Study for Inline-4 Cylinder Gas Engines

Contract No. 7F-30004

18 January 2017

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Content

This report captures three (3) primary tasks:

1. Review and answer outstanding questions from report issued March 13, 2014 titled " Impact of Advanced Engine and Powertrain Technologies on Targets and Fuel Displacement"
2. Document updated engine maps for turbocharged engines #12-16 based on operation on 87 AKI fuel

Description	Gas/Dies	AKI	#cyl	Disp	DOHC/SOHC	PFI/DI	CR	VVT	VVL	DEAC	Turbo	bar	CEGR
Engine 12Reg - Turbo 1.6L 18 bar BMEP	Gas	87	4	1.6	DOHC	DI	10.5			0	1	18	0
Engine 13Reg - Turbo 1.2L 24 bar BMEP	Gas	87	4	1.2	DOHC	DI	10.5			0	1	24	0
Engine 14Reg - Turbo 1.2L 24 bar BMEP + cooled EGR	Gas	87	4	1.2	DOHC	DI	10.5			0	1	24	1
Engine 15Reg - Turbo 1.0L 27 bar BMEP + cooled EGR	Gas	87	4	1	DOHC	DI	10.5			0	1	27	1
Engine 16Reg - Turbo 1.0L 27 bar BMEP + cooled EGR (3 cyl)	Gas	87	3	1	DOHC	DI	10.5			0	1	27	1

3. Document four (4) new maps for Engines #18-21 which reflect naturally aspirated variants that were not covered in the initial study

Description	Gas/Dies	AKI	#cyl	Disp	DOHC/SOHC	PFI/DI	CR	VVT	VVL	DEAC	Turbo	bar	CEGR
Engine 18 (NEW) - VVT + SGDI	Gas	87	4	2	DOHC	DI		1	0	0	0		0
Engine 19 (NEW) - VVT + DEAC	Gas	87	4	2	DOHC	PFI		1	0	1	0		0
Engine 20 (NEW) - VVT + VVL + DEAC	Gas	87	4	2	DOHC	PFI		1	1	1	0		0
Engine 21 (NEW) - VVT + SGDI + DEAC	Gas	87	4	2	DOHC	DI		1	0	1	0		0

Responses to Alliance of Automobile Mfg

- Pages 4 to 12 of this report include responses to comments made by “Alliance of Automobile Manufactures Comments on Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025 (EPA-420-D-16-900, July 2016)”
- Note that some questions raised by the Alliance of Automobile Manufactures addressed in following slides are a result of direct comparison of IAV’s map to a specific production engine. There are numerous factors stemming from hardware, software and calibration differences such that two engines with the same displacement and overall general technology may have gross differences in BSFC when comparing the overall map.

Engine 1 MAP

The Alliance has the following concerns with IAV Gasoline Engine1 Map (NHTSA Base Engine Map). This map was compared to two similar production engines.

 For low- to medium-load and sub-1,000 revolutions-per-minute (RPM) conditions, the brake specific fuel consumption (BSFC) data was deemed optimistic for typical dual overhead cam (DOHC) engines. The NHTSA Base Engine Map does not reflect cam control limitations that are typical of commercial calibrations.

Aside from idle fuel flow, data was not provided <1000rpm. From Figure A-1, the concern stems from extrapolation of data <1000rpm.

IAV's maps provides fuel flow (BSFC) down to 1 bar BMEP. Fuel flow data for idle and no load was also provided, but it was not intended to be "blended" with the overall map. Interpolating between the two sets to provide data <1000rpm may result in inaccuracies. Figure A-2 comparison to the Honda Accord 2.4L <1 bar BMEP is an example of the inaccuracy resulting from limited data.

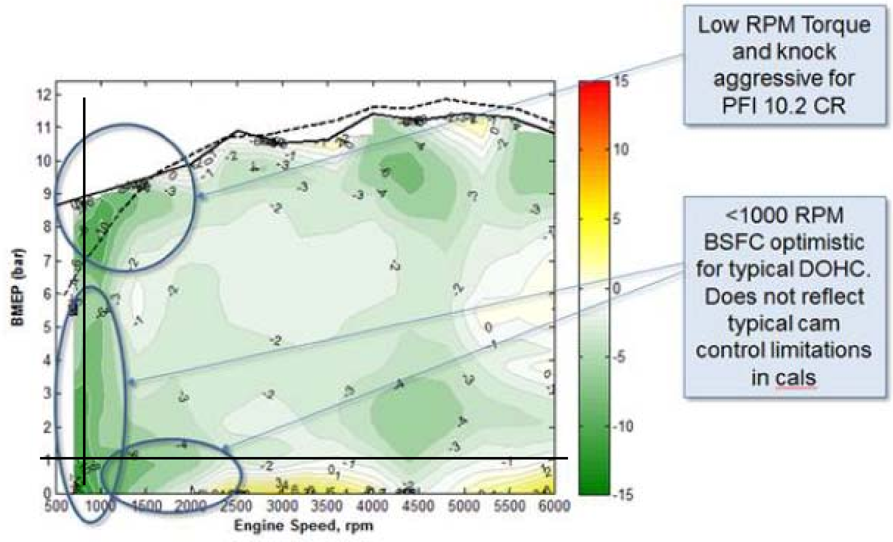
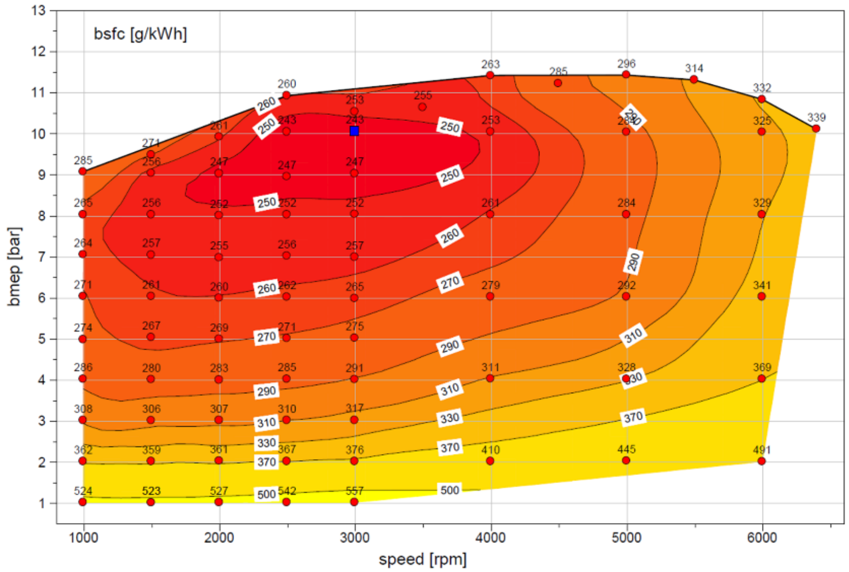


Figure A-1: Comparison of NHTSA Base Engine Map to similar OEM 2.0L Benchmark Engine

Engine 1: 2.0L, NA, PFI DOHC VVT, PFI, 10.2CR



Engine 1 MAP

- Low RPM torque and knock are aggressive for a port fuel injection (PFI) gasoline engine with 10.2 compression ratio (CR).
The low speed torque is provided for the sake of completeness as it is possible to operate the engine at that torque level. However, for practical reasons due to excessive fuel consumption, poor NVH, shift scheduling, etc., the engine would not typically operate in that area of the map. It is therefore possible/practical to reduce the engine performance <1500rpm, but this is expected to have zero impact on the vehicle level fuel consumption modeling or vehicle performance.

- The NHTSA Base Engine Map is also very aggressive at lower loads. This is evidenced by a comparison of industry benchmark data for an engine that has the benefit of additional technology such as variable valve lift (VVL) and higher compression ratio.
The benchmark Honda Accord 2.4L is a larger displacement engine that is of higher performance. As such it will carry more friction which is especially detrimental at lower loads. The Honda engine is also a 2-step VVL system with a switching point that is speed dependent, therefore it is unclear whether there would be any BSFC benefits at low loads.

Figures A-1 and A-2 below capture the BSFC delta comparison with the key findings.

Figure A-1 is a comparison to an original equipment manufacturer (OEM) benchmark 2.0L, four cylinder (cyl), naturally aspirated (NA), PFI, DOHC, dual cam variable valve timing (VVT), 10.2 CR engine.

Figure A-2 is a comparison to a Honda Accord 2.4L, 4cyl, NA, gasoline direct injected (GDI), DOHC, VVT, 2-step VVL, 11.1 CR engine benchmarked by the United States Council for Automotive Research (USCAR). These comparisons illustrate the optimistic assumptions in the NHTSA Base Engine Map, as the efficiency of the NHTSA Base Engine Map is similar to a production engine with much more technology.

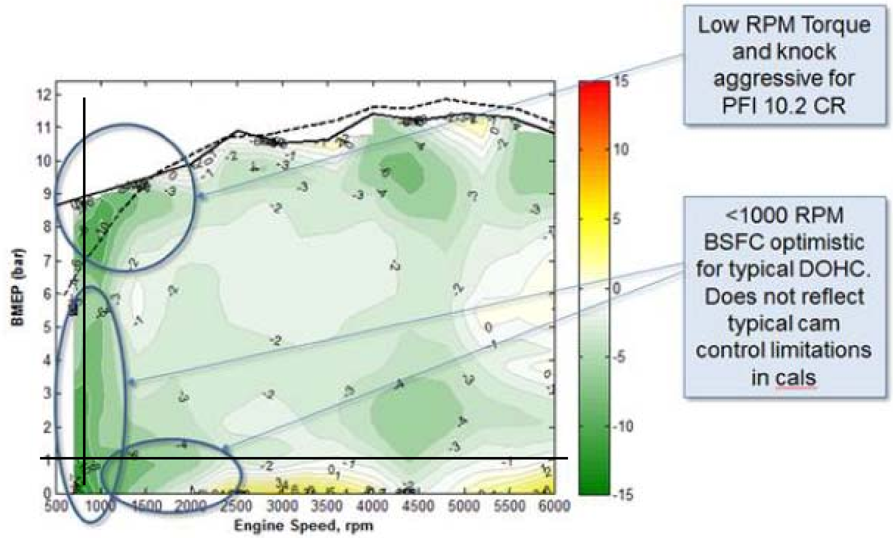


Figure A-1: Comparison of NHTSA Base Engine Map to similar OEM 2.0L Benchmark Engine

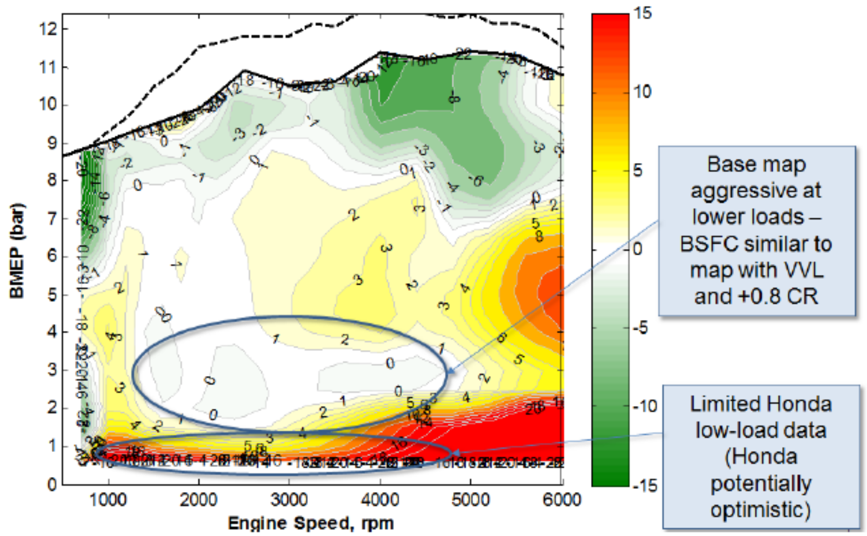


Figure A-2: Comparison of NHTSA Base Engine Map to Honda Accord 2.4L Engine

Engine 2 Map

The following concerns are based on the analysis of the IAV Gasoline Engine2 Map,49 which adds VVL to the NHTSA Base Engine Map:

- The increased torque and knock relief levels at low RPM are aggressive for just the addition of VVL to the base engine.

The low speed torque is provided for the sake of completeness as it is possible to operate the engine at that torque level. However, for practical reasons due to excessive fuel consumption, poor NVH, shift scheduling, etc., the engine would not typically operate in that area of the map. It is therefore possible to reduce the engine performance <2000rpm, but this will have zero impact on the vehicle level fuel consumption modeling or vehicle performance.

- The variable valve lift modeled appears to be continuously variable valve lift (CVVL); this should be clarified by NHTSA.

It is confirmed that the engine map represents an engine with CVVL.

- At low load (less than two bar) the CVVL benefit modeled assumes excellent combustion, and the pumping work reduction with CVVL is overstated.

Honda's VVL is a 2-step system that operates independent of load. IAV's model is for an engine with CVVL that is optimized for each load and speed point, hence true benefits from "unthrottled" operation is realizable at low loads.

Figure A-3 compares the BSFC of the NHTSA Base Engine Map to the IAV Gasoline Engine2 Map with the key findings highlighted.

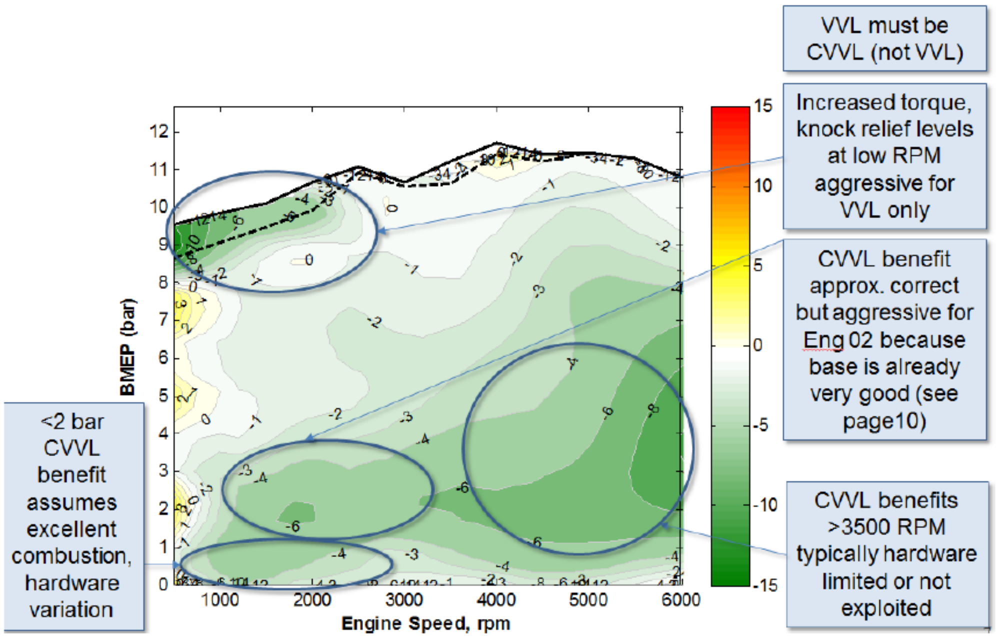


Figure A-3: Comparison of IAV Gasoline Engine2 Map to NHTSA Base Engine Map

Engine 3 Map

IAV Gasoline Engine3 Map50 adds GDI technology and increases compression ratio by 0.8. When compared to IAV Gasoline Engine3 Map and the Honda 2.4L engine map the following observations are made:

- The GDI pump friction isn't properly taken into account (Figure 1-4).
The additional loading from a GDI pump in the low load region is very low at ~0.2kW. This is readily offset by the benefits from direct injection.

- Optimistic knock relief assumptions are used (Figure 1-4).
At low speeds and high loads most engines are knock limited, engine 3 is no exception to this. There are however many factors that will influence the knock tolerance including volumetric efficiency, mixture formation, swirl, tumble, TKE, local hot spots in the combustion chamber, cooling, injection timing, calibration…Short of comparing the exact attributes of the Honda Engine it is not possible to compare the two engines, because it's clear that in certain areas engine 3 performs better whereas in other areas the Honda engine shows much better results.

- Aggressive CVVL assumptions for low load operation were made across the speed band (Figure 1-5).
With CVVL, it is possible to optimize phasing and lift to minimize pumping losses at all speed and load. Additionally the CVVL system scales both lift and duration by the same ratio, i.e. if lift is reduced 50% than duration is also reduced by 50%.

- The pumping work reduction is overstated, especially considering that the benchmark Honda engine used for comparison here is already a 2-Step VVL engine (Figure 1-5).
A 2-step VVL system has a reduced range of efficiency compared to a CVVL system. Further more the Honda engine VVL switch point is speed dependent.

Figures A-4 and A-5 below capture the BSFC comparison with the key findings. Figure A-4 is a
comparison to IAV Engine2 Map to isolate estimated GDI benefits. Figure A-5 is a comparison
to the USCAR benchmarked Honda 2.4L engine with similar technologies.

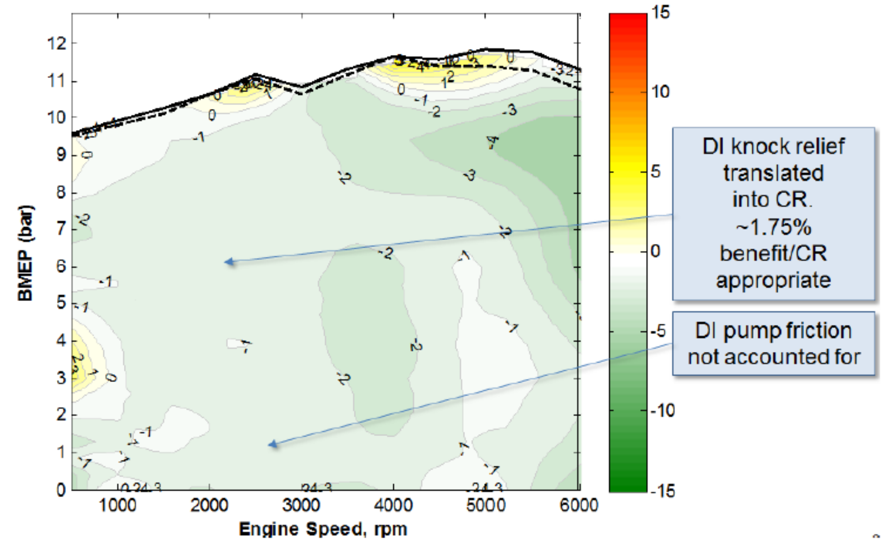


Figure A-4: Comparison of IAV Engine3 Map to IAV Engine2 Map

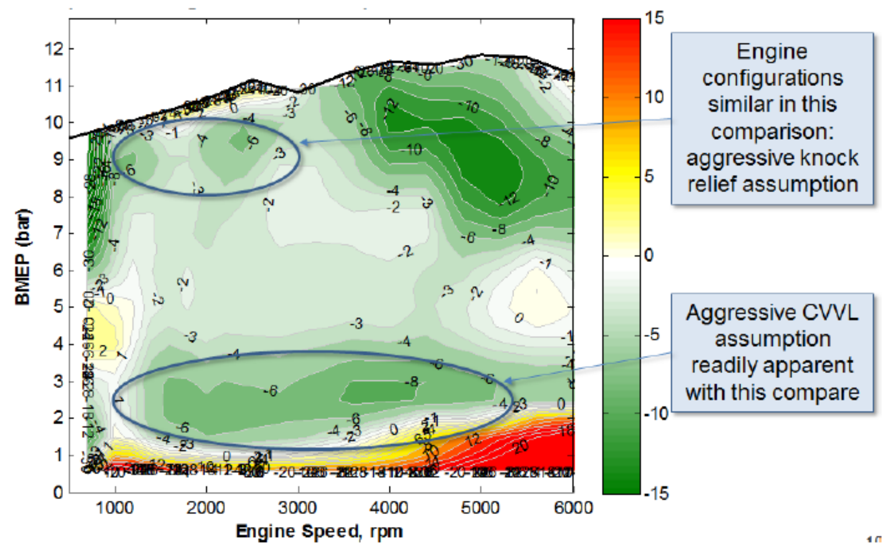


Figure A-5: Comparison of IAV Engine3 Map to Honda Accord 2.4L Engine

Engine 4 Map

The following issues were identified with IAV Engine4 Map,51 which adds cylinder deactivation technology to IAV Engine3 Map:

- The typical range of cylinder deactivation for production engines is limited to engine operation greater than 1,000 RPM to avoid idle interaction. However, IAV Engine4 Map does not display a low RPM limitation.

Specific to cylinder deactivation, due to reasons of NVH and efficiency, cylinder deactivation is limited to 1000-3000rpm and below 4 bar. Note that it is incorrect to interpolate data points that reside outside the immediate boundaries of deac operation. Meaning that outside the deac range results from engine 3 should be used explicitly. This is a communication error on the part of IAV, we should have provided only the data for the region of cylinder deac.

- Low load two-cylinder deactivation benefit is typically limited to the value seen at one bar brake mean effective pressure (BMEP). The IAV Engine4 Map suggests benefits below the one bar threshold and the map is overly optimistic in this area.

Operation of the engine in deac mode down to 0 bar BMEP is technically possible. However, the practical implementation is determined by the vehicle system.

- The cylinder deactivation control system hysteresis for the transitions in and out of cylinder deactivation mode has been neglected. Hysteresis is required to prevent frequent switching from normal to deactivated mode.

The level of hysteresis is dictated by ANL's modeling. IAV's map provide only the possible benefits of operating in cylinder deactivation.

- The approach of using a single map to characterize engines with cylinder deactivation technology may not take into account the transitional fuel usage during transitions in and out of cylinder deactivation mode.

Vehicle level modeling needs to use both maps from engine 3 (non deac) and engine 4 (with cylinder deac), in addition to applying hysteresis to prevent frequent mode switching in order to accurately model the fuel consumption. IAV would recommend a 1 bar BMEP hysteresis to prevent frequent switching.
For cold start, cylinder deactivation may not be feasible due to actuator and/or emissions limitation. Switching from deac to fired operation, an additional correction to compensate for "re-wetting" of previously deactivated cylinders may also be required.

Figure A-6 below captures the BSFC comparison with the key findings.

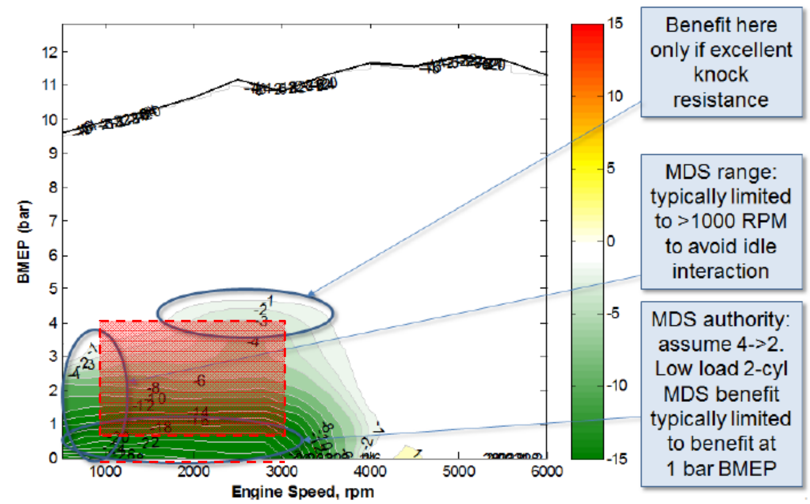
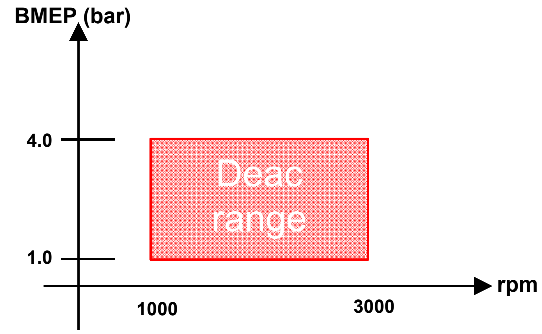


Figure A-6: Comparison of IAV Engine4 Map to IAV Engine3 Map



SOHC Map

There are broad concerns with the four engine maps with single overhead cam (SOHC) technology. These include IAV Engine Maps 5b,52 6a,53 7a,54 and 8a.55

- All four engine maps assume a large friction reduction (0.1 bar) across the board.

It is correct that a 0.1 bar reduction in friction is aggressive. The value was chosen as a demonstration of the possible benefits of friction reduction which may be possible via the combination of reduced valvetrain friction, lower viscosity oil with added friction modifiers, coatings, etc.

- Additional losses, due to loss in Effective Expansion Ratio (EER) and the change to a fixed overlap volume (OLV), are not taken into account.

Models with SOHC have a fixed overlap.

- Lower RPM torque reduction does not appear to be accounted for accurately.

Similar to engine 1, the low speed torque is provided for the sake of completeness as it is possible to operate the engine at that torque level. However, for practical reasons due to excessive fuel consumption, poor NVH, shift scheduling, etc., the engine would typically not operate in that area of the map. It is therefore possible/practical to reduce the engine performance but this is expected to have zero impact on the vehicle level fuel consumption modeling or vehicle performance.

- The benefit in the 2-4 bar region appears to be overstated given that the cams cannot move relative to each other in SOHC engines.

Data < 1000rpm is due to extrapolation. The difference at 1000rpm and 4 bar equates to a difference of 2g/kWh or 0.6%. The low RPM extrapolation exaggerates the small reduction

Figures A-7, A-8, A-9, and A-10 below capture the BSFC comparisons to with the key findings:

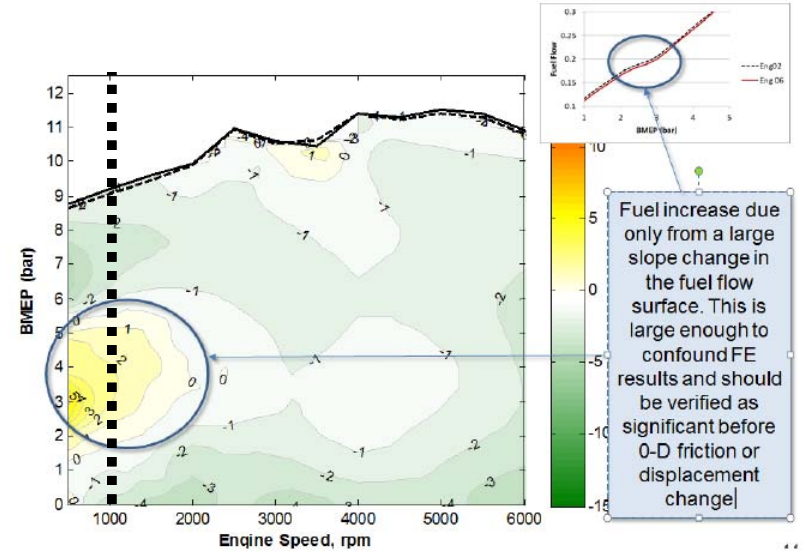


Figure A-7: Comparison of IAV Engine 5b Map to NHTSA Base Engine Map

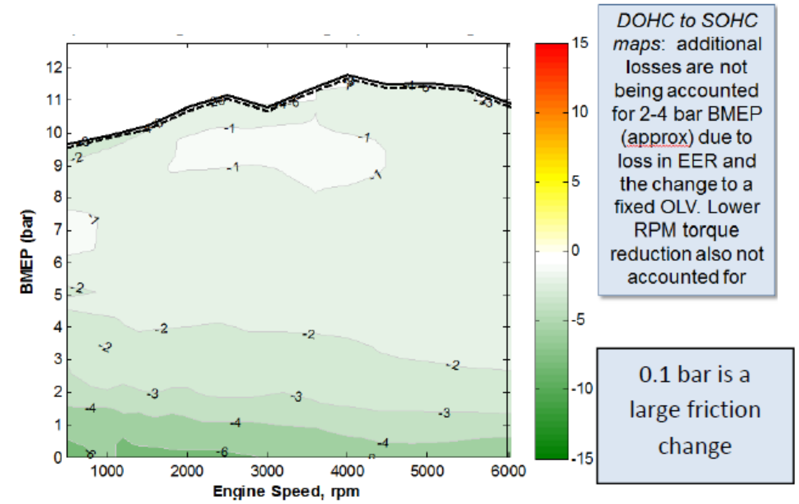


Figure A-8: Comparison of IAV Engine6a Map to IAV Engine2 Map

SOHC Map

There are broad concerns with the four engine maps with single overhead cam (SOHC) technology. These include IAV Engine Maps 5b,52 6a,53 7a,54 and 8a.55

- All four engine maps assume a large friction reduction (0.1 bar) across the board.
- Additional losses, due to loss in Effective Expansion Ratio (EER) and the change to a fixed overlap volume (OLV), are not taken into account.
- Lower RPM torque reduction does not appear to be accounted for accurately.
- The benefit in the 2-4 bar region appears to be overstated given that the cams cannot move relative to each other in SOHC engines.

Figures A-7, A-8, A-9, and A-10 below capture the BSFC comparisons to with the key findings:

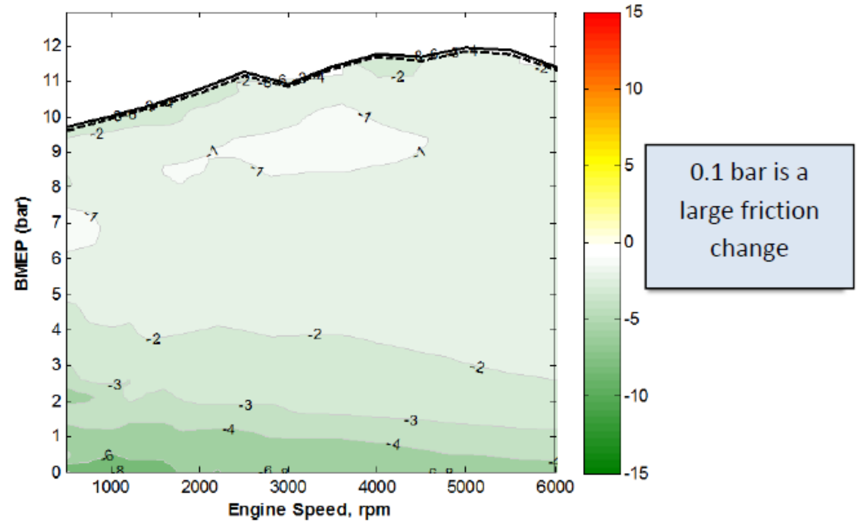


Figure A-9: Comparison of IAV Engine 7a Map to IAV Engine3 Map

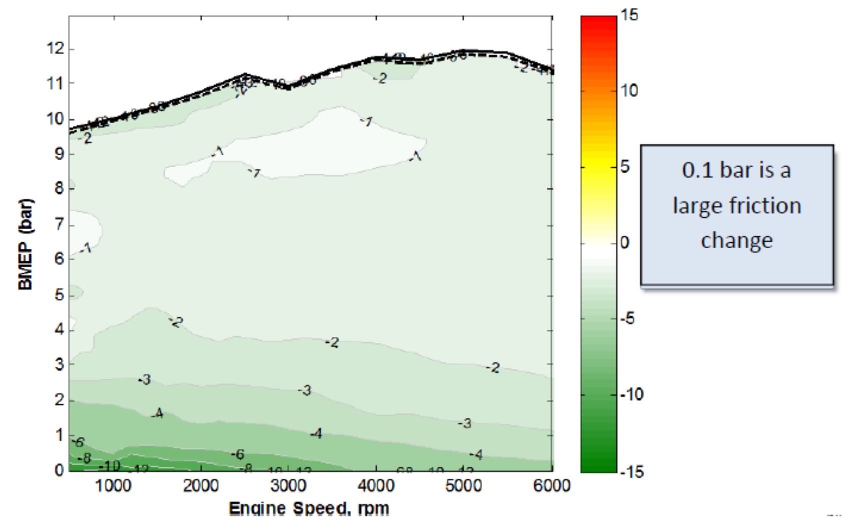


Figure A-10: Comparison of IAV Engine8a Map to IAV Engine4 Map

Boosted Engine Maps

We have concerns with IAV maps Engine12, Engine13,Engine14, and Engine15. The Draft TAR states, “IAV used gasoline with LHV = 41.3 MJ/kg for the mapping but the naturally aspirated engines were calibrated with 87 (R+M)/2 rating fuel and the turbocharged engines used 93 octane fuel.” The Alliance has grave concerns with NHTSA using premium fuel for turbocharged engines that do not otherwise require premium. As the Agencies are aware, automakers have to design for much lower octane commercial fuel available in the marketplace and Tier 3 91 RON certification fuel, unless the engine is one that requires premium fuel.

The broad concerns with the boosted engine maps used by NHTSA are listed below:

- The engine maps for boosted engines show best BSFC all the way to full load; this is not typical.

Engine 12 is a max 18 bar BMEP engine and on 93 octane fuel is only knock limited at the very low and high speeds; below 2500rpm and above 5000rpm. This allows for high combustion efficiency with no enrichment up to max load.

Engine 13 as a max 24 bar BMEP engine is more knock limited even on 93 octane fuel. This results in an average spark retard of approximately 4-5deg in the areas of knock.

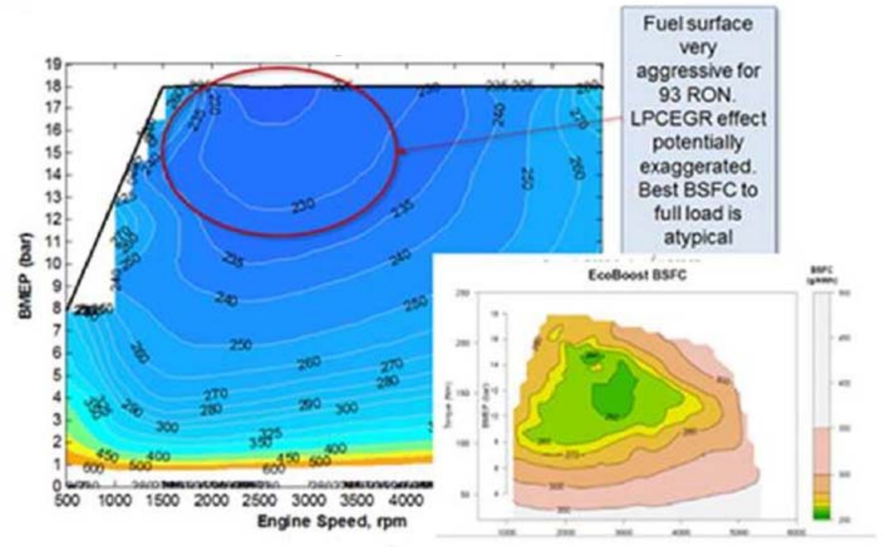


Figure A-11: IAV Gasoline Engine12 Map - Atypical Fuel Surface for Downsized Turbocharged Engines

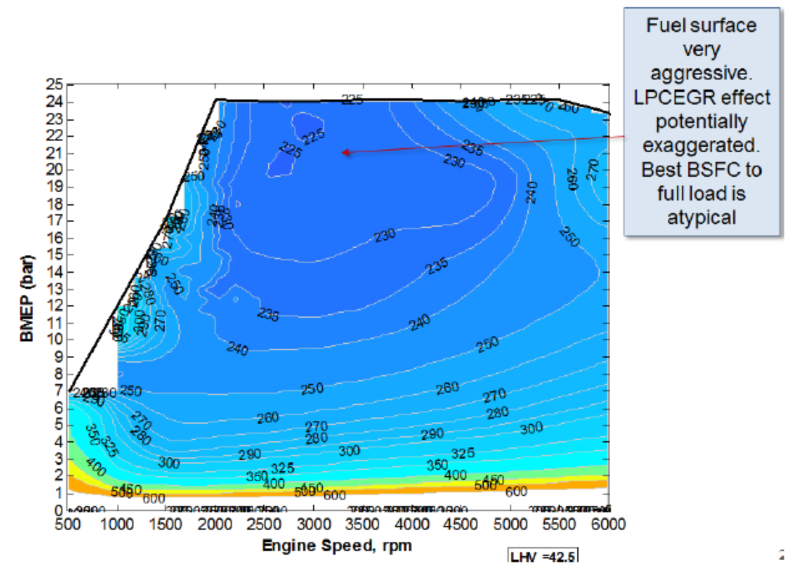


Figure A-12: IAV Gasoline Engine13 Map - Aggressive Fuel Surface With Atypical Results

Boosted Engine Maps

- For boosted engines with CEGR, the low-pressure CEGR (LPCEGR) effect appears exaggerated.
CEGR is used to manage regions that require fuel enrichment to control exhaust temperatures.

- Low load BSFC data for some boosted engine maps assumes exceptional stability or low friction.
CEGR is not implemented at low loads, therefore the issue with combustion stability is not relevant. The other problem appears to be extrapolation of data <1000rpm.

- The optimum use of LPCEGR relative to the intake cam movement appears to result in overstated efficiency improvements.
Unclear what this is in reference to.

Figures A-11 and A-12 illustrate the above issues with the key findings with the IAV Gasoline Engine12 Gasoline Engine13 maps.
Figure A-13 captures the effect of a 0-D displacement change from 1.6L to 1.2L (downsizing effect).
Figure A-14 below illustrates the effect of aggressive LPCEGR on the 1.0L 3-cylinder engine.

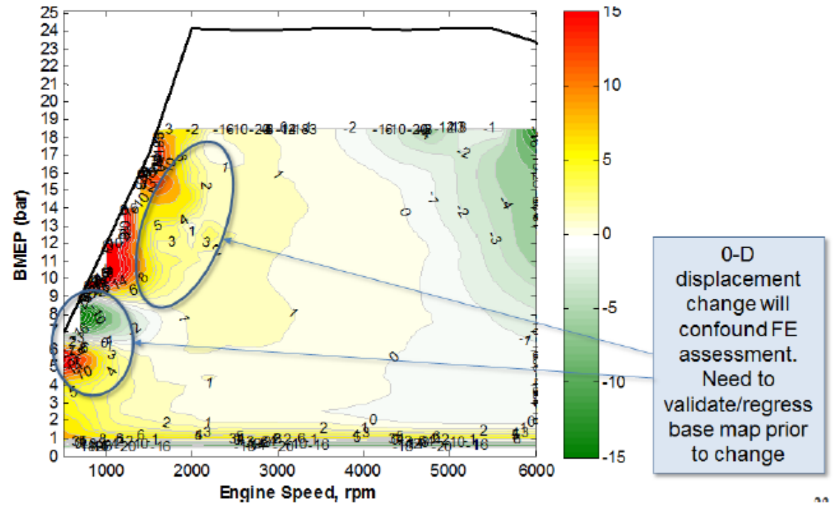


Figure A-13: Comparison between IAV Gasoline Engine12 Map and IAV Gasoline Engine13 Map; Displacement Change without Full Modeling Questionable

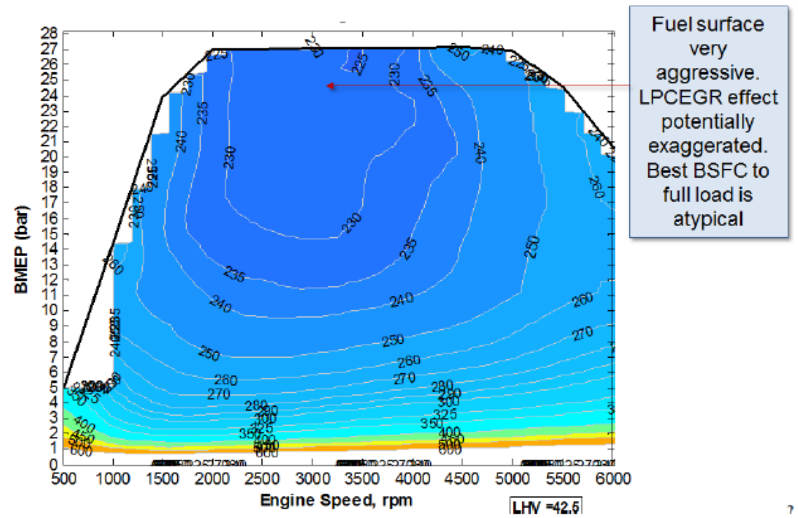


Figure A-14: IAV Gasoline Engine14 Map - Aggressive Fuel Surface With Atypical Results

Turbocharged Engines 12-16
Updated to 87 Octane Fuel

Rerun engine models and update for 87 octane fuel	
	Engine 12Reg - Turbo 1.6L 18 bar BMEP
	Engine 13Reg - Turbo 1.2L 24 bar BMEP
	Engine 14Reg - Turbo 1.2L 24 bar BMEP + cooled EGR
	Engine 15Reg - Turbo 1.0L 27 bar BMEP + cooled EGR
	Engine 16Reg - Turbo 1.0L 27 bar BMEP + cooled EGR (3 cyl)

- Engine 12-16 were all remodeled with 87 octane fuel
- All engines include the following:
  - Initially modeled with 93 octane
  - CR 10.5 is unchanged
  - Continuously variable valve lift on intake with duration scaled 1:1 with lift (i.e. 50% lift also results in 50% duration)
  - Exhaust valve lift is fixed
  - Independent cam phasing on intake and exhaust
  - Direct injection
  - Twin scroll turbocharger

Turbocharged Engines 12-16
Note on Knock Model

- Most significant change going from 93 octane to 87 octane fuel is to the knock model
- Knock models are based on Gamma Technology's kinetic fit model per the technical paper titled, "A combustion model for IC engine combustion simulations with multi-component fuels" by YoungChul Ra, Rolf D. Reitz – Engine Research Center, University of Wisconsin-Madison
  - Each knock model was trained on production and development engines tested at IAV to quantify the effects of different octane fuels
- Below the knock threshold, there is no change to the fuel consumption maps
- Generally, in regions where the engine is knock limited there are two major effects:
  - Spark timing is retarded causing a reduction in combustion efficiency and hence an increase in BSFC
  - Increase in combustion temperature requires fuel enrichment for component protection and a resultant increase in BSFC
- EGR added at to higher speed where further reduction in combustion temperature was required

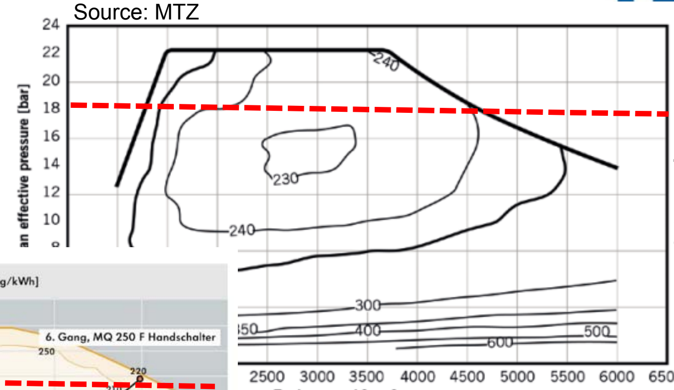
Turbocharged Engines 12-16
Note on EGR

- Exhaust gas temperatures and knock primarily addressed via spark retard and fuel enrichment.
- On engines with dVVT, internal EGR was induced via valve overlap through cam phasing. This was done at the low speeds and loads as a means to improve breathing efficiency.
- For engines with cooled external EGR (cEGR), cEGR was added at the higher speeds where further reduction in combustion temperature was required. Due to the higher specific heat capacity of cEGR, it's addition:
  - Reduced the need for fuel enrichment by lowering combustion temperatures
  - Limited the amount of spark retard necessary to manage spark knock
- With increasing load, cEGR is also used as a means to lower combustion temperatures to reduce NOx emissions. Since IAV's models are not calibrated for emissions, cEGR was only considered for areas that are knock limited and/or to reduce combustion temperatures.
- Since cEGR has the impact of slowing down burn rates, the amount of EGR that could be utilized was balanced in order to still maintain efficient combustion.

Engine 12 (93 vs 87) BSFC

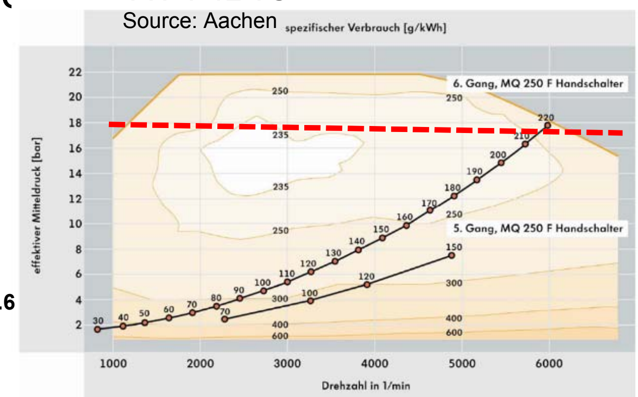
- Turbocharged 1.6l, 4 cyl, 18 bar bmep
- DOHC, dVVT, cVVL, GDI, 10.5CR
- 77.0 bore x 85.8 stroke

Audi 1.8L TFSI
Source: MTZ



Turbo GDI 82.5x84.1 9.6CR

VW 1.4L TSI
Source: Aachen



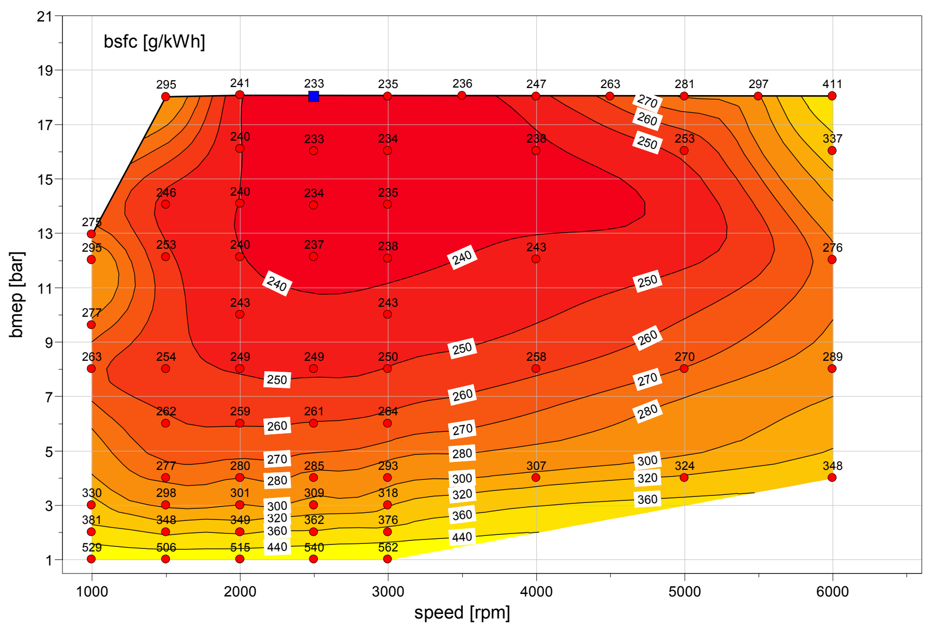
Turbo GDI 76.5x75.6 10.1CR

Areas where 93 octane engine was knock limited

Customer	ANL	Data Source	Data
Project	GTPower_Maps	Owner	Vishnu Nair IAV Inc.
Vehicle		Load/Cycle	
Engine		bsfc_Eng12reg	
Variation			

FinalMapsDelivered_Added V2.xlsx [12 Reg]

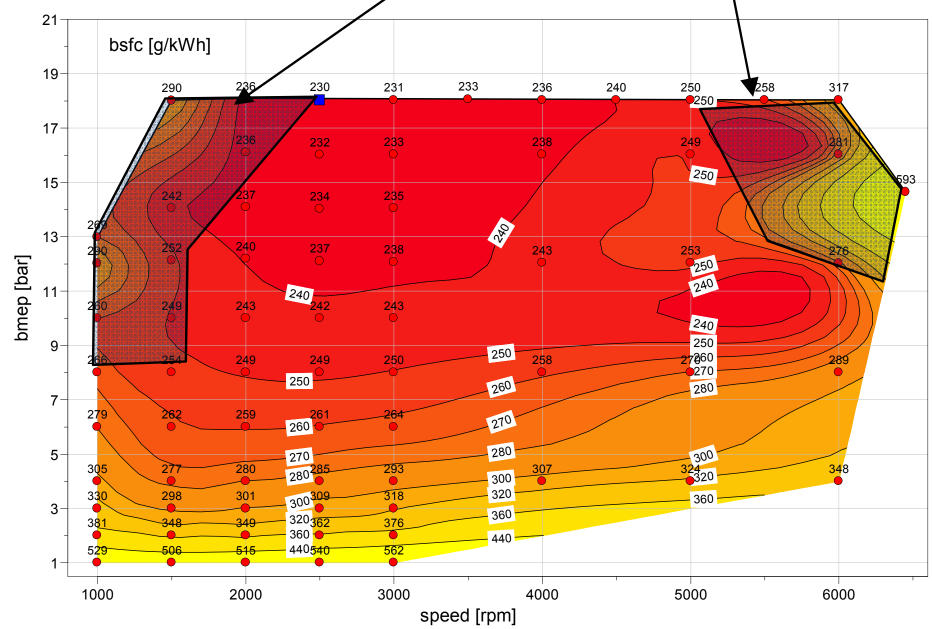
87 octane



Customer	ANL	Data Source	Data
Project	GTPower_Maps	Owner	Vishnu Nair IAV Inc.
Vehicle		Load/Cycle	
Engine		bsfc_Eng12	
Variation			

FinalMapsDelivered_Added V2.xlsx [Eng12]

93 octane



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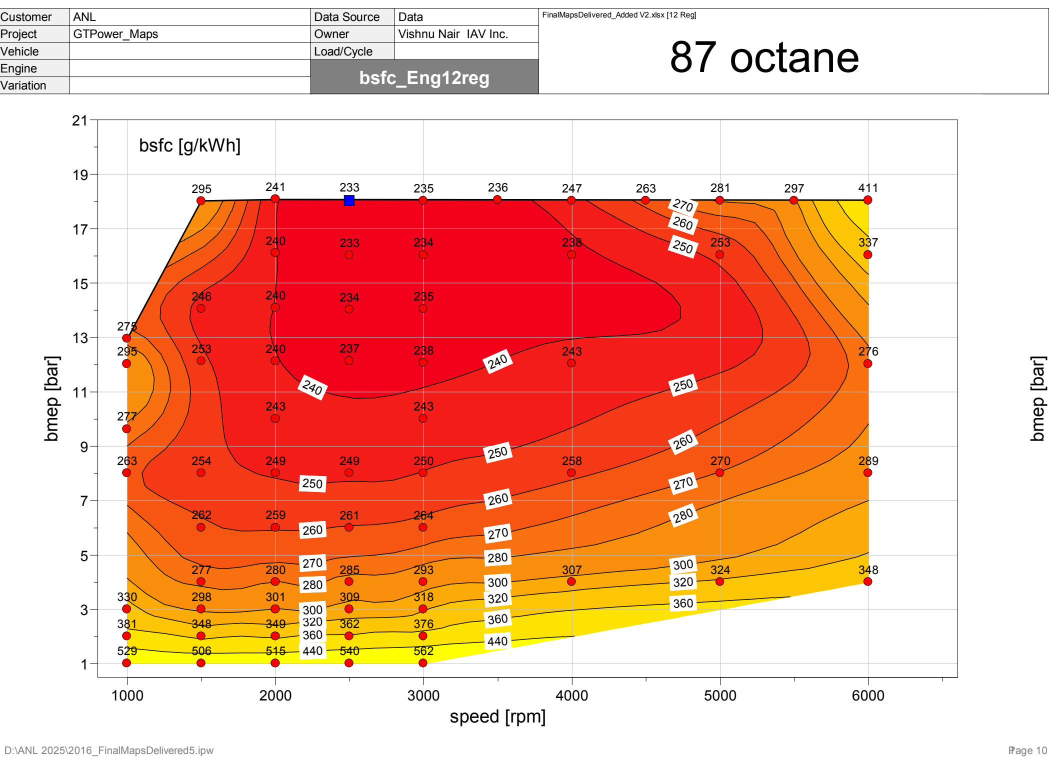
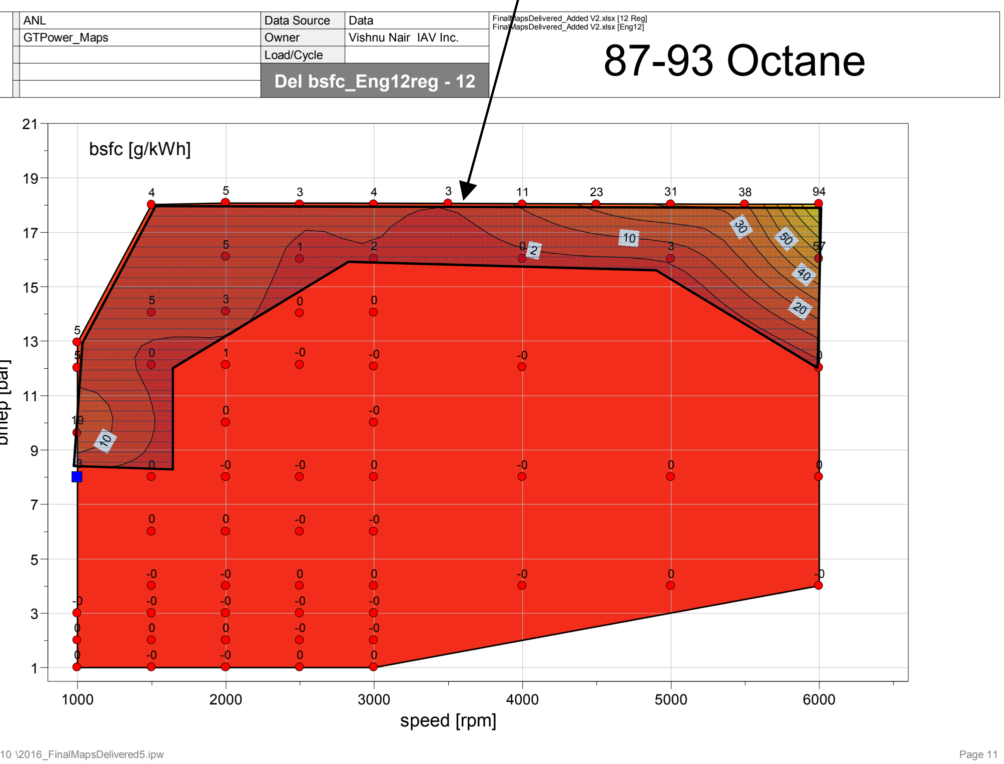
Engine 12 (93 vs 87) Δ BSFC

- Δ = 87 – 93 octane

Decreased knock tolerance = higher BSFC

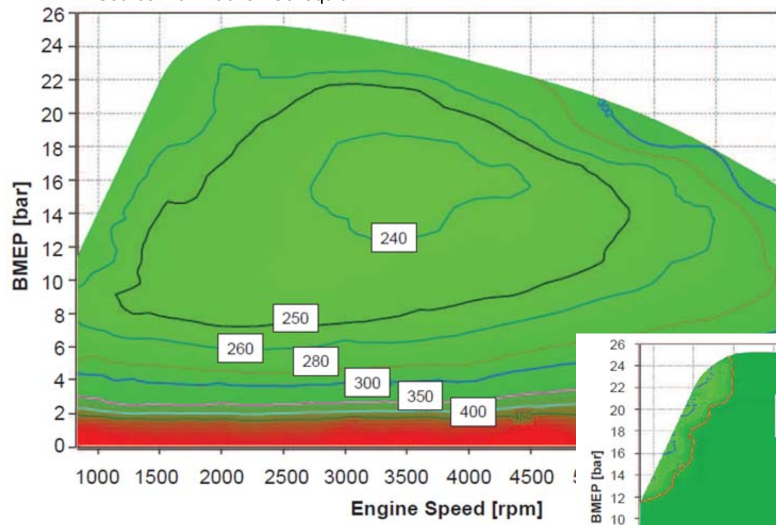




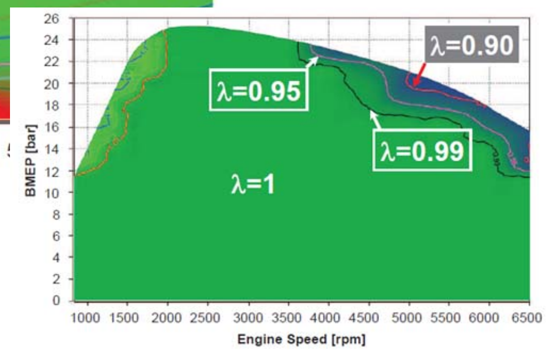
Engine 13 (93 vs 87) BSF(

- Turbocharged 1.2l, 4 cyl, 24 bar bmep
- DOHC, dVVT, cVVL, GDI, 10.5CR
- 71.0 bore x 76.0 stroke

Ford 1.0L Ecoboost
Source: 20th Aachen Colloquium

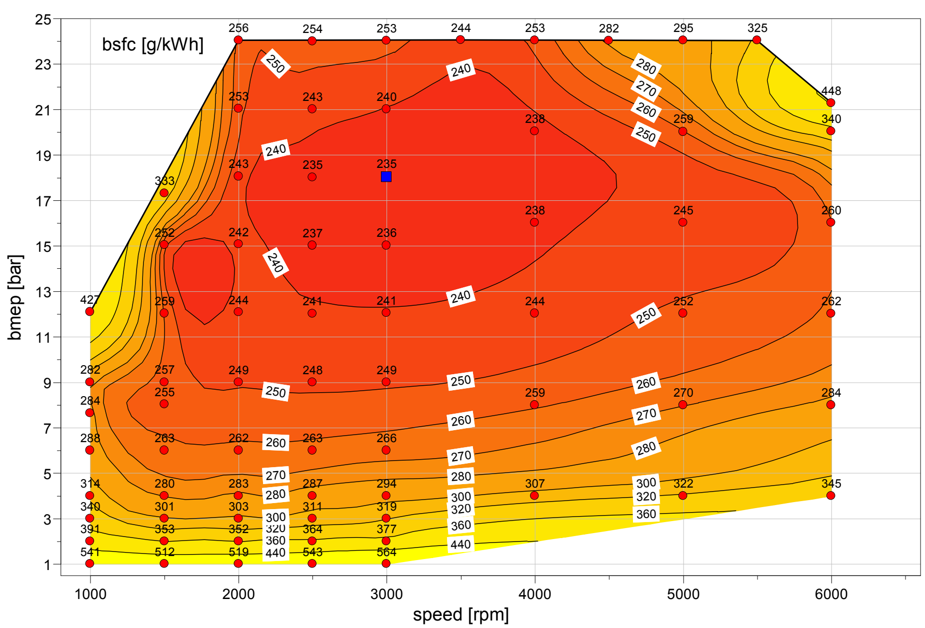


Turbo
GDI
71.9x82.0
10.1 CR

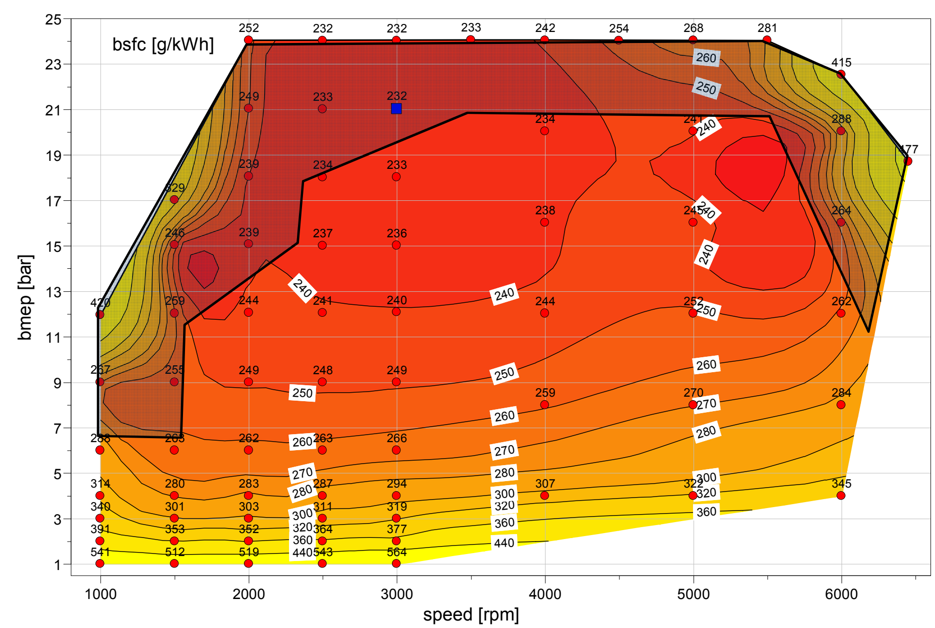


Higher CR, cVVL and shorter stroke (reduces thermal area)

Customer	ANL	Data Source	Data	FinalMapsDelivered_Added V7.xlsx [13 Reg ExT-map5]
Project	GTPower_Maps	Owner	Vishnu Nair IAV Inc.	87 octane
Vehicle		Load/Cycle		
Engine		bsfc_Eng13reg ExTmap5		
Variation				



Customer	ANL	Data Source	Data	FinalMapsDelivered_Added V7.xlsx [Eng13]
Project	GTPower_Maps	Owner	Vishnu Nair IAV Inc.	93 octane
Vehicle		Load/Cycle		
Engine		bsfc_Eng13		
Variation				



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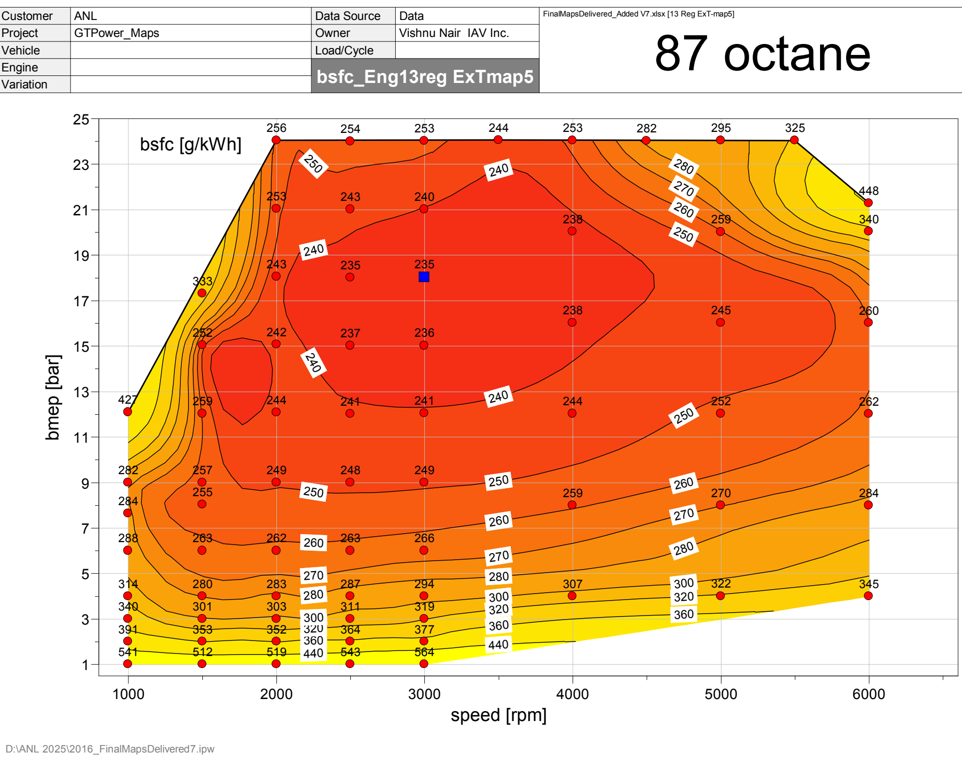
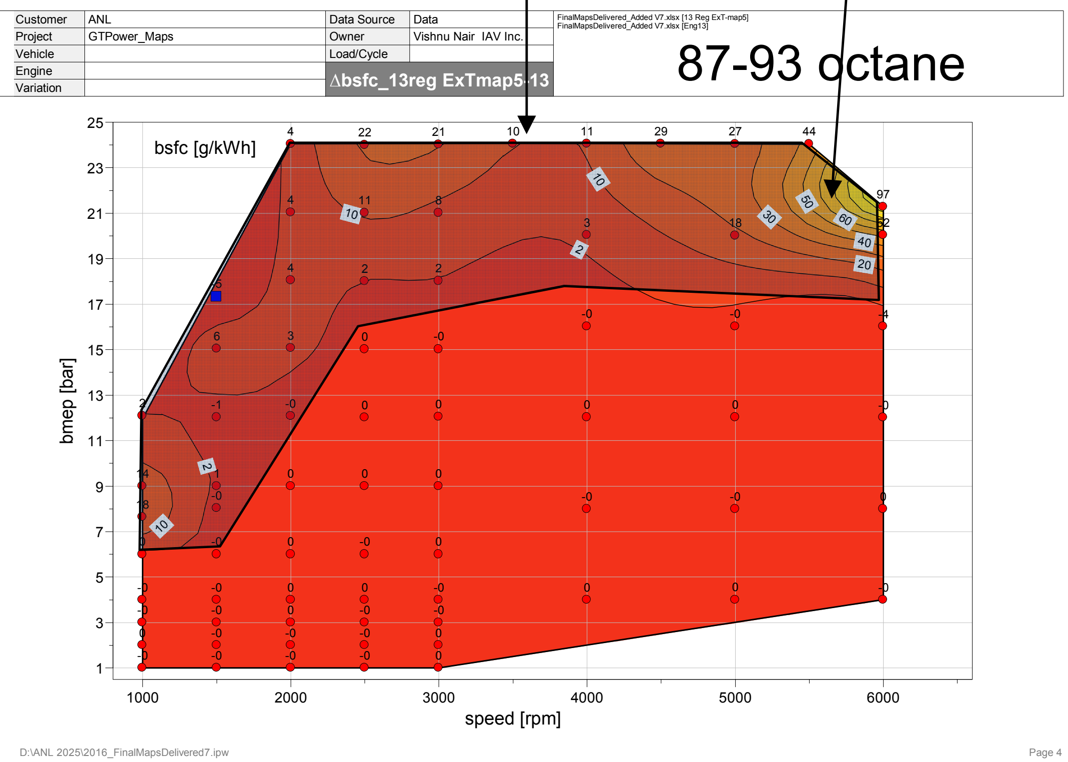
Engine 13 (93 vs 87) Δ BSFC

- Δ = 87 – 93 octane

Further enrichment needed for combustion temperature control

Decreased knock tolerance = higher BSFC



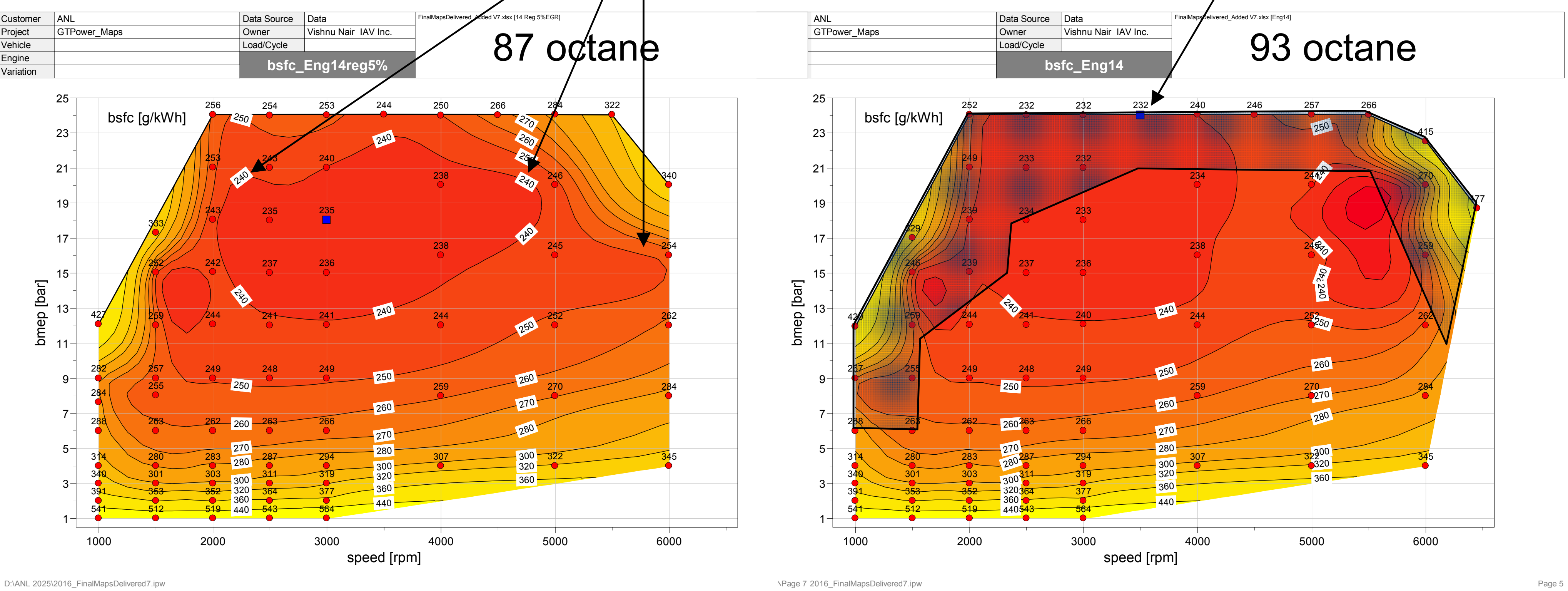


Engine 14 (93 vs 87) BSFC

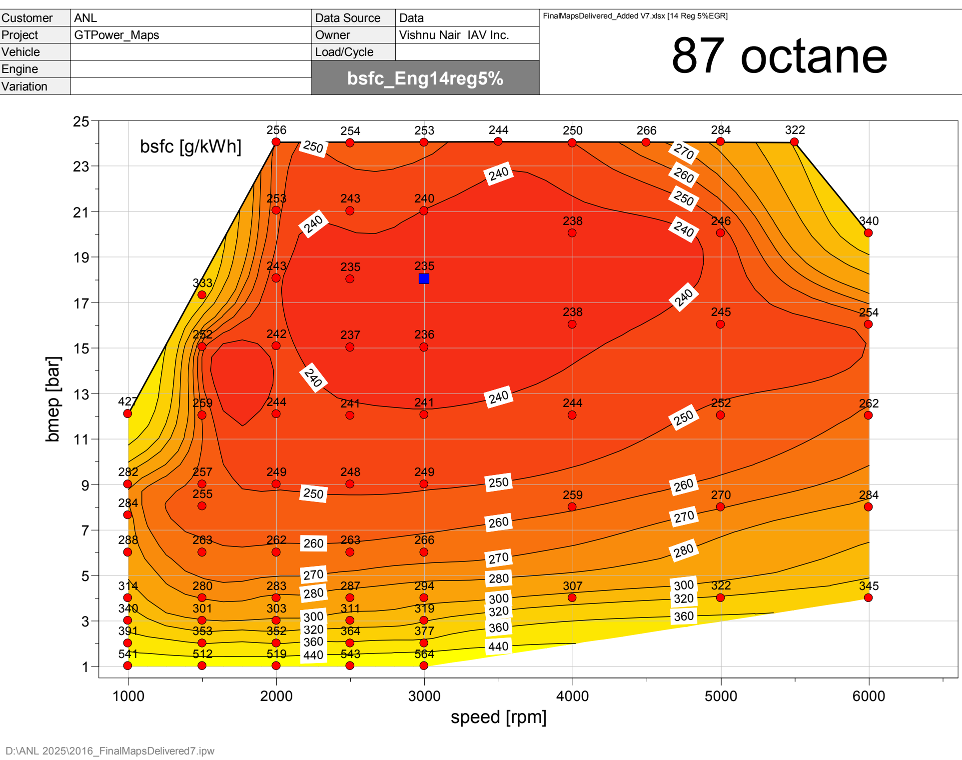
- Turbocharged 1.2l, 4 cyl, 24 bar bmep
- DOHC, dVVT, cVVL, GDI, 10.5CR
- + cEGR
- 71.0 bore x 76.0 stroke

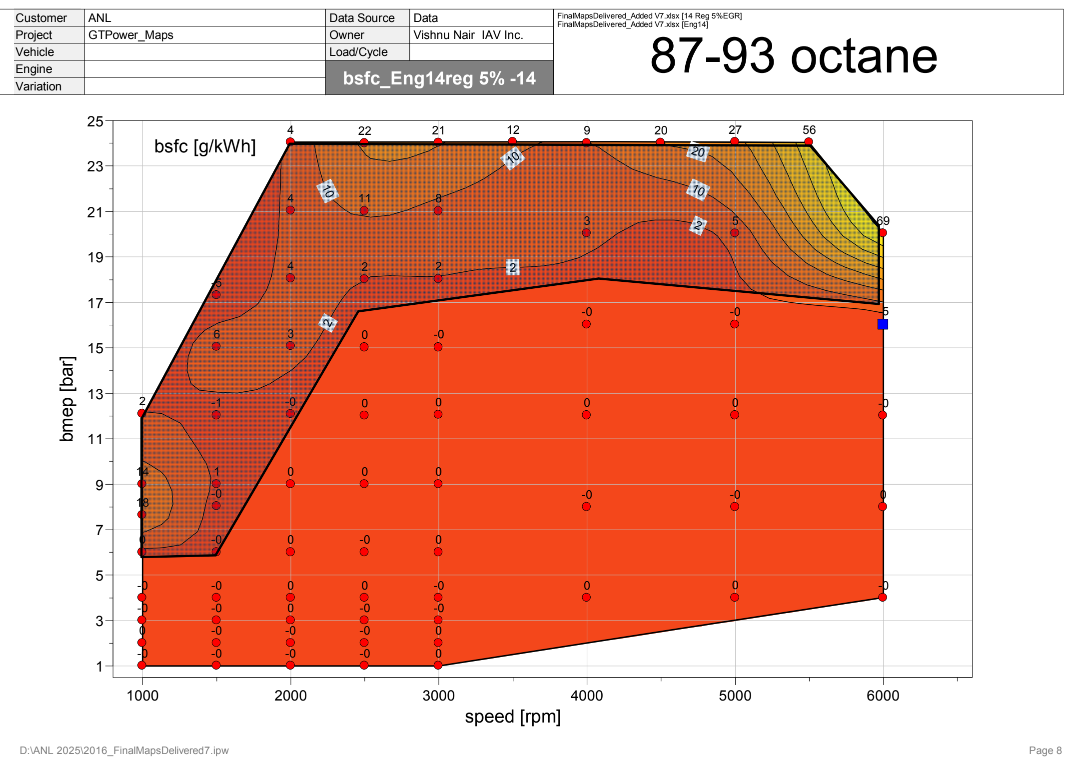
Areas aided by EGR, allowing more spark advance for improved combustion efficiency and reduced combustion temperatures. In production implementation cEGR may be included more broadly for NOx reduction.

Areas where 93 octane engine was knock limited



Engine 14 (93 vs 87) Δ BSFC



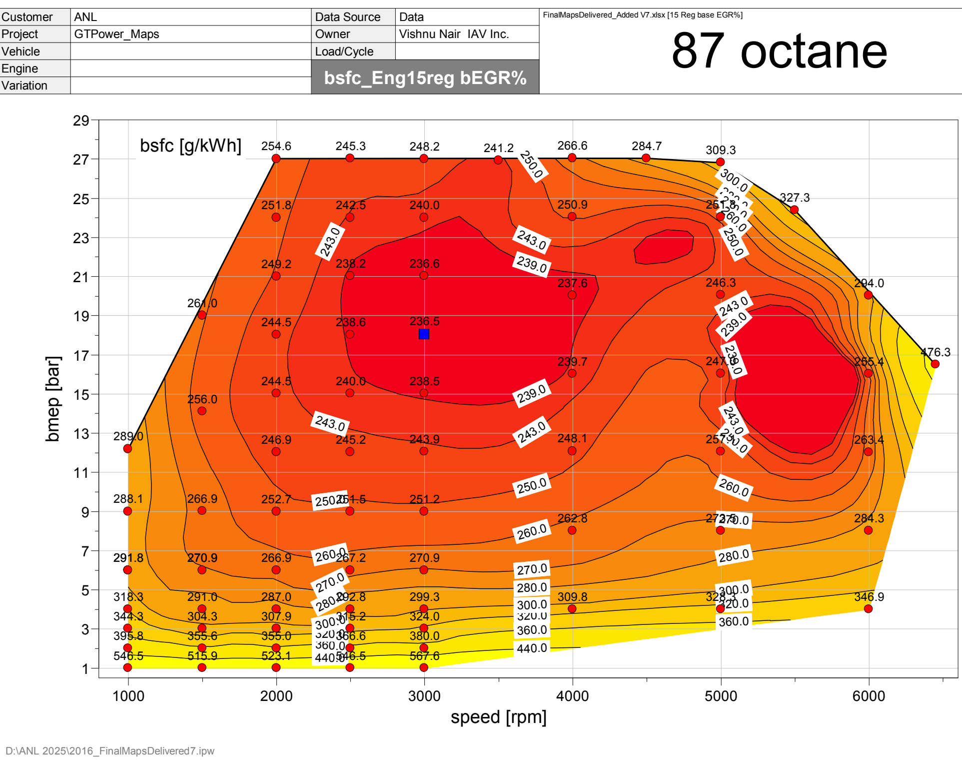


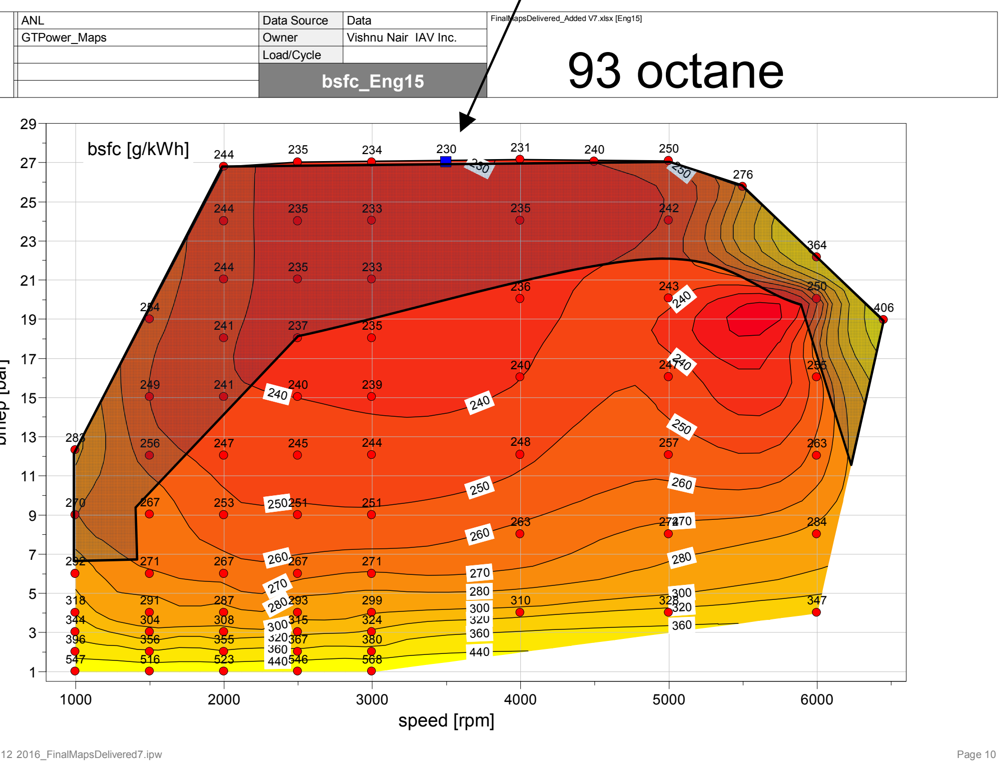
Engine 15 (93 vs 87) BSFC

- Turbocharged 1.0l, 4 cyl, 27 bar bmep
- DOHC, dVVT, cVVL, GDI, 10.5CR
- + cEGR
- 65.8 bore x 73.4 stroke

- Small bore diameter improves knock tolerance by reducing burn duration
- Trade-off is reduced thermal efficiency due to greater area for heat loss

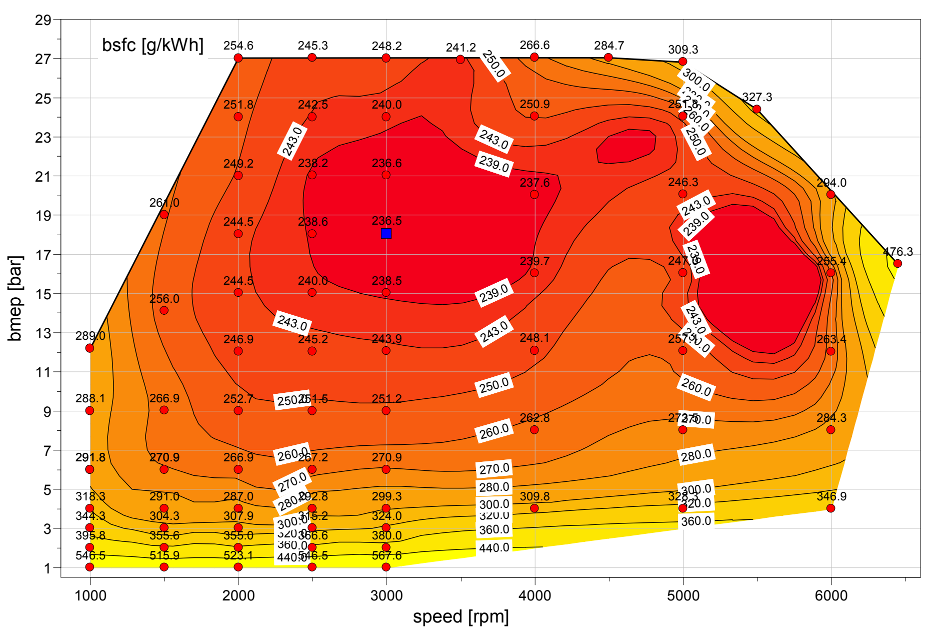
Areas where 93 octane engine was knock limited



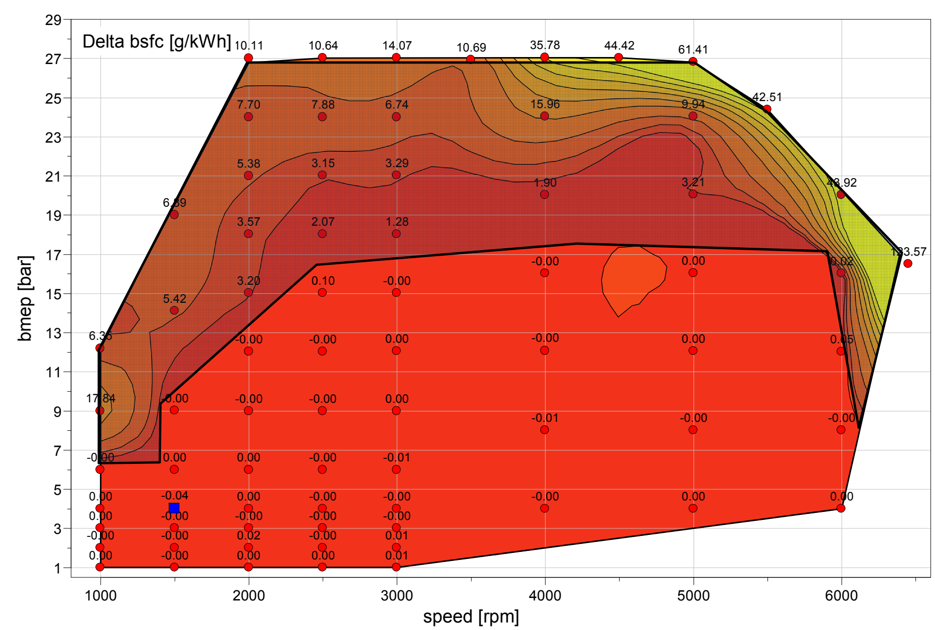


Engine 15 (93 vs 87) Δ BSFC

Customer	ANL	Data Source	Data	FinalMapsDeliverd_Added V7.xlsx [15 Reg base EGR%]
Project	GTPower_Maps	Owner	Vishnu Nair IAV Inc.	87 octane
Vehicle		Load/Cycle		
Engine		bsfc_Eng15reg bEGR%		
Variation				



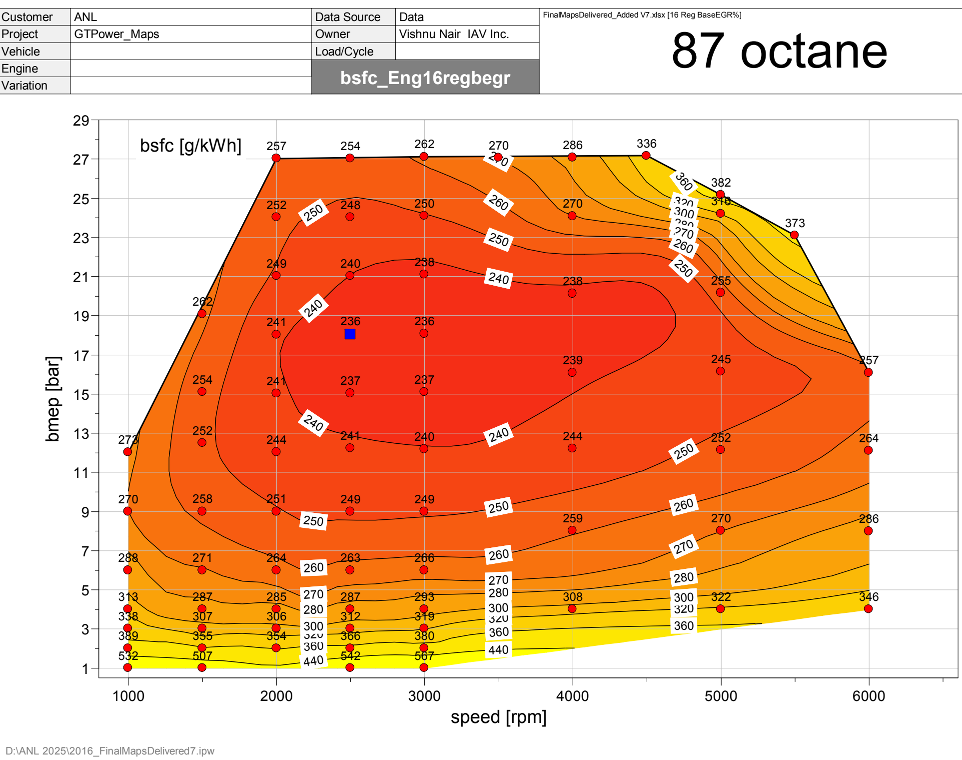
Customer	ANL	Data Source	Data	FinalMapsDeliverd_Added V7.xlsx [15 Reg base EGR%] FinalMapsDeliverd_Added V7.xlsx [Eng15]
Project	GTPower_Maps	Owner	Vishnu Nair IAV Inc.	87-93 octane
Vehicle		Load/Cycle		
Engine		Δbsfc Eng15regbEGR-15		
Variation				

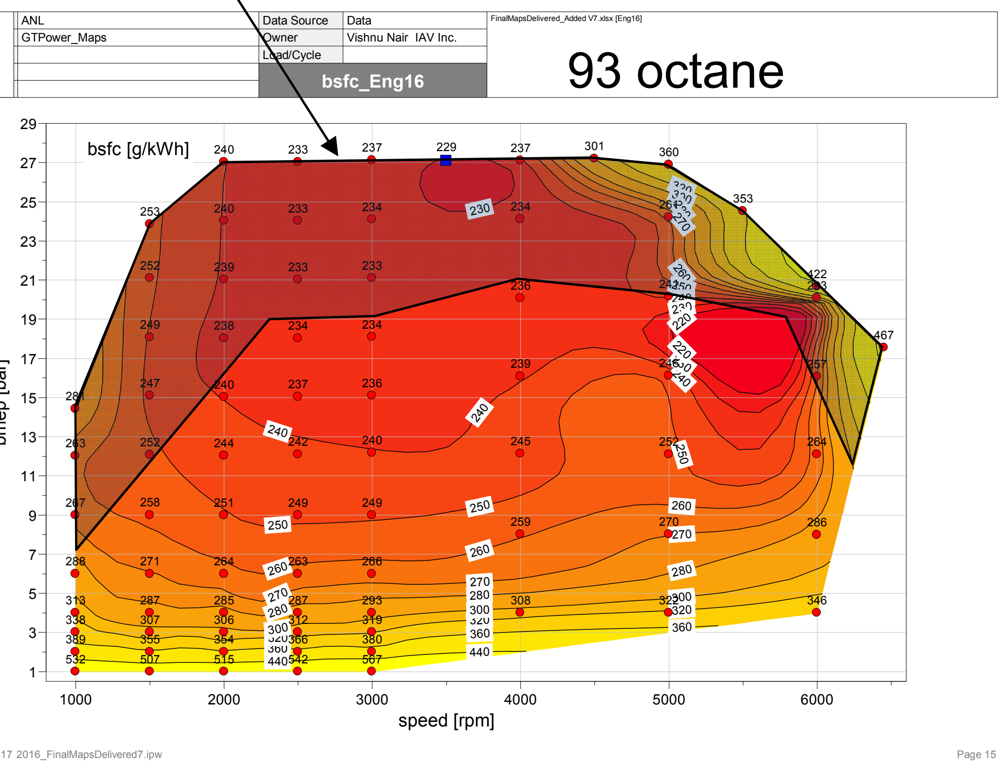


Engine 16 (93 vs 87) BSFC

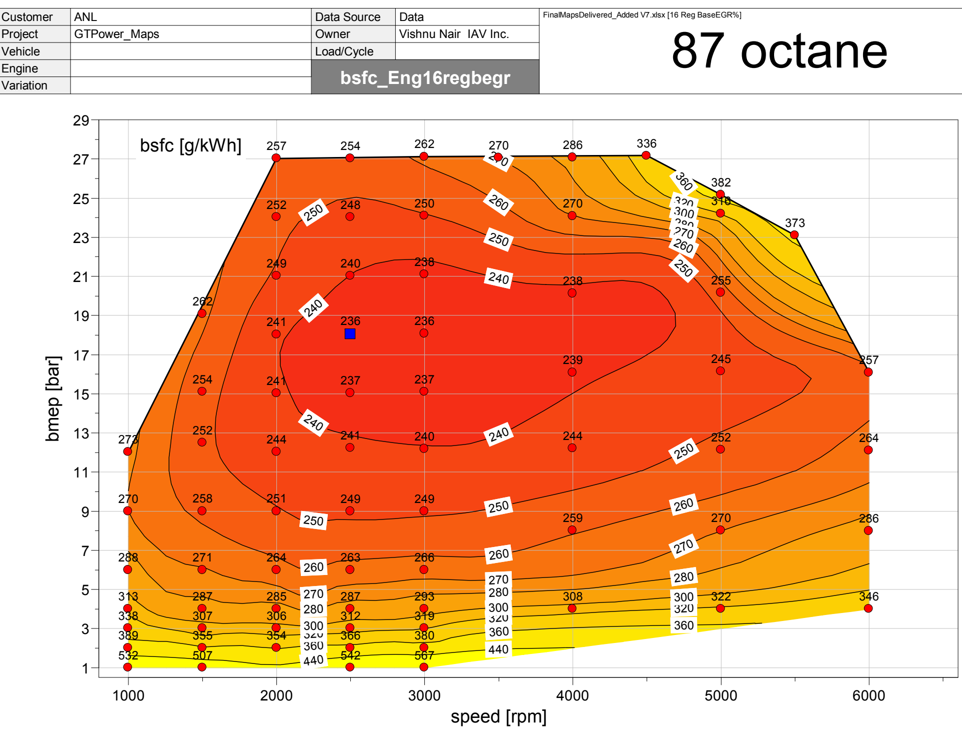
- Turbocharged 1.2l, 3 cyl, 27 bar bmep
- DOHC, dVVT, cVVL, GDI, 10.5CR
- + cEGR
- 72.4 bore x 81.0 stroke

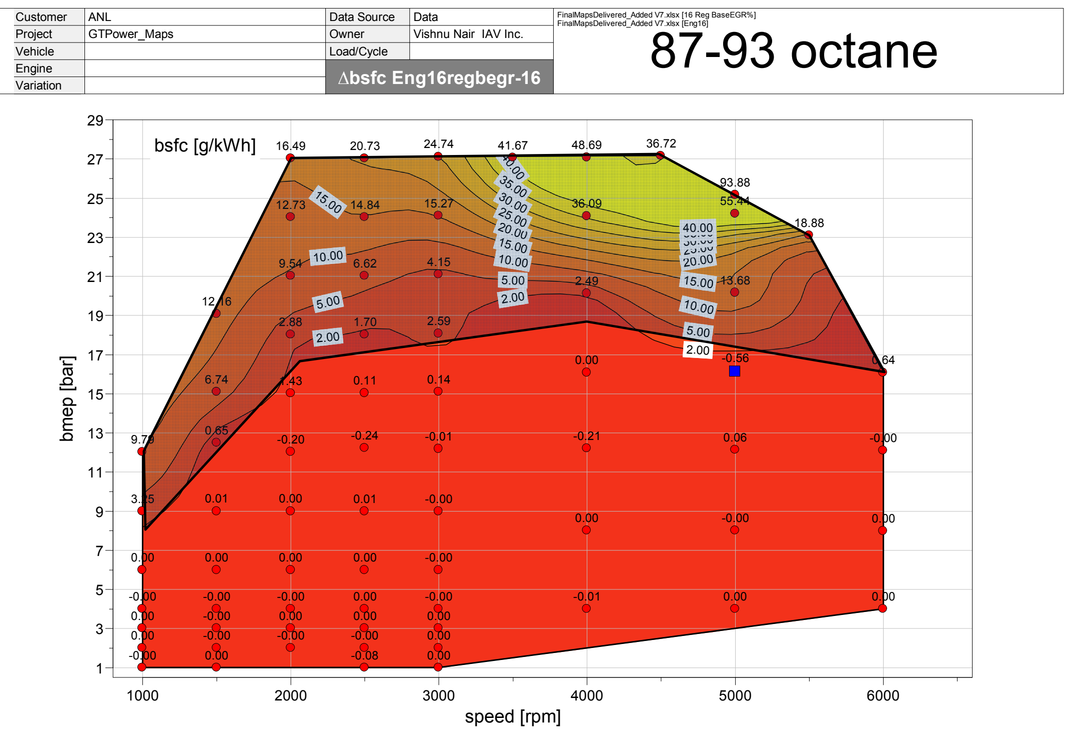
Areas where 93 octane engine was knock limited





Engine 16 (93 vs 87) Δ BSFC





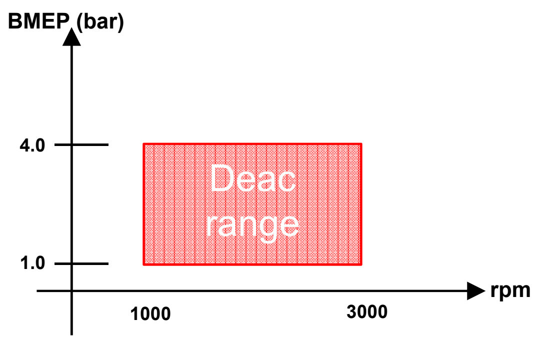
Results For New Engines 18 - 21

Engine	Description
18	**2.0l, 4cyl, NA, DOHC, dual VVT + Direct Injection** Developed from Engine 1 – NA, DOHC, dVVT Principal effects captured • Increased knock resistance and volumetric efficiency due to in cylinder vaporization of the fuel • Open valve injection and homogeneous operation assumed
19	***2.0l, 4cyl, NA, PFI, DOHC, dual VVT + Cyl DEAC** Developed from Engine 1 - NA, DOHC, dVVT VVT timing map of active cylinders based on cylinder IMEP (of non deac engine) Effect of change in manifold pressure dynamics not large enough to re-optimize valve timings in the deac zone
20	***2.0l, 4cyl, NA, PFI, DOHC, dual VVT + intake VVL + Cyl DEAC** Developed from Engine 2 with cylinder deac added The VVT maps and intake valve map lift of active cylinders based on the cylinder IMEP (of non deac engine)
21	***2.0l, 4 cylinder, NA, DOHC, dual cam VVT + Direct Injection + Cylinder DEAC** Developed from Engine 18 with cylinder deac added VVT timing map of active cylinders based on cylinder IMEP (of non deac engine)

– *Changes to deactivated cylinders
  - Mass trapped in the cylinder initialized to equilibrium mass based on test data

Note on Cylinder Deactivation

- Note for all engines which include cylinder deactivation, due to reasons of NVH and fuel efficiency, cylinder deactivation range is limited to 1000-3000rpm and 1-4 bar BMEP.



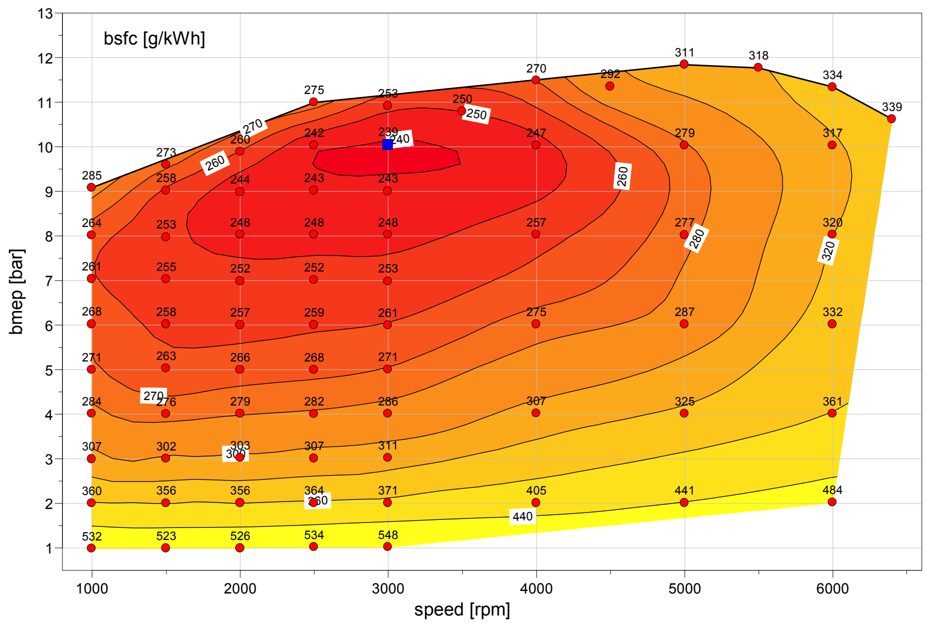
- It is incorrect to interpolate data points that reside outside the immediate boundaries of deactivated operation. Meaning that the engine operates either with all 4 cylinders firing or with only 2 cylinder firing when in deactivated mode. There are no states in between therefore interpolating between the two maps is incorrect.
- To prevent constant switching between normal and deactived mode, a level of hysteresis is recommended for the vehicle modeling. The hysteresis could be both time based, i.e. the required condition would need to be met for 3-5 seconds before a mode switch and/or pressure base via a 1 bar threshold.

Engine 18 (VVT+GDI) – BSFC

– Engine 18 - VVT + GDI

– Engine 1 - VVT

Customer	ANL	Data Source	Data	FinalMapsDelivered_Added V2.xlsx [Engine 18]
Project	GTPower_Maps	Owner	Vishnu Nair IAV Inc.	
Vehicle		Load/Cycle		
Engine		**bsfc_Eng18**		
Variation				



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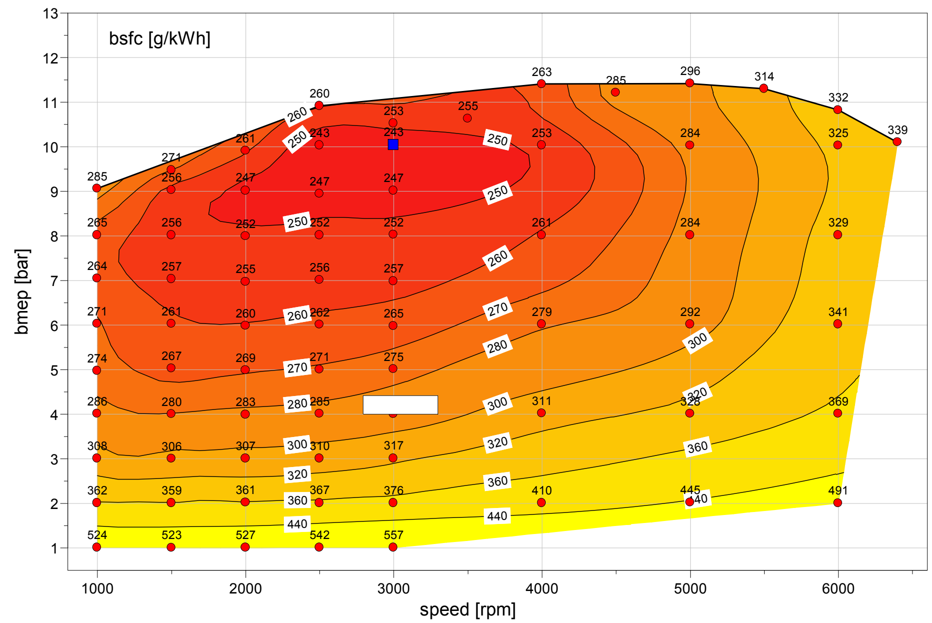
Customer	ANL	Data Source	Data	FinalMapsDelivered_Added V2.xlsx [Eng1]
Project	GTPower_Maps	Owner	Vishnu Nair IAV Inc.	
Vehicle		Load/Cycle		
Engine		**bsfc_Eng1**		
Variation				



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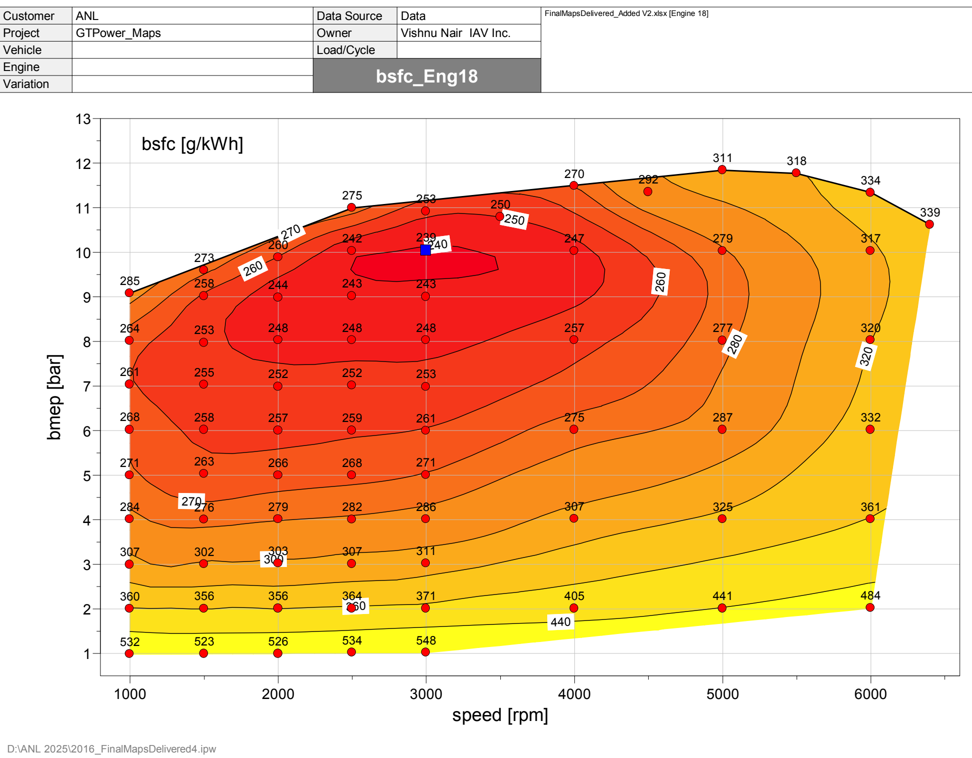
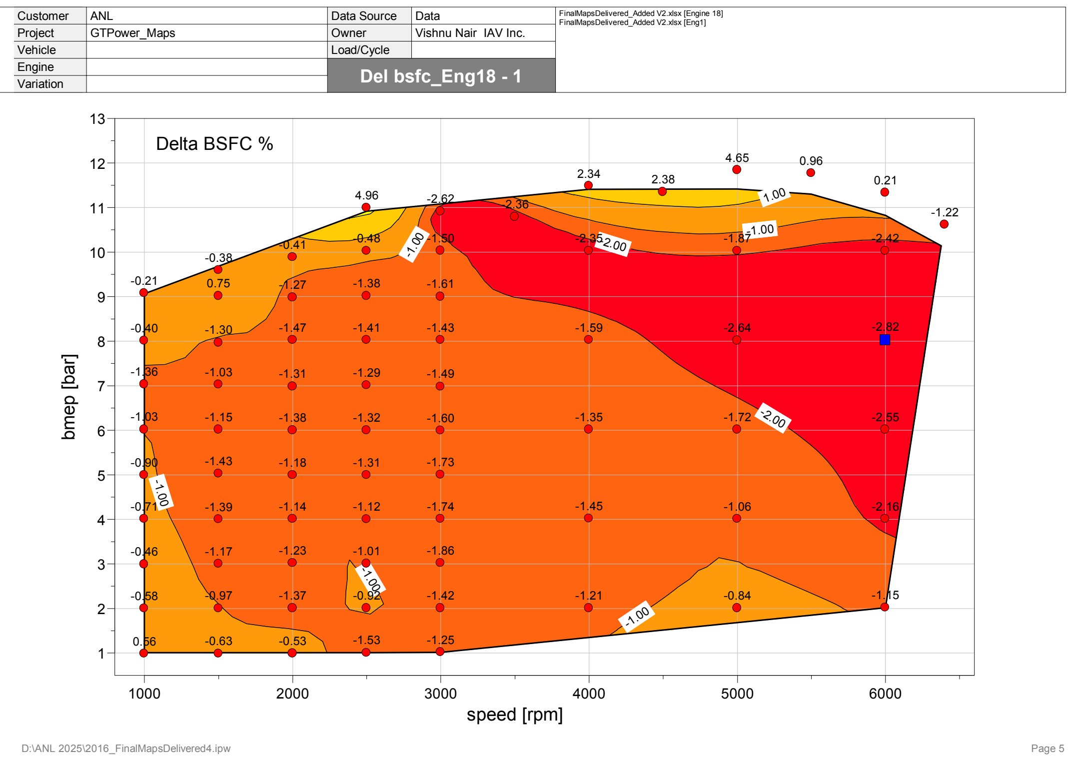
Engine 18 Vs Engine 1 ΔBSFC%

- Engine 18 - Engine 1(VVT) + GDI
- Delta BSFC (Eng 18-Eng 1)/Eng 1 %

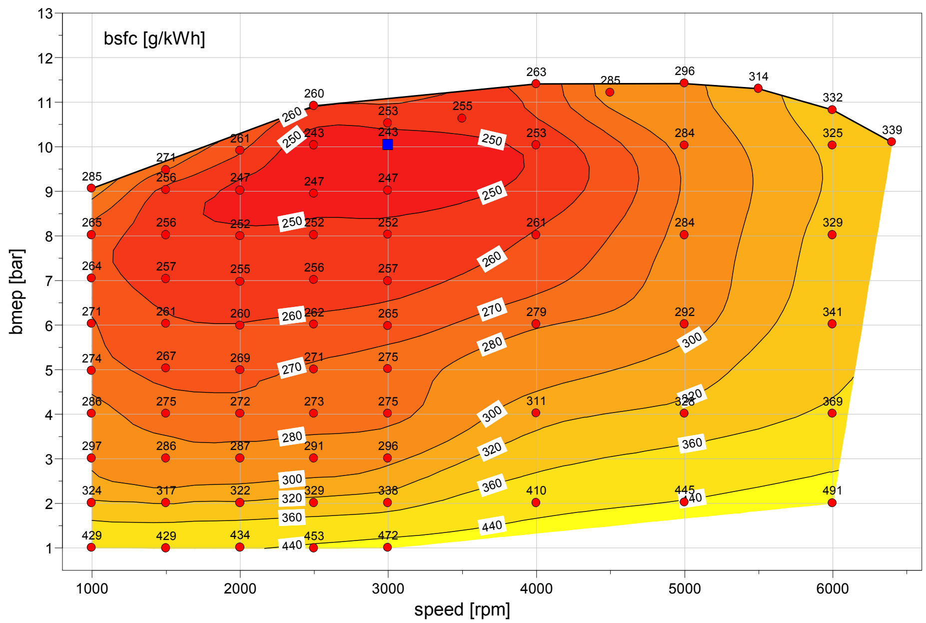




Engine 19 (PFI+VVT+DEAC) BSFC

– Engine 19 = Engine 1 (VVT + PFI) + Deac

Customer	ANL	Data Source	Data	FinalMapsDelivered_Added V2.xlsx [Engine 19 full]
Project	GTPower_Maps	Owner	Vishnu Nair IAV Inc.	
Vehicle		Load/Cycle		
Engine		bsfc_Eng19		
Variation				



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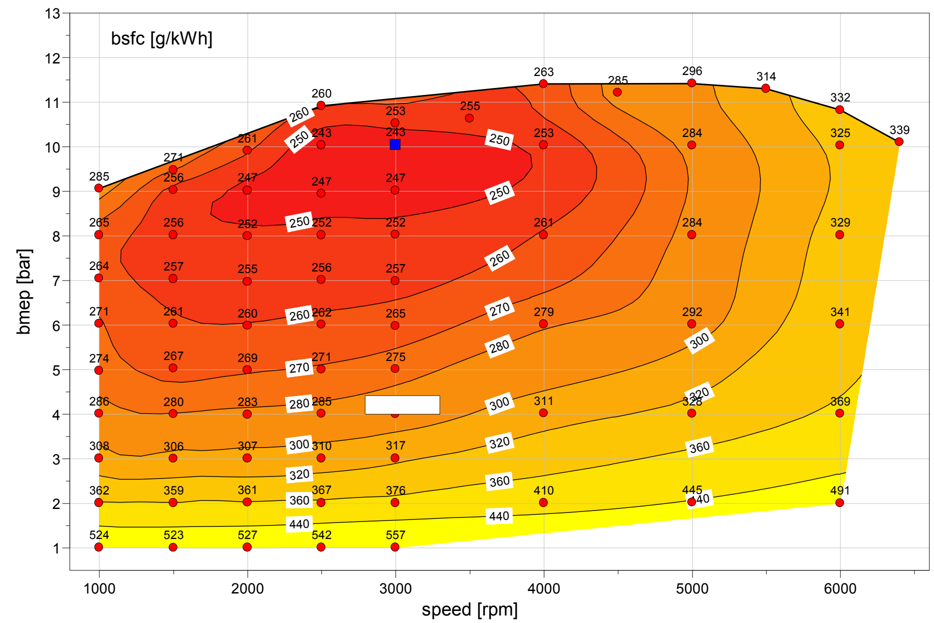
Customer	ANL	Data Source	Data	FinalMapsDelivered_Added V2.xlsx [Eng1]
Project	GTPower_Maps	Owner	Vishnu Nair IAV Inc.	
Vehicle		Load/Cycle		
Engine		bsfc_Eng1		
Variation				



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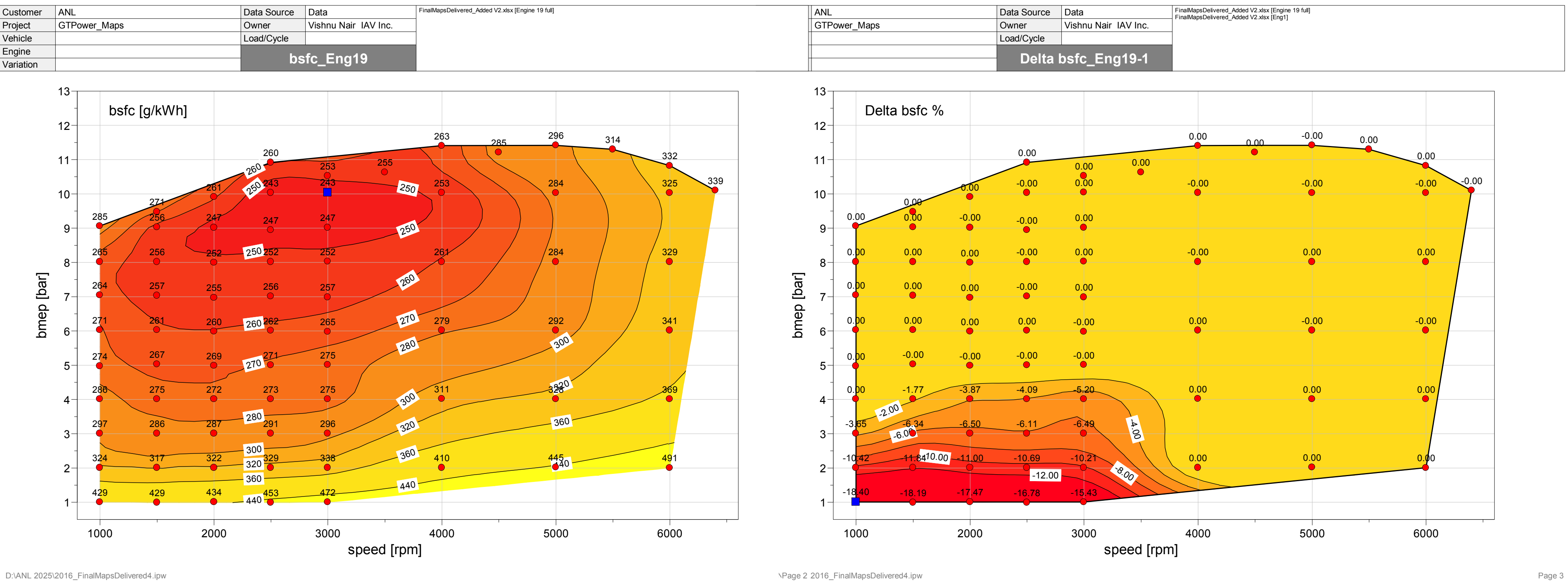
Engine 19 (PFI+VVT+DEAC) BSFC

– Engine 19 = Engine 1 (VVT + PFI) + Deac

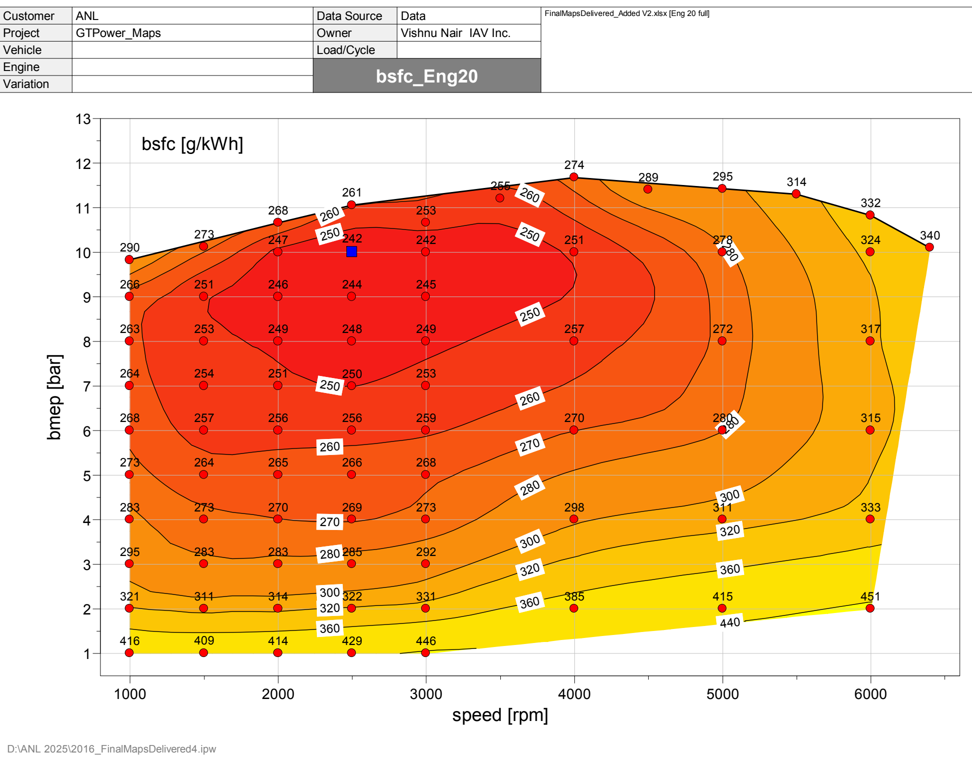
– Delta BSFC (Eng 19-Eng 1)/Eng 1 %

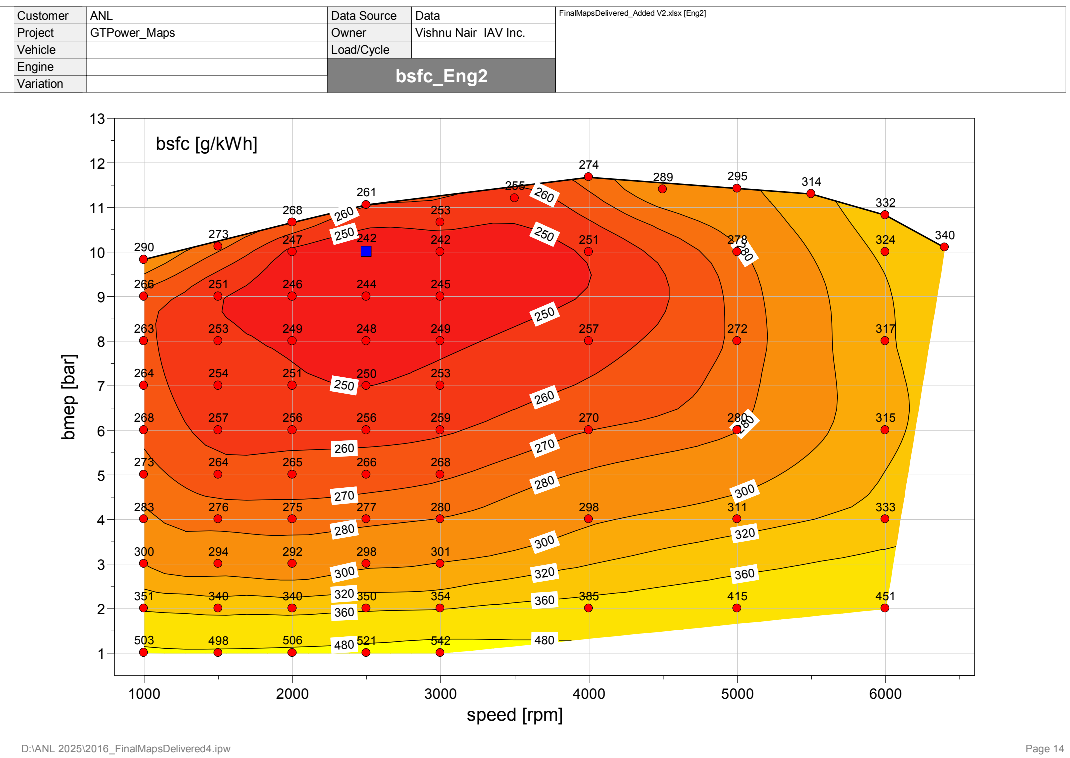


Note: Only reference data for deac-mode in the range of 1000-3000rpm and 1-4 bar BMEP

Engine 20 (VVT+VVL+DEAC) BSFC

– Engine 20 = Engine 2 (VVL + VVT + PFI) + Deac

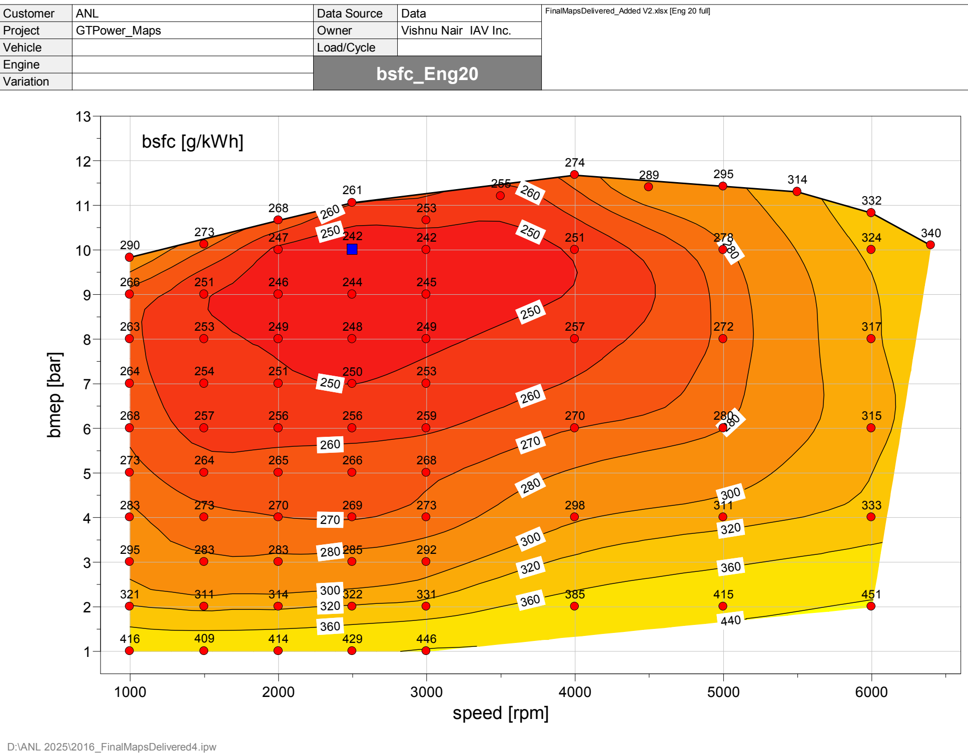


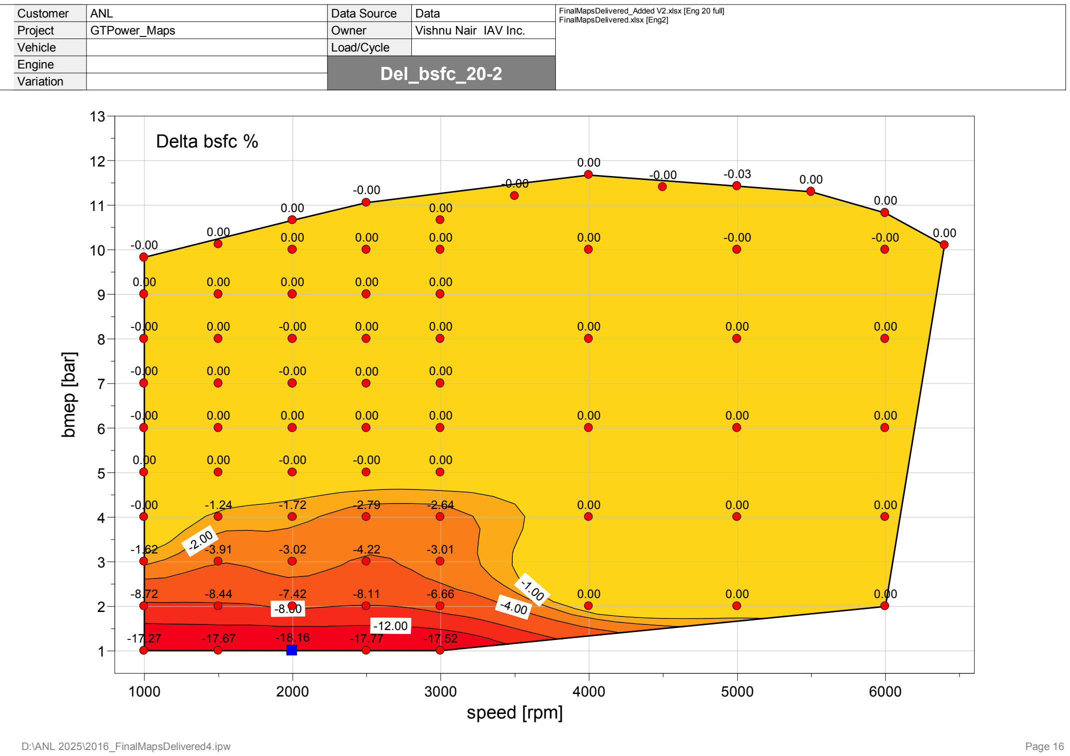


Engine 20 (VVT+VVL+DEAC) BSFC

– Engine 20 = Engine 2 (VVL + VVT + PFI) + Deac

– Delta BSFC (Eng 18-Eng 2)/Eng 2 %



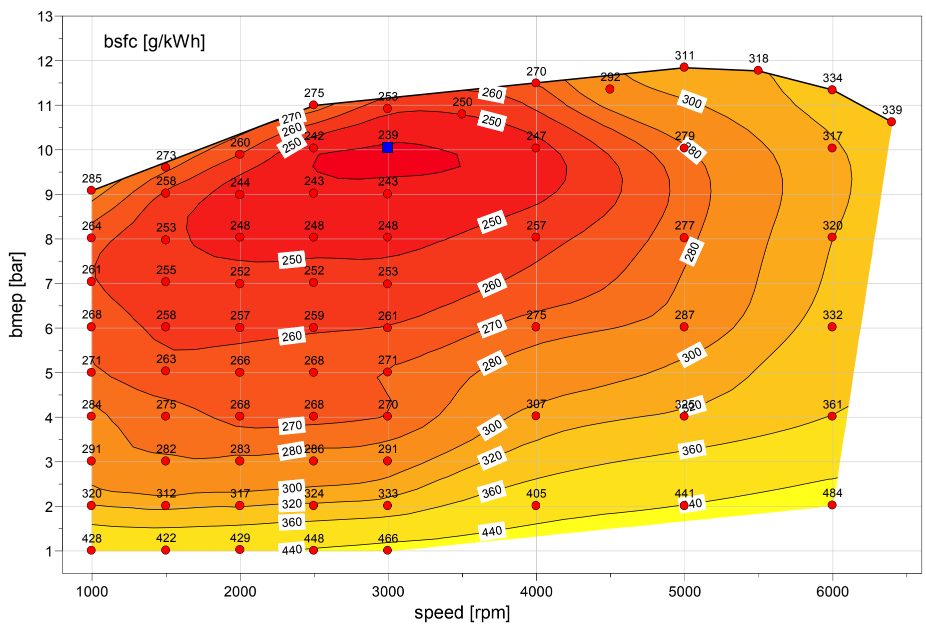


Note: Only reference data for deac-mode in the range of 1000-3000rpm and 1-4 bar BMEP

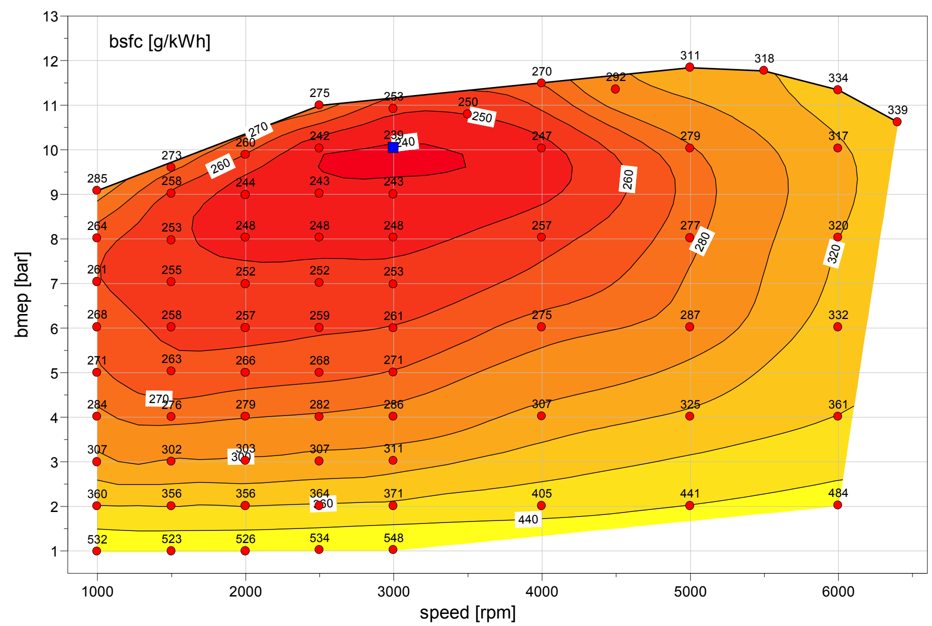
Engine 21 (VVT+GDI+DEAC) BSFC

– Engine 21 = Engine 18 (VVT+GDI) + Deac

Customer	ANL	Data Source	Data	FinalMapsDelivered_Added V2.xlsx [Engine 21 full]
Project	GTPower_Maps	Owner	Vishnu Nair IAV Inc.	
Vehicle		Load/Cycle		
Engine		**bsfc_Eng21**		
Variation				



ANL	Data Source	Data	FinalMapsDelivered_Added V2.xlsx [Engine 18]
GTPower_Maps	Owner	Vishnu Nair IAV Inc.	
	Load/Cycle		
	bsfc_Eng18		



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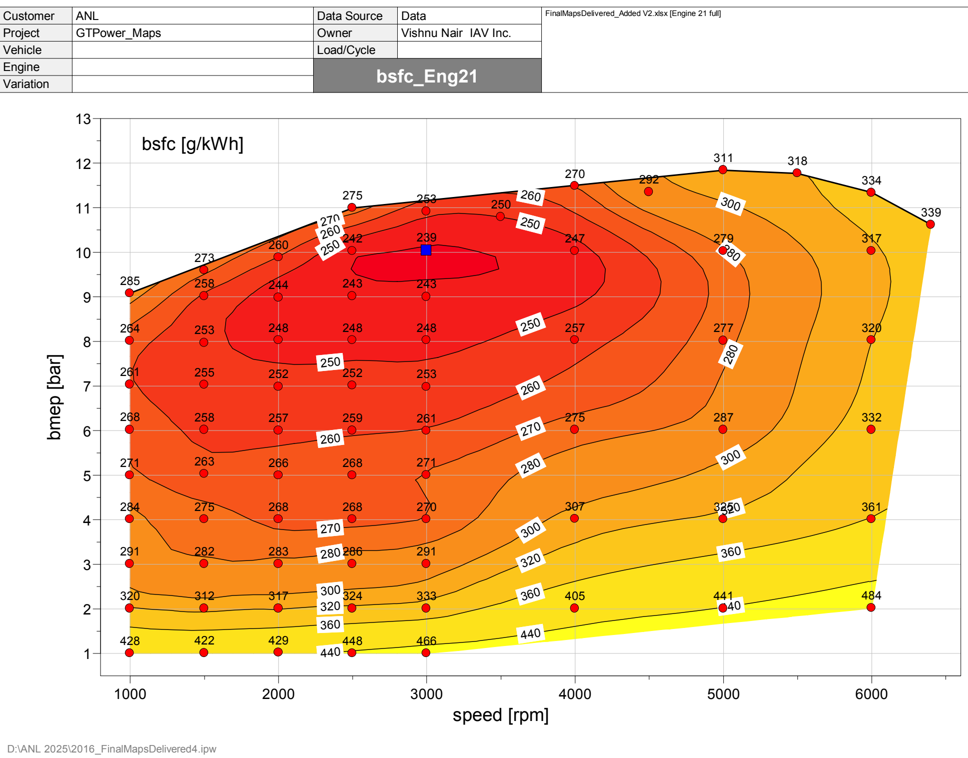
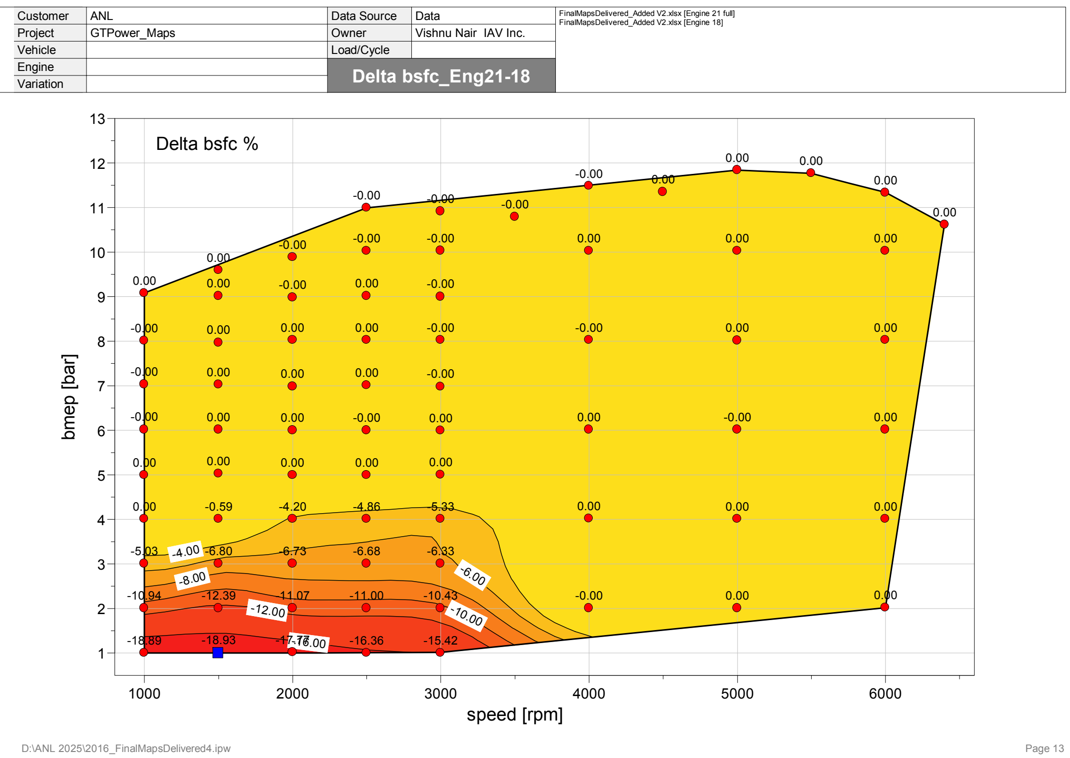
Engine 21 (VVT+GDI+DEAC) BSFC

– Engine 21 = Engine 18 (VVT+GDI) + Deac

– Delta BSFC (Eng 21-Eng 18)/Eng 18 %





Thank You

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