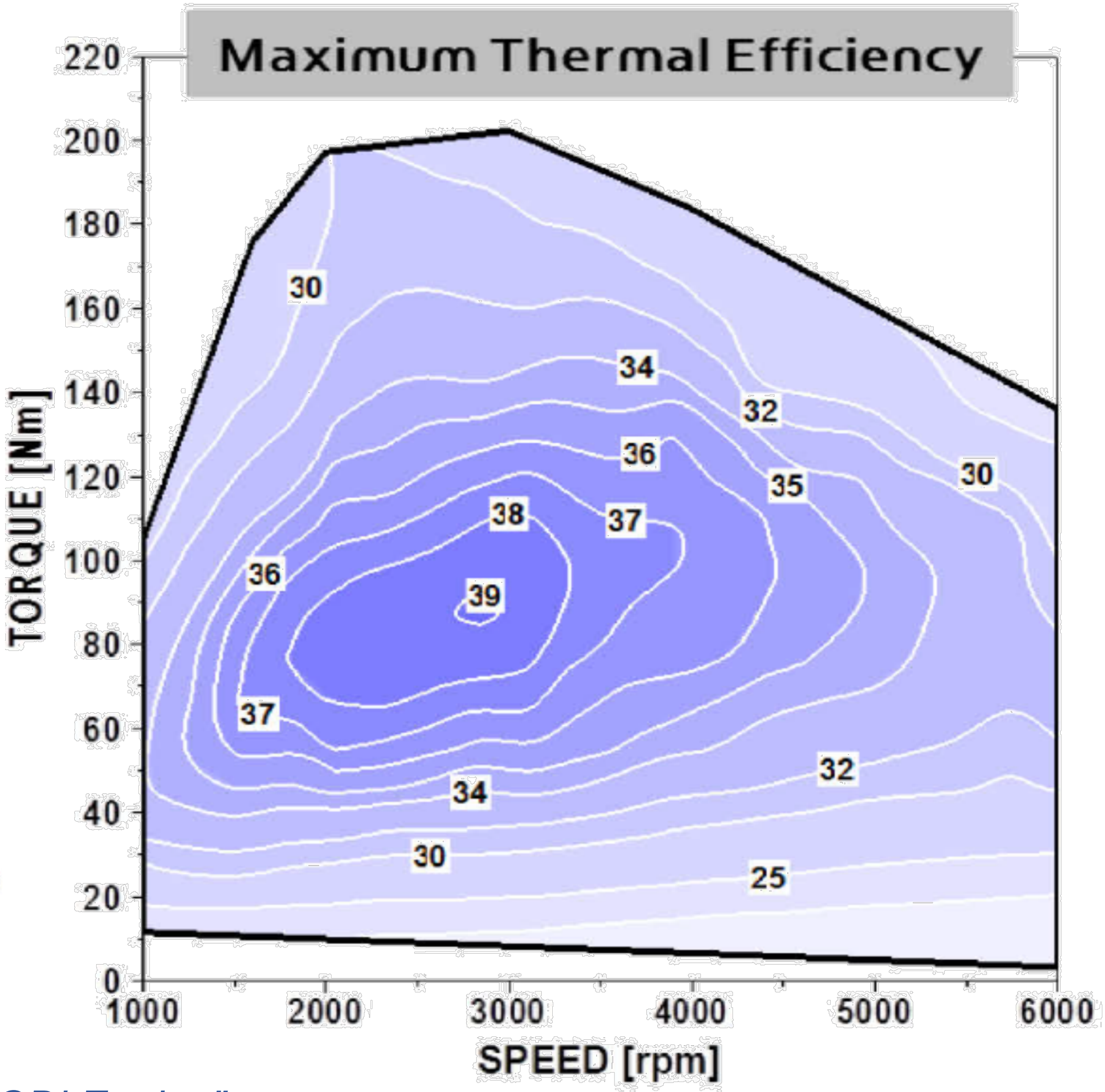
Hyundai-Kia Smartstream 1.0L GDI Turbo

Intake Valve Duration



EGR

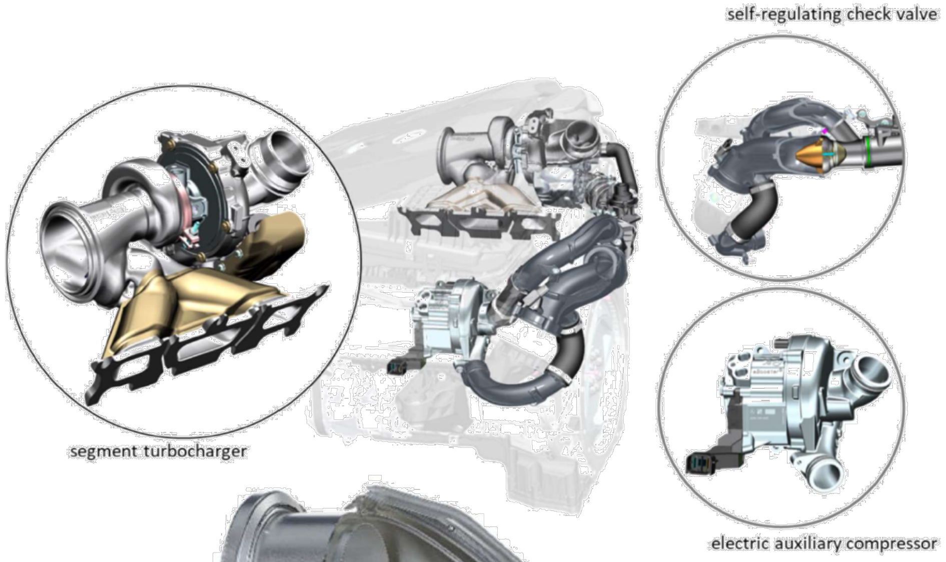




K. Hwang et al. (2020) "The New Hyundai-Kia's Smartstream 1.0L Turbo GDi Engine"

NEW ENGINE: Mercedes M254 GDI Turbo

- 2021 E-class
- 48V P1 integrated into 9-spd planetary automatic
  - 15 kW continuous
  - 180 N-m torque
- 2-stage boosting system
  - Twin-scroll turbocharger
  - 48V electric compressor
- 200 kW @ 5800 rpm
  - 100 kW/L
    - λ=1 over full range
  - 230 kw @ 6200 rpm with overboost
- 400 N-m from 1800-3000 rpm
  - 25 bar BMEP
  - 1800-4500 rpm with overboost
- Close-coupled TWC/GPF/TWC



T. Schell et al. (2020) M 254 – the Mercedes-Benz 4-Cylinder Gasoline Engine of the Future

NEW ENGINE: Mercedes-AMG M139 GDI Turbo

- High performance GDI Turbo
- 2.0 L I4
- 155 kW/L and 32 bar BMEP
- Dual fuel injection
- Exhaust-valve-only CVVL
- 3 cooling circuits

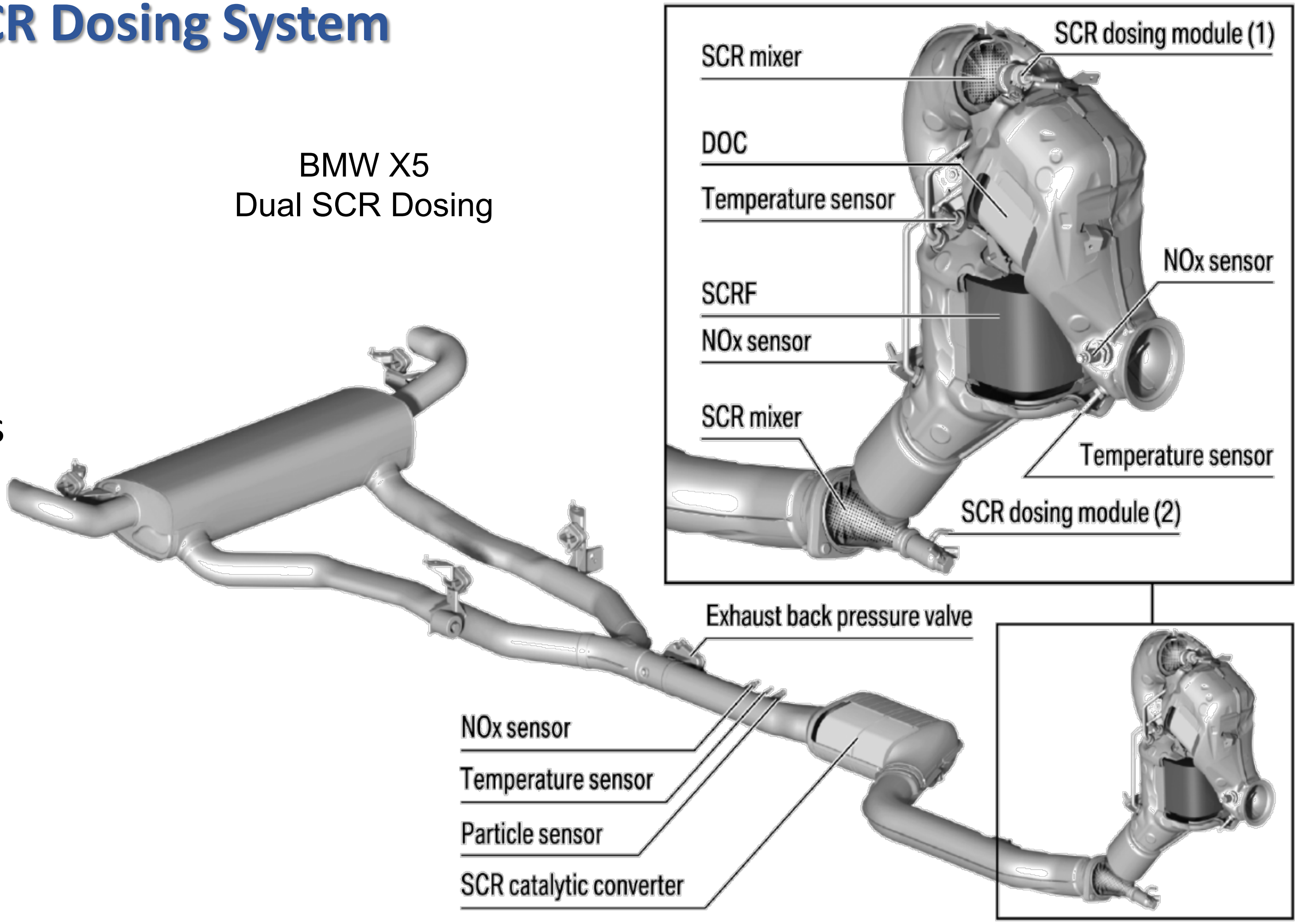
R. Illenberger et al. (2020) "Super Sports Cars in the Compact Class; the world's most powerful four-cylinder engine in series production, made in Affalterbach"

Light-duty Diesels with Dual-SCR Dosing System

- VW 2.0L EA288
- BMW 3.0
  - Dual VGT
  - Up to 40% EGR at light loads
  - 48-volt P0

Note: VW and BMW have no plans to bring either engine to the U.S.

BMW X5
Dual SCR Dosing



C. Helbing et al. (2020) *"Volkswagen's TDI-Engines for Euro 6d – Clean Efficiency for Modern Mobility"*

F. Steinparzer et al. (2020) *"The technical concept of the new BMW 6-cylinder 2nd generation modular Diesel engines"*