Benchmarking and Characterization of a Full Continuous Cylinder Deactivation System

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Benefits and Challenges of Cylinder Deactivation

CDA has the potential to improve engine efficiency at relatively low cost.

- Reduced pumping
- Reduced cylinder heat transfer
- Improved throttle response

Challenges:

- Transitions
- NVH
- Durable deactivation system
- Benefit limited to low engine load

Types of Cylinder Deactivation

EPA considering two types of CDA:

deacPD = partial discrete (e.g., 8 or 4 cylinders)

deacFC = full continuous (e.g., continuous between 0-8 cylinders)

Why is EPA Interested?

EPA continuously evaluates advanced technologies to support the setting of appropriate GHG standards.

- Light-duty GHG standards through 2025 are being reconsidered and revised.

EPA's prior analysis[1] considered deacPD but not deacFC.

DeacFC is a potential enabler for meeting GHG standards[2].

This investigation was conducted to benchmark and characterize deacFC and evaluate its potential as an advanced, production-ready technology for reducing GHG emissions.

1) EPA, 2017, EPA-420-R-17-001
2) Younkins et al., 2017, 38th International Vienna Motor Symposium

Objectives

Characterize effectiveness and fly zone of deacFC

- Steady-state tests
  - ✓ EPA chassis benchmarking – V8
  - ✓ Tula engine publications – V8, I4

effectiveness curves
for I3, I4, V6, V8

- Drive cycle tests
  - ✓ EPA benchmarking – V8
  - ✓ Tula publications – V8

deacFC fly zone

Initial full vehicle modeling using ALPHA

Compare drive cycle
efficiencies from
simulation and lab

Compare deacFC benefit
on two vehicle types

deacFC Vehicles

Photo by Tula

Tula Technology Dynamic Skip Fire (DSF) applied to 2011 GMC Yukon Denali 6.2L L94

- fires 0-8 cylinders
- EPA and Tula

Photo by Tula

Tula Technology DSF applied to 2015 VW Jetta 1.8L EA888

- fires 0-4 cylinders
- Tula

Steady-State Operation

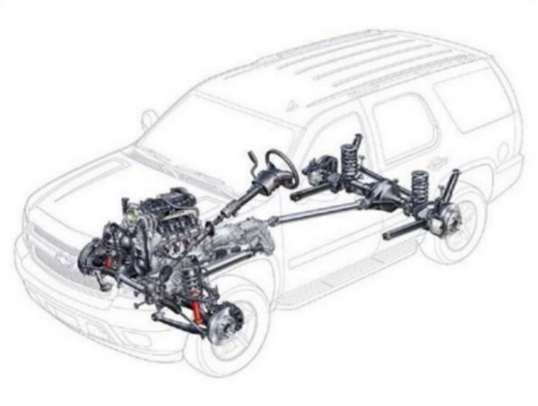
deacFC benefit on V8 (EPA benchmarking)

Test vehicle provided by Tula Technology
MY2011 GMC Yukon Denali 2WD
6.2L L94 V8 PFI gasoline engine
6L80 6-speed automatic transmission
Tier 2, 93 AKI test fuel

“V8 mode”
- GM ECU, disabled AFM
- Torque converter slip: 17-39 rpm

“deacFC mode”
- Tula ECU, deacFC
- Torque converter slip: 28-85 rpm

Steady-State Chassis Tests (EPA benchmarking)



Vehicle

- 49 and 81 mph

Engine

- deacFC and V8 mode
- 1200 – 2600 rpm
- 0.3 – 5.8 bar BMEP (add variable gradient load to SET road load)

Torque Converter

- 17 – 85 rpm slip

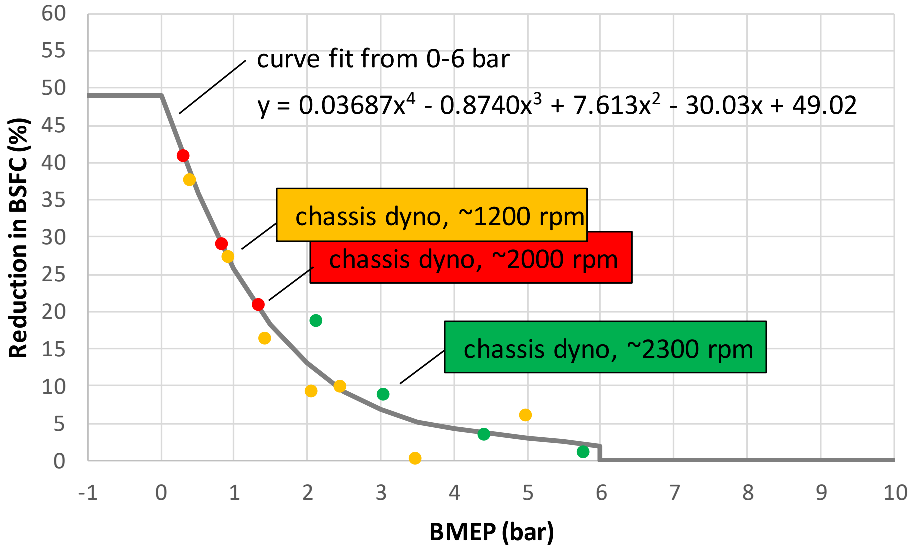
Transmission

- 5^{th} and 6^{th} gear

Component	Loss	Source
Electrical load	0.42 kW	benchmarking
Torque converter	0.03 – 2.17 kW	engine speed and torque, chassis roll speed
Transmission	1.31 – 3.82 kW	2014 GM 6L80 benchmarking[3]
Differential	0.38 – 2.65 kW	1999 Ford 3.55 differential/axle benchmarking[4]
Drive tires	2.35 – 3.90 kW	C_{rr}=0.009[5], test weight=6000 lbs, wt dist.=55/45

3) Stuhldreher et al., SAE 2017-01-5020
4) EPA and SwRI, 1999, Contract No. 68-C7-0012
5) NAS, 2006, Tires and Passenger Vehicle Fuel Economy

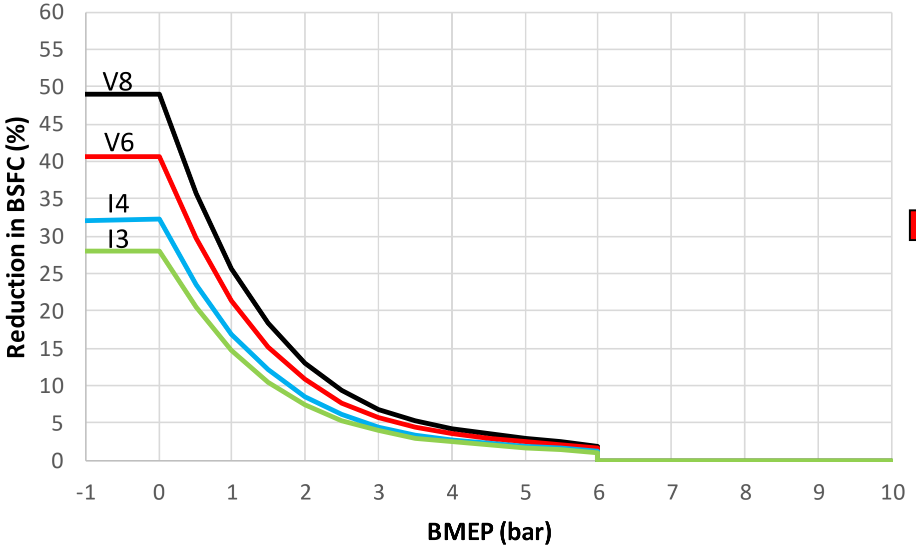
deacFC benefit on V8 (EPA benchmarking)



curve fit from 0-6 bar

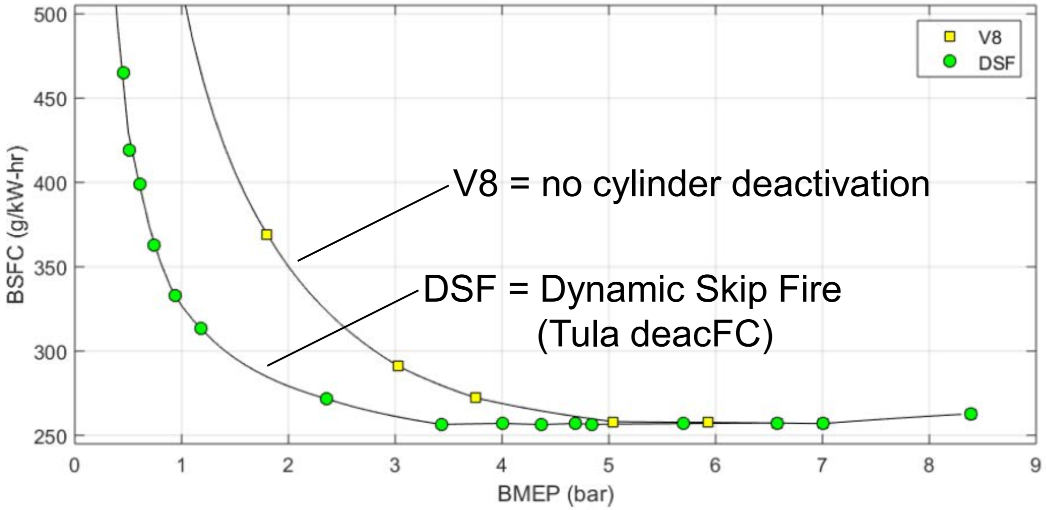
$y = 0.03687x^4 - 0.8740x^3 + 7.613x^2 - 30.03x + 49.02$

<u>chassis dynamometer testing</u>
MY2011 Yukon Denali
GM 6.2L L94 V8 PFI engine
Tier 2, 93 AKI test fuel



ALPHA full vehicle model
(EPA effectiveness)

deacFC benefit on V8 (Tula publication)



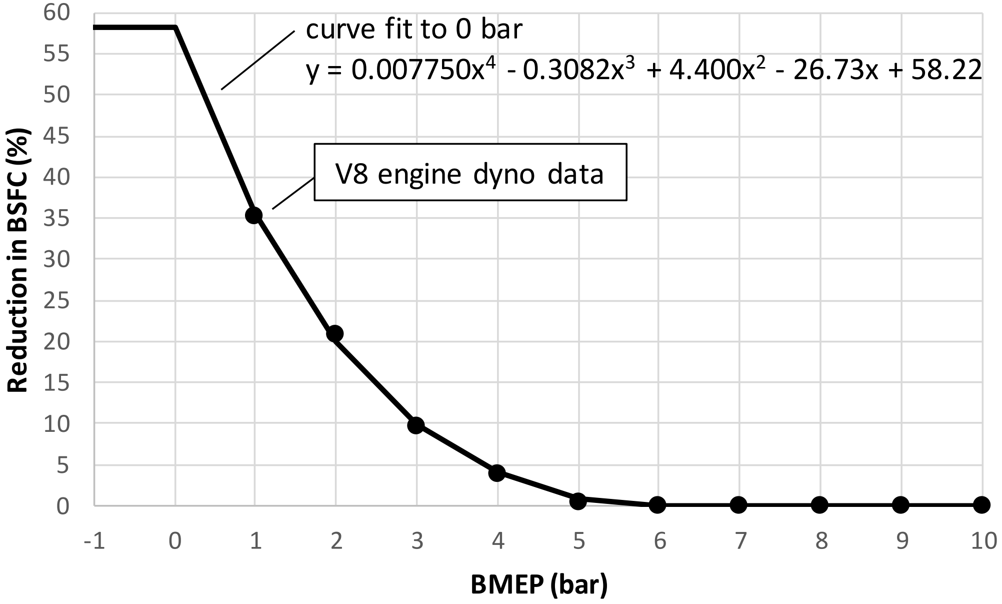
V8 = no cylinder deactivation

DSF = Dynamic Skip Fire
(Tula deacFC)

Figure 7: Fuel Consumption for DSF and V8 operation, 1600 RPM

<u>engine dynamometer testing</u>[2]
GM 6.2L L94 V8 PFI engine
1600 rpm
93 AKI fuel

* GHG standards call for Tier 2 test fuel
* deacFC benefit would be lower with lower AKI



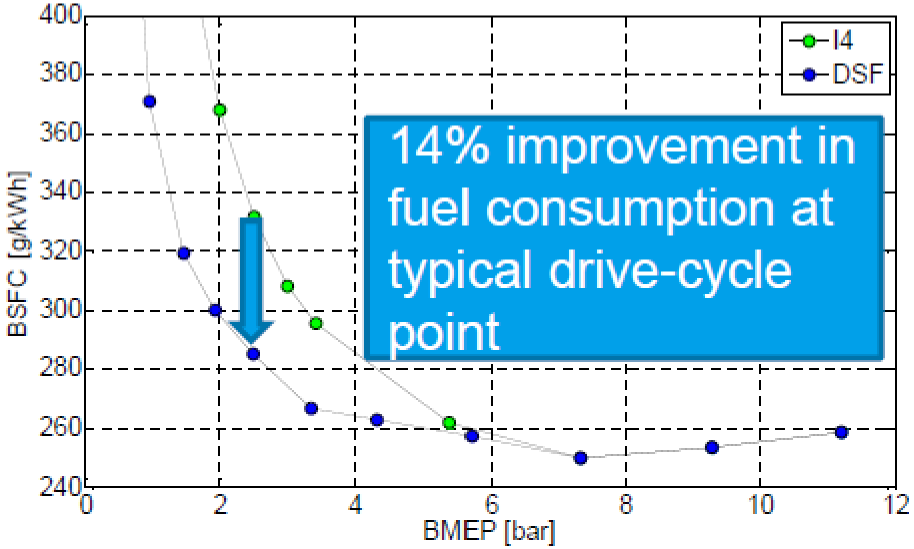
curve fit to 0 bar
$y = 0.007750x^4 - 0.3082x^3 + 4.400x^2 - 26.73x + 58.22$

V8 engine dyno data

- Extrapolating benefit to -2 bar adds less than 0.1% benefit in FTP-75 (simulation result) because engine doesn't spend time here.

[2] Younkins et al., 2017, 38th International Vienna Motor Symposium

deacFC benefit on I4 turbo (Tula publication)



14% improvement in fuel consumption at typical drive-cycle point

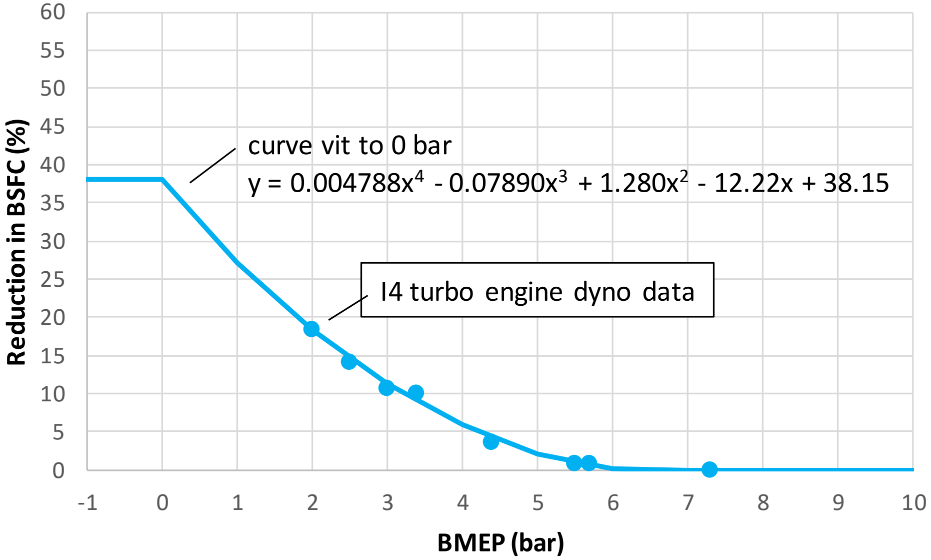
<u>engine dynamometer testing</u>[6]

VW 1.8L EA888 I4 turbo engine

1600 rpm

87 AKI CARB fuel

- GHG standards call for Tier 2 test fuel
- Use of 87 AKI gives a lower (conservative) deacFC benefit



curve vit to 0 bar

$y = 0.004788x^4 - 0.07890x^3 + 1.280x^2 - 12.22x + 38.15$

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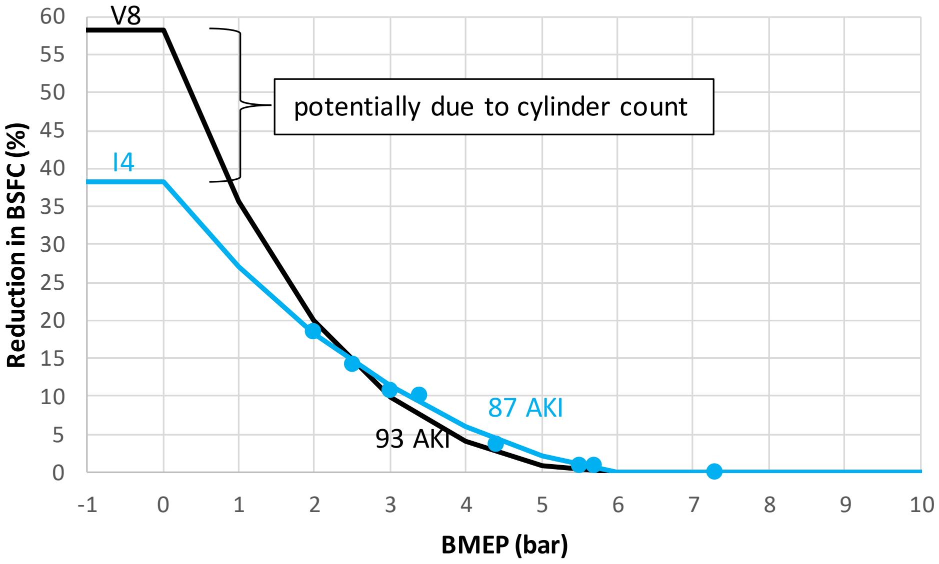
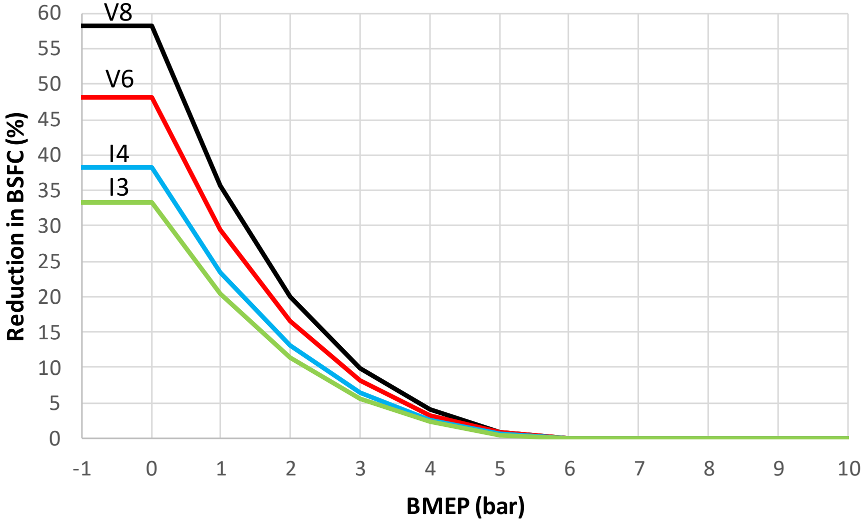
[6] Fuschetto et al., 2017, Oral-Only Presentation, SAE World Congress

deacFC benefit scaled to V8, V6, I4, I3 (Tula publication)

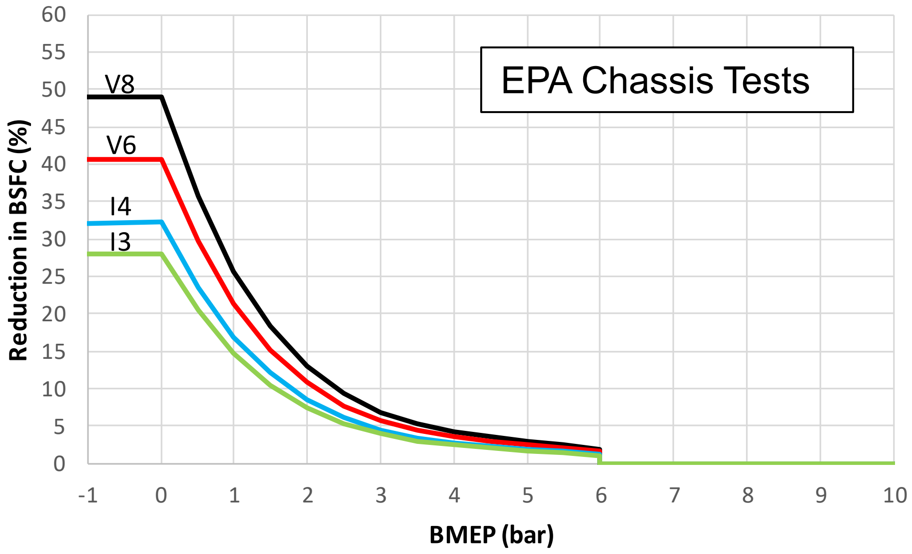


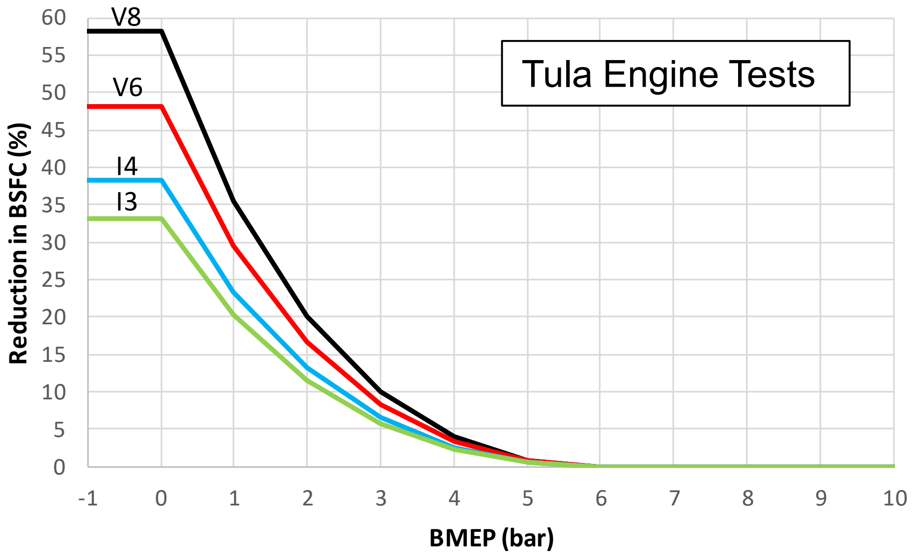
Assume benefit at 0 bar scales with cylinder number (NVH)
I3, I4, V6 curves for 87 AKI tests (conservative) since GHG standards specify 93 AKI

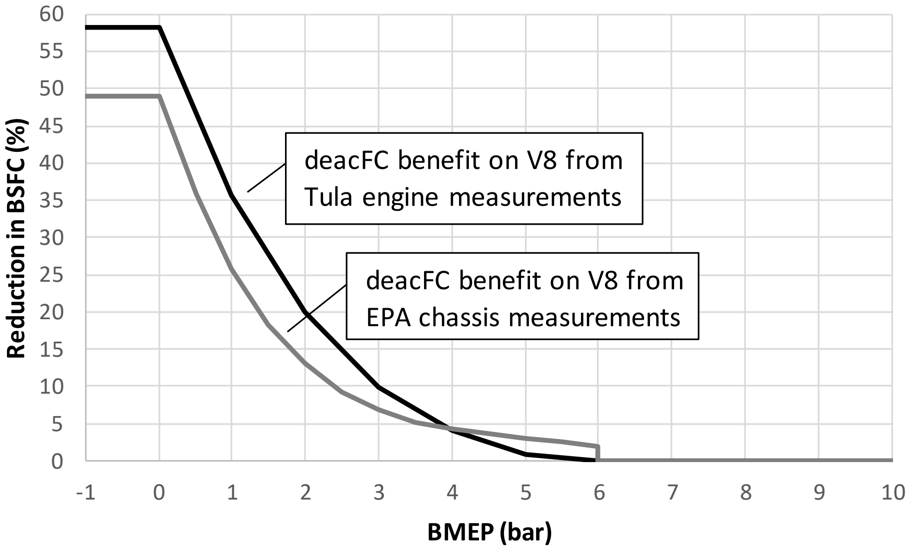


ALPHA full vehicle model
(Tula effectiveness)

Comparing EPA Chassis and Tula Engine deacFC Effectiveness







- ❖ EPA and Tula effectiveness curves are very similar.

Drive Cycle Operation

deacFC benefit on V8 (Tula publication[2])

Chassis dynamometer testing
MY2011 GMC Yukon Denali 2WD
6.2L L94 V8 PFI gasoline engine
6L80 6-speed automatic transmission
Tier 2, 93 AKI test fuel

Photo by Tula

“V8 mode”

- GM ECU, disabled AFM and DFSO
- GM transmission shift strategy

“deacFC mode”

- Tula ECU, deacFC and DFSO
- Slightly higher torque converter slip

[2] Younkins et al., 2017, 38th International Vienna Motor Symposium

deacFC benefit on V8 (Tula publication[2])

FTP-75 | **HWFET** | **US06**

17% FE Improvement | *9.0% FE Improvement* | *6.1% FE Improvement*

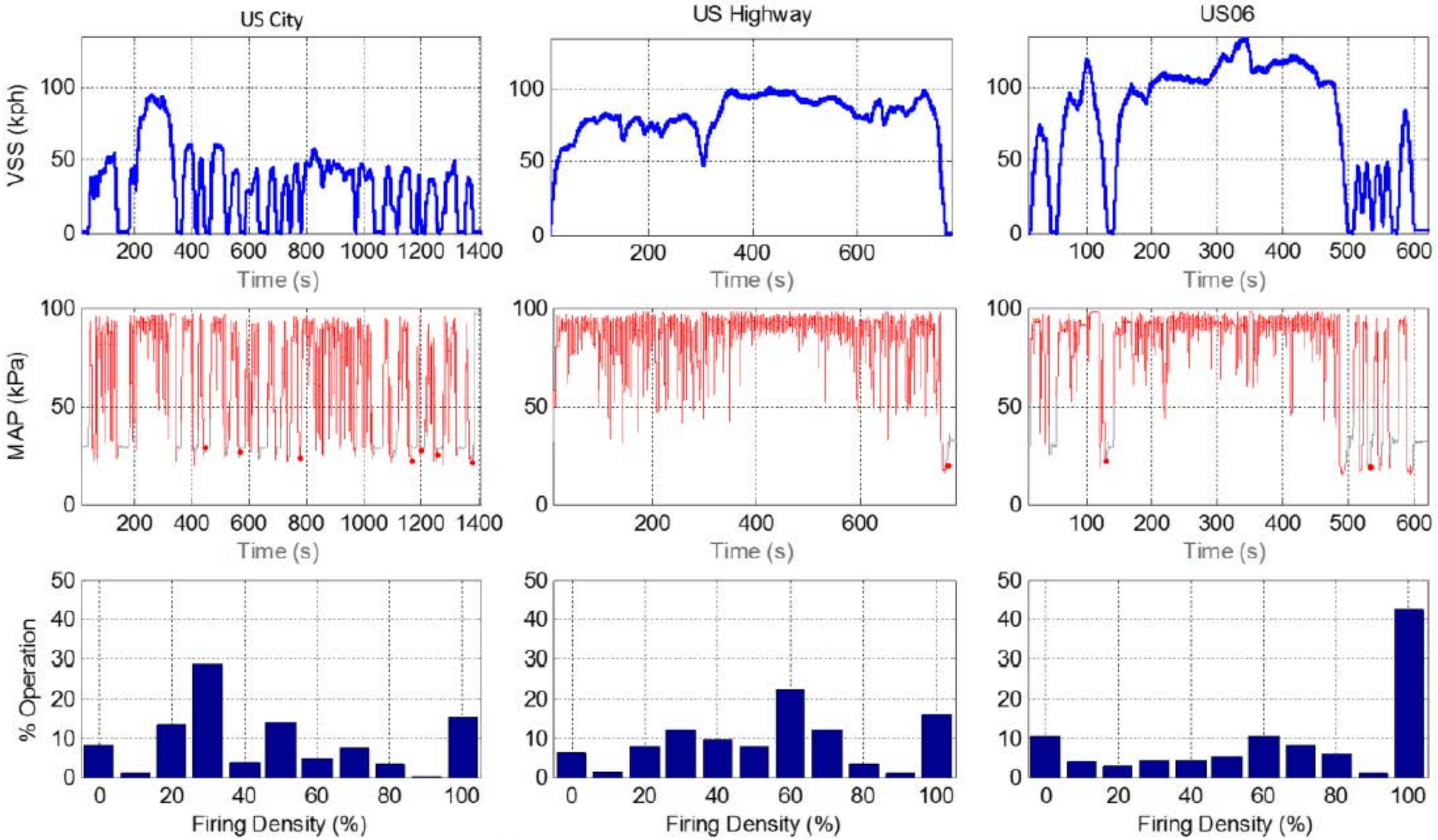


Figure 12: Results of Fuel Economy Testing with DSF, compared to V8 operation

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[2] Younkins et al., 2017, 38th International Vienna Motor Symposium

deacFC benchmarking at EPA

Drive cycle benchmarking performed to:

1) Compare EPA and Tula results
2) Quantify deacFC ‘fly zone’ needed for vehicle modeling

Test vehicle:

MY2011 GMC Yukon Denali 2WD
6.2L L94 V8 PFI gasoline engine
6L80 6-speed automatic transmission
Tier 2, 93 AKI test fuel

“V8 mode”

- GM ECU, disabled AFM and DFSO
- GM transmission shift strategy
- Passed Tier 2 bin 5 NMOG, CO, NO_x, PM

“deacFC mode”

- Tula ECU, deacFC and DFSO
- Slightly higher torque converter slip
- Passed Tier 2 bin 5 CO, NO_x, PM

deacFC benefit on V8

	Tula publication[2]	EPA benchmarking*
FTP-75	17.0 %	13.4 % (14.6 → 16.5 mpg)
HWFET	9.0 %	9.9 % (25.0 → 27.5 mpg)
US06	6.1 %	9.5 % (14.4 → 15.7 mpg)

EPA benchmarking shows:

- Smaller deacFC benefit in FTP-75, higher deacFC benefit in HWFET and US06
- Average of 3 cycles almost identical (10.9% versus 10.7% improvement)

Why the difference?

- different driver, different lab, different day
- deacFC benefit is the ratio of 2 tests (MPG_{deacFC}/MPG_{V8}); error stacking

Note

- DFSO is active in deacFC mode but not in V8 mode
- Full vehicle modeling[7] shows DSFO provides 2.5% benefit in FTP-75 and 1.2% in HWFET in V8 mode.

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[2] Younkins et al., 2017, 38th International Vienna Motor Symposium

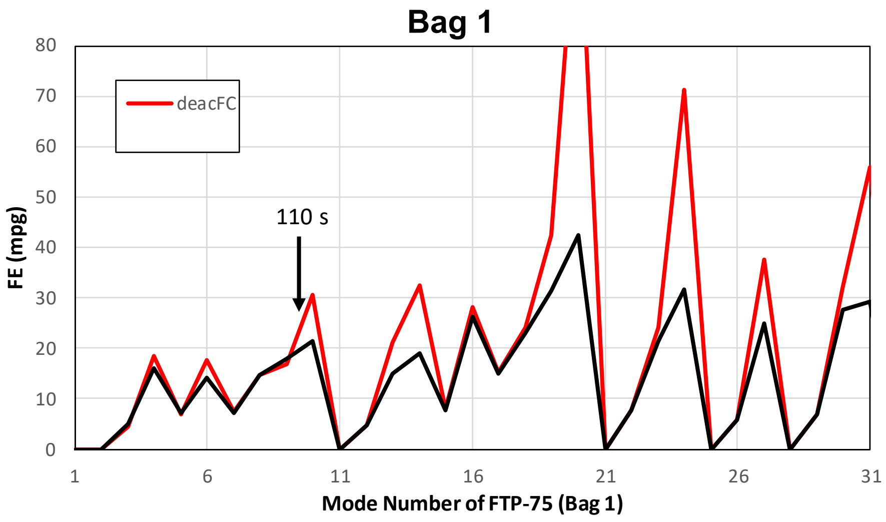
[7] ALPHA model introduced by Lee et al., SAE 2013-01-0808

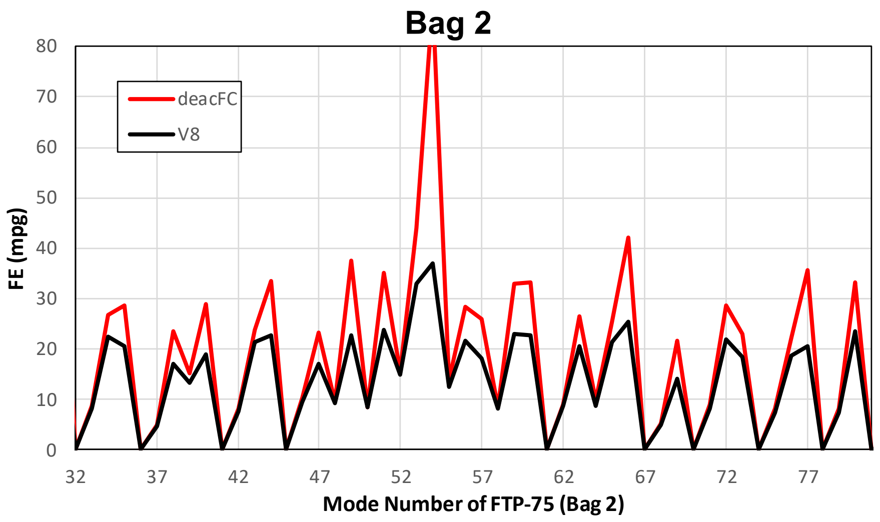
* Average of 2 tests in V8 mode / average of 2 tests in V8 mode

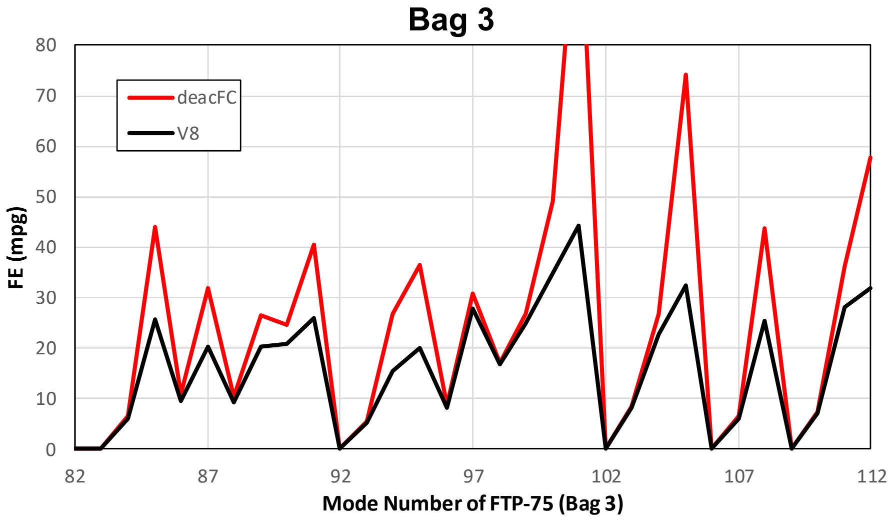
deacFC benefit on V8 – FTP-75 by Bag (EPA benchmarking)

	deacFC relative to V8 (% improvement in MPG)	**Comment**
Bag 1	7.1 %	deacFC inactive until oil warms
Bag 2	15.8 %	Lowest engine loads
Bag 3	14.0 %	Higher loads than bag 2

deacFC benefit on V8 – FTP-75 by Mode (EPA Benchmarking)







- deacFC becomes active after 110 s.
- deacFC advantage only present when FE is high (low engine load).

deacFC Fly Zone on V8 (EPA benchmarking)

Used FTP-75, HWFET, US06 tests and MAP to quantify V8 deacFC fly zone.

Activate deacFC if all conditions are true:

1) $T_{coolant} > 47.3°C$
2) Engine speed > 940 rpm
3) Gear = 2-6

ALPHA full vehicle model

Full Vehicle Modeling

ALPHA Full Vehicle Model of V8 Yukon

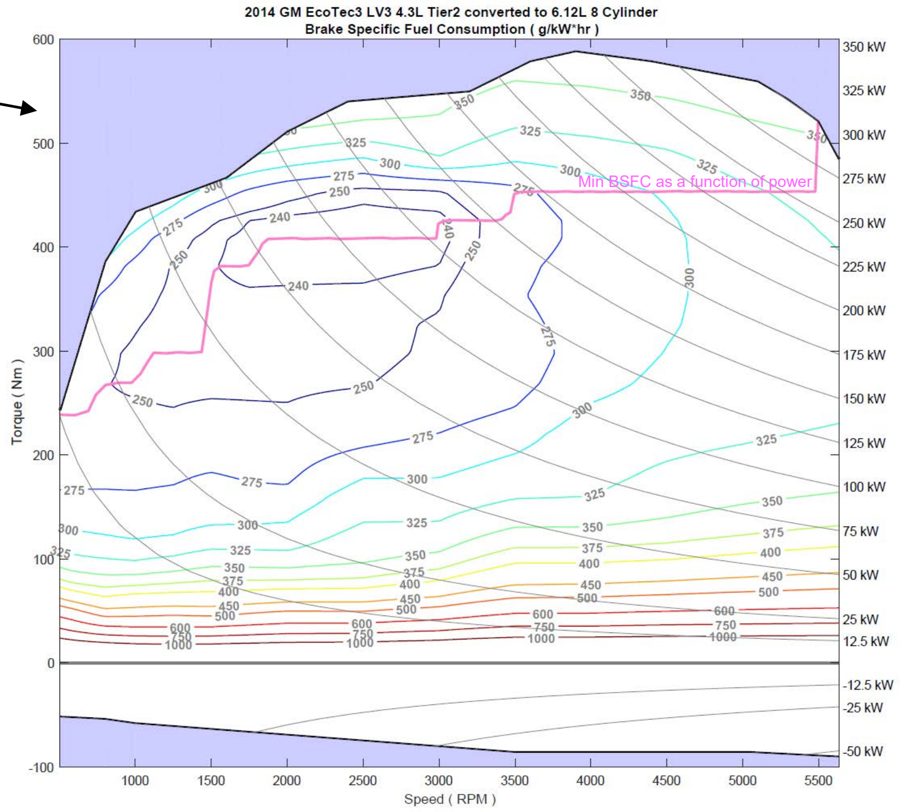
ALPHA full vehicle model[7]

Vehicle characteristics

- Test weight=6000 lbs
- Road load coefficients: A=32.15 lb, B=1.0382 lb/mph, C=0.02111 lb/mph^2

Engine

- GM 4.3L LV3 engine[8] scaled to GM 6.2L L94 considering[9]:
  - Heat transfer
  - Friction
  - Knock propensity
- Engine inertia=0.33 kg/m^2 (scaled based on displacement)
- deacFC effectiveness curve from
  - a) EPA chassis tests
  - b) Tula engine tests
- deacFC fly zone from EPA chassis tests
- DFSO
  - allowed in deacFC mode
  - not allowed in V8 mode



Torque converter

- Locked
- Semi-locked
  - 26 rpm slip in V8 mode
  - 55 rpm slip in deacFC
- Unlocked

Transmission

- 2014 GM 6L80 benchmarking[3]
- Min. downshift speed=540 rpm
- Min. upshift speed=1200 rpm

Differential

- 3.42 ratio
- 1999 Ford 3.55 differential/axle benchmarking[4]

Tier 2 Fuel:

- ρ=0.74277 g/cm^3@60F
- H/C=1.836 molar ratio
- LHV=42.898 MJ/kg

3) Stuhldreher et al., SAE 2017-01-5020
4) EPA and SwRI, 1999, Contract No. 68-C7-0012
7) Lee et al., SAE 2013-01-0808
8) Stuhldreher, SAE 2016-01-0622
9) Dekraker et al., SAE 2017-01-0899

Chassis Tests and Full Vehicle Model – V8 Yukon

	EPA chassis dyno	**ALPHA model EPA chassis dyno effectiveness**
FTP-75	14.6 → 16.5 mpg 13%	14.7 → 16.5 mpg 13%
HWFET	25.0 → 27.5 mpg 10 %	24.9 → 27.5 mpg 11 %

- deacFC mode (with DFSO) compared to V8 mode (no DFSO)
- DFSO provides 2.5% benefit in FTP-75 and 1.2% in HWFET in V8 mode

	Tula chassis dyno[2]	**ALPHA model Tula engine dyno effectiveness**
FTP-75	17%	18%
HWFET	9%	16%

- deacFC mode (with DFSO) compared to V8 mode (no DFSO)
- DFSO provides 2.5% benefit in FTP-75 and 1.2% in HWFET in V8 mode

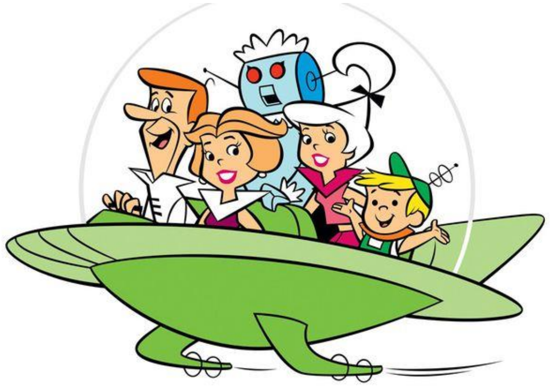
[2] Younkins et al., 2017, 38th International Vienna Motor Symposium

Combined Cycle Simulation Results
2011 Large SUV and 2025 Midsize Car

Vehicle	Description	CO$_2$ Reduction (g/mi) Only Adding deacFC Combined Cycle

2011 Large SUV

Photo by Tula
	Vehicle: 2011 GM Yukon Denali
	Engine:
	  2014 GM 4.3L LV3 scaled to 6.2L[9]
	  DFSO
	  no stop/start
	  no AFM
	  2011 GM Yukon accessories
	  deacFC effectiveness from EPA chassis tests
	Transmission: 6-speed GM 6L80
		8.8%

2025 Midsize Car

The Jetsons
	Vehicle: typical 2016 midsize car[10] with:
	  7.5% curb weight reduction
	  10% aerodynamic improvement
	  10% coefficient of rolling resistance reduction
	Engine:
	  2016 Honda 1.5L L15B7 scaled to 1.42L[9,10]
	  DFSO
	  stop/start
	  no CDA
	  high efficiency accessories[11]
	  deacFC effectiveness from EPA chassis tests, scaled to I4
	Transmission: future 8-speed[11]
		2.6%

9) Dekraker et al., SAE 2017-01-0899
10) Stuhldreher et al., SAE 2018-01-0319
11) EPA, 2016, EPA-420-R-16-021

Summary and Conclusions

Characterized deacFC effectiveness and fly zone

- Demonstration vehicle that met NVH and emissions constraints
- Benefit curves for I3, I4, V6, V8
- Fly zone

Conducted preliminary full vehicle modeling

- deacFC-equipped 6.2L Yukon
- Compared drive cycle efficiencies from chassis tests and full vehicle model
- Compared combined cycle CO_2 reduction for 2011 large SUV and 2025 midsize car

Based on this investigation, EPA considers deacFC to be a promising production-ready technology for reducing GHG emissions.

Acknowledgements

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