NCAT – National Center for Advanced Technology

National Vehicle and Fuel Emissions Laboratory
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

The following presentation material was prepared by FEV Engine Technology under EPA Contract EP-C-12-014 and describes the test procedures performed by FEV on the 3.0L N57 engine. Use of any NCAT material provided below, included as part of the complete test data package, should reference the suggested citation provided.

SUGGESTED CITATION: *2015 BMW 3.0L N57 Engine Diesel Fuel – Test Data Package*. Version 2018-06. Ann Arbor, MI: US EPA, National Vehicle and Fuel Emissions Laboratory, National Center for Advanced Technology, 2018.

Contract No. EP-C-12-014, Work Assignment 3-11
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EP-C-12-014 WA 3-11

BMW X5 35d Benchmarking

prepared for:

U.S. Environmental Protection Agency

1/29/2016

Marvin Duggan, Roger Van Sickle Light-Duty Diesel

FEV

Agenda

- Introduction
- Vehicle Break in
- DPF Regeneration Interval Investigation
- Engine Mapping
- EGR Mapping
- Urea Course Engine Mapping
- Continuous Data
- ASCMO Simulations
- Conclusion

Introduction

- The purpose of this testing was to benchmark the 2015 BMW X5 35d vehicle for the U.S. Environmental Protection Agency in order to determine unique features of the powertrain aftertreatment technology associated with this vehicle.
- The 2015 BMW X5 35d is classified as a Tier 2 Bin 5 vehicle that encompasses a lean NOx trap, diesel particulate filter, and selective catalytic reduction in order to meet emission standards. The vehicle also uses engine start/stop technology in order to increase fuel efficiency and reduce emissions output.
- Vehicle and engine testing included:
  - DPF regeneration interval testing.
  - Engine mapping with emissions analysis.
  - Course engine mapping urea injection event activeness.

Introduction

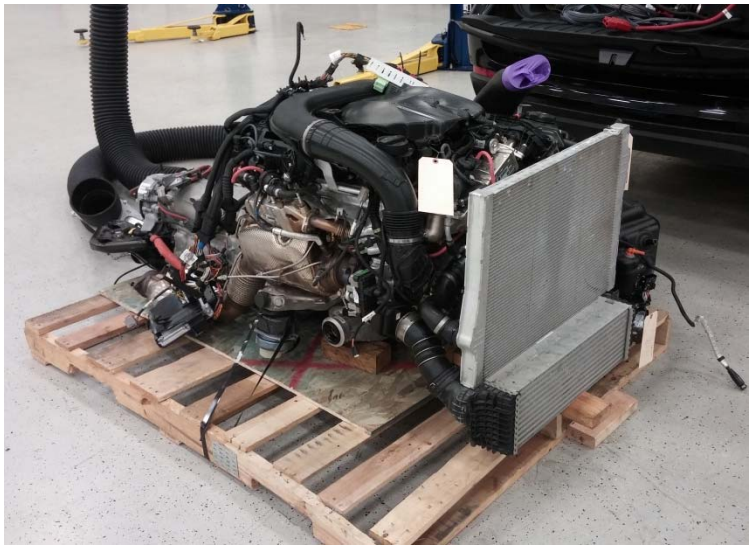
Vehicle specification	
Model Year	2015
Engine	Turbocharged intercooled DOHC 24-valve Inline 6
Engine Displacement	2993 cc
Curb Weight	5173 lbs
MPG	23/31 city/hwy
Transmission	8 speed automatic

BMW X5 35d

Introduction

Engine Specification	
Max Torque	560 Nm
Max Power	255 hp
Max Engine Speed	4400 rpm
Engine Volume	3.0 L
Cylinder Number	6
Compression ratio	16.5
Bore	84 mm
Stroke	90 mm
Connecting Rod Length	138 mm

BMW X5 35d



Introduction

Engine Aftertreatment	
Lean NOx Trap volume	1.96 L
Diesel Particulate Filter volume	2.94 L
Selective Catalytic Reduction volume	4.58 L

BMW X5 35d

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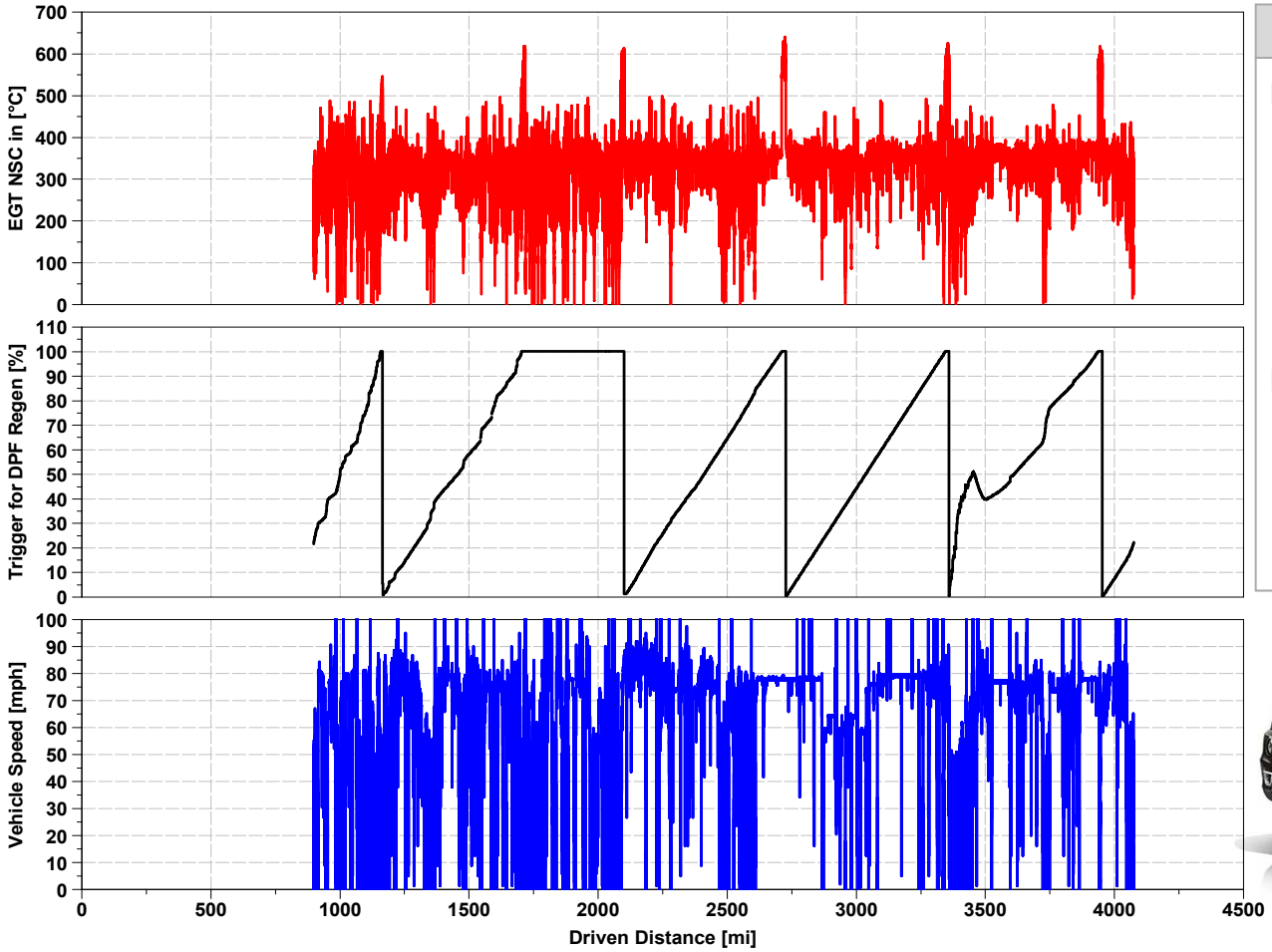
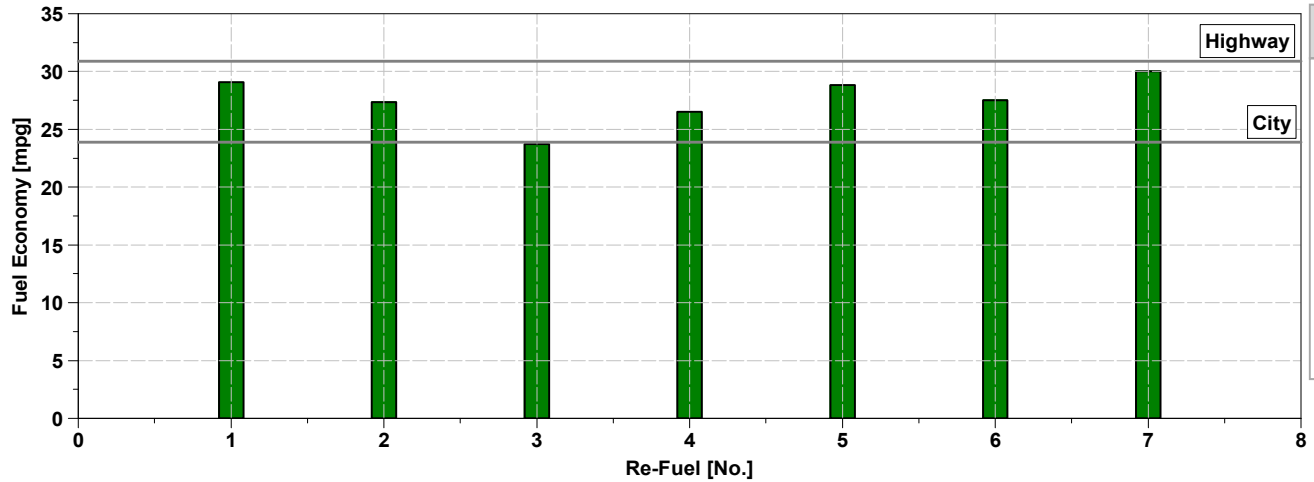
FEV Benchmarking
BMW X5d 35d: Break-In

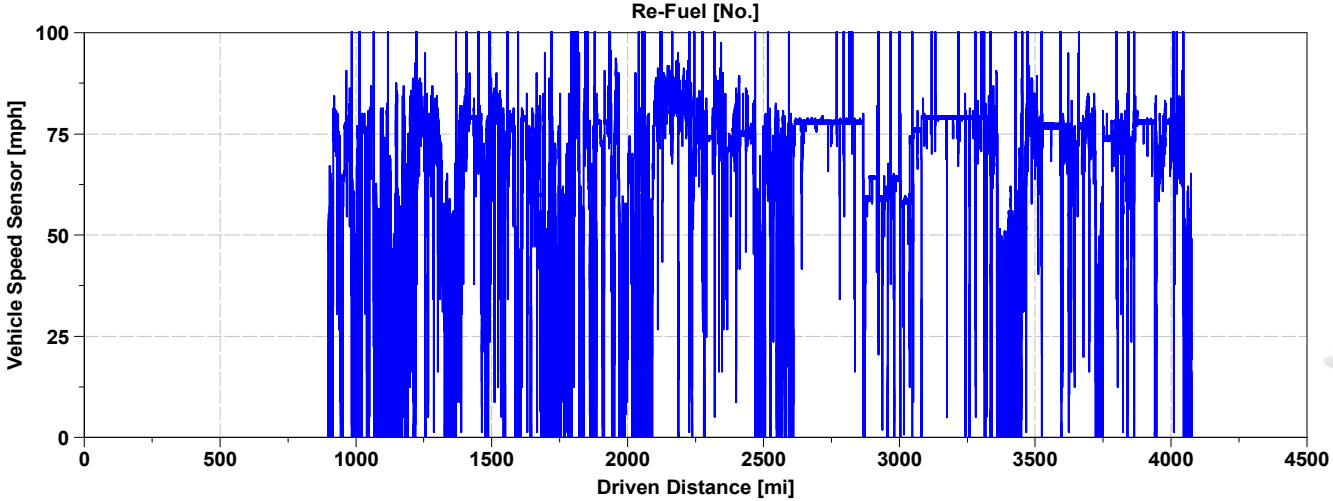


Comments

- A DPF regeneration occurred approximately every 600 miles dependent on driving conditions (i.e. highway or city).
- Five DPF regenerations occurred during the vehicle break-in.

FEV Benchmarking
BMW X5d 35d: Break-In





Comments

- The fuel economy was within the EPA estimated city/highway fuel economy of 23 mpg and 31 mpg, respectively.

Agenda

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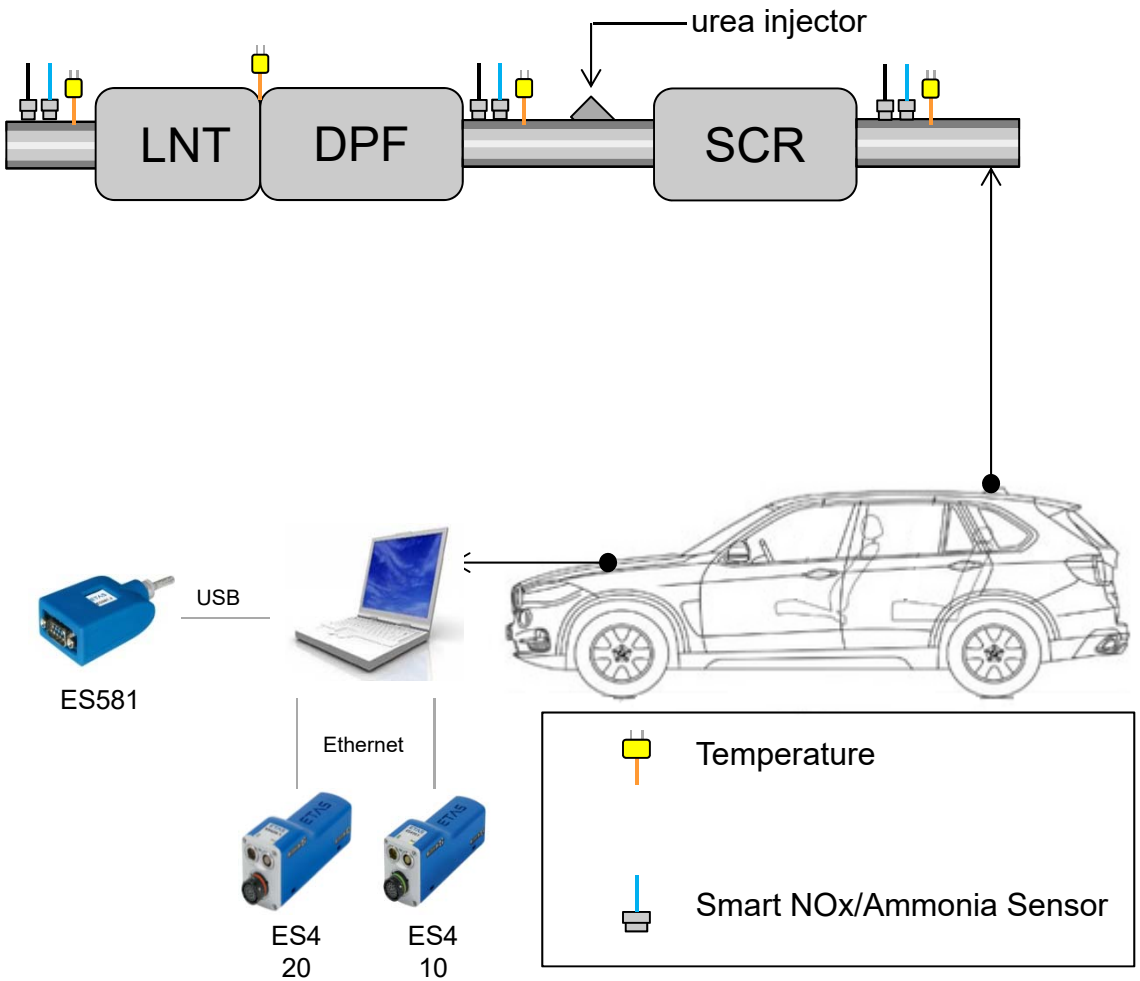
Setup: Vehicle Testing

Setup

- NOx emissions were measured using a smart NOx sensor pre and post LNT/DPF catalyst as well as pre and post SCR catalyst.
- Engine parameters were measured of OBD using ETAS Inca.



Setup: Vehicle Testing

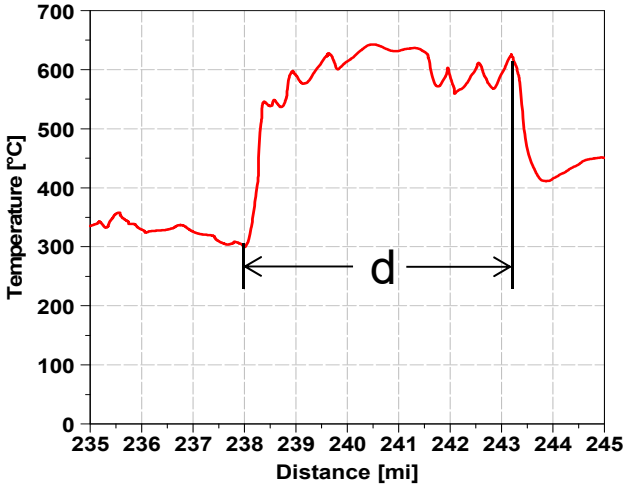
DPF Interval Frequency Factor

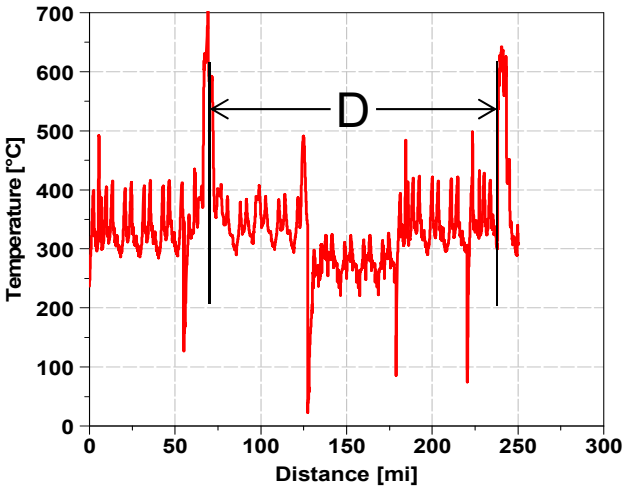
- DPF interval characterized by distance between the end and beginning of a regen event as well as the distance during a regen event.
- The FTP75 drive cycle was repeated continuously and the 10 minute soak was omitted.

$$F = \frac{d}{D + d}$$

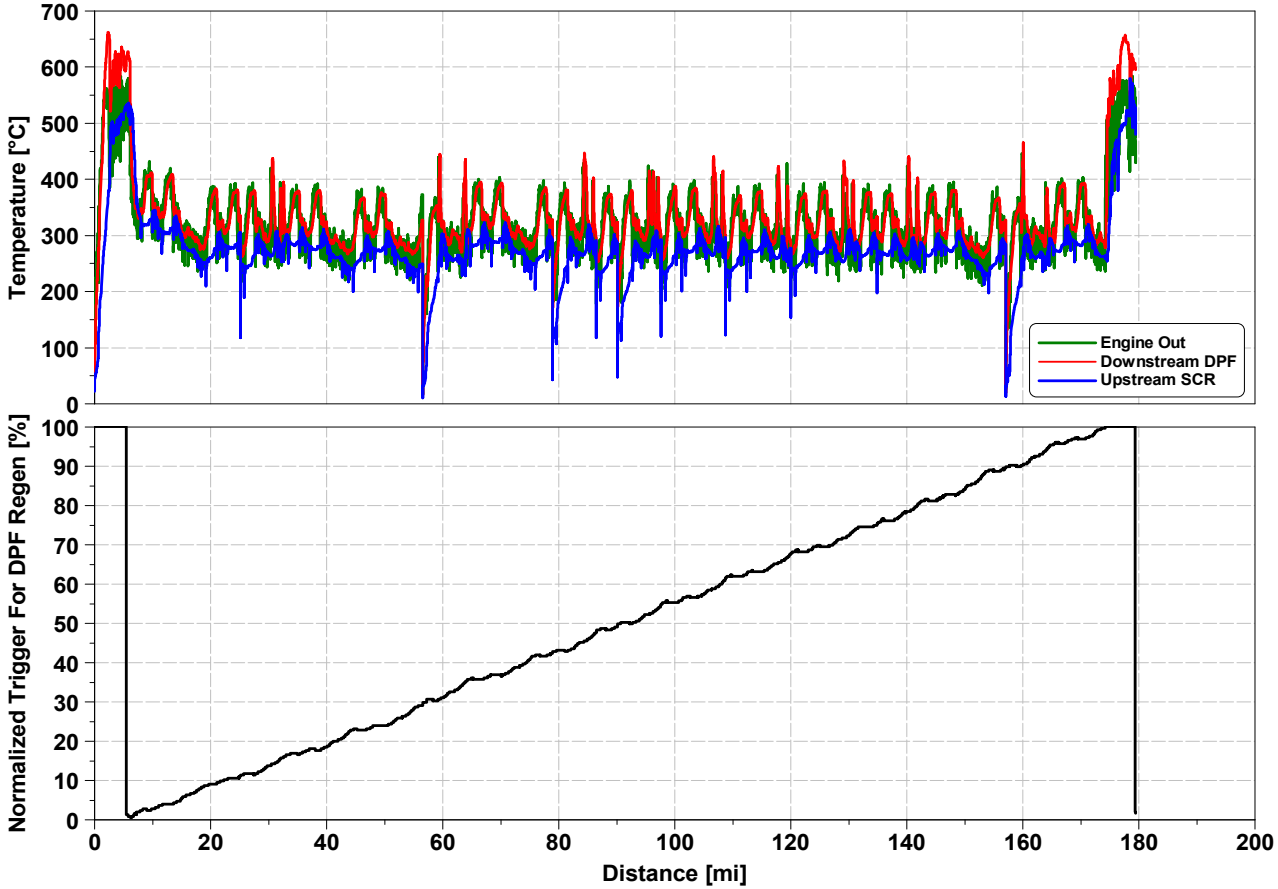
$d - distance\ driven\ during\ a\ regen\ event.$

$D - distance\ between\ regen\ events.$





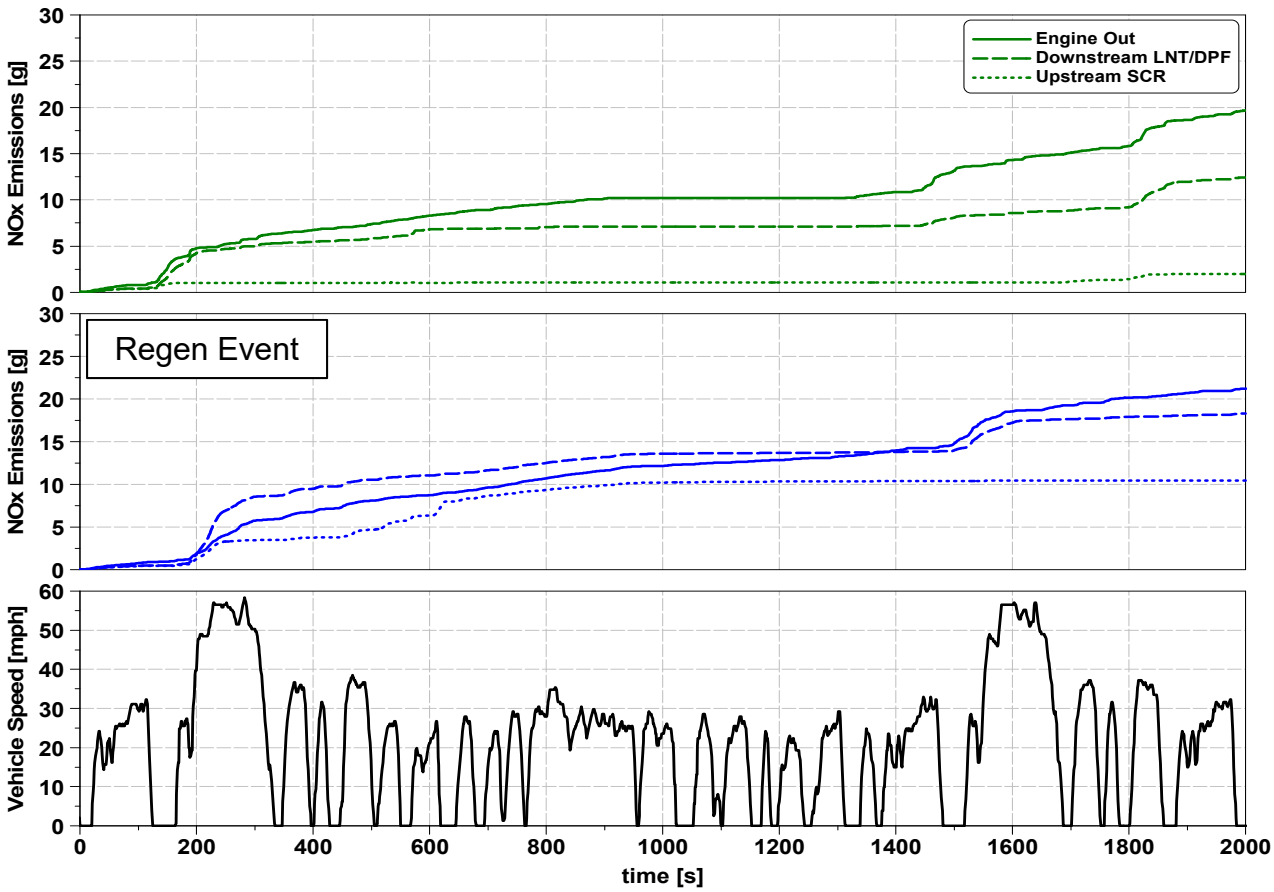
FEV Benchmarking
BMW X5d 35d: DPF Regeneration Interval



Comment

- The FTP75 cycle was driven continuously from DPF regeneration to the next in order to determine the regeneration interval.
- The distance between regens for the X5d was approximately 168 miles.
- The X5d resulted in a regen interval factor of 0.026.

FEV Benchmarking
BMW X5d 35d: DPF Regeneration Interval



Comment

- The LNT releases NOx stored during a regeneration and becomes inactive.
- NOx conversion efficiency is greatly impacted during DPF regeneration.

LNT	SCR	Total
14%	43%	56%
41%	87%	90%

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Engine Testing Setup

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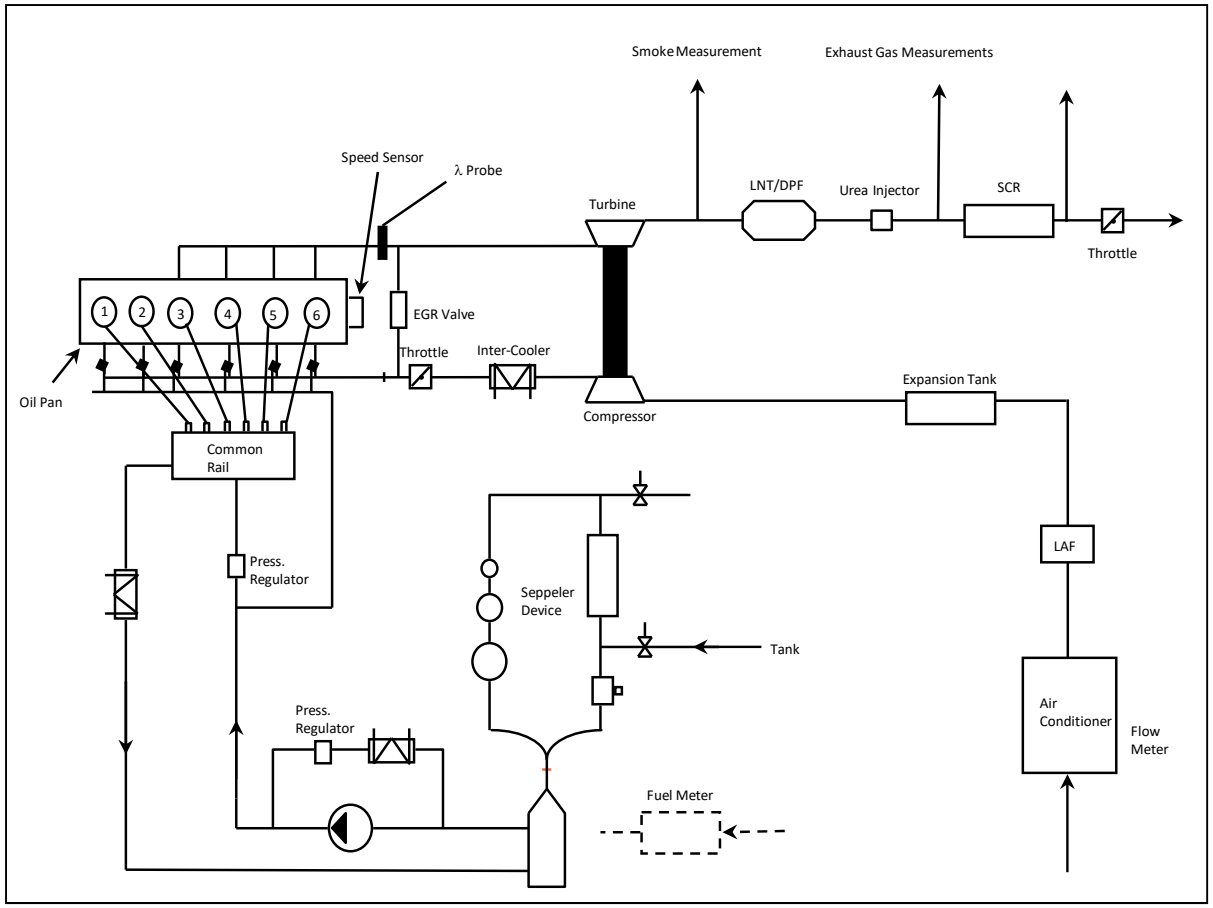
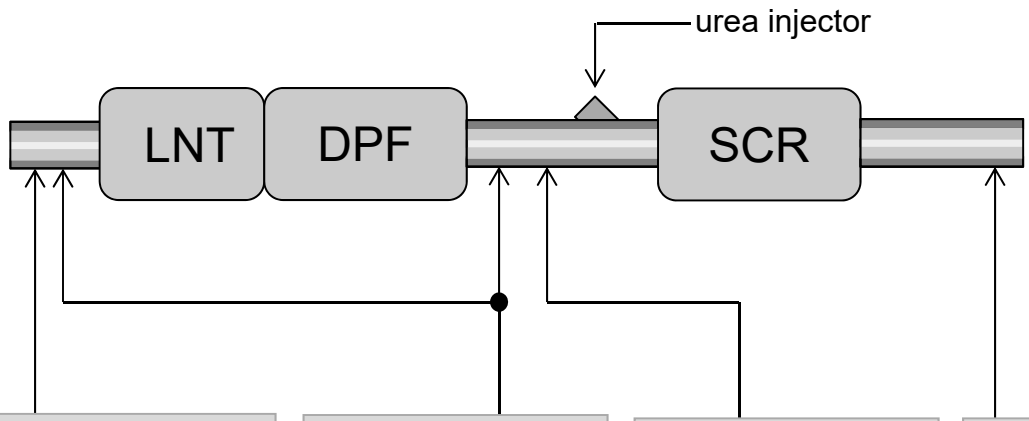


Engine Aftertreatment Setup: Engine Mapping

Setup

- An emissions bench use to measure emissions across the LNT/DPF catalyst.
- Two separate FTIR's were used to measure emissions across the SCR catalyst.



Smoke Meter

- FSN

Emissions Bench

- NOx
- NO
- CO
- THC
- CH4

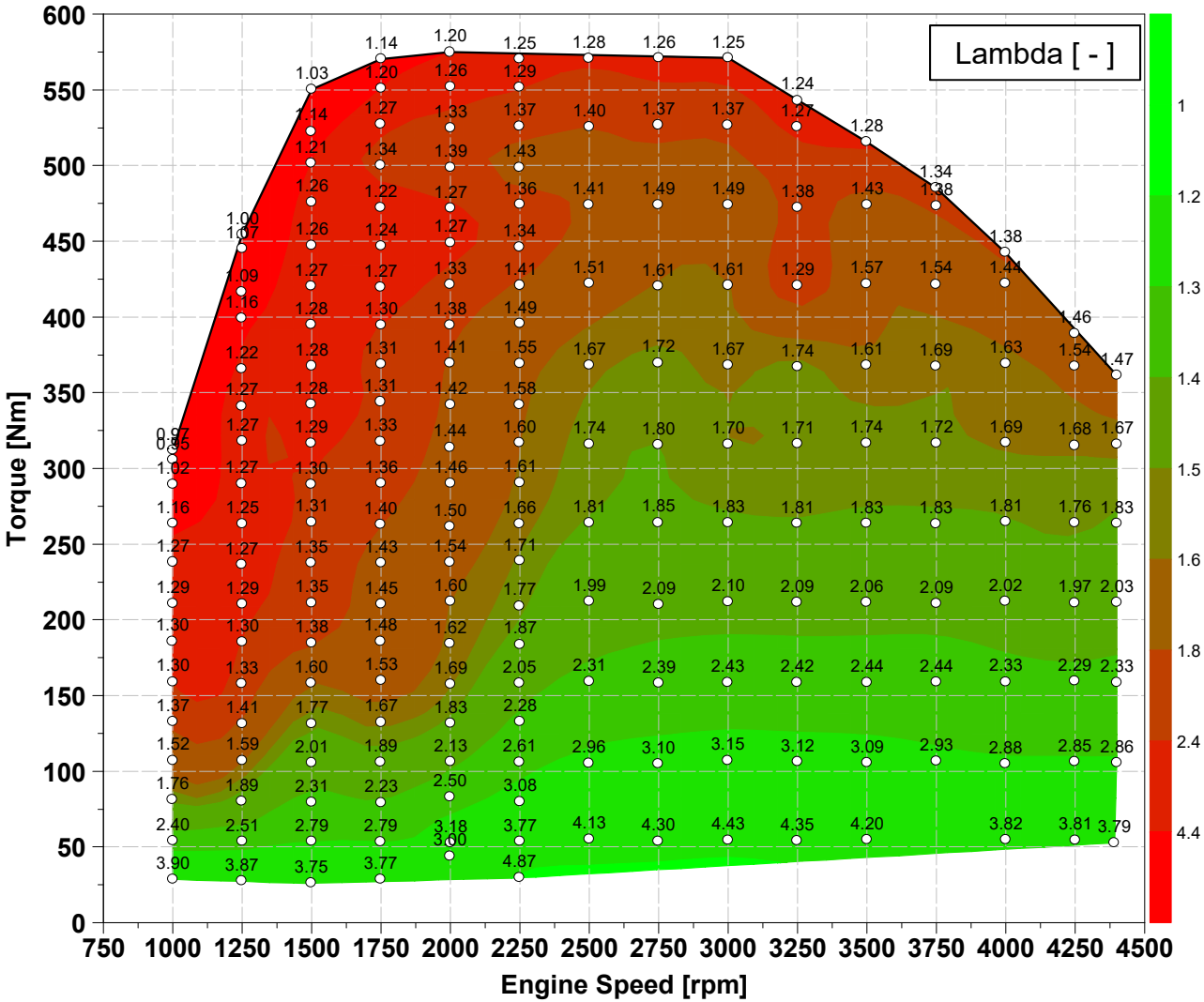
FTIR

- NOx
- NO
- NO2
- N2O
- NH3
- HCHO
- CH4

FTIR

- NOx
- NO
- NO2
- N2O
- NH3
- HCHO
- CH4

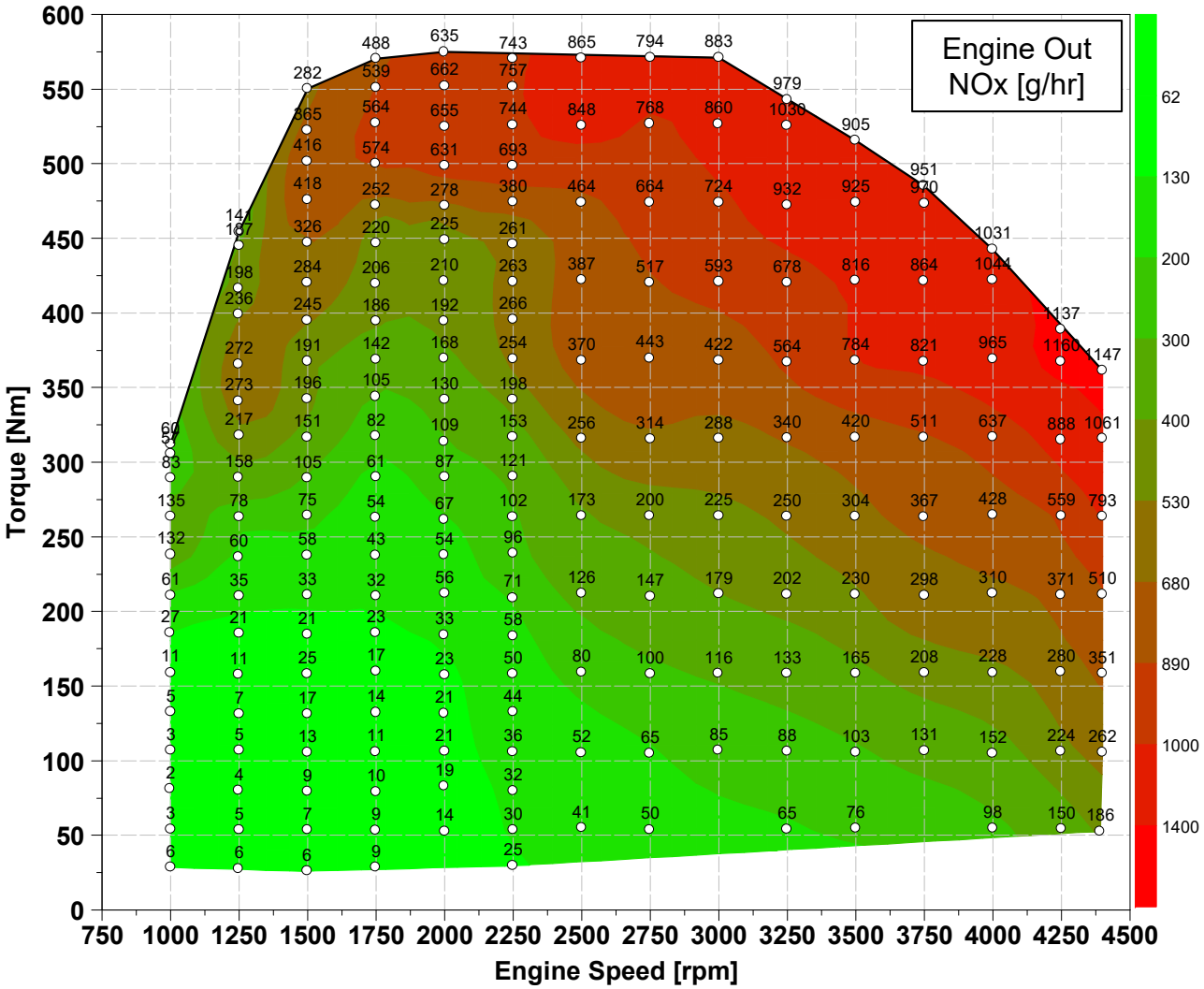
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Lambda values ranged from 1.30 – 4 over then entire map.
- At full load the engine runs near rich lambda values of approximately 1 while at lower speeds and typically increase with speed.

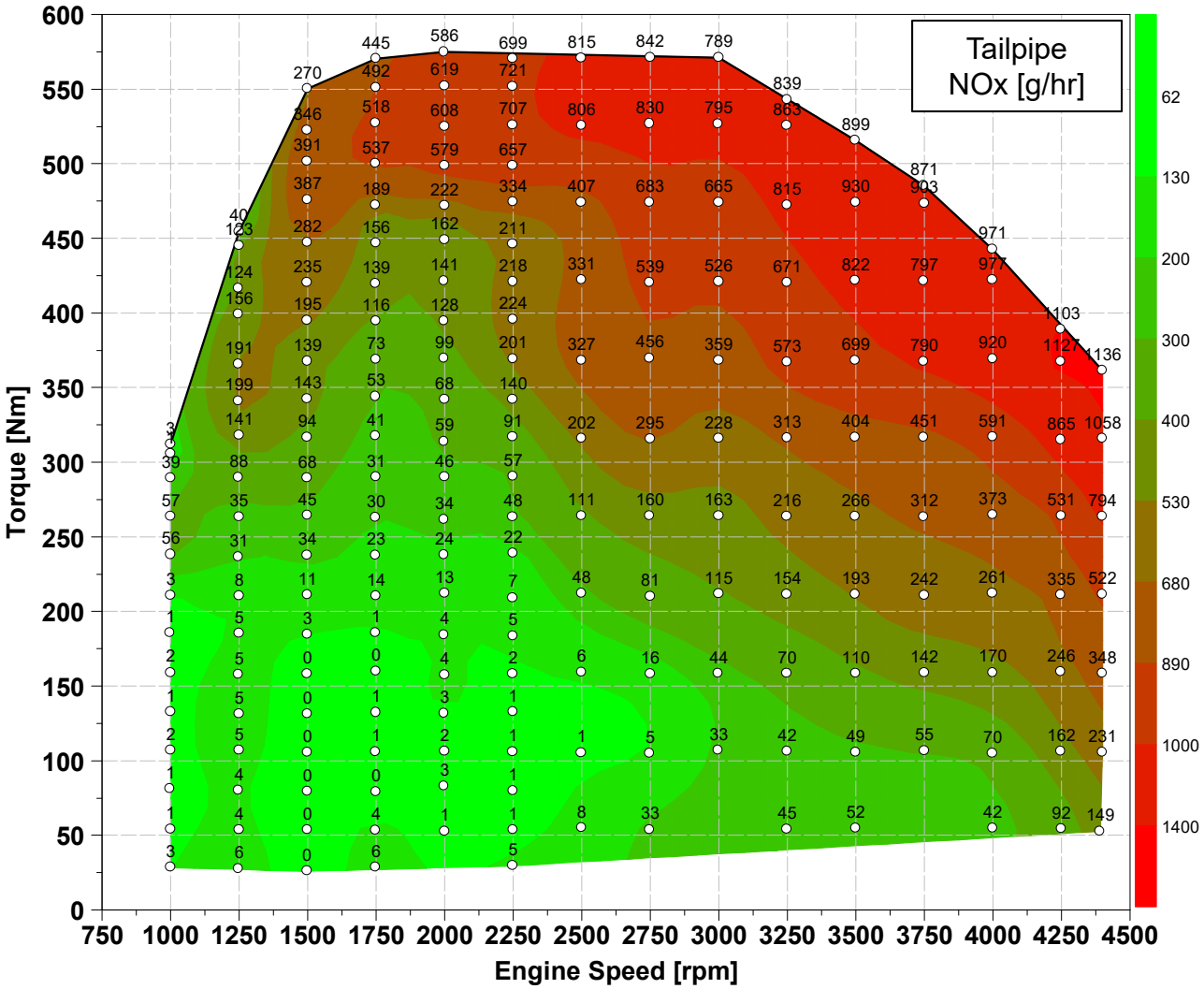
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Engine out NOx was relatively low from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm below approximately 30 g/hr.
- Outside of this range the engine out NOx is much higher at 30 g/hr or more.
- The NOx emissions are more impacted by load than speed.

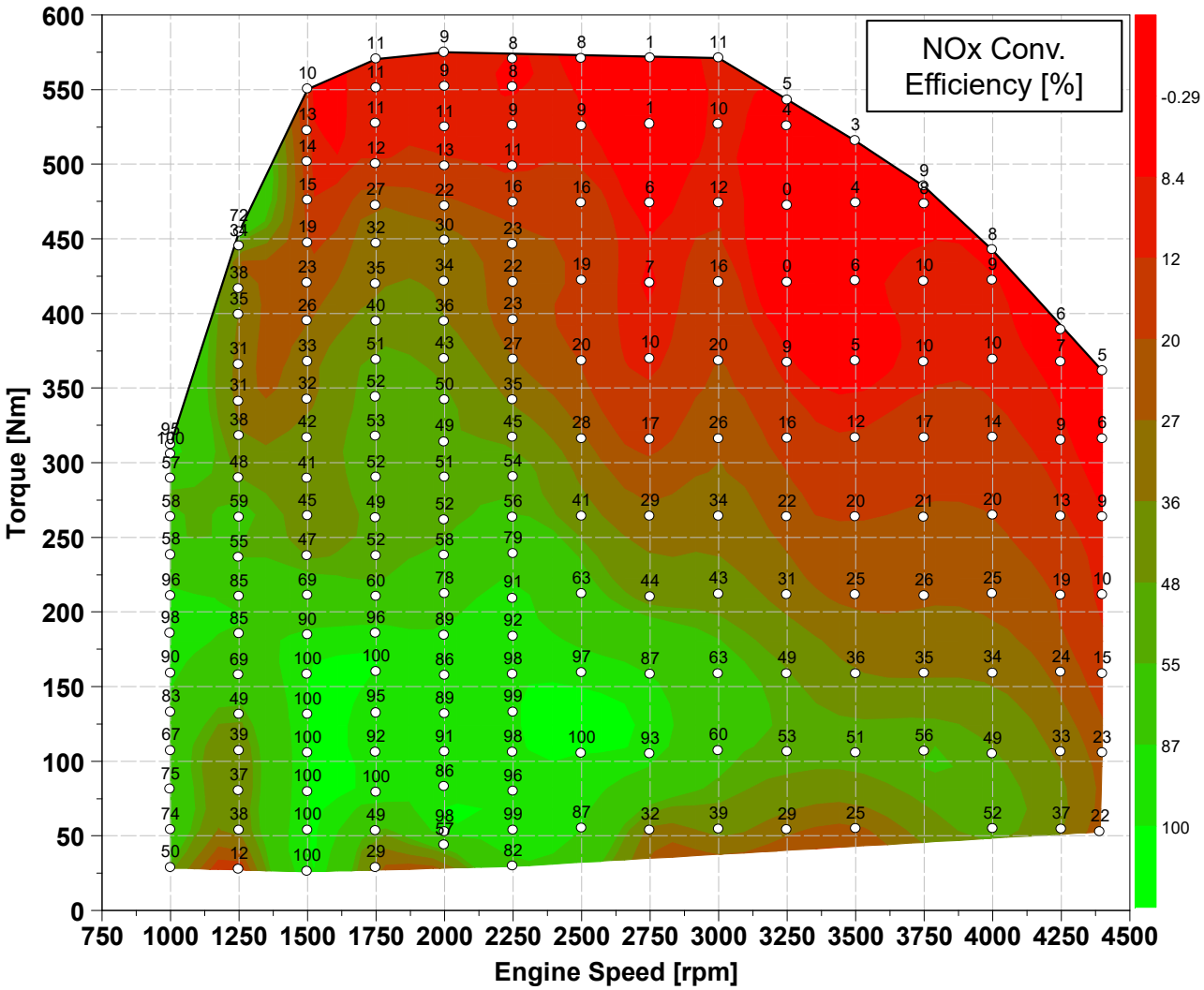
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The tailpipe NOx was very low at, less than 10 g/hr from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm.

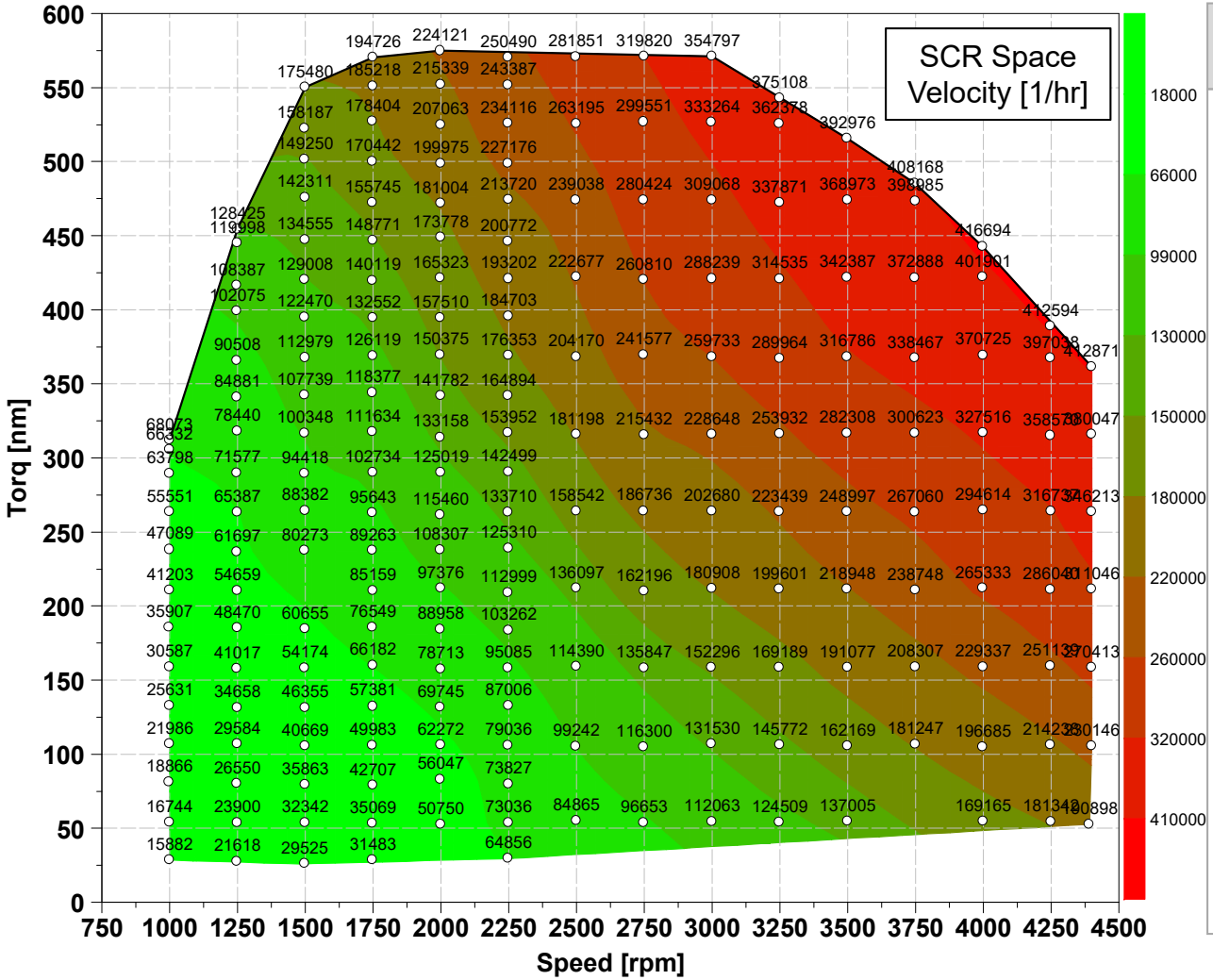
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The total aftertreatment NOx conversion efficiency (including lean NOx trap and SCR system) was most efficient from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm.
- With efficiencies reaching to as high as 100% at 1500 rpm.
- At high load and speed areas on the map the ATS efficiency was lower than 20% for most area's within the 2500 rpm to 4400 rpm and 250 Nm to 570 Nm.

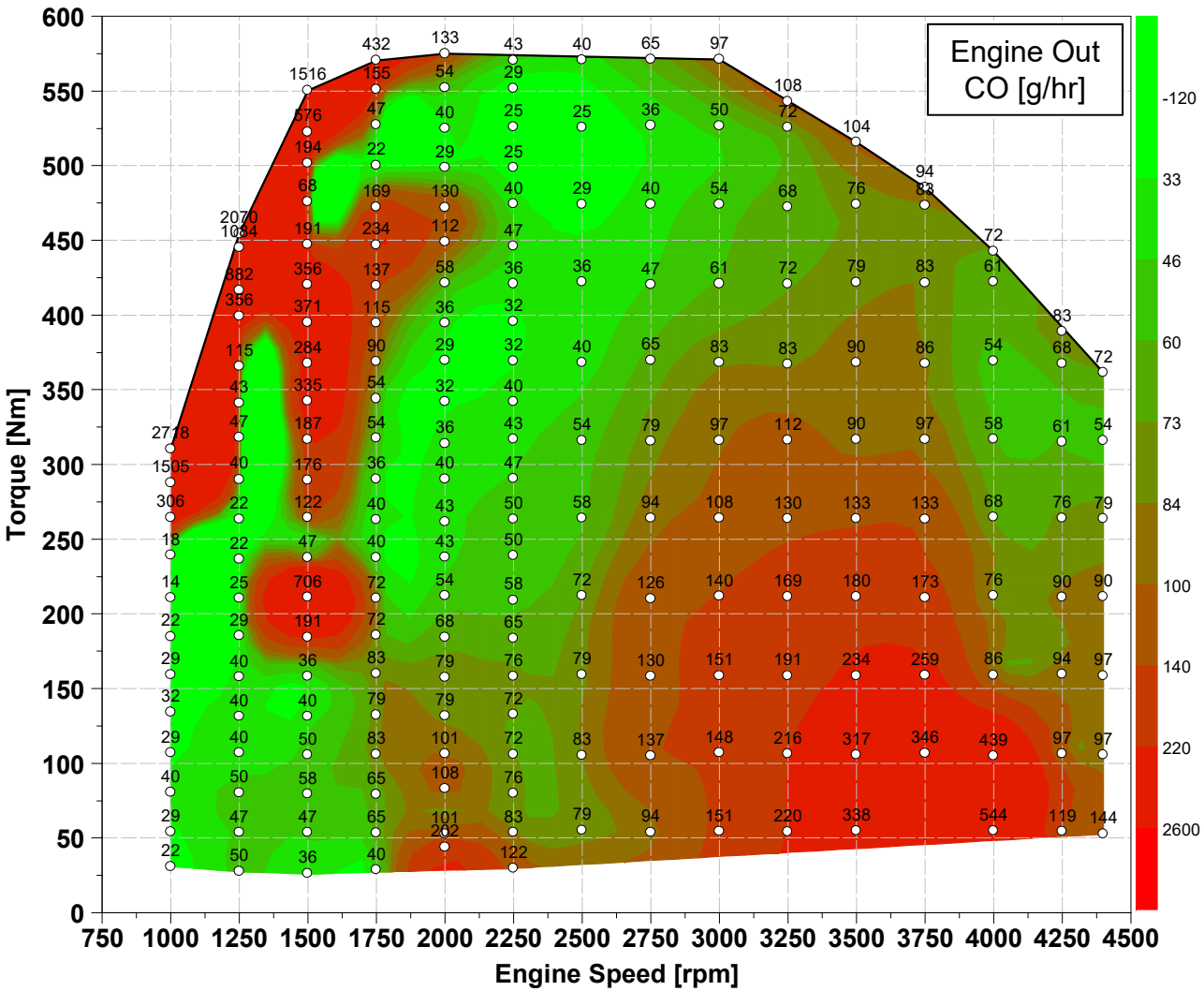
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The SCR space velocity was lowest from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm.
- The space velocity value increased substantially at full load and peak power at 4000 rpm

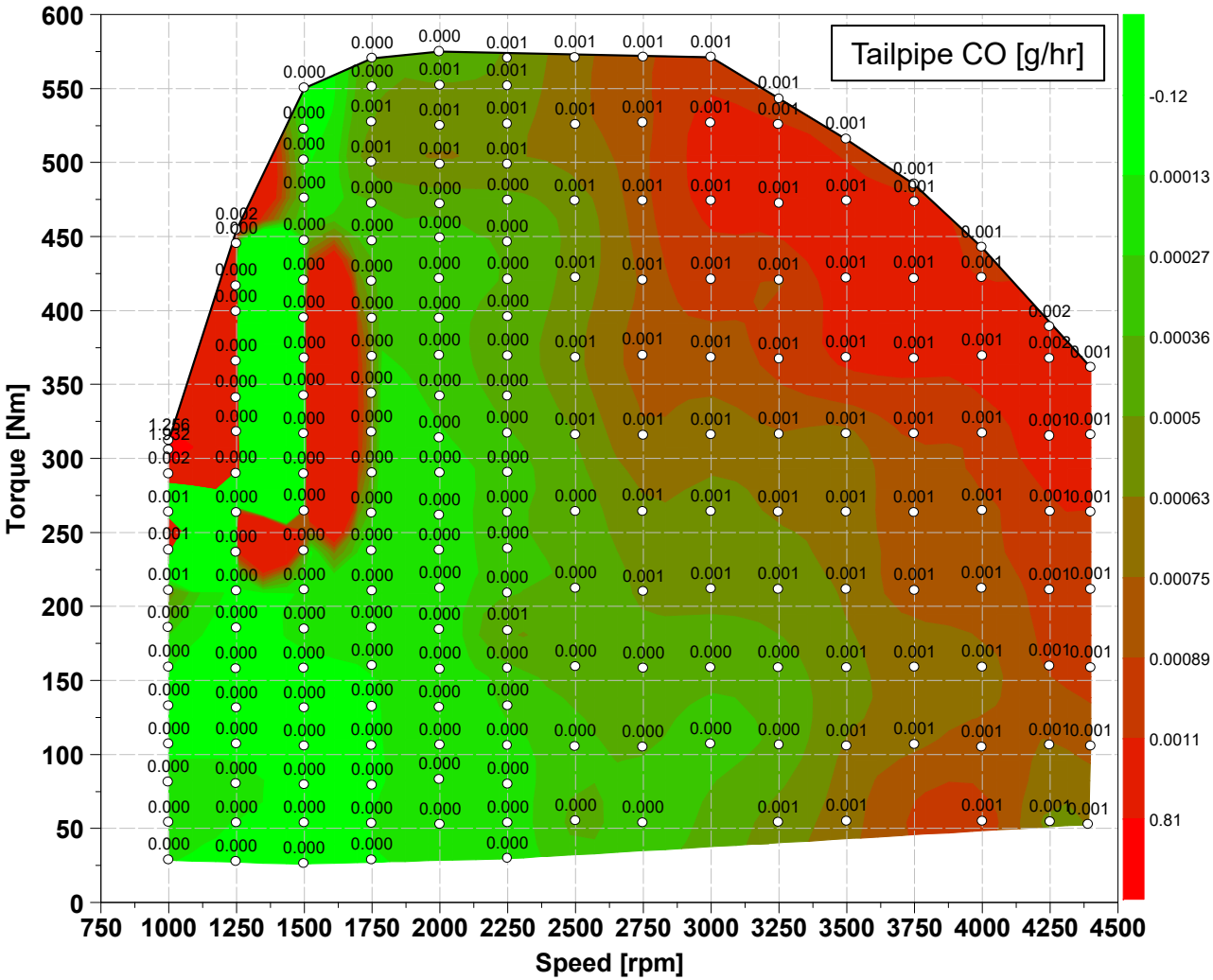
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Engine out CO was highest at 3000 rpm to 4000 rpm.
- The engine out CO emissions were much higher at full load on the lower speeds (1000rpm to 1750 rpm) on the engine map.

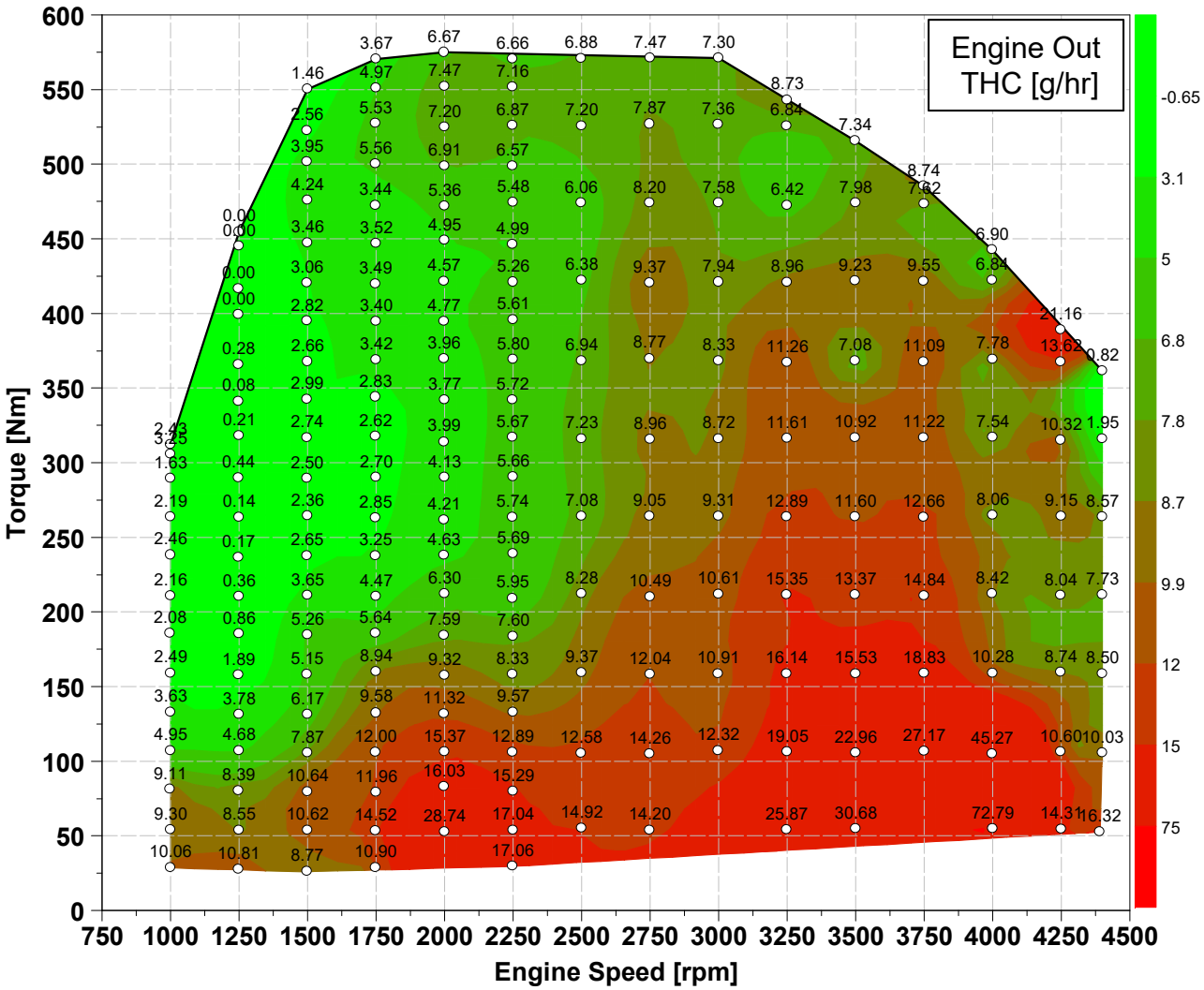
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The tailpipe CO is much lower, less than 1 g/hr, for the entire engine map.

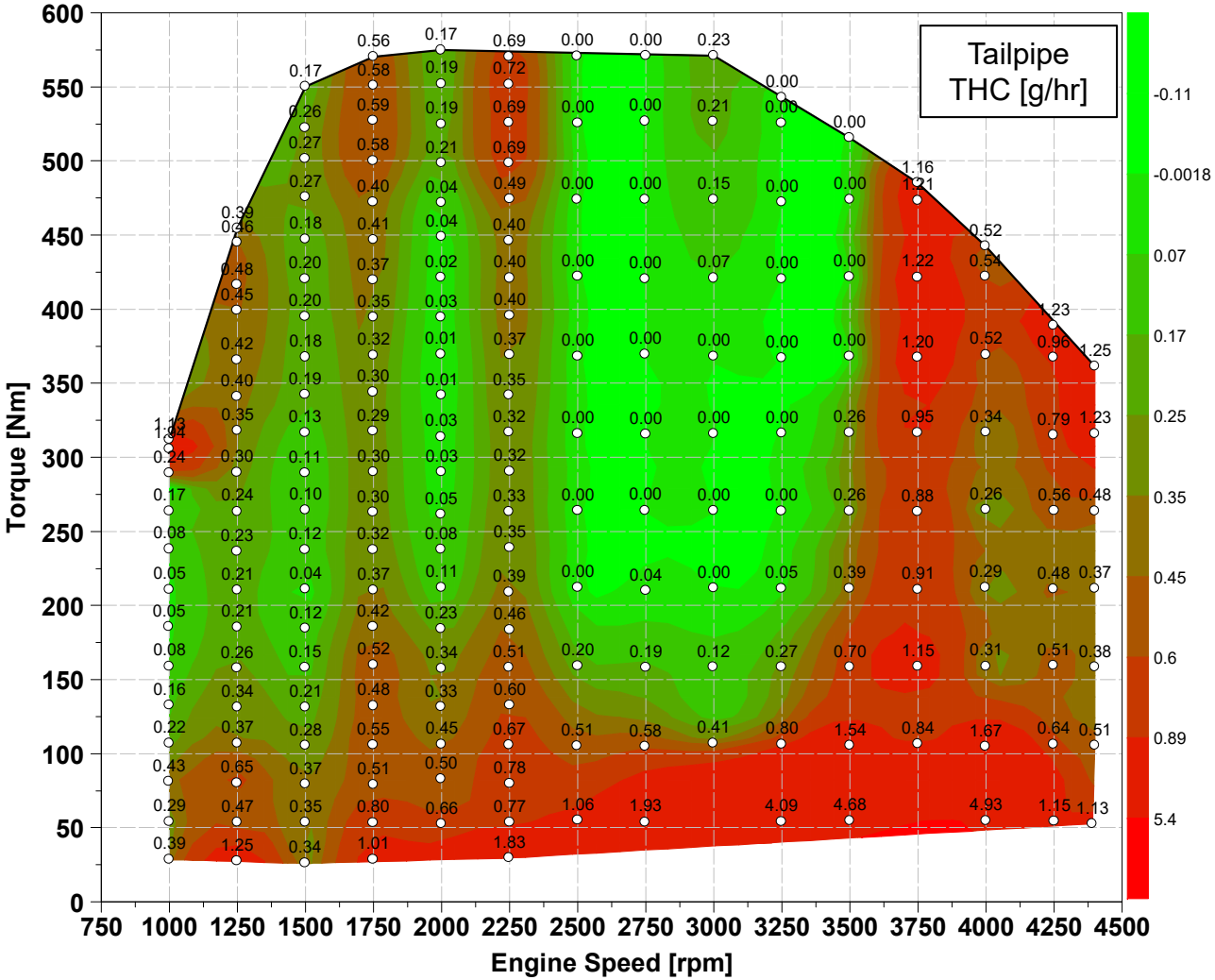
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The engine out THC emissions were highest at the low load high speed range on the map from 3000 rpm to 4000 rpm and 50 Nm to 200 Nm.
- THC mass flow was calculated assuming all exhaust THC species were propane.

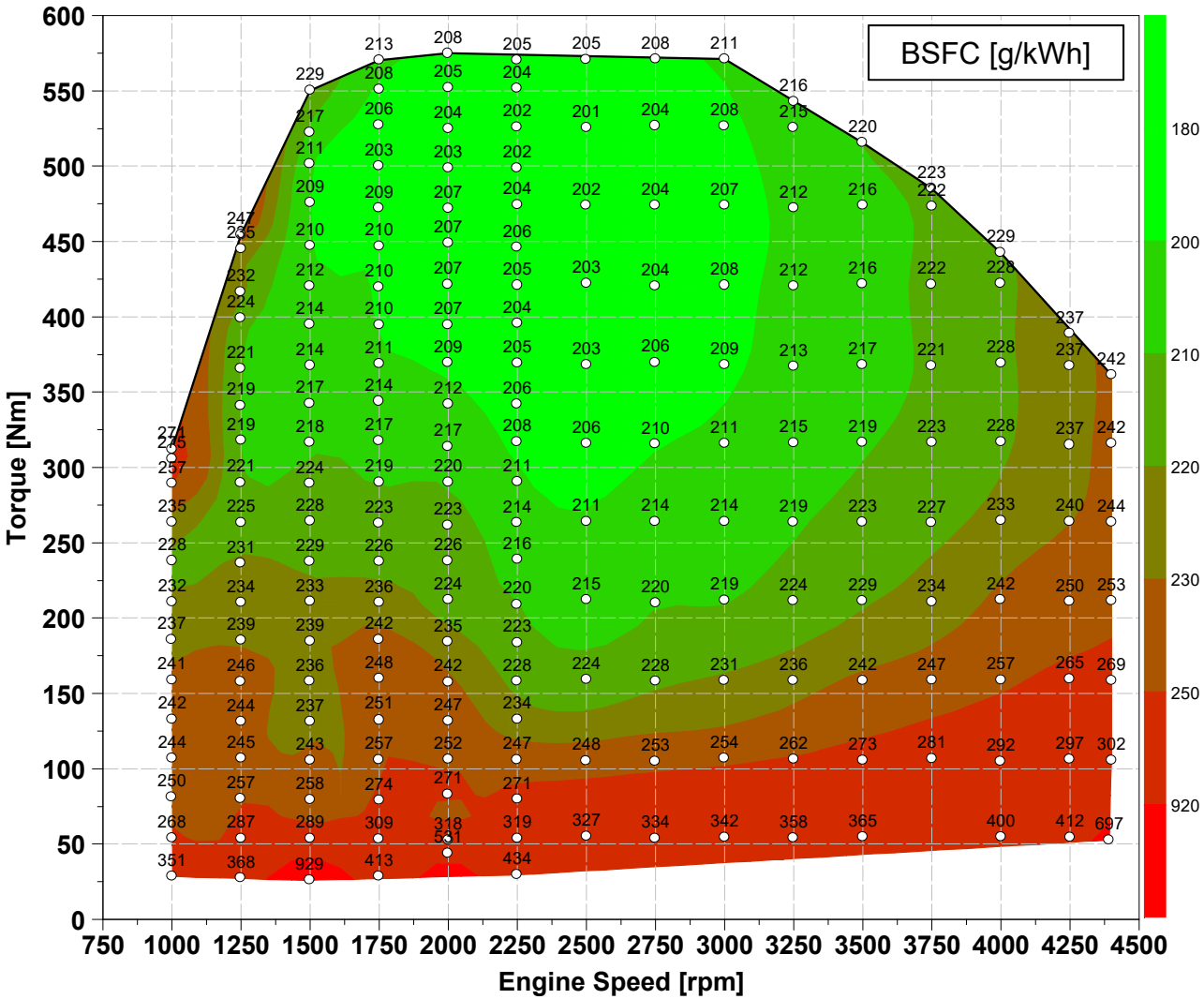
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Tailpipe THC emissions were low at most points on the engine map excluding the low load high speed range on the map from 3250 rpm to 4000 rpm and 50 Nm to 100 Nm.
- THC mass flow was calculated assuming all exhaust THC species were propane.

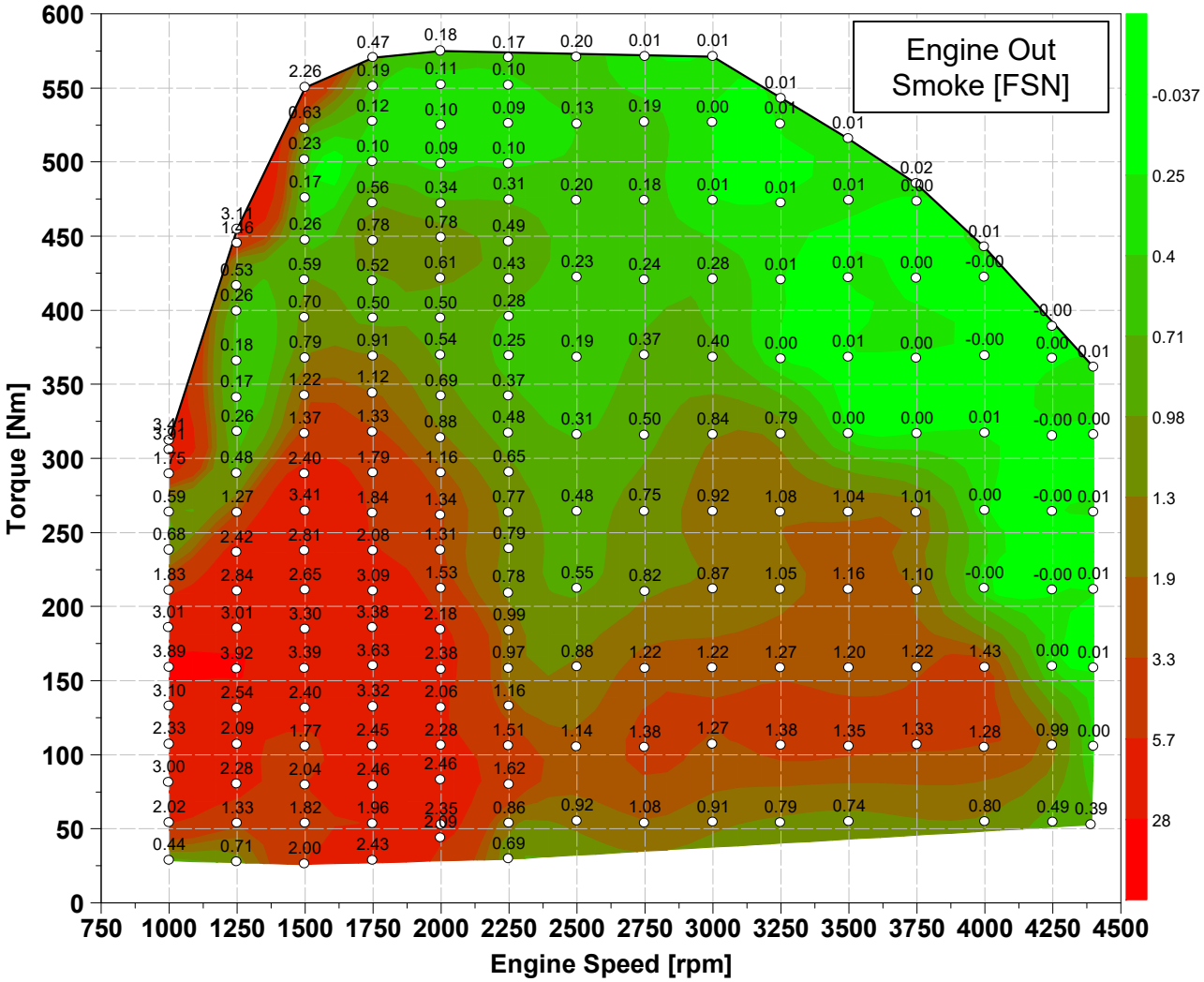
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The BSFC began to decrease in as there were increases in load.
- The engine operating area consisted of BSFC values of approximately 240 g/kWh or higher.

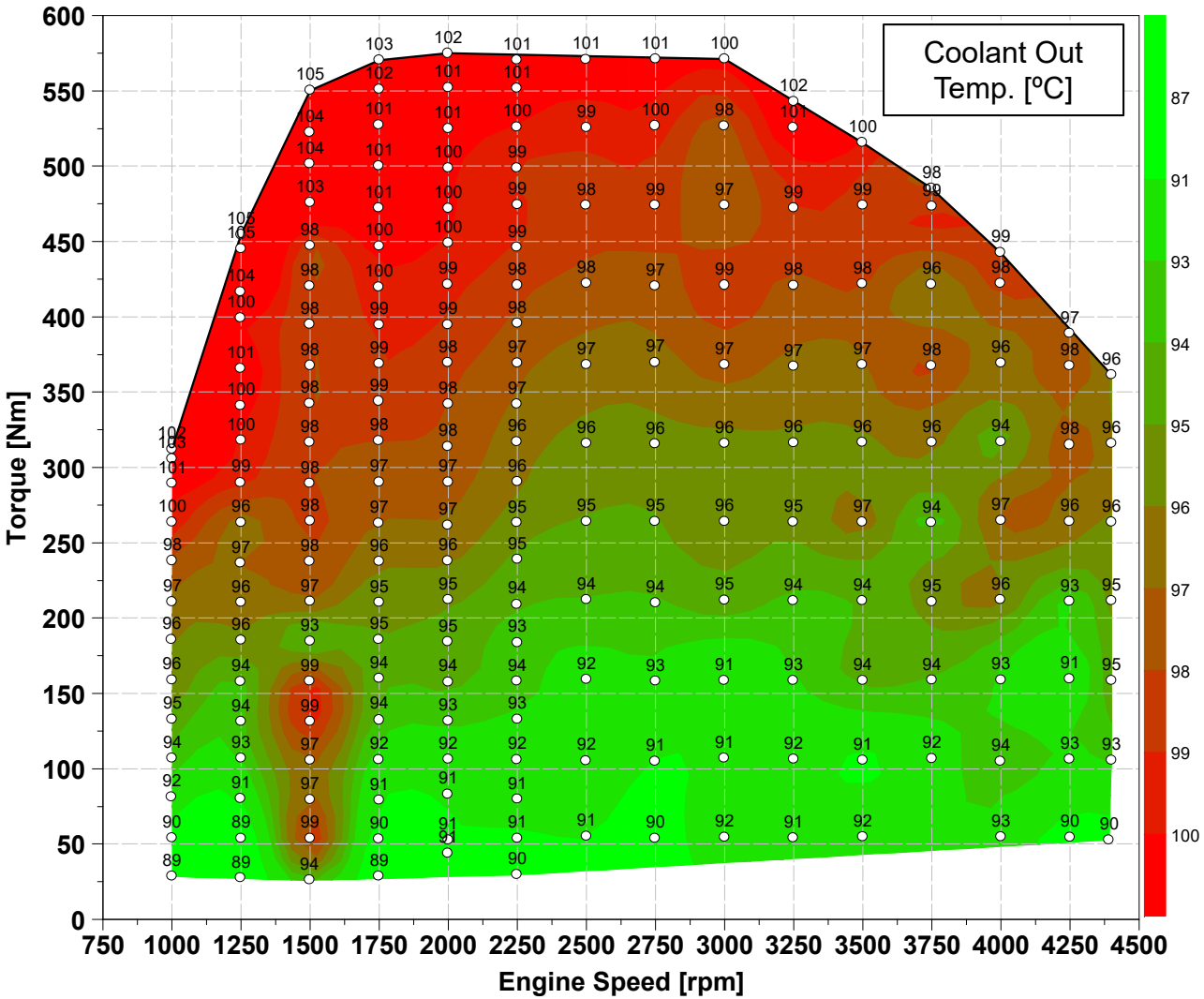
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Engine out smoke emissions were highest from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm.
- This correlates well with the low NOx emissions within the same area.

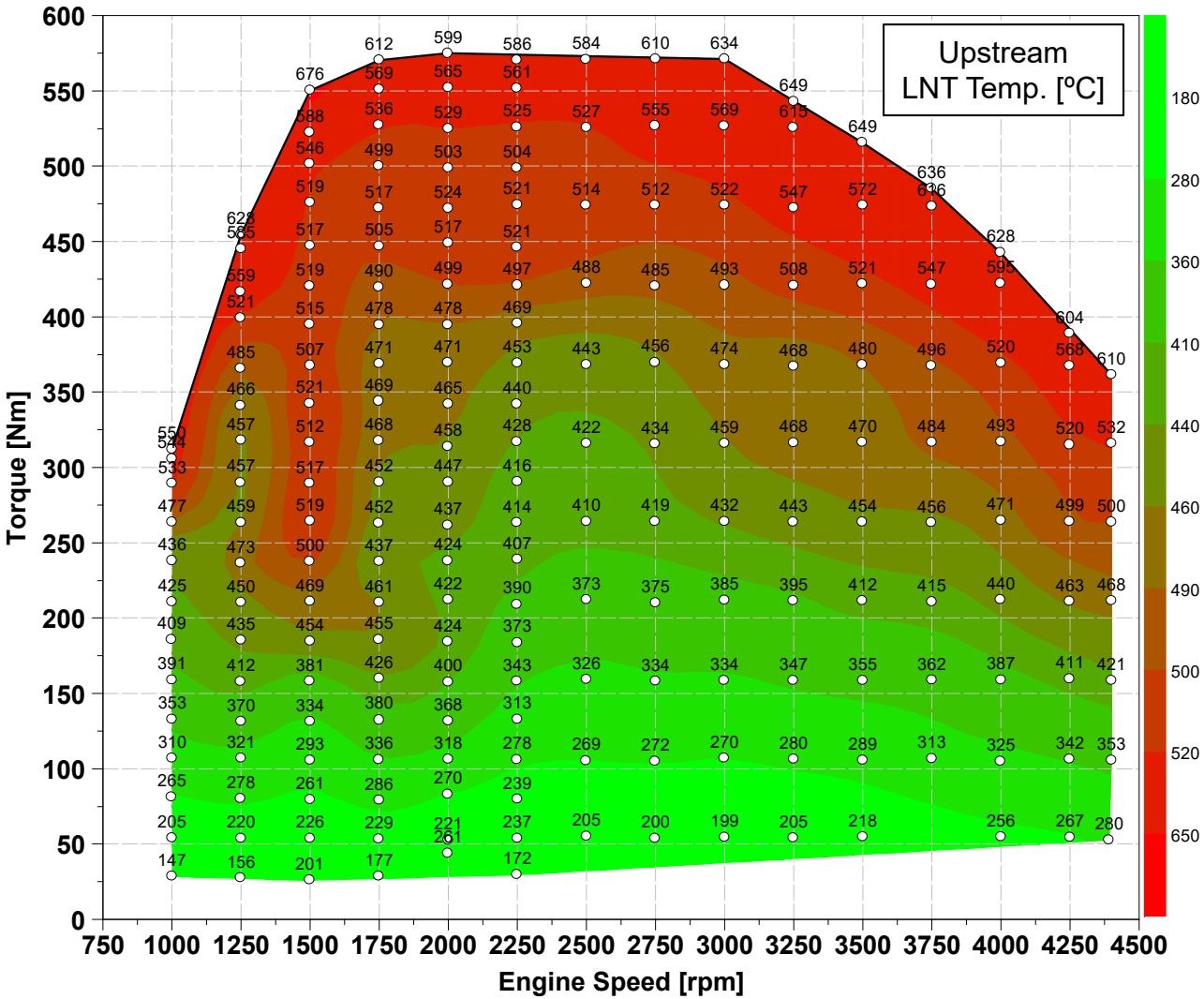
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The coolant out temperature was in the range of 90ºC and 100ºC throughout the entire engine map.
- Increases in load led to increases to coolant out temperatures.

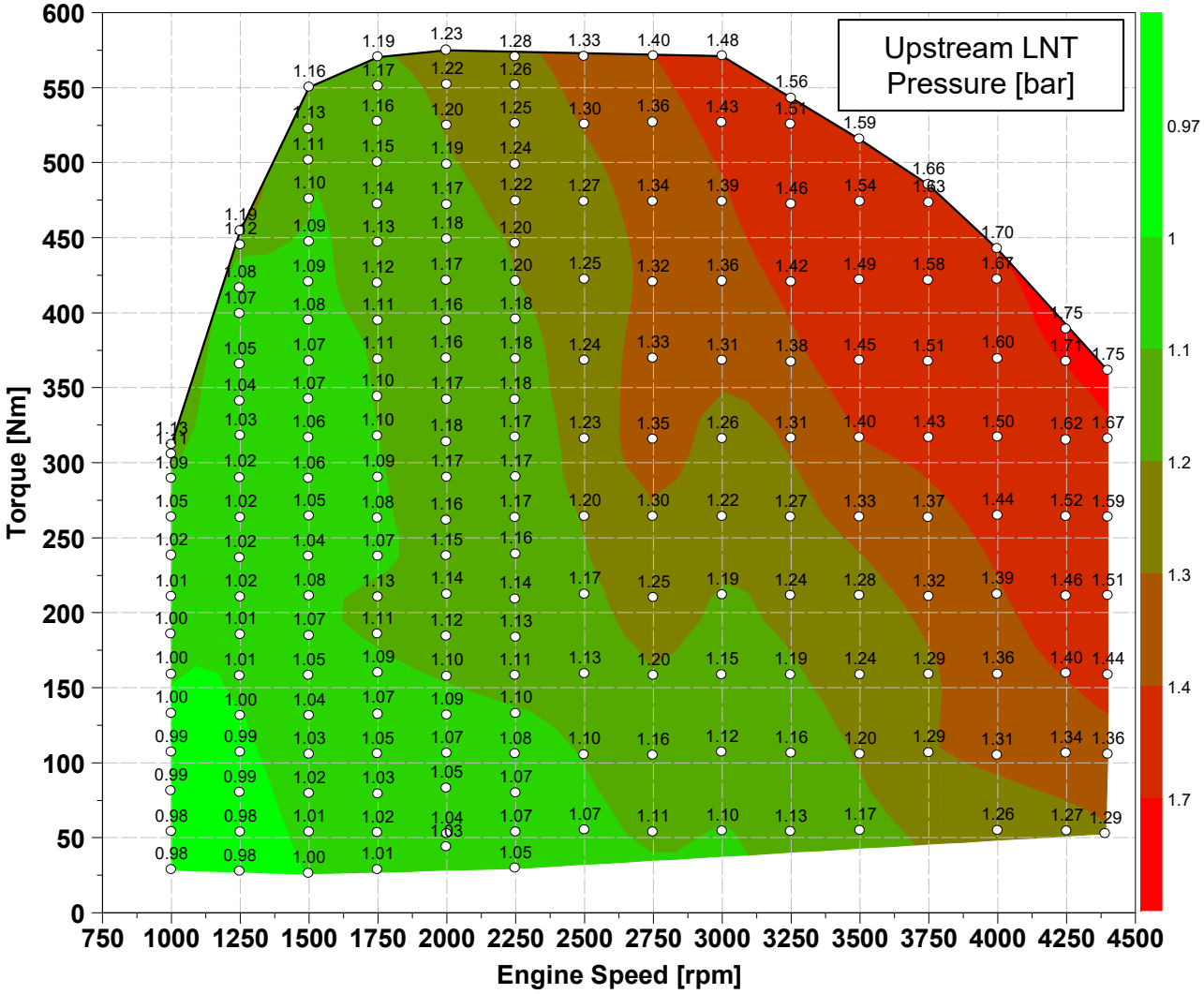
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Exhaust gas temperature at the engine out positions were load dependent.
- The LNT temperature ranged from 150ºC to 450ºC from low load to 200 Nm.

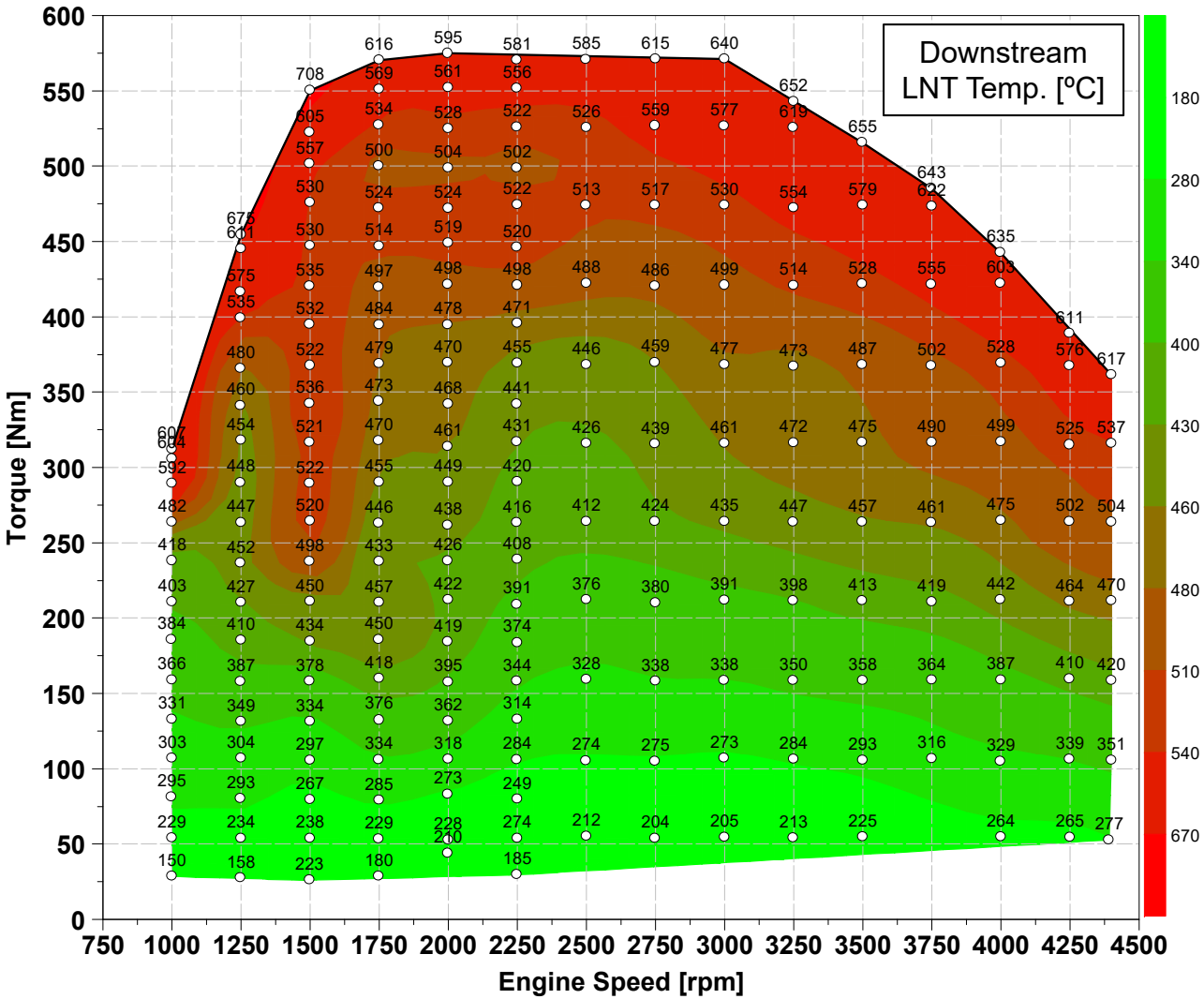
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Exhaust gas pressure at the engine out positions were more speed dependent.

FEV Benchmarking
BMW X5d 35d: Engine Mapping



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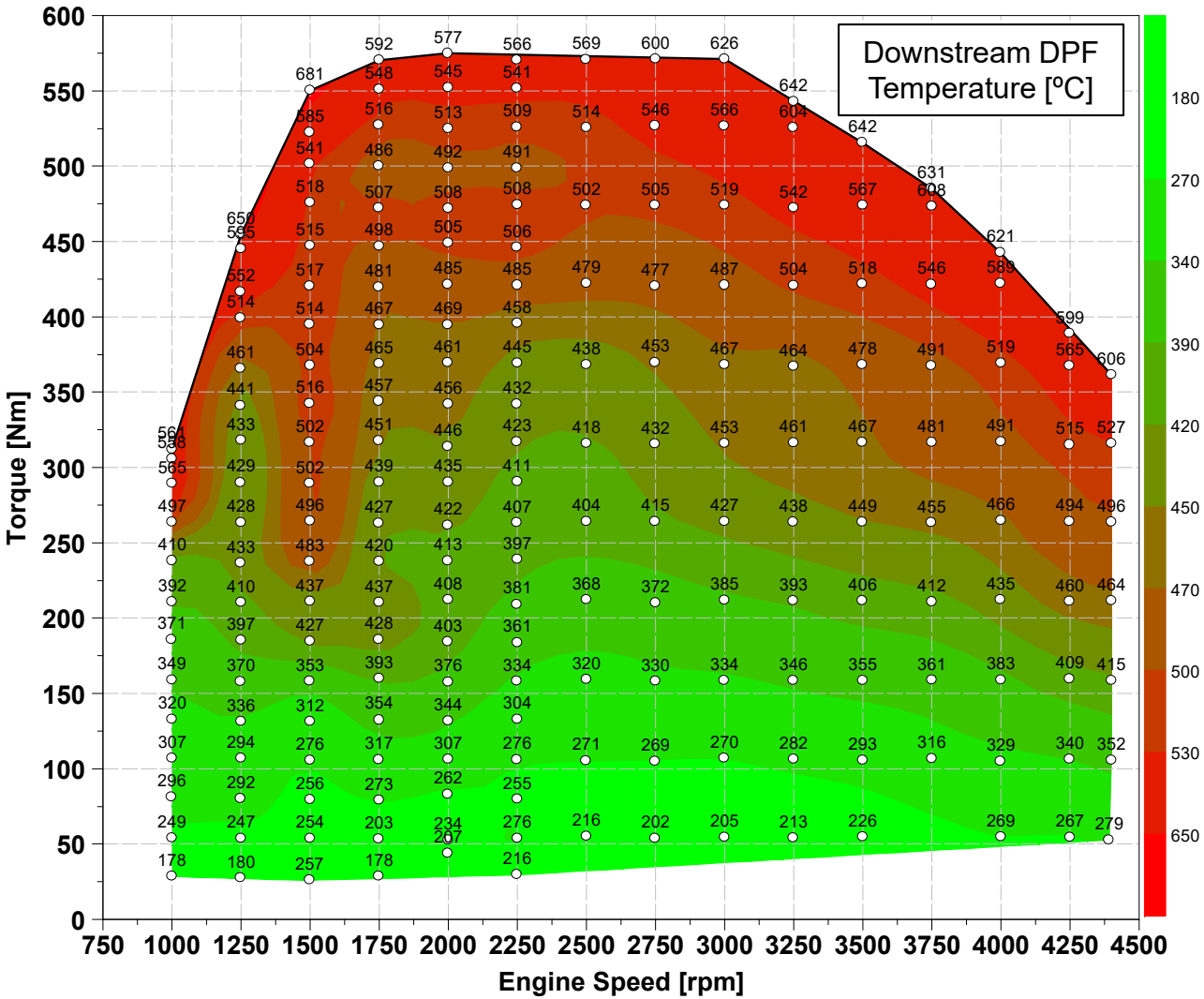
FEV Benchmarking
BMW X5d 35d: Engine Mapping



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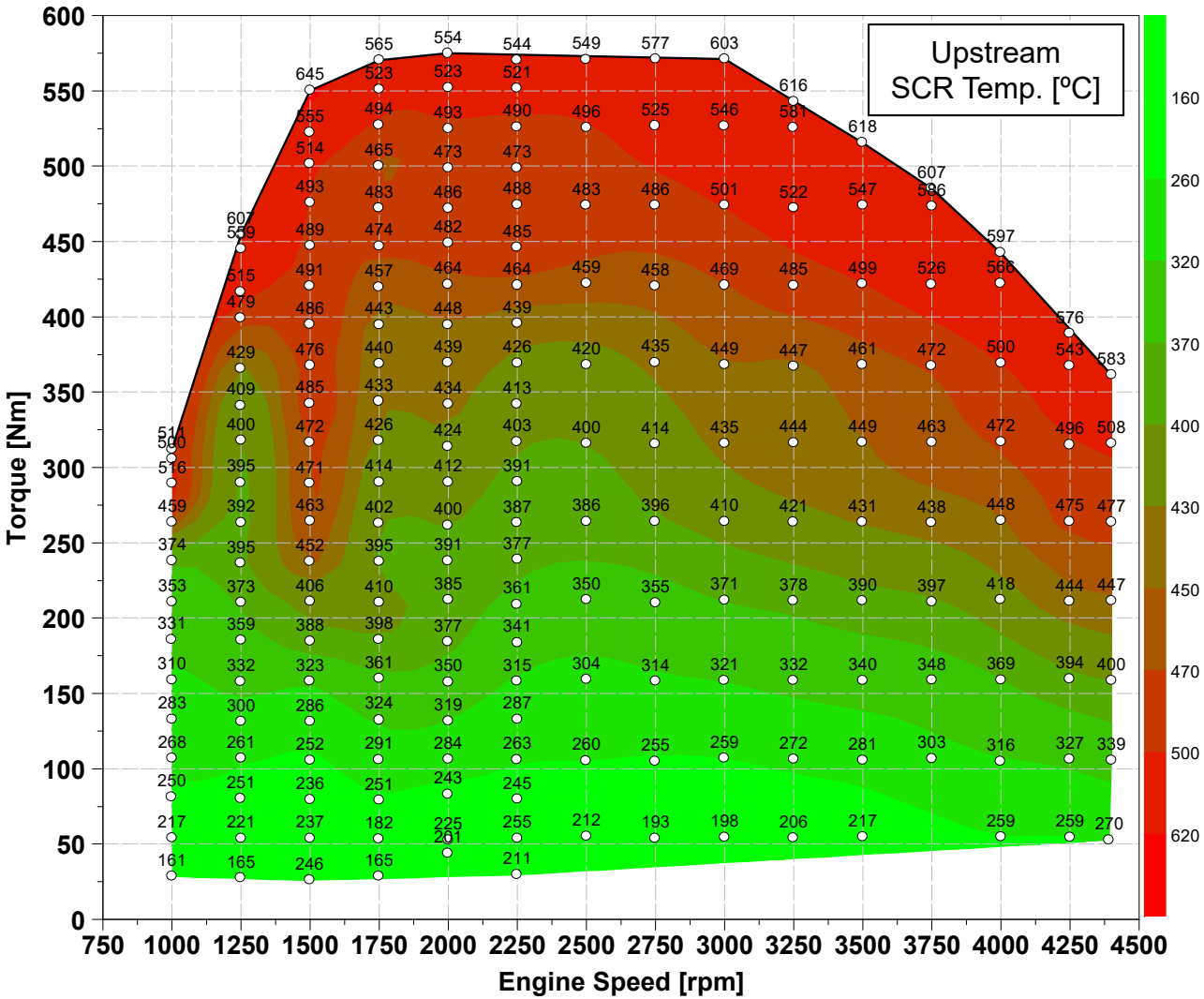
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

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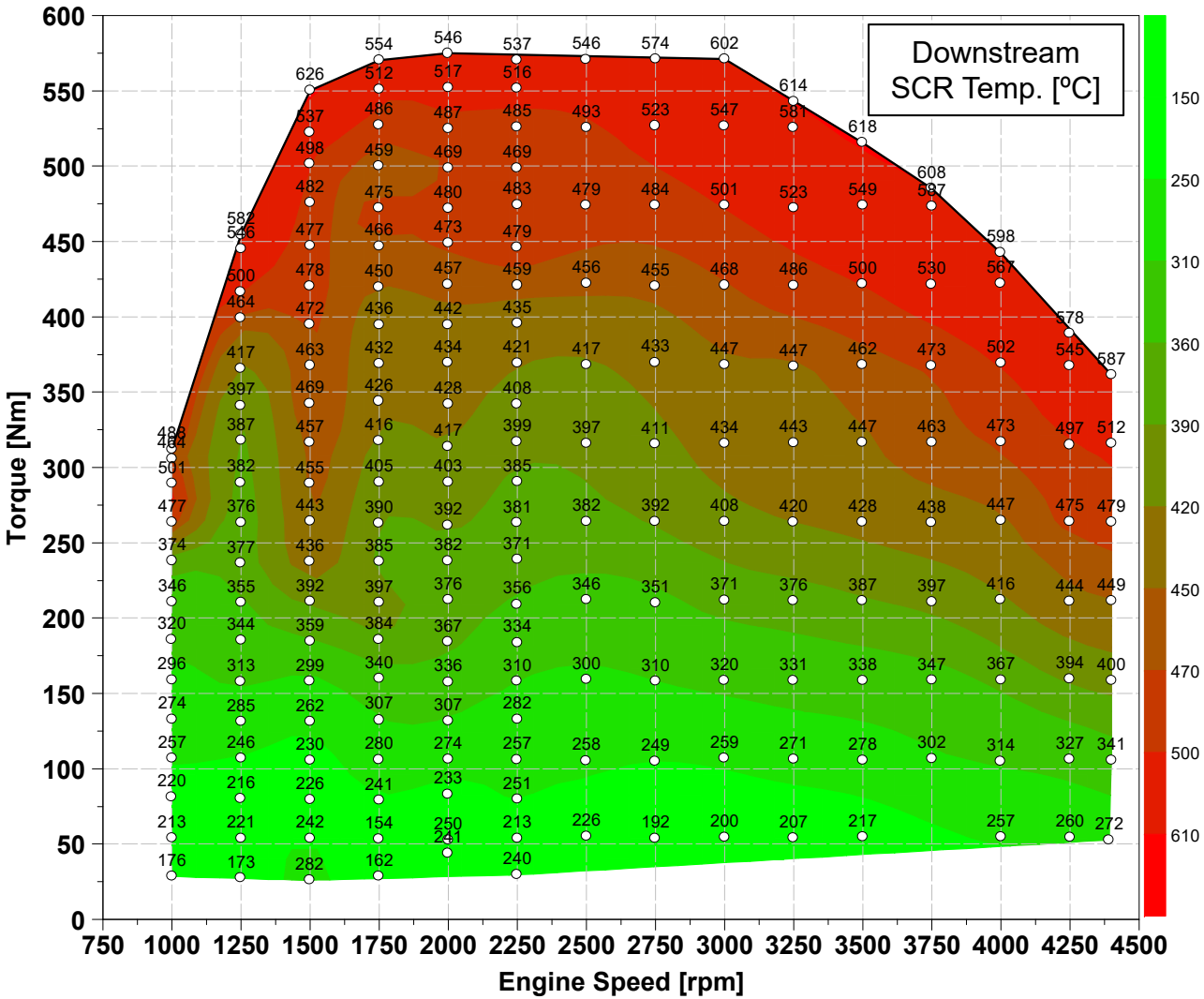
- The SCR temperature ranged from 150ºC to 450ºC from low load to 200 Nm.

FEV Benchmarking
BMW X5d 35d: Engine Mapping



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FEV Benchmarking
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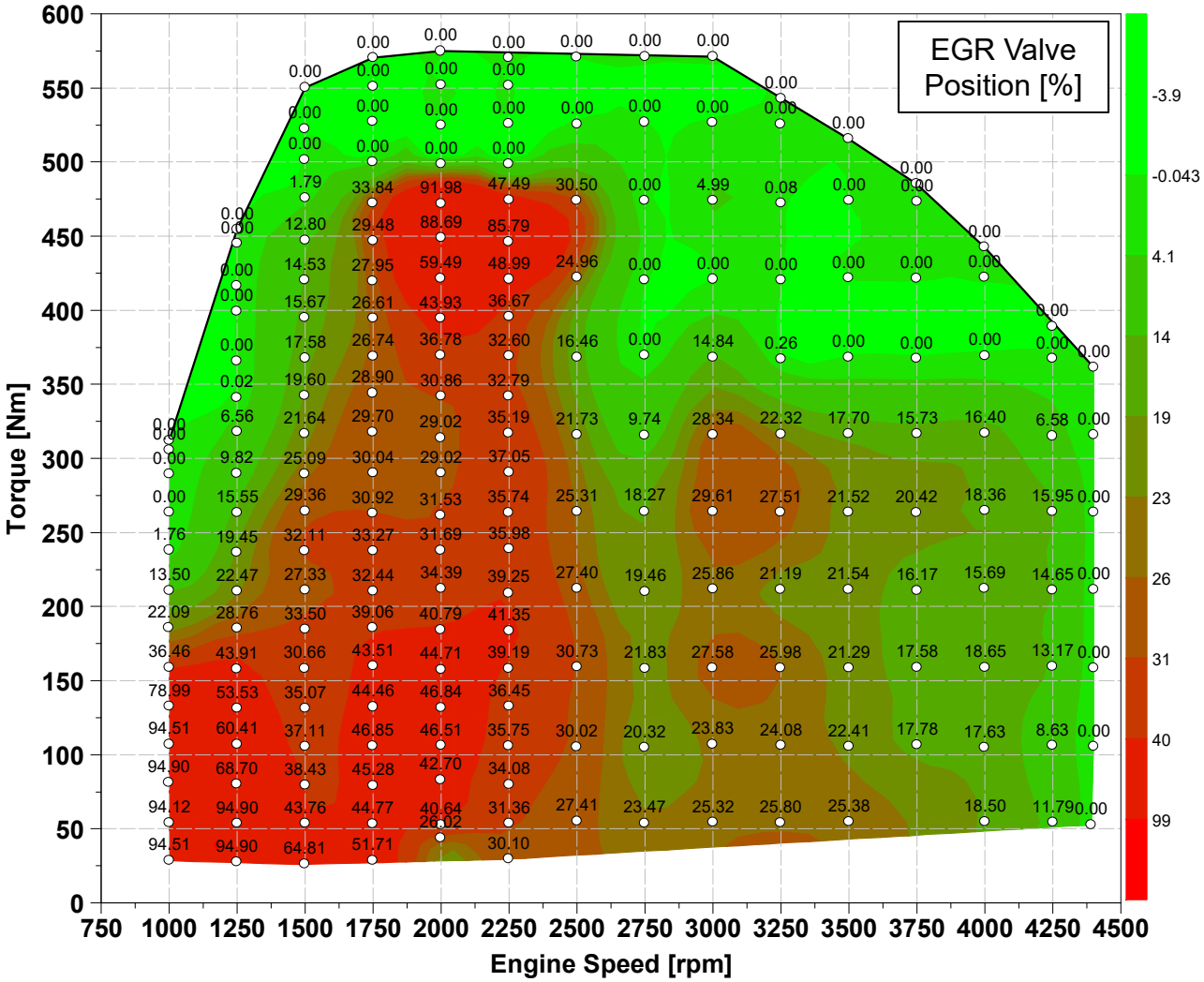
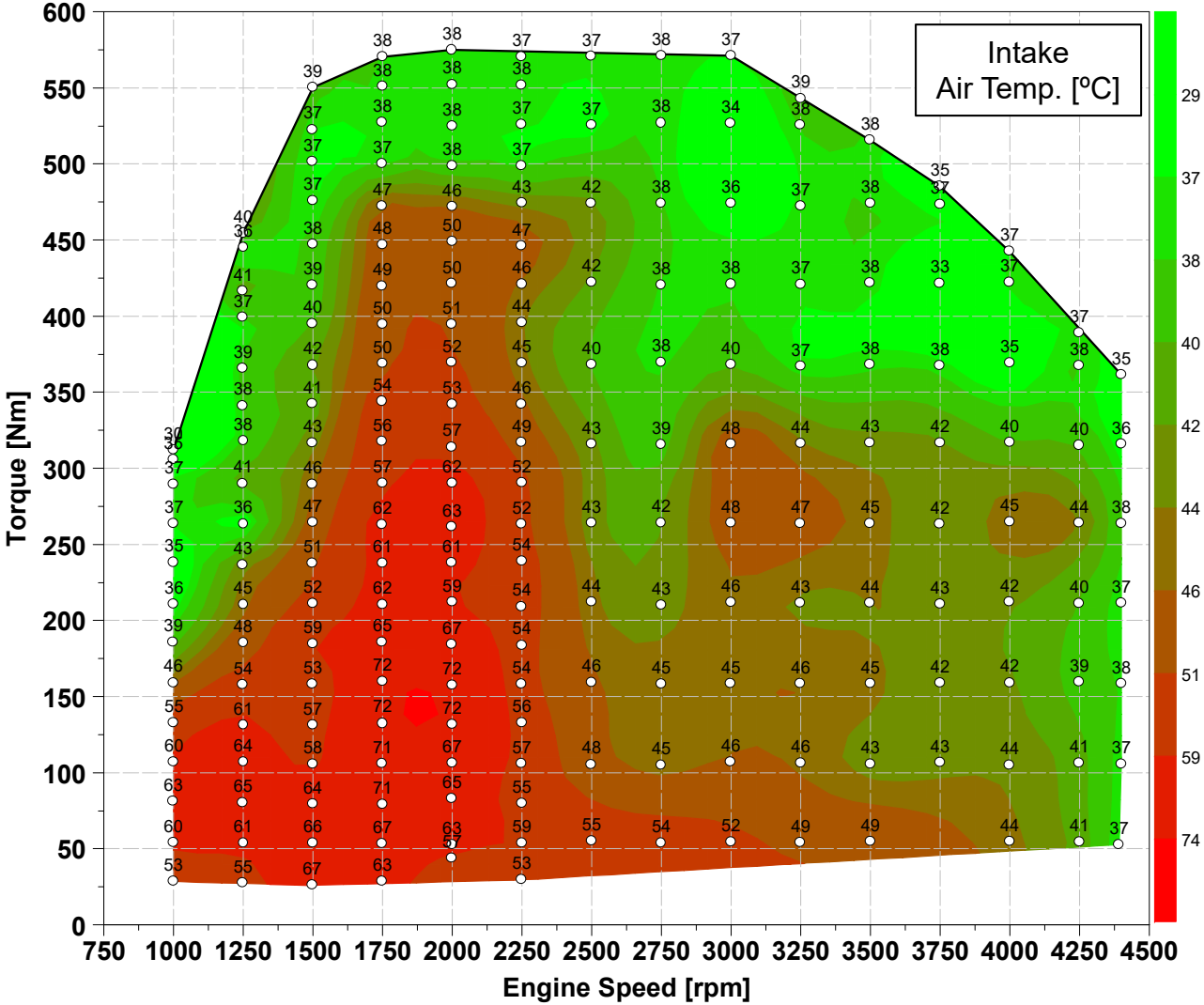


Comment

- The EGR valve was very active between 1000 rpm and 2500 rpm.
- At engine speeds higher than 2500 rpm the valve position did not open more than 30%.

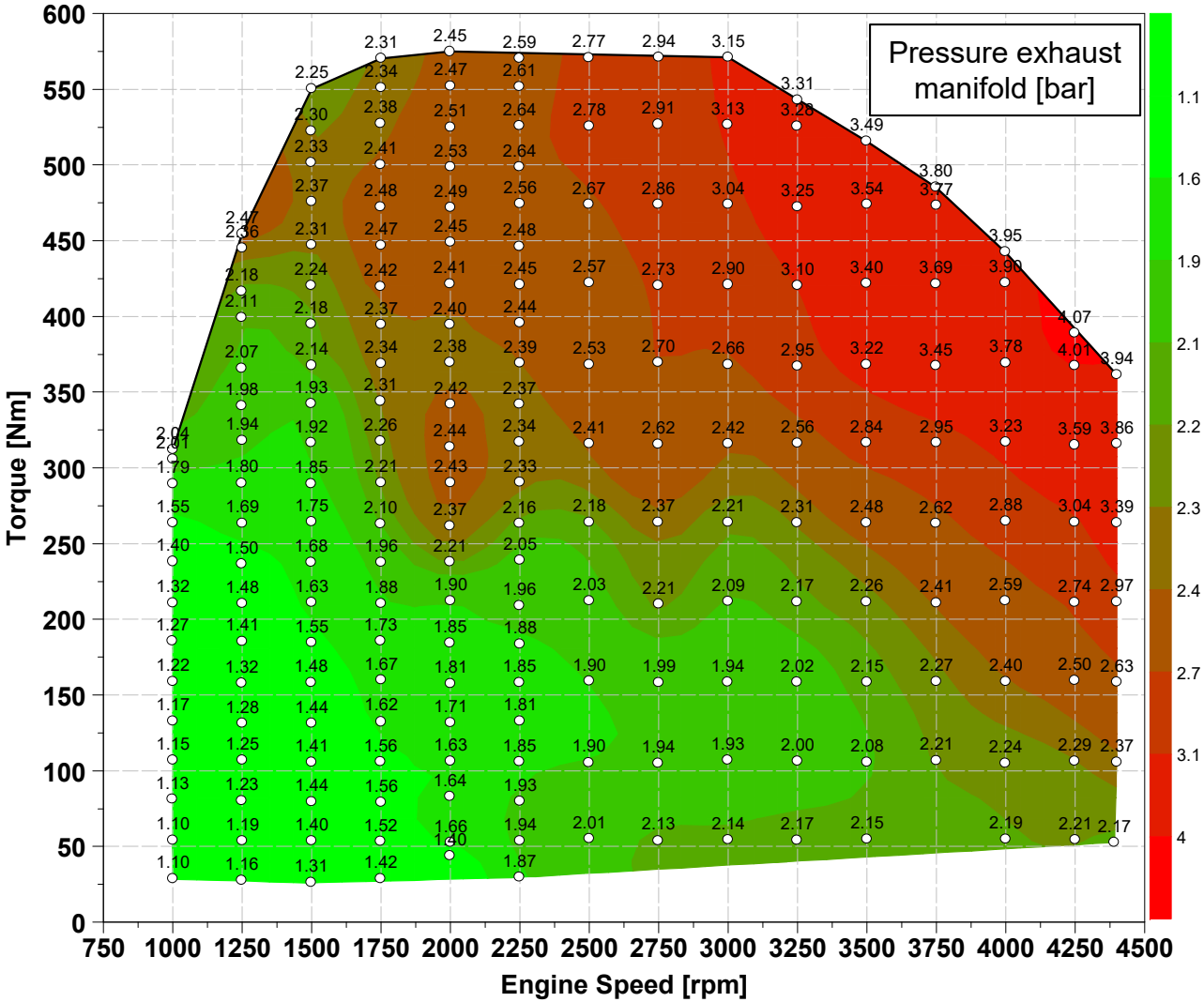
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Intake air temperature decreases with speed and was higher in the range of 1000 rpm to 2250 rpm and 25 Nm to 300 Nm due to the higher EGR percentages in this area of the map.

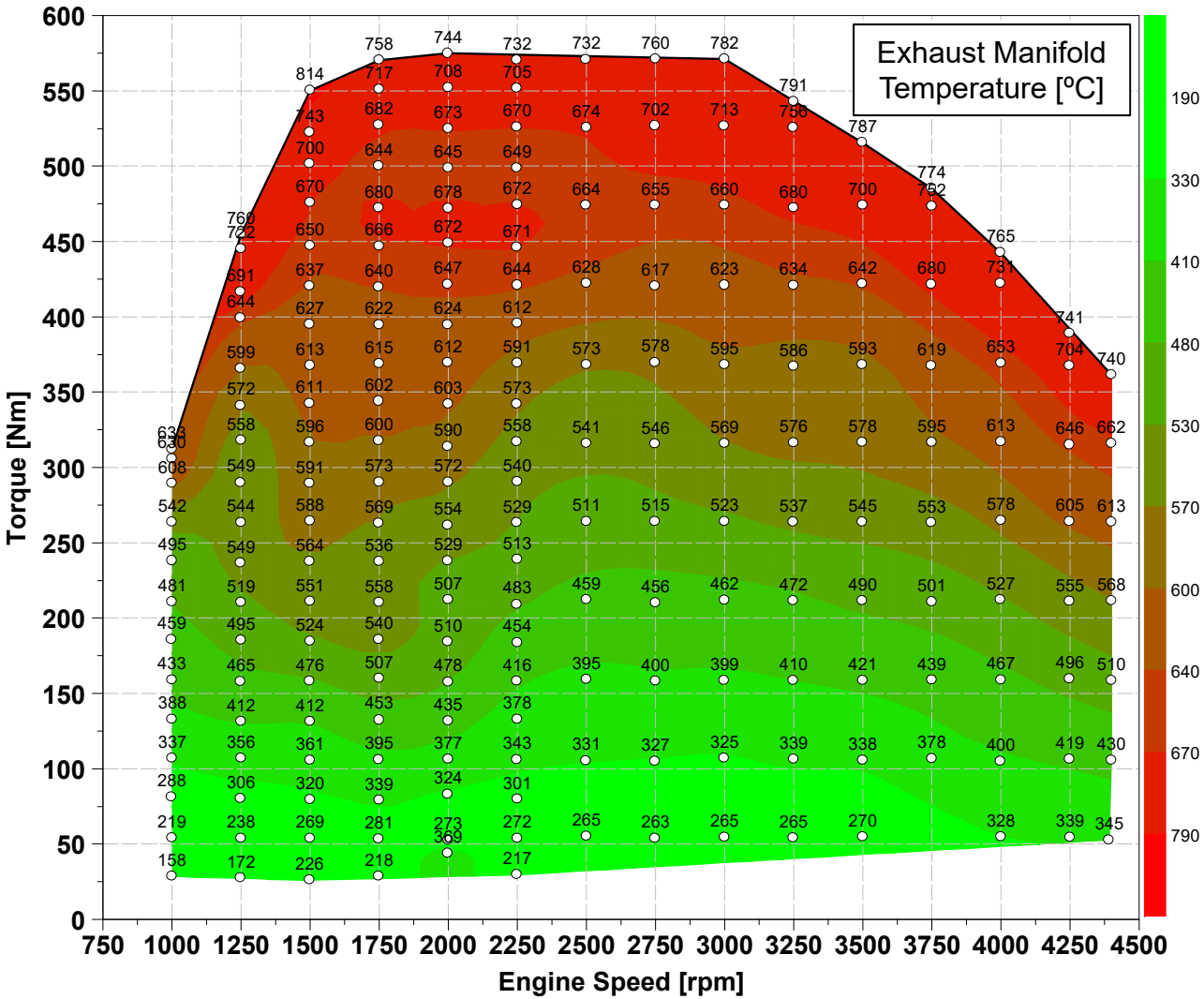
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Exhaust gas temperature at the engine out position (pre-turbo) were load dependent.

FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

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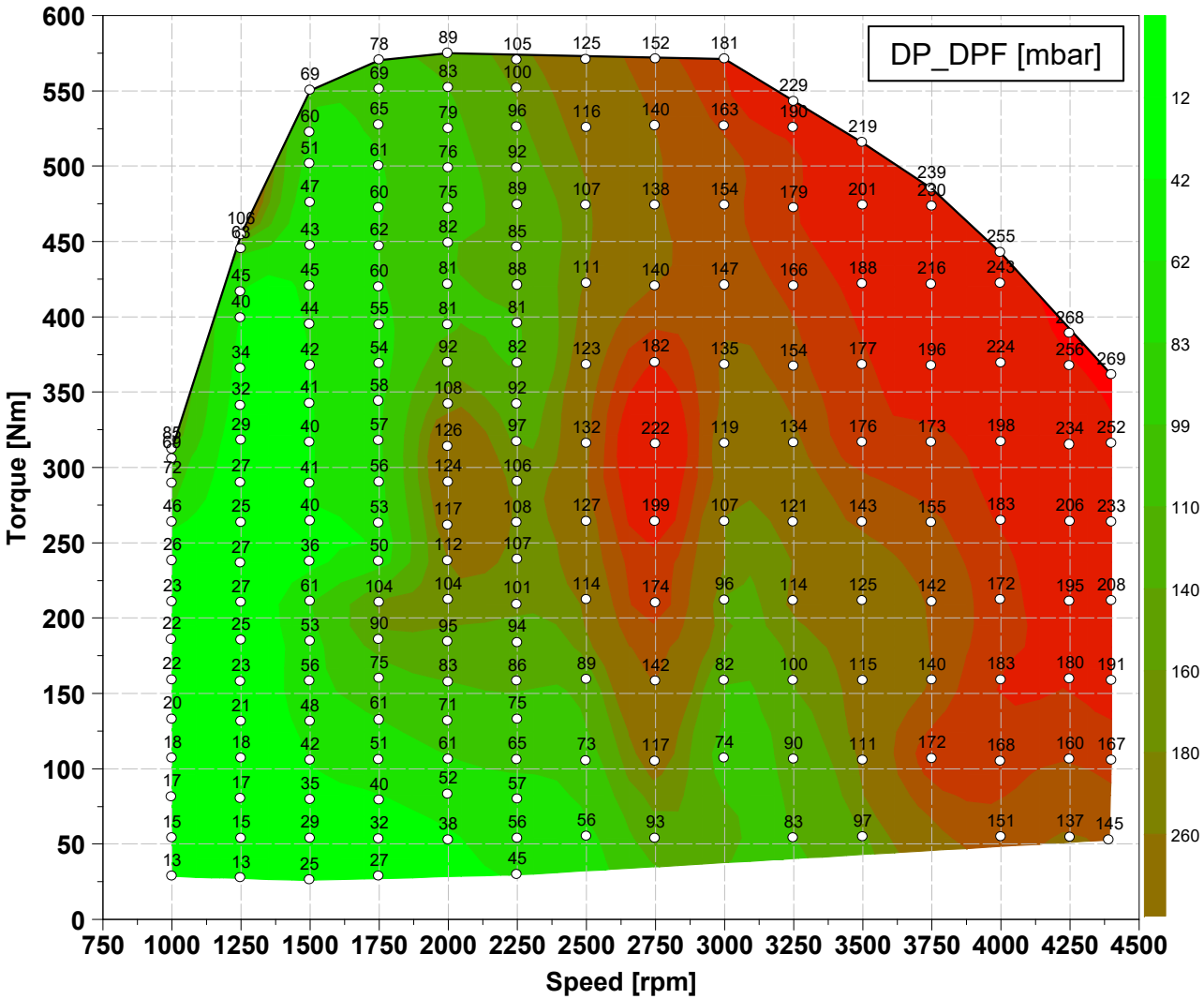
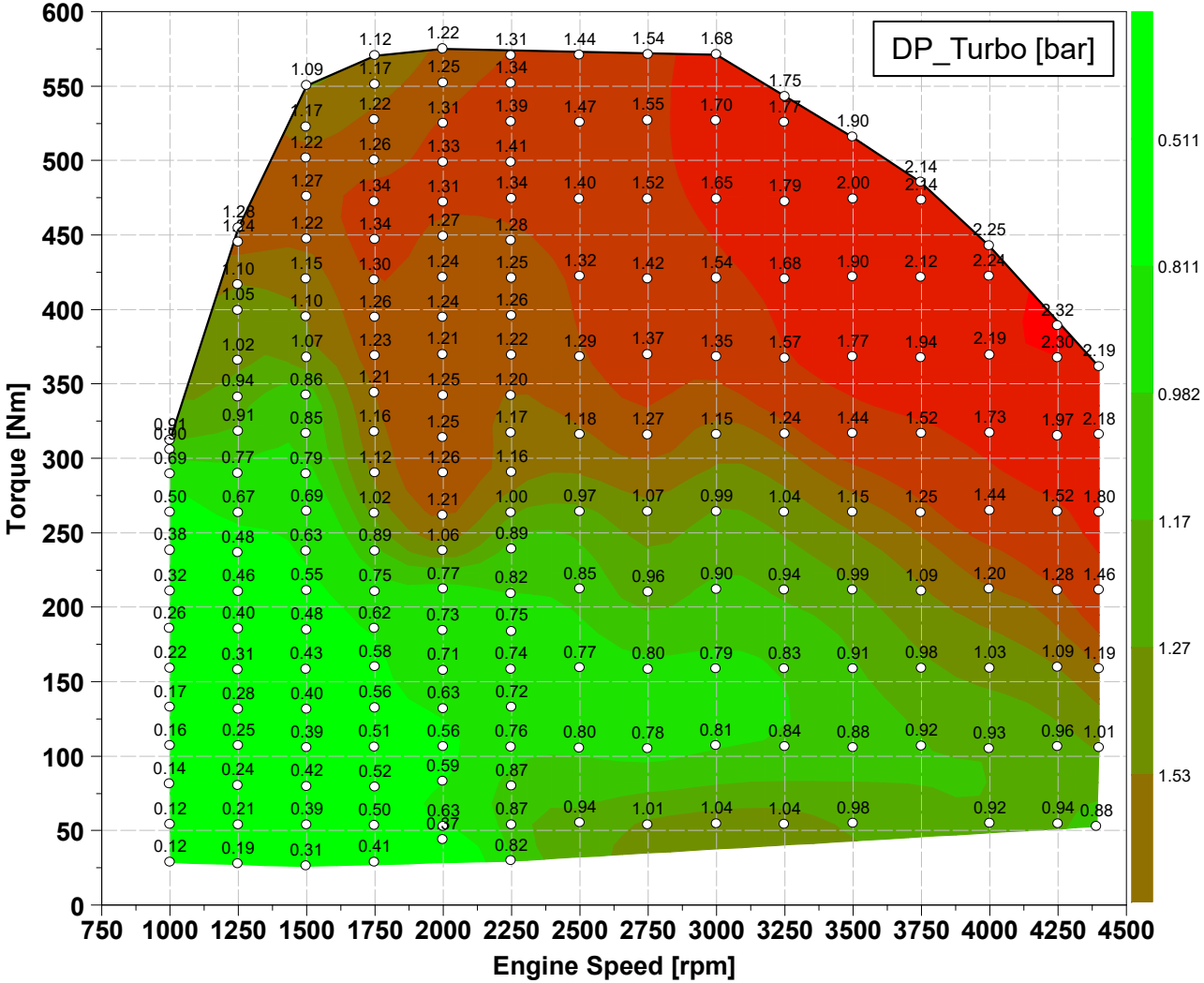
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The change in pressure , Δp, across the DPF increased with speed and load.
- With the maximum Δp achieved at the point of highest power out on the engine map (full load 4000 rpm).

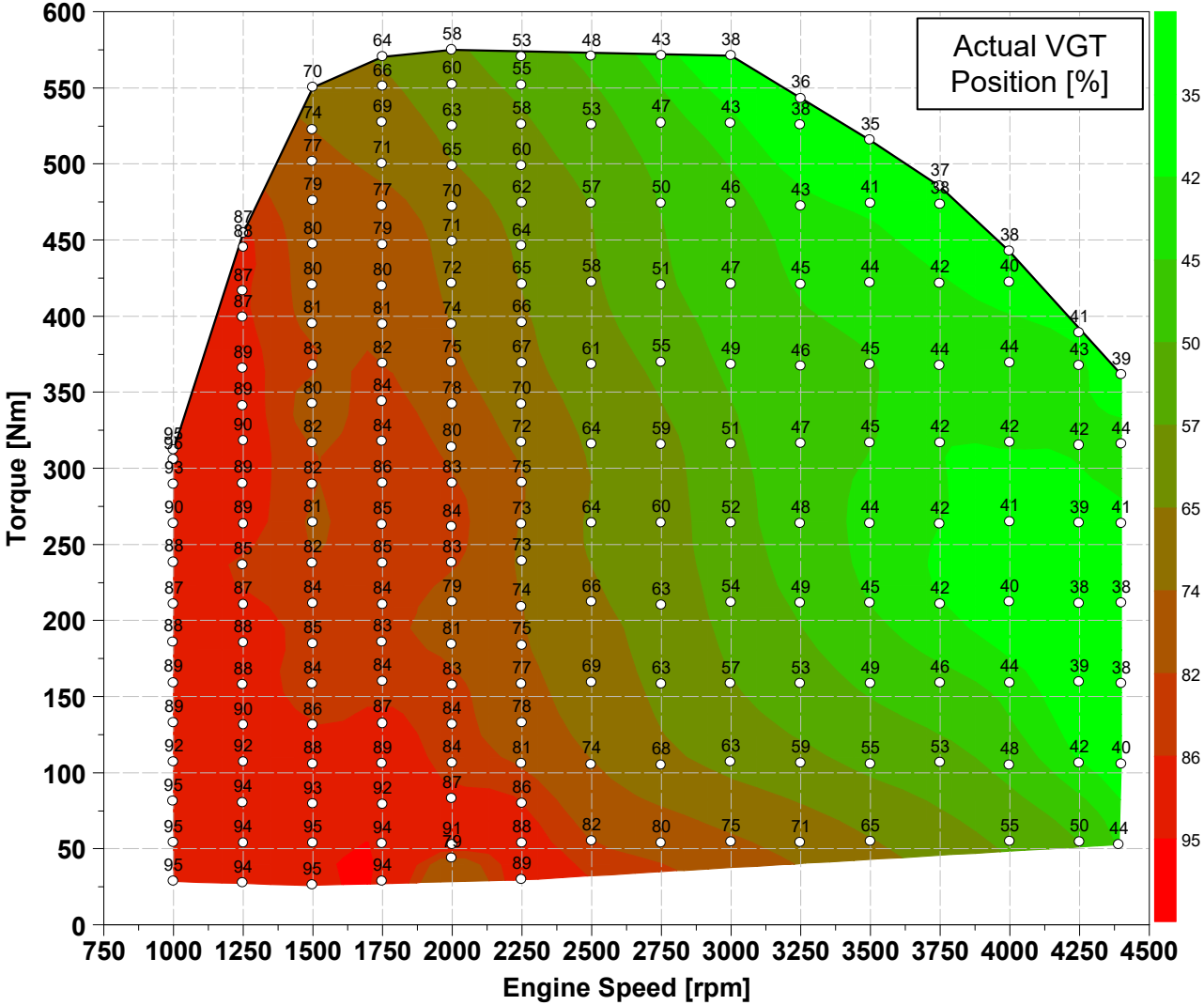
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The change in pressure , Δp, across the turbo increased with speed and load.
- With the maximum Δp achieved at the point of highest power out on the engine map (full load 4000 rpm).

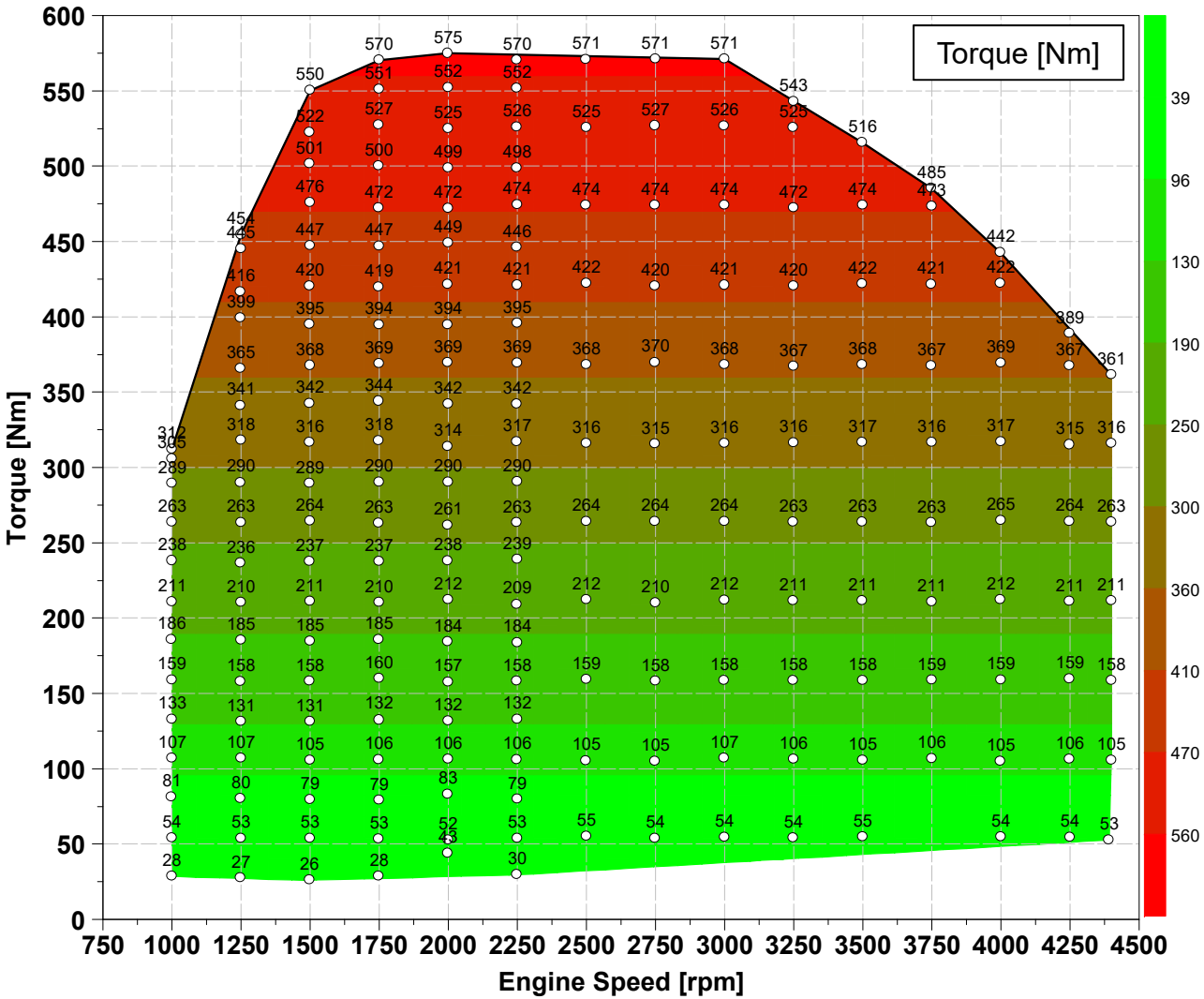
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- VGT position changed inversely with the change in the pressure drop across the turbo.
- The VGT position decreases with increase in speed and load on the engine map.
- In the engine operating area the VGT position is approximately 80% or greater.

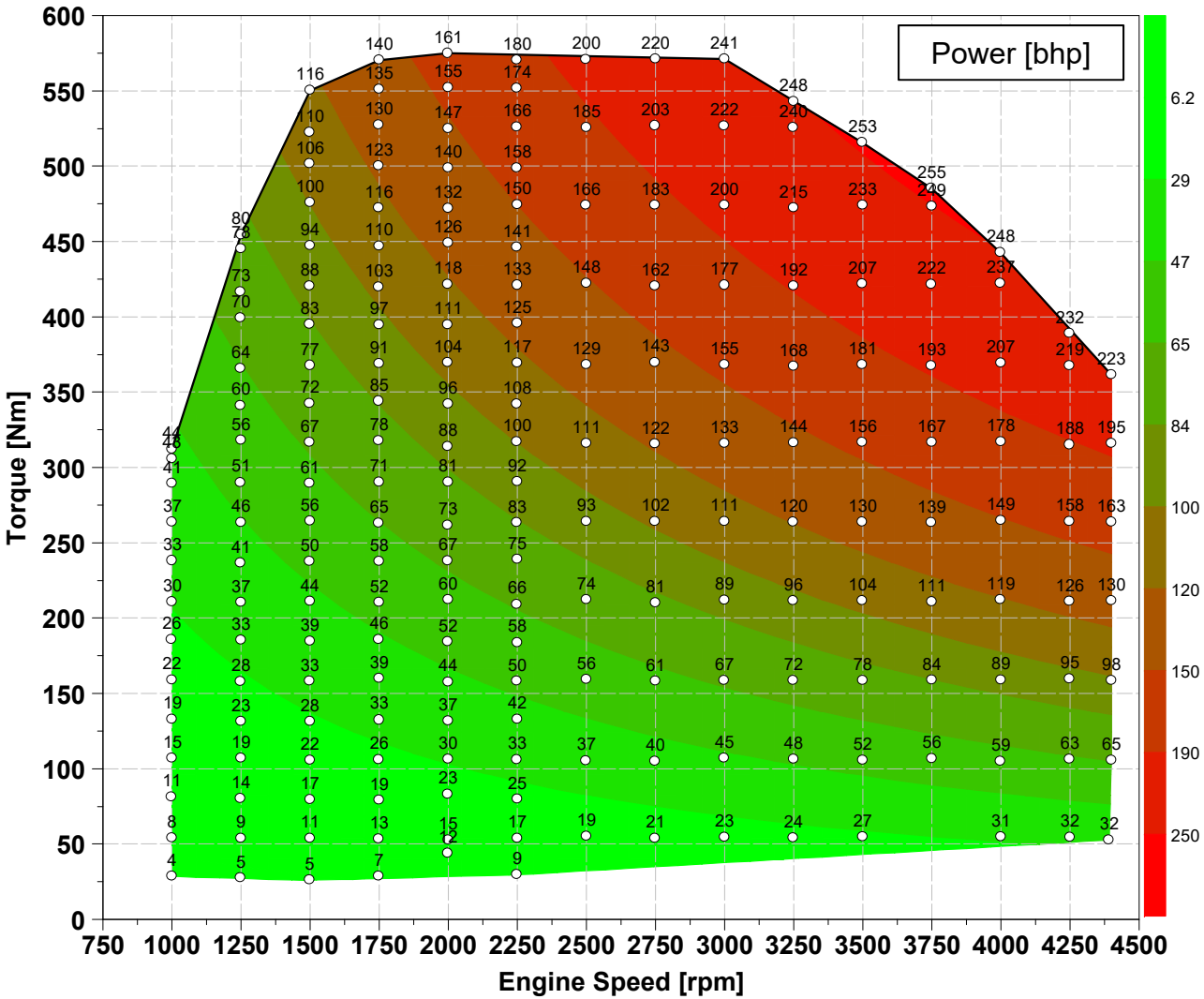
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The engine is rated to produce 560 Nm of torque at full load. At full load during testing the engine was capable of reaching 570 Nm on average.

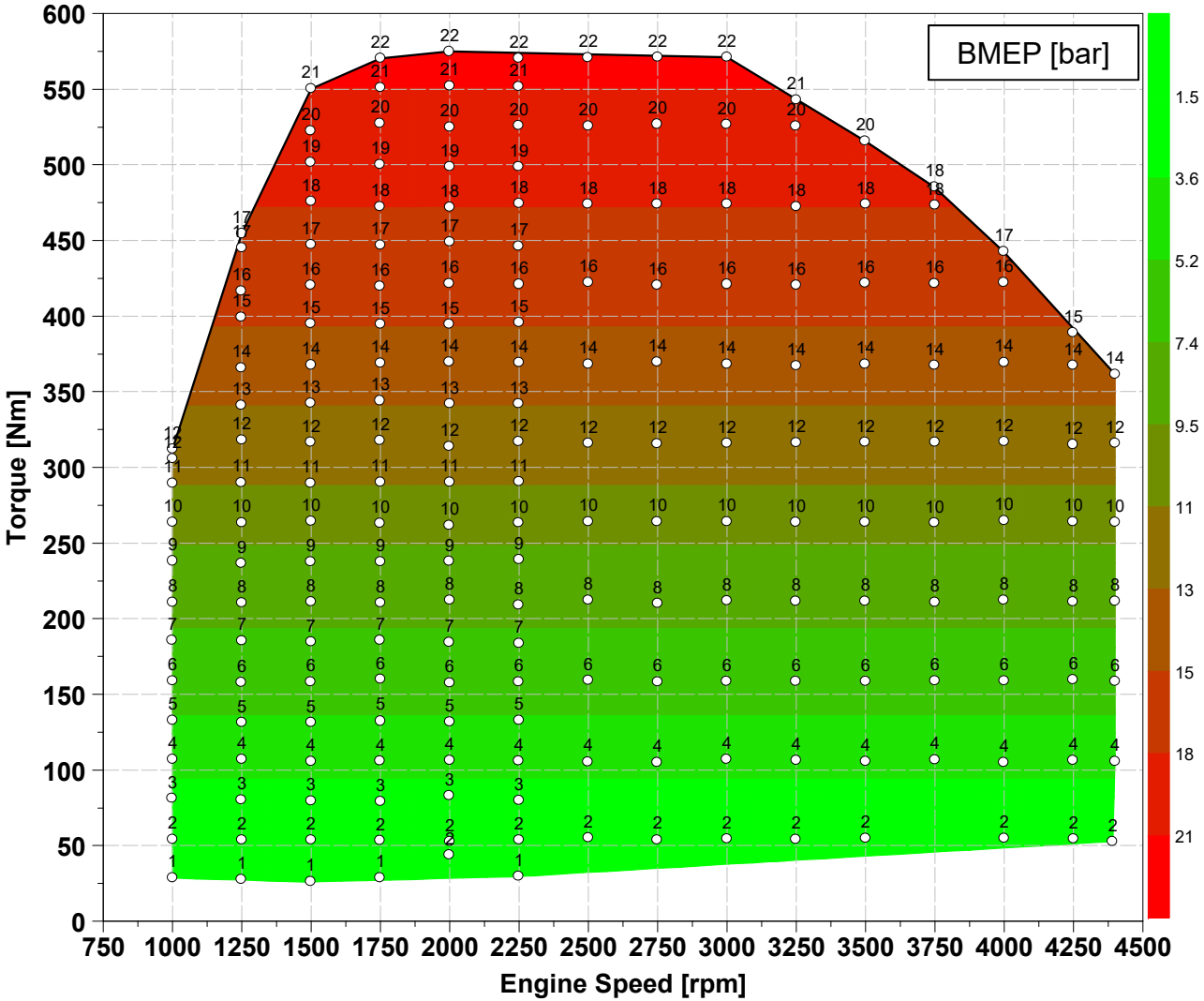
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The engine is rated to produce 255 bhp of torque at full load. The engine was capable of reaching peak power from 3500 rpm to 4000 rpm.

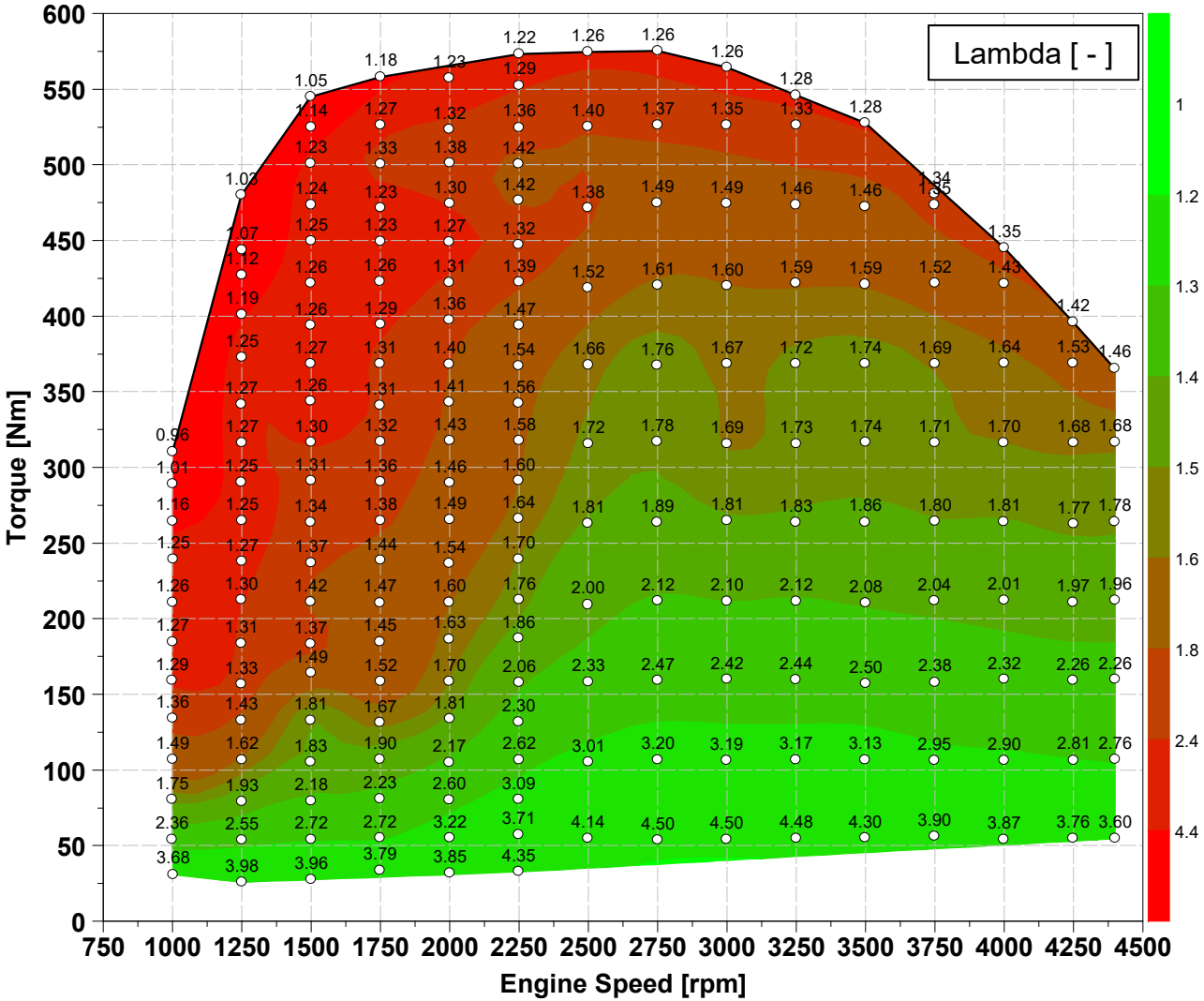
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The engine produced peak BMEP of approximately 22 bar in the full range of the engine map.

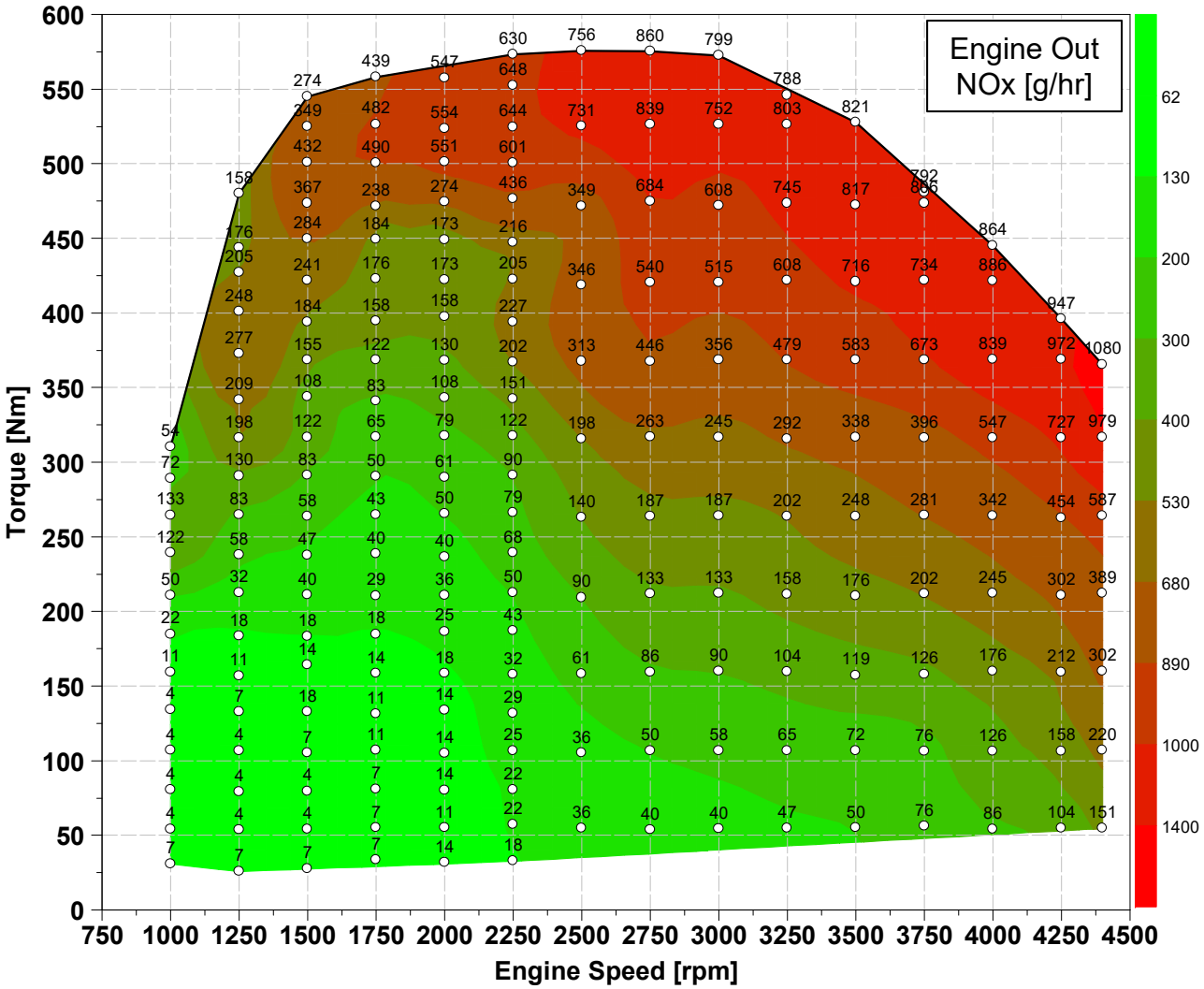
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Lambda values ranged from 1.30 – 4 over then entire map.
- At full load the engine runs near rich lambda values of approximately 1 while at lower speeds and typically increase with speed.

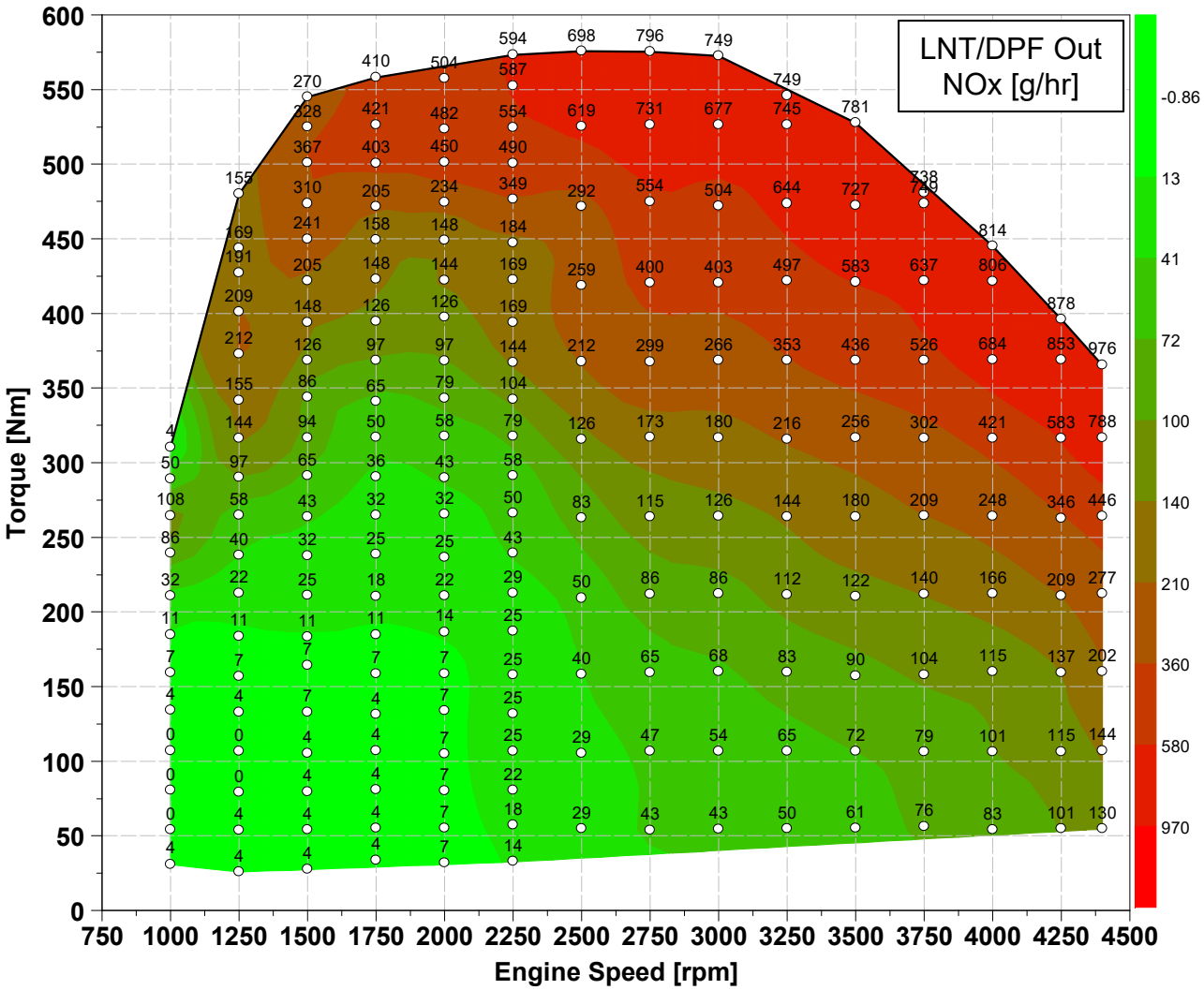
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Engine out NOx was relatively low from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm on the map below approximately 20 g/hr.
- Outside of this range the engine out NOx is much higher at 20 g/hr or more.
- The NOx emissions are more impacted by load than speed.

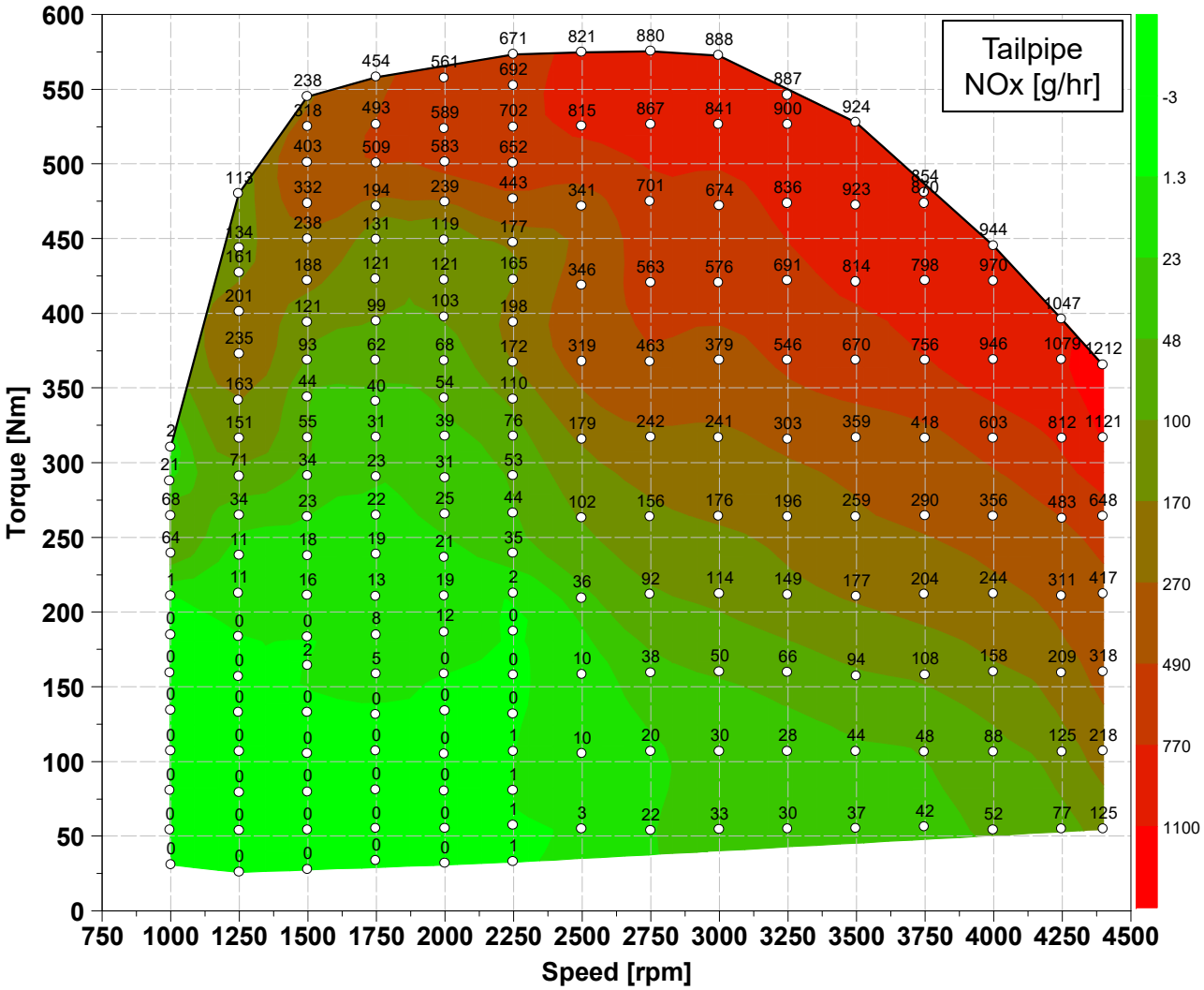
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The engine out NOx was slightly reduced across the LNT catalyst. With some reduction up to 3 g/hr.

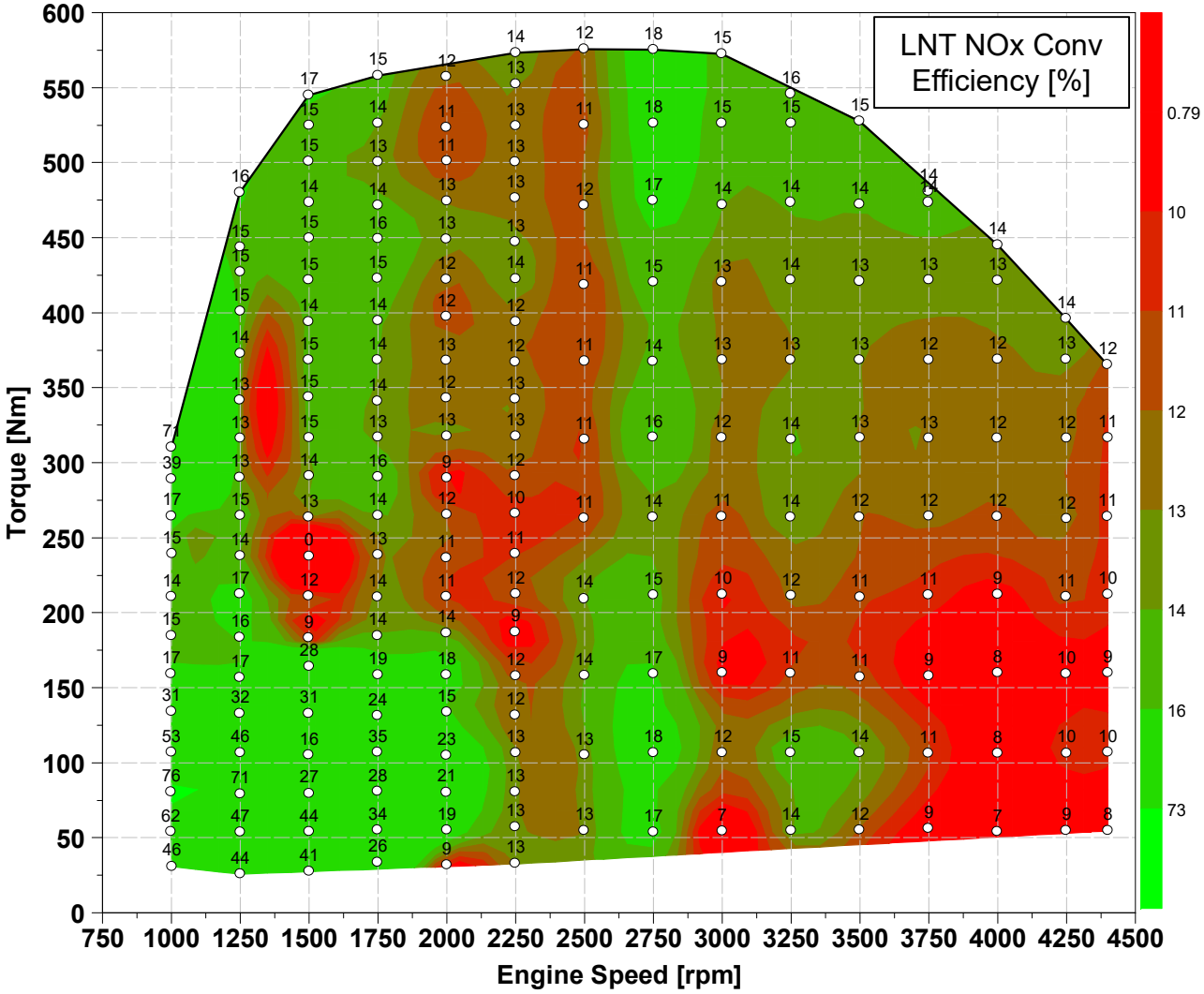
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The tailpipe NOx was significantly lower compared to engine out, less than 1 g/hr from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm.

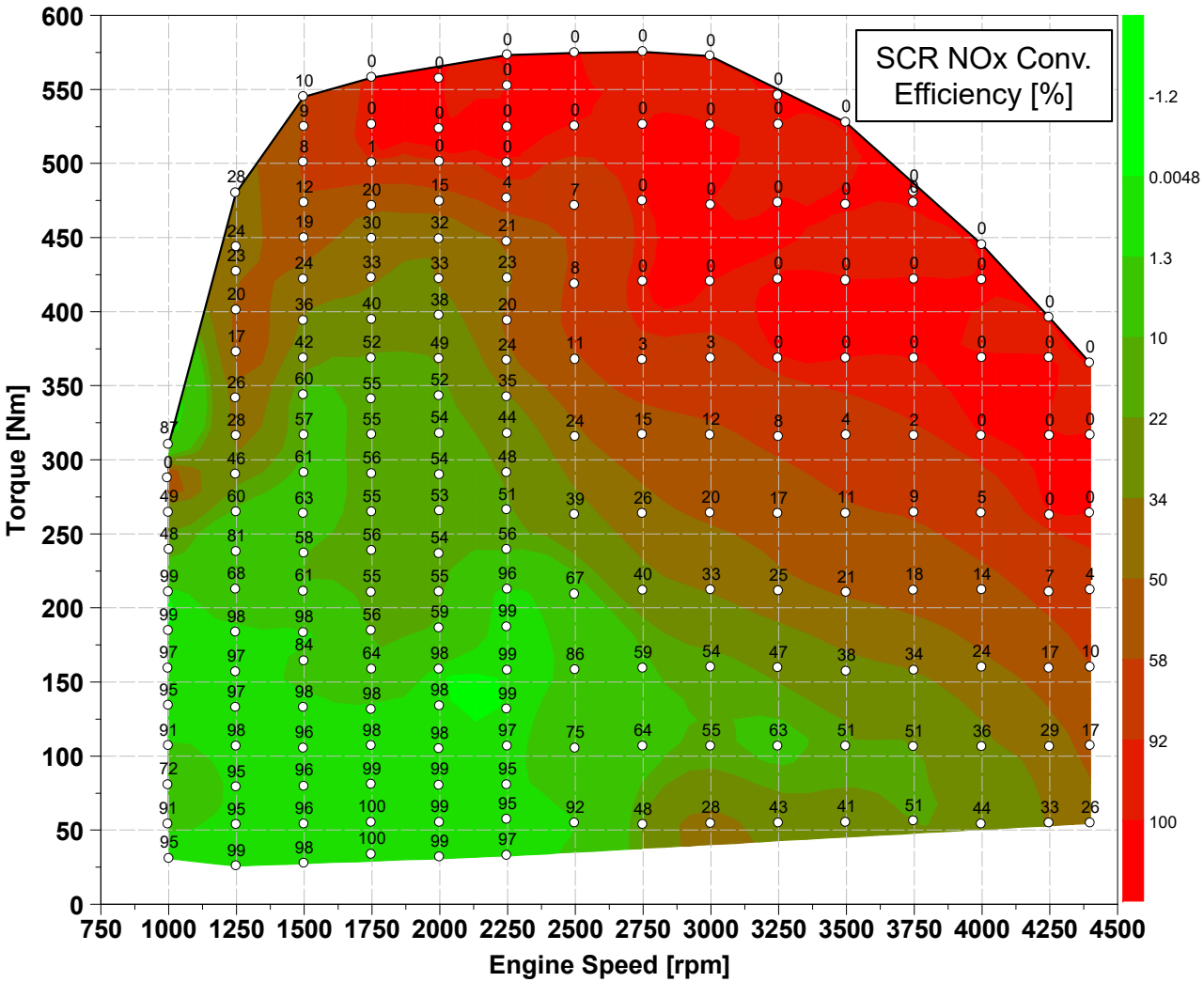
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The LNT/DPF NOx conversion efficiency was most efficient from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm.
- With NOx conversion efficiencies reaching to as high as 71% at 1250 rpm.
- At high load and speed areas on the map the LNT/DPF NOx conversion efficiency was lower than 20% for most area's within the 2500 rpm to 4400 rpm and 250 Nm to 570 Nm.

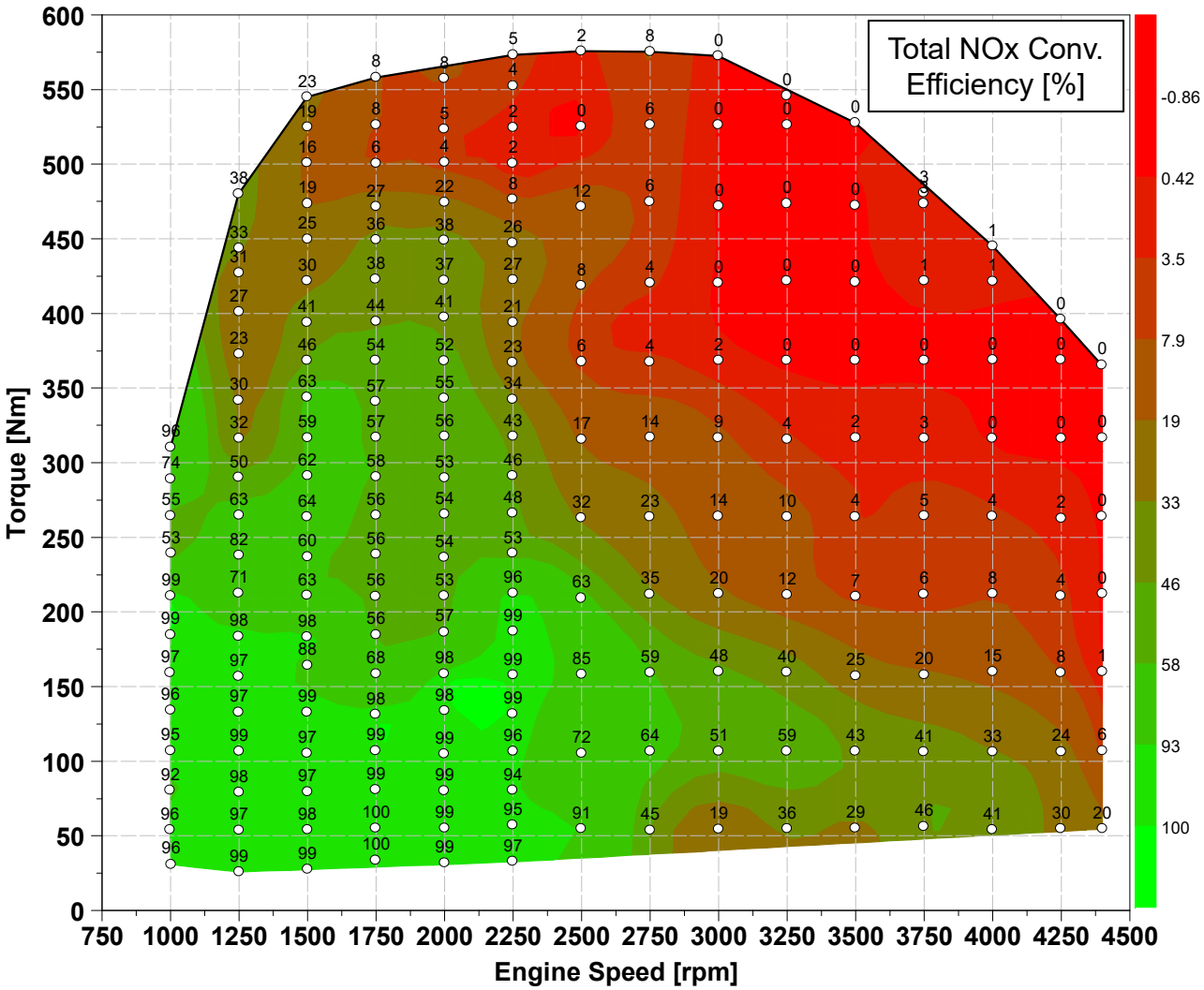
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The SCR NOx conversion efficiency was most efficient from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm.
- With efficiencies reaching to as high as 100%.
- High load and speed areas on the map the ATS efficiency was lower than 20% for most area's within the 2500 rpm to 4400 rpm and 250 Nm to 570 Nm.

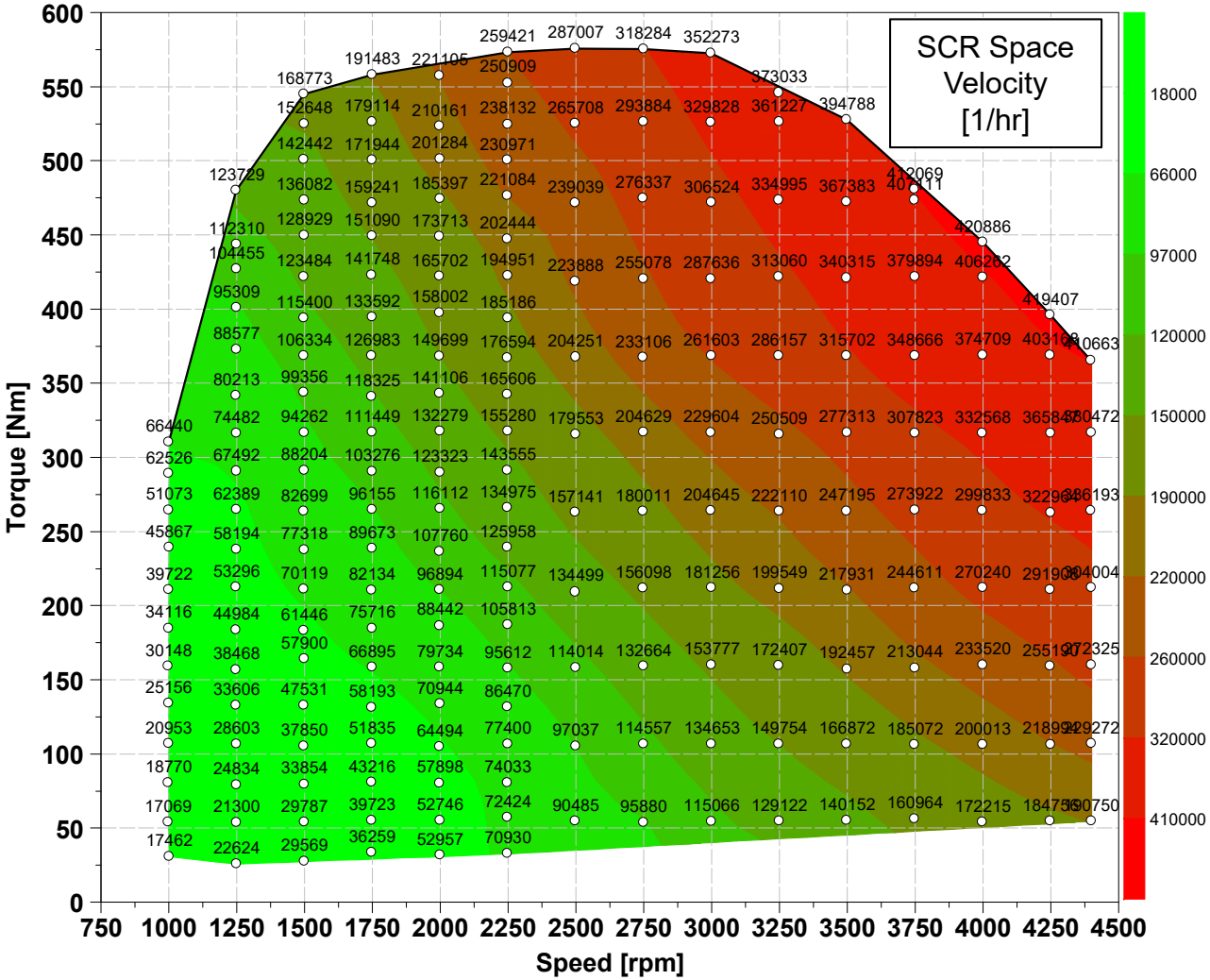
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The total NOx conversion efficiency was most efficient from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm
- With efficiencies reaching to as high as 100%
- High load and speed areas on the map the ATS efficiency was lower than 20% for most area's within the 2500 rpm to 4400 rpm and 250 Nm to 570 Nm

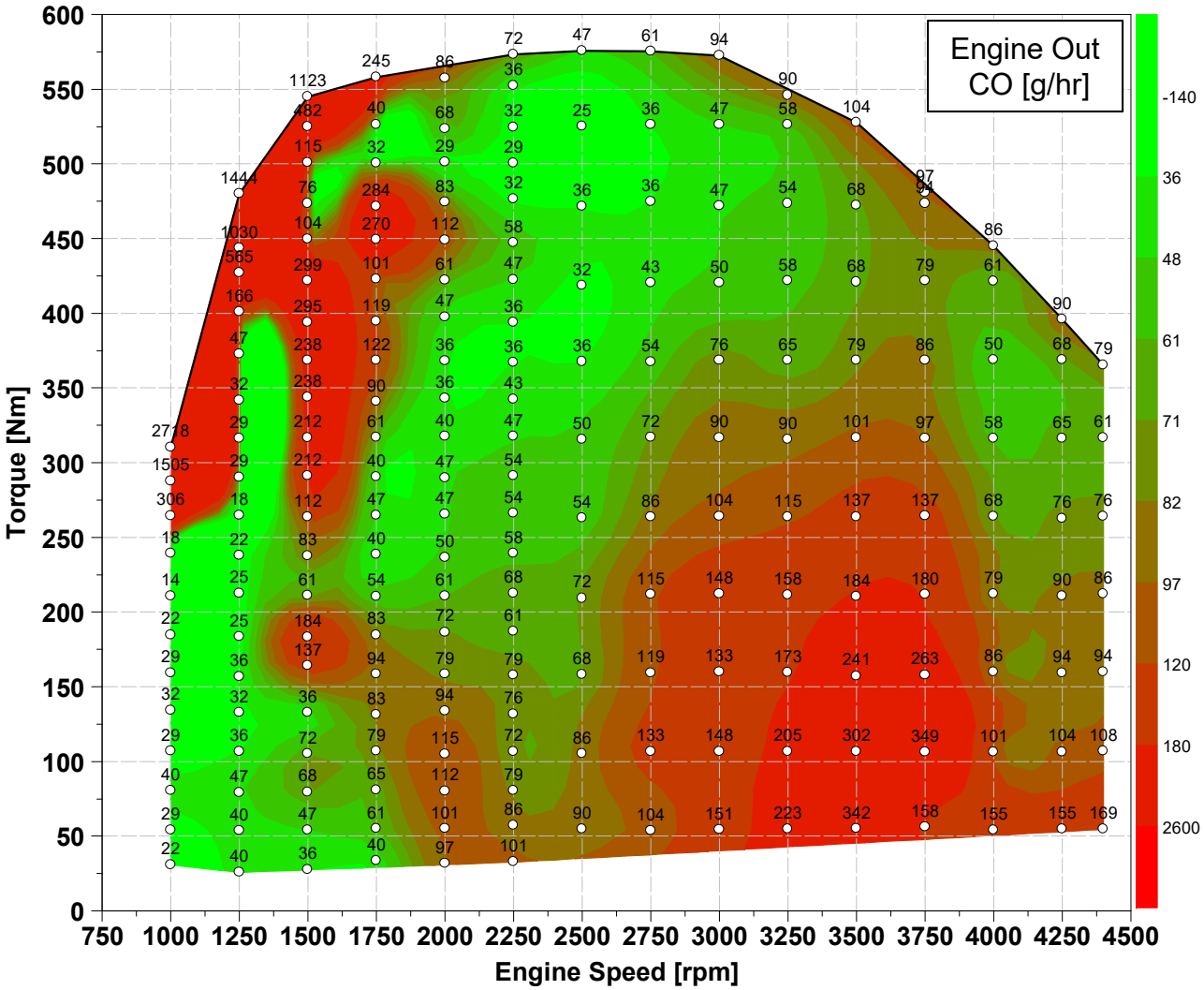
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The SCR space velocity was lowest from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm.
- The space velocity value increased substantially at full load and peak power at 4000 rpm.

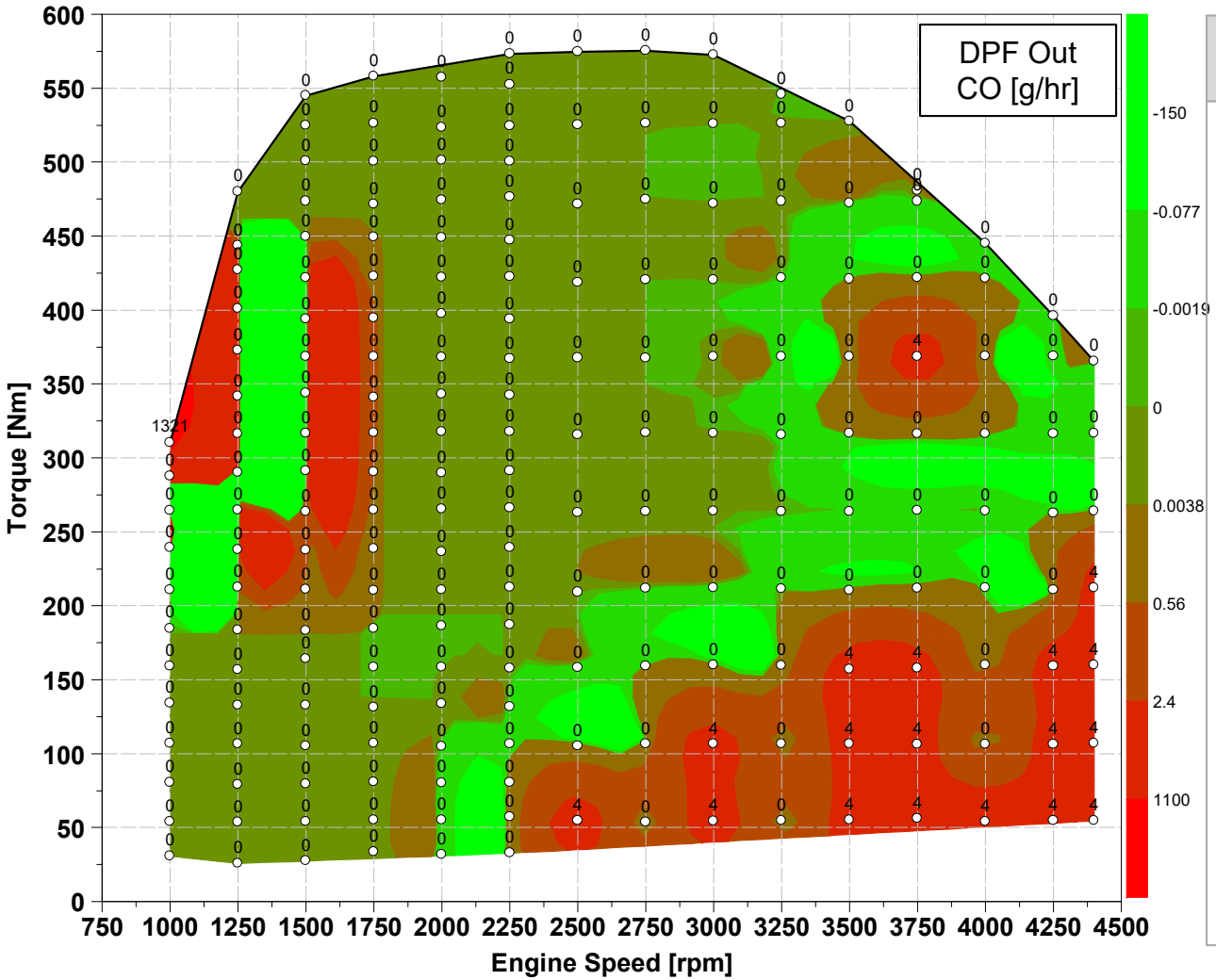
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Engine out CO was much higher at the high engine speed, low load range.
- The increase in engine speed significantly impacts the engine out CO emissions as they increase from 2000 rpm to 4400 rpm.

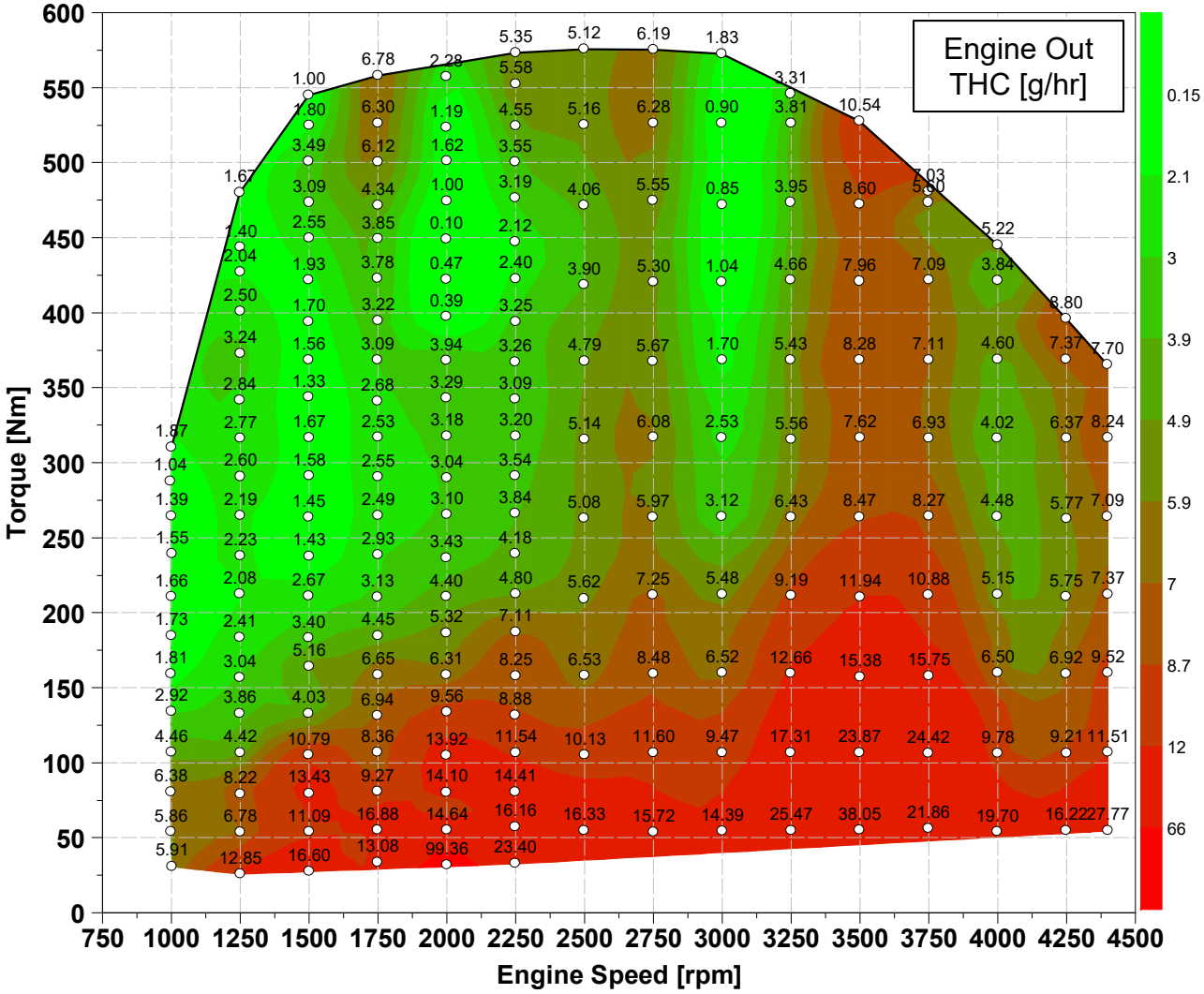
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The tailpipe CO is much lower, less than 2 ppm, for most areas on the engine map.
- The highest CO emission measured was at full load at 1000 rpm.
- This point however is very unlikely to be ran under normal vehicle operating conditions due to the automatic transmission.

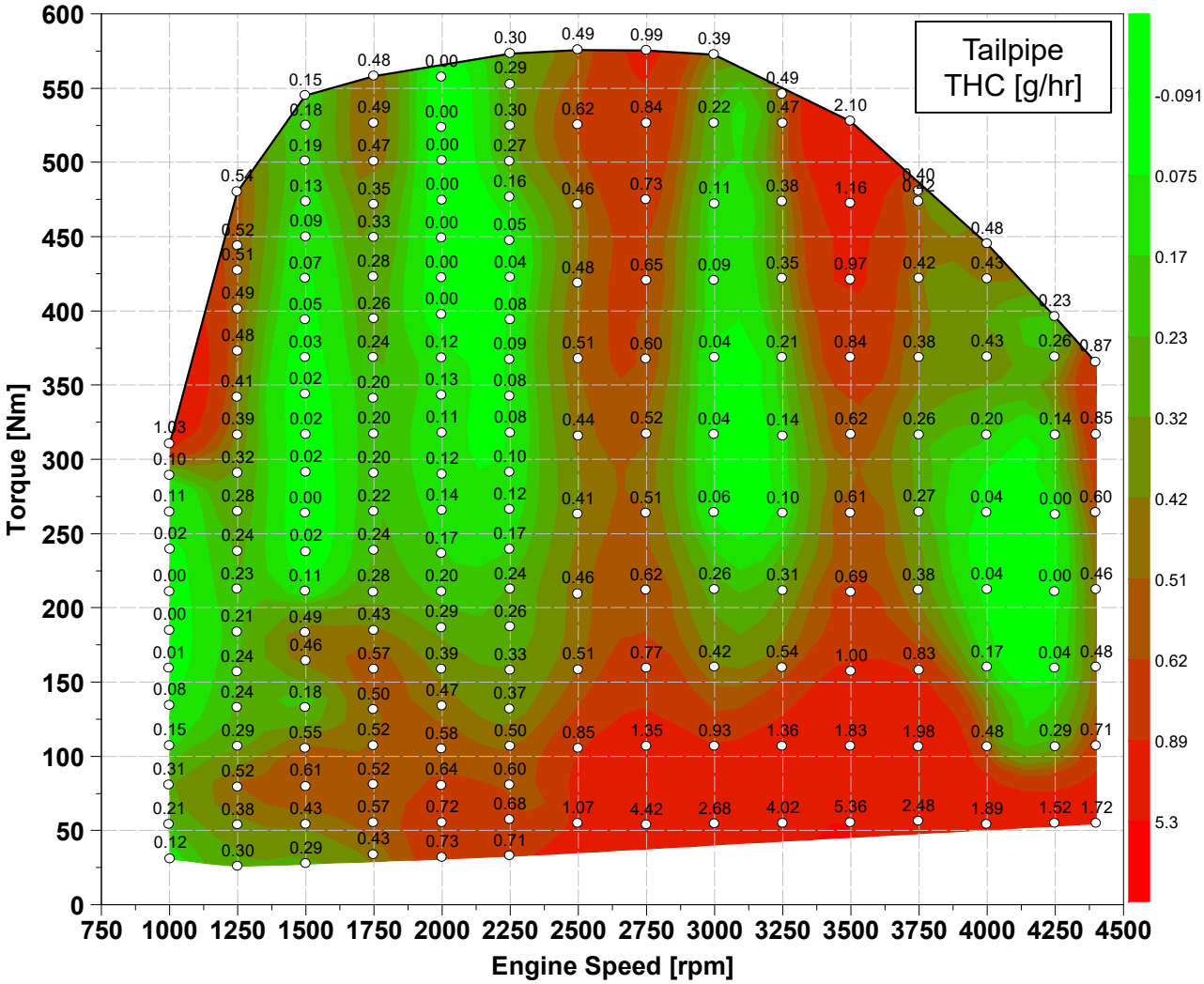
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The highest THC emissions were from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm and were typically lower at low loads on the engine map.
- THC mass flow was calculated assuming all exhaust THC species were propane.

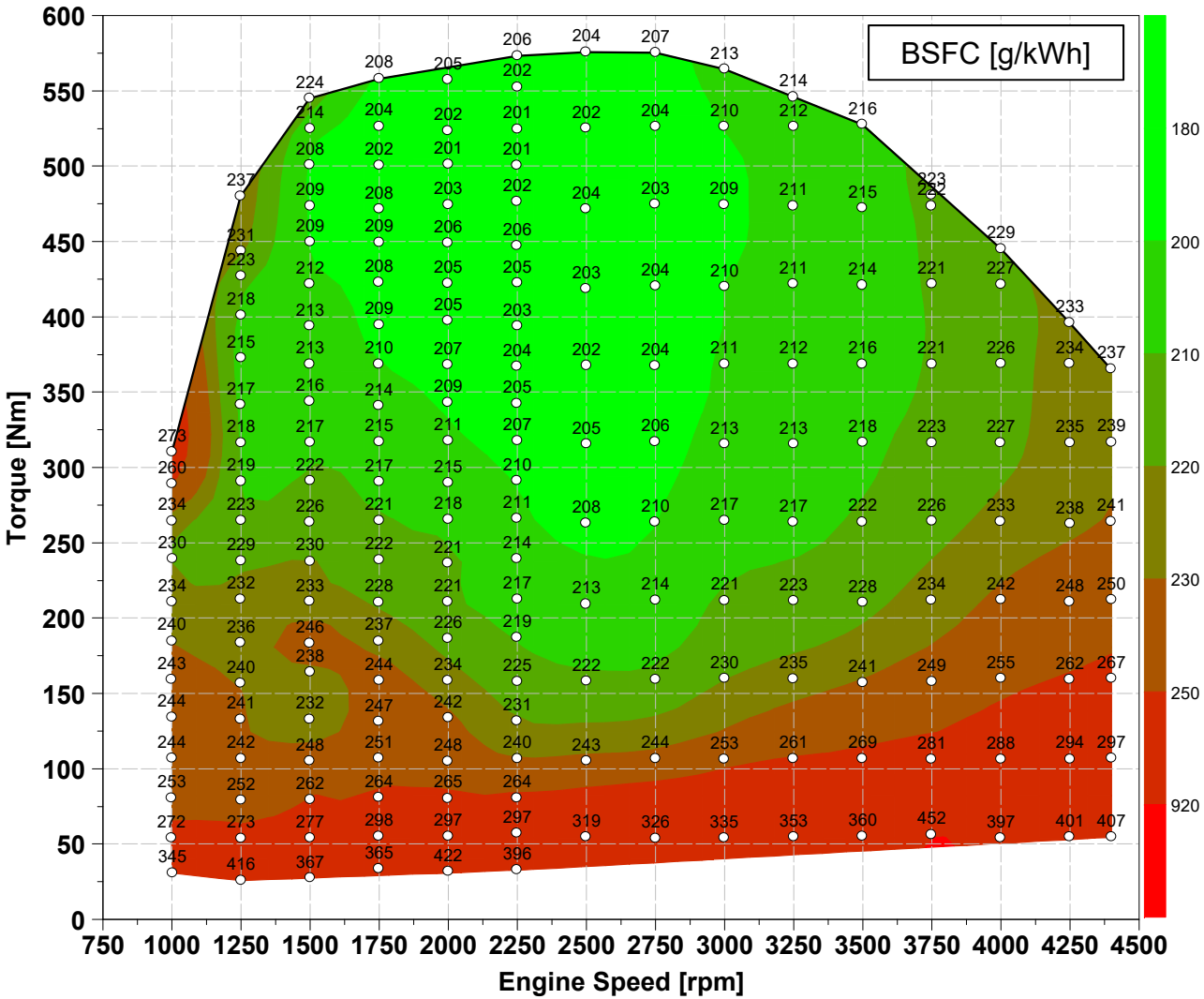
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The tailpipe THC was less than 6 g/hr for most points on the engine map, with the exception of a few outliers.
- THC mass flow was calculated assuming all exhaust THC species were propane

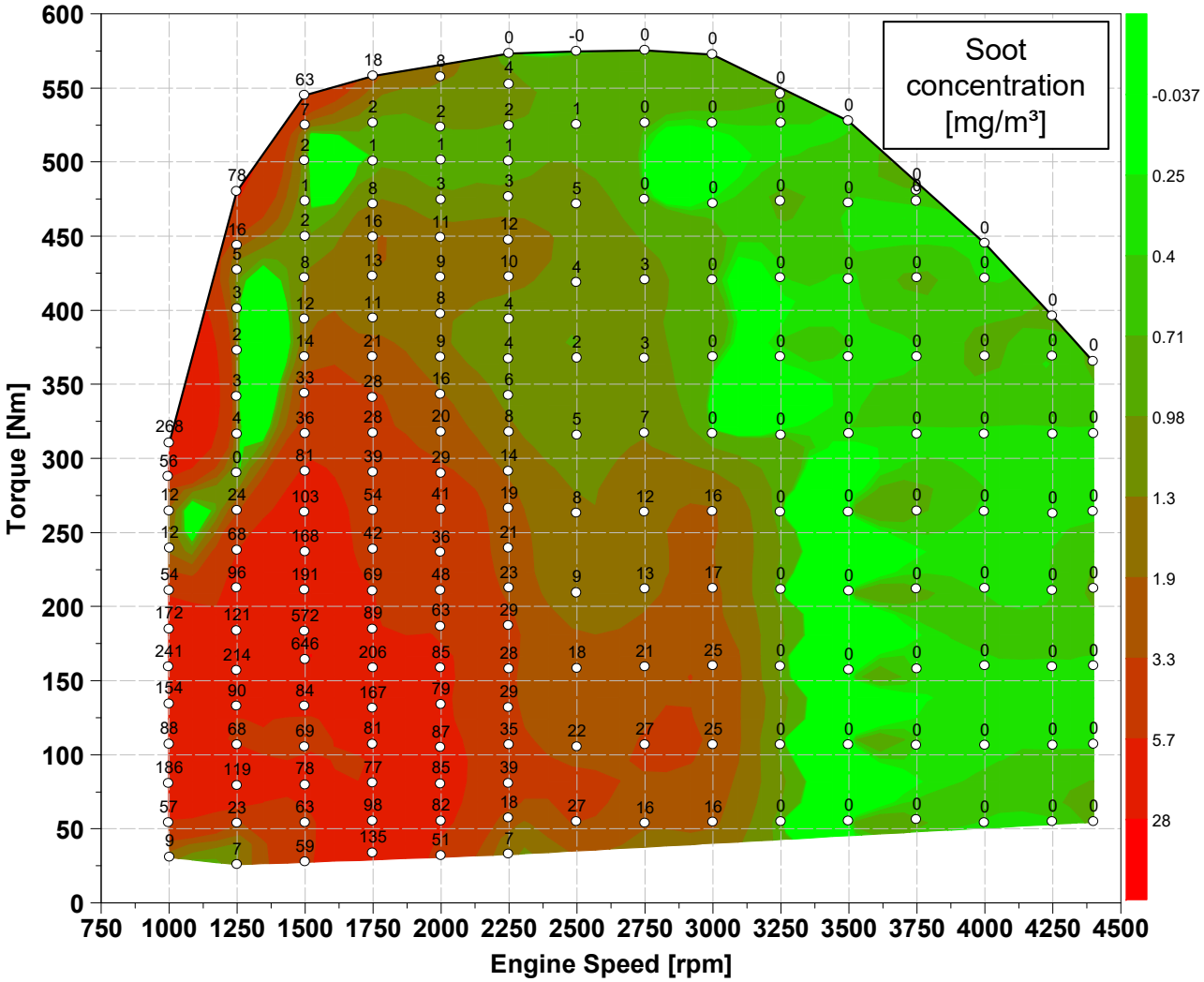
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The BSFC began to decrease in as there were increases in load.
- The engine operating area consisted of BSFC values of approximately 240 g/kWh or higher.

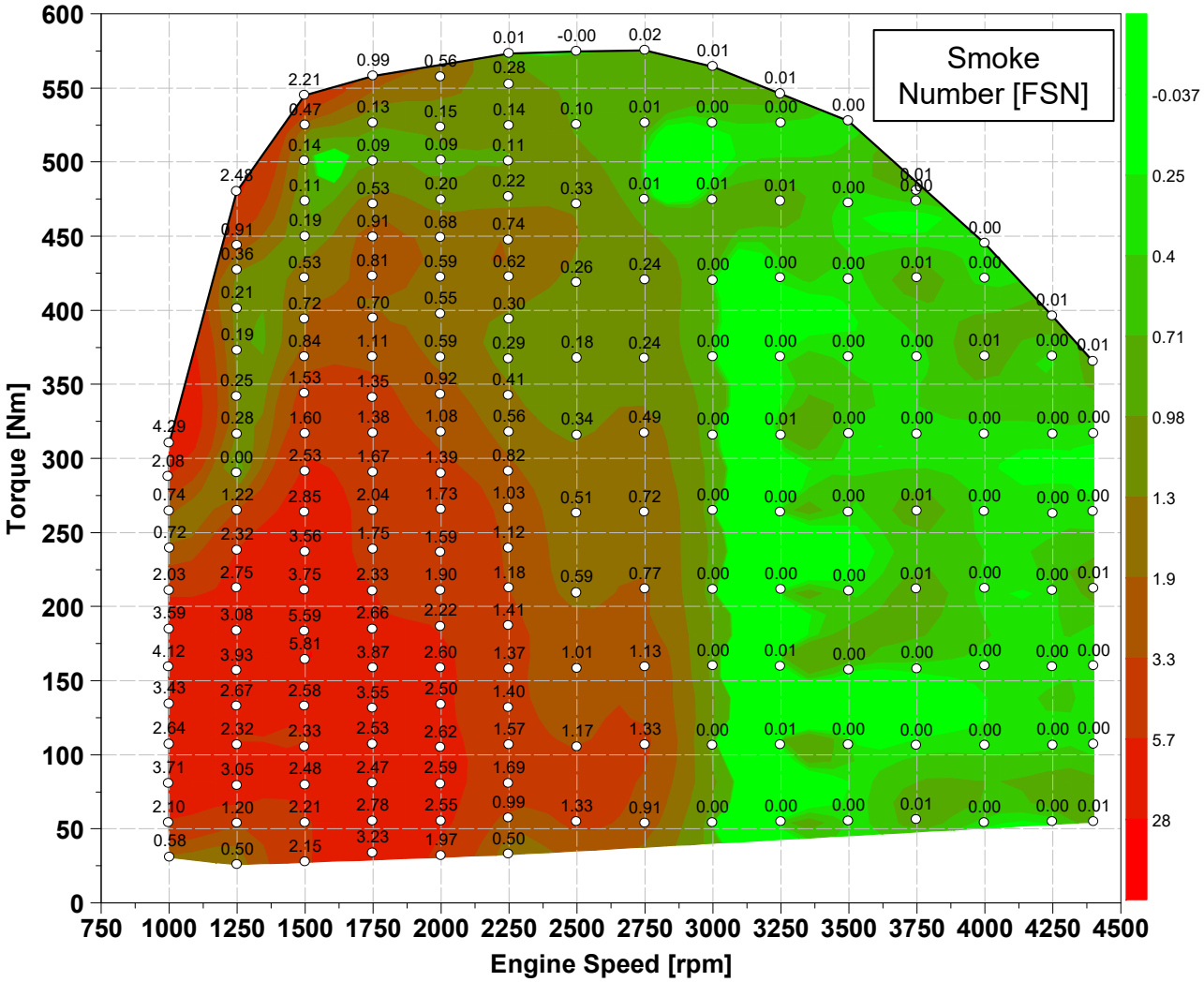
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The engine out soot was high in the from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm with values higher than 60 mg/m3.

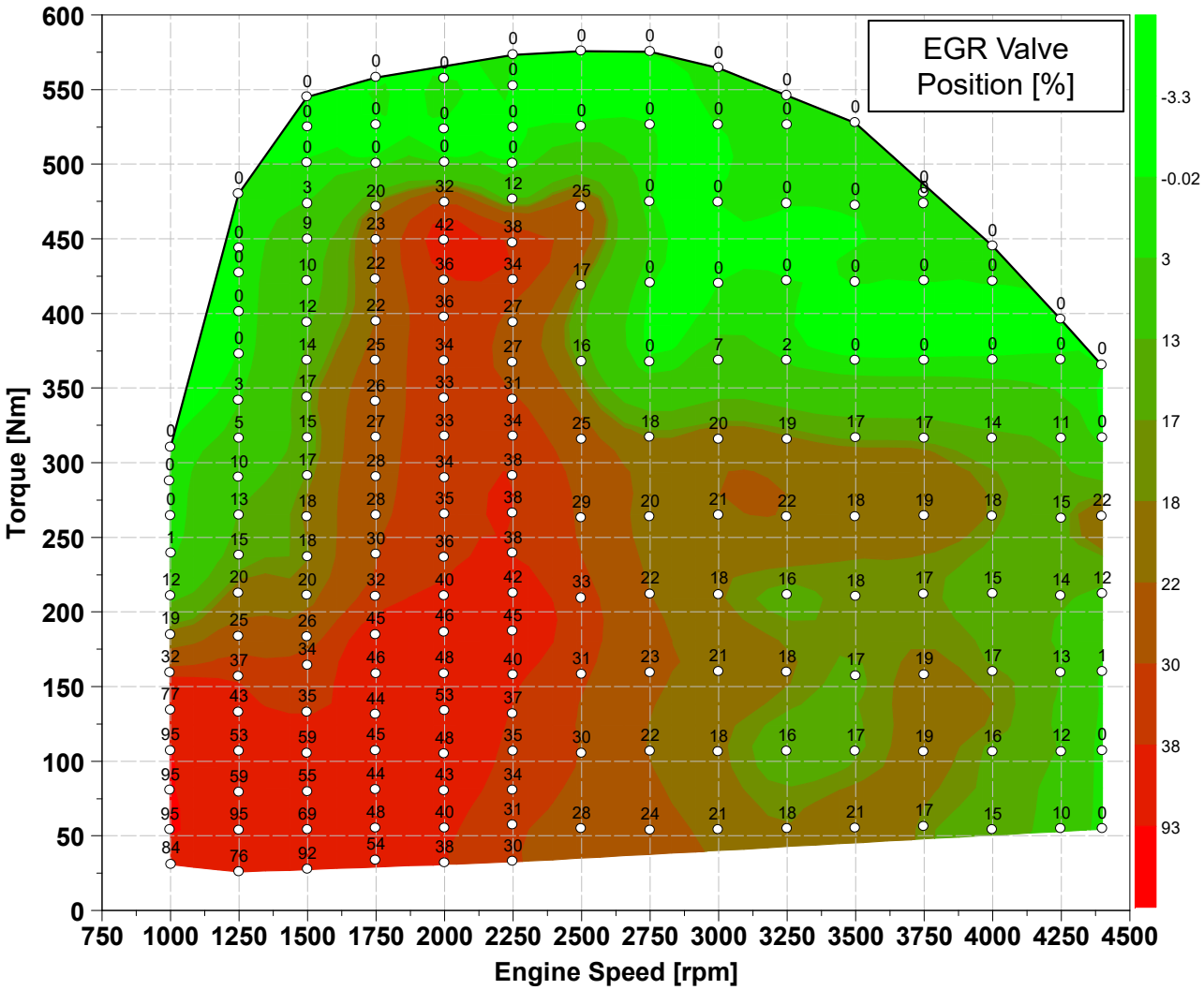
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The engine out smoke was high in the engine operating range.
- Most of the smoke numbers recorded were higher than 2 FSN.

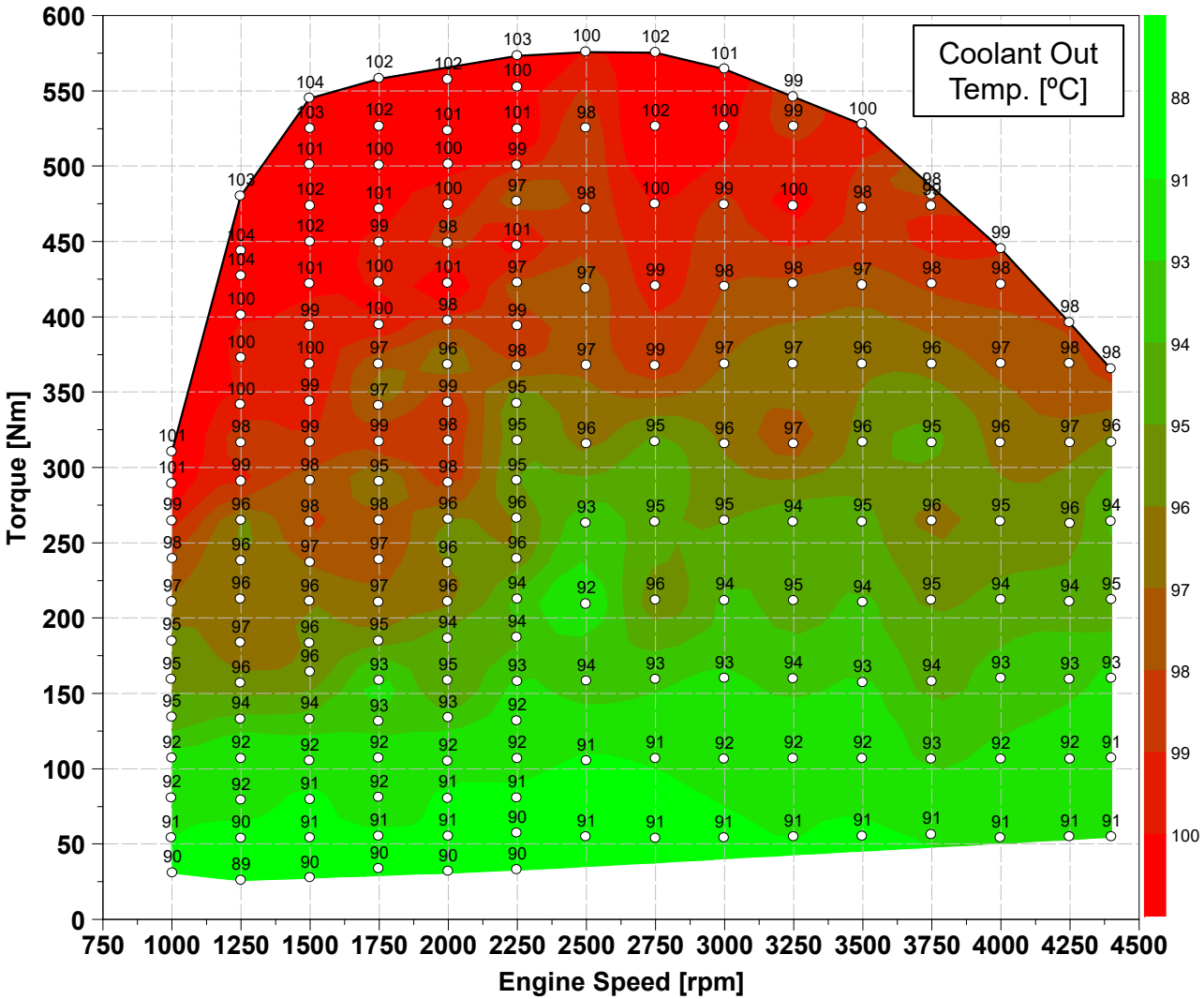
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The EGR valve was position was most open in the engine operating area.
- Beyond 2500 rpm the EGR valve position was 25% or lower.

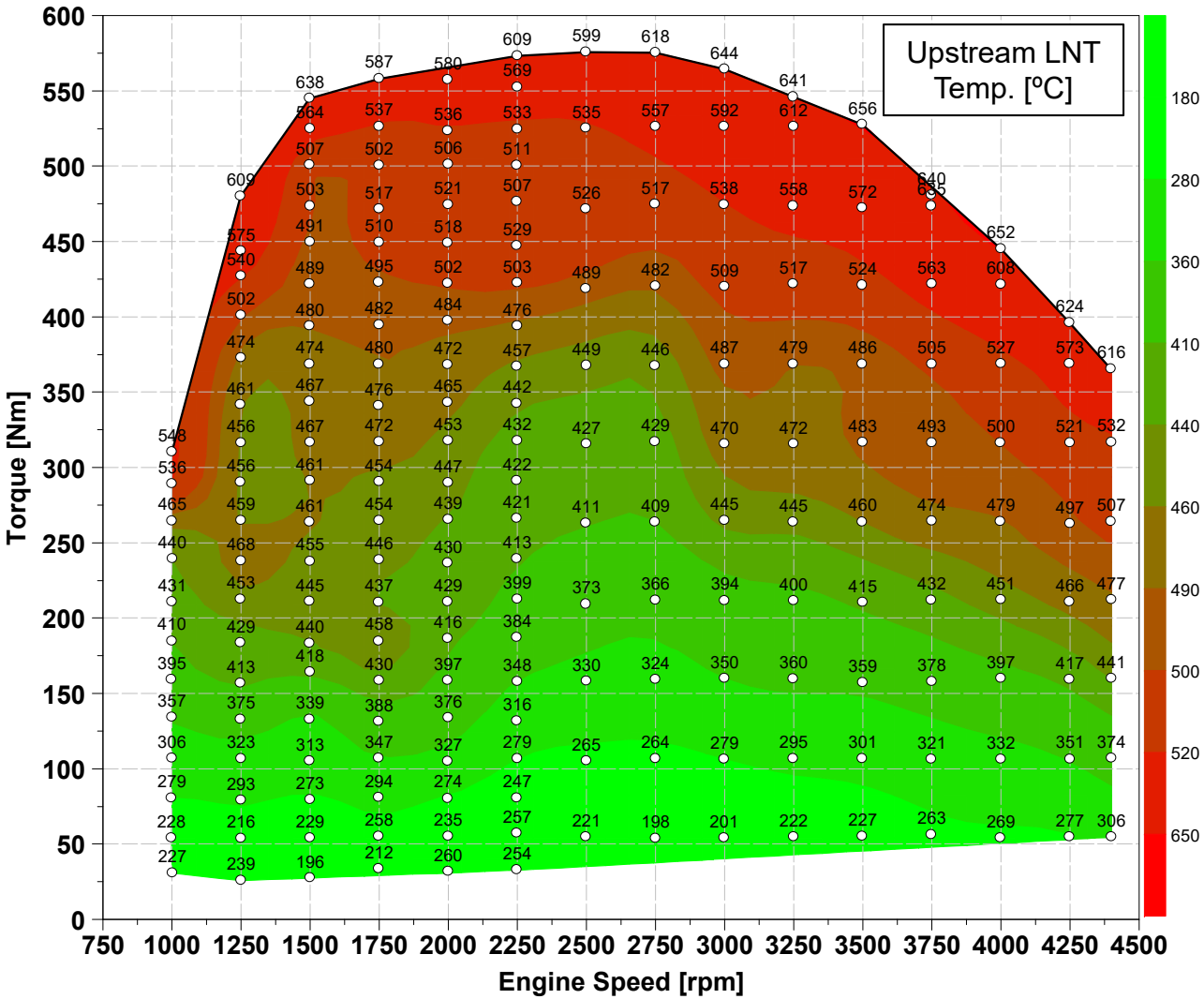
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The coolant out temperature was in the range of 90ºC and 100ºC throughout the entire engine map.
- Increases in load led to increases to coolant out temperatures.

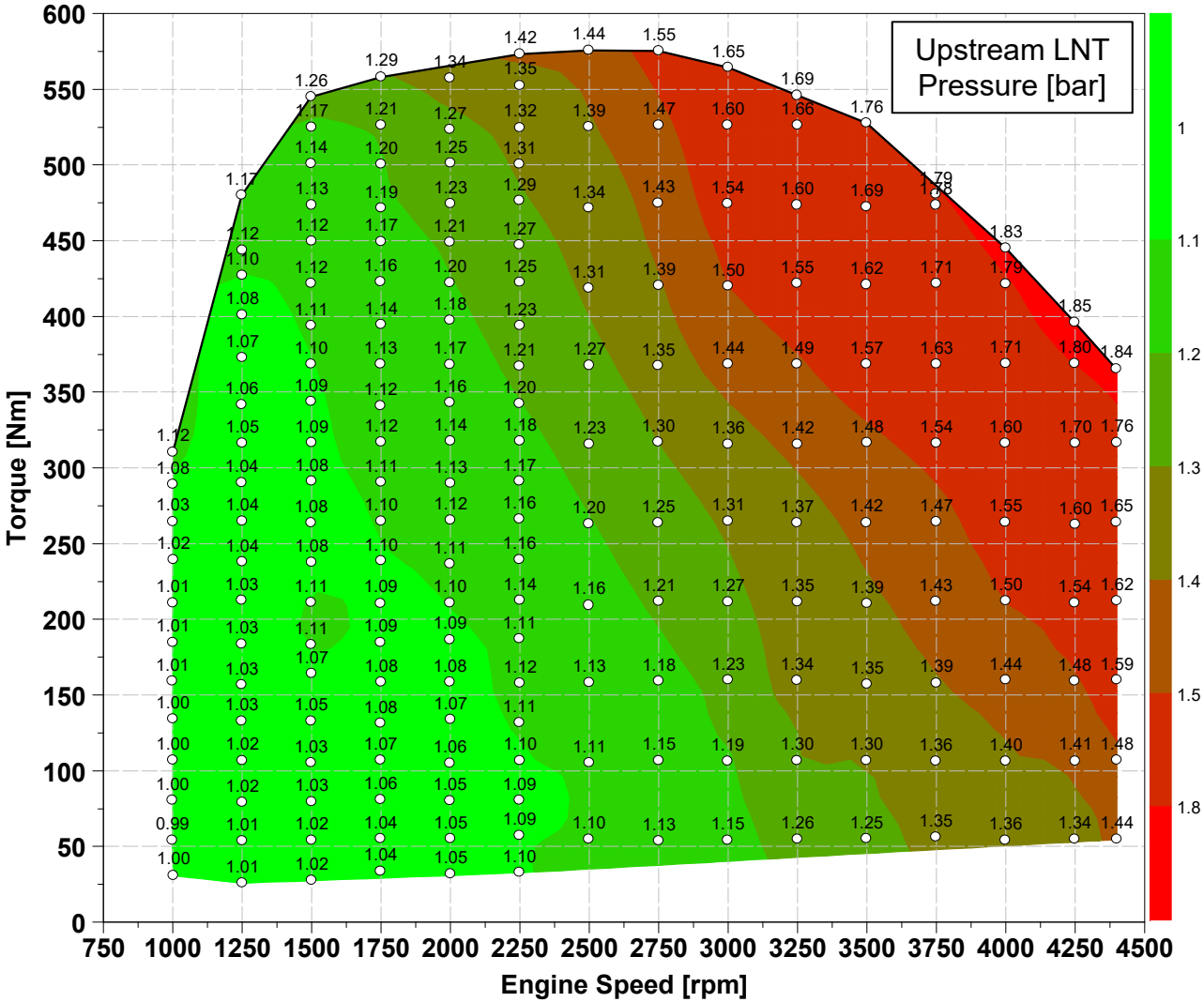
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Exhaust gas temperature at the engine out positions were more speed dependent.

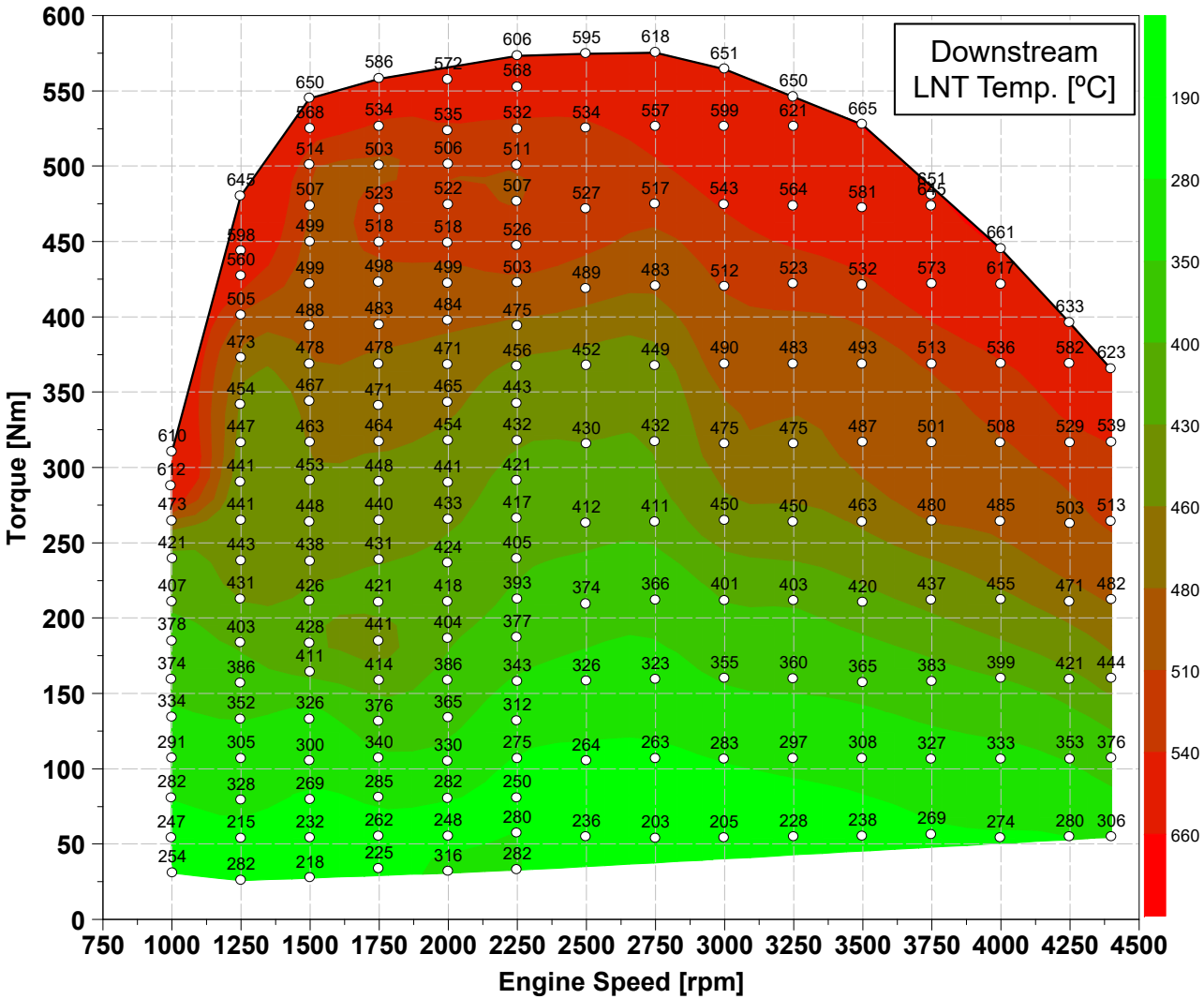
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Exhaust gas pressure at the engine out positions were more speed dependent.

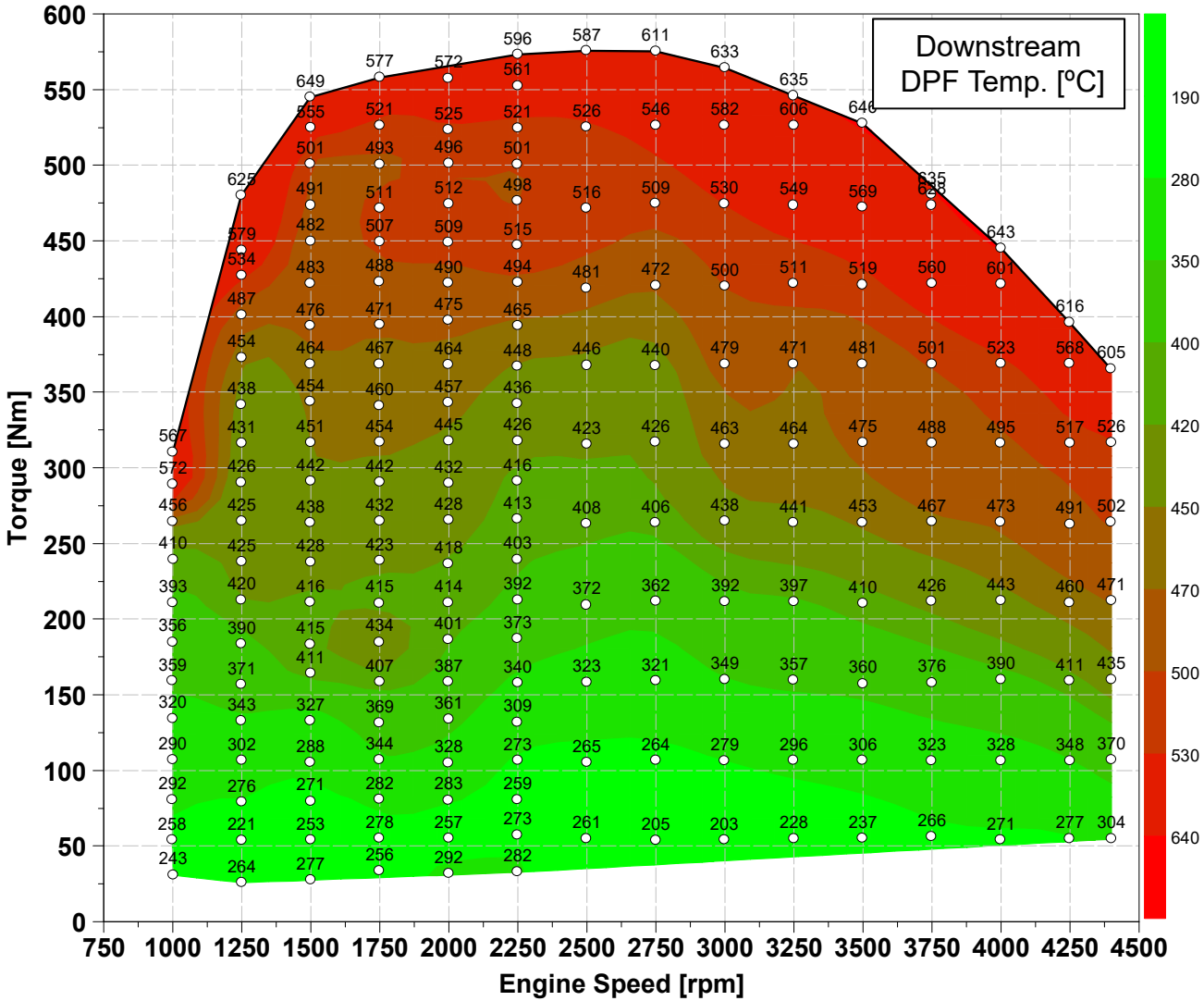
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Exhaust gas temperature at the engine out positions were load dependent.

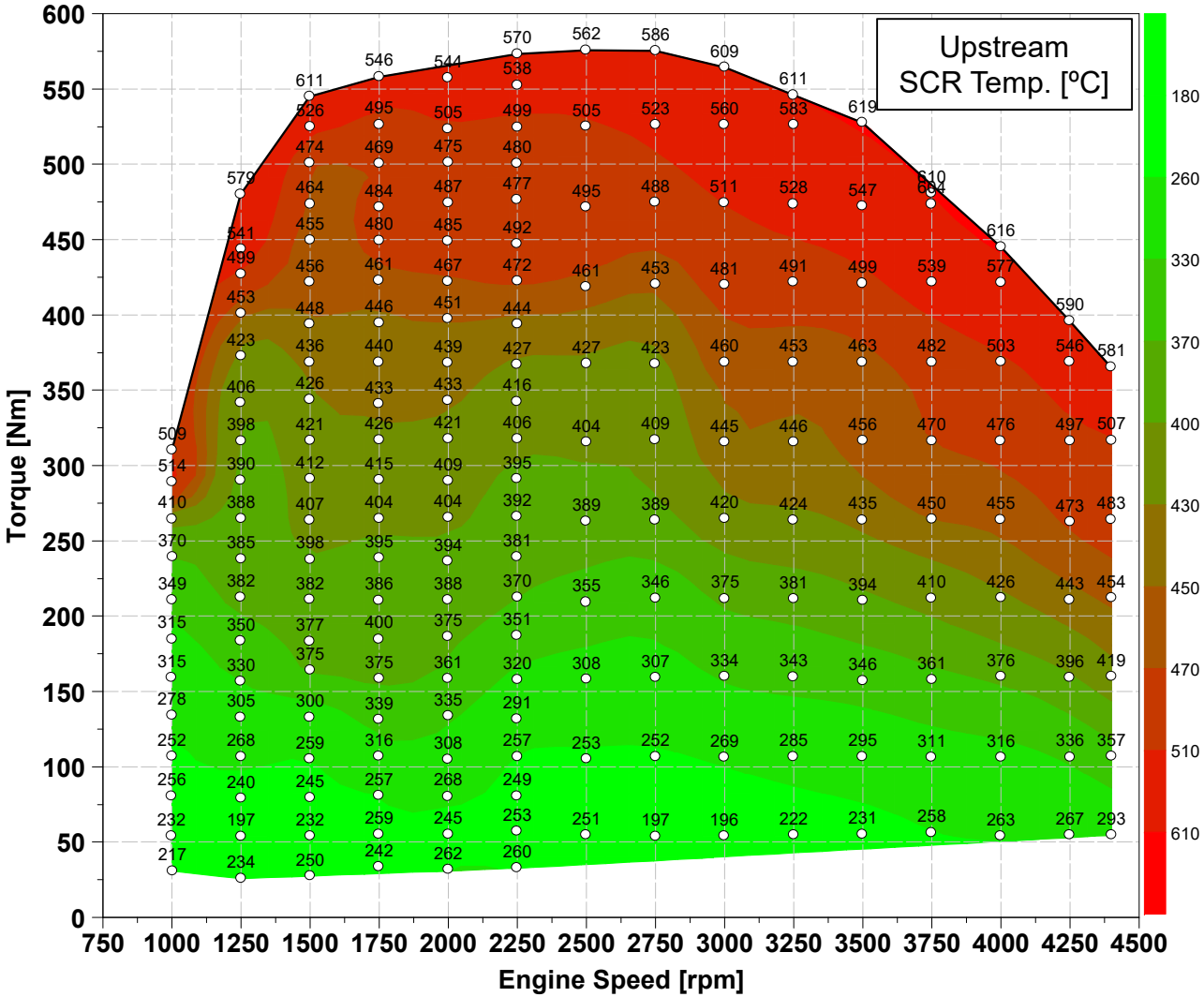
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Exhaust gas temperature at the engine out positions were load dependent.

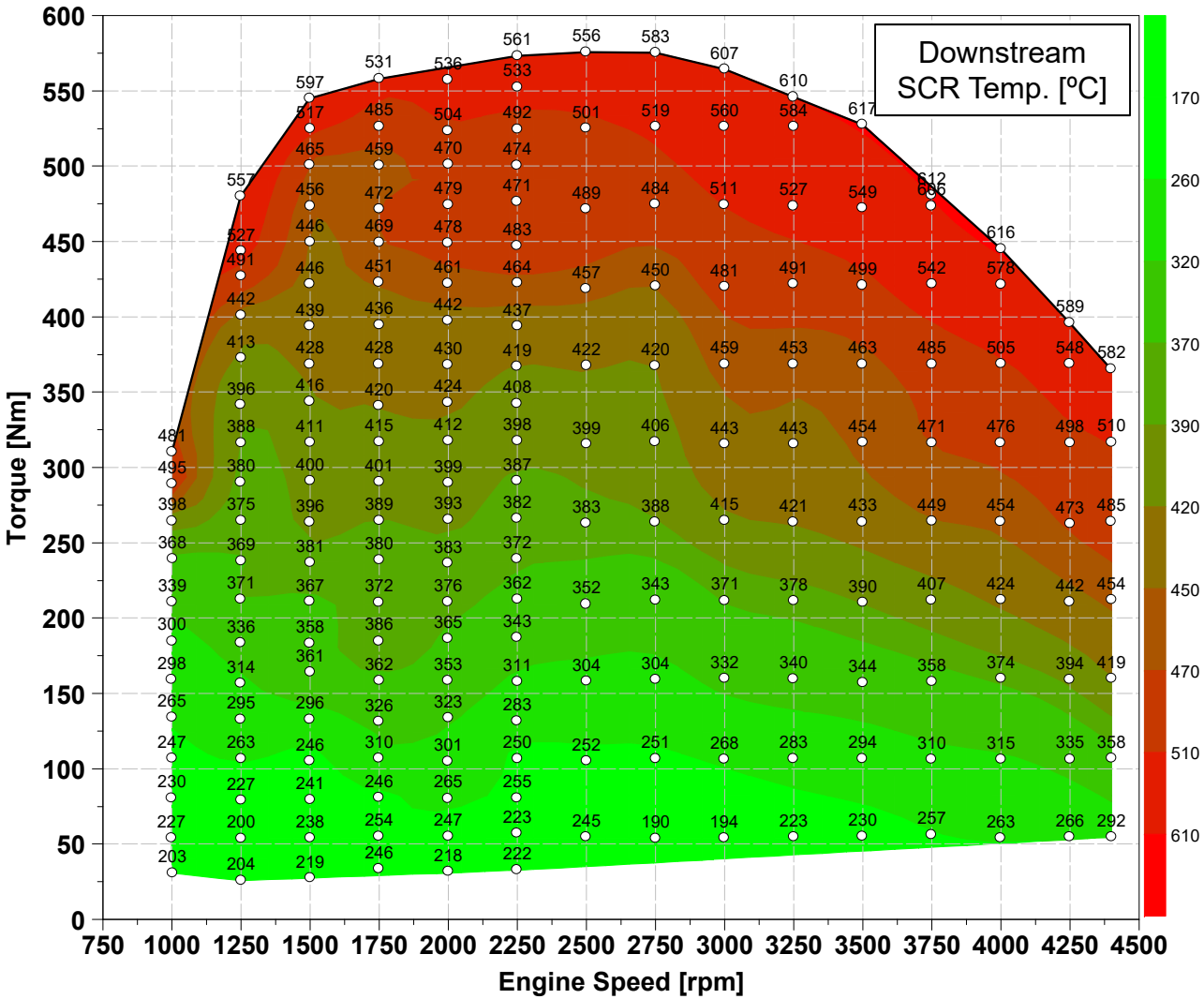
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Exhaust gas temperature at the engine out positions were load dependent.

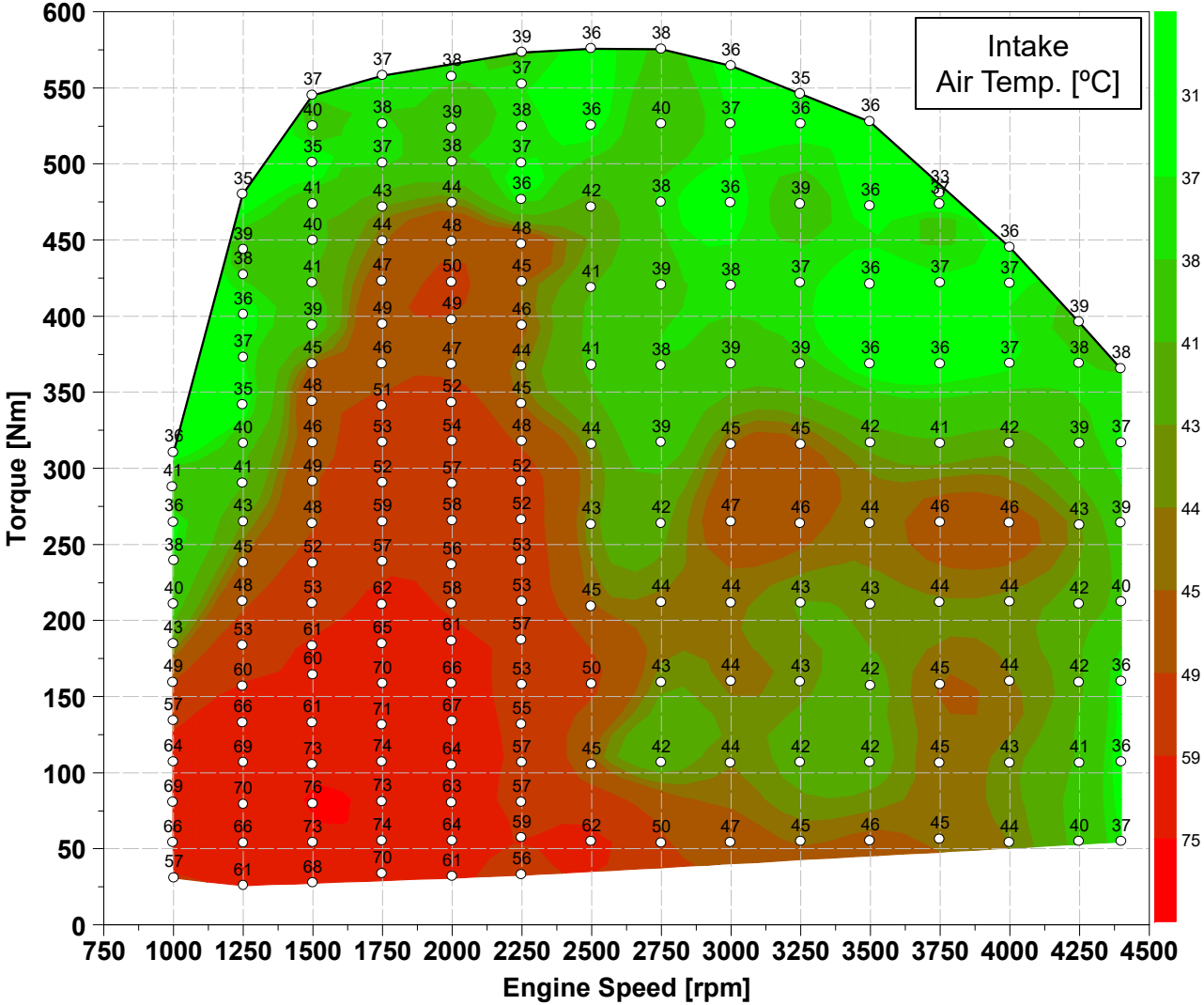
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Exhaust gas temperature at the engine out positions were load dependent.

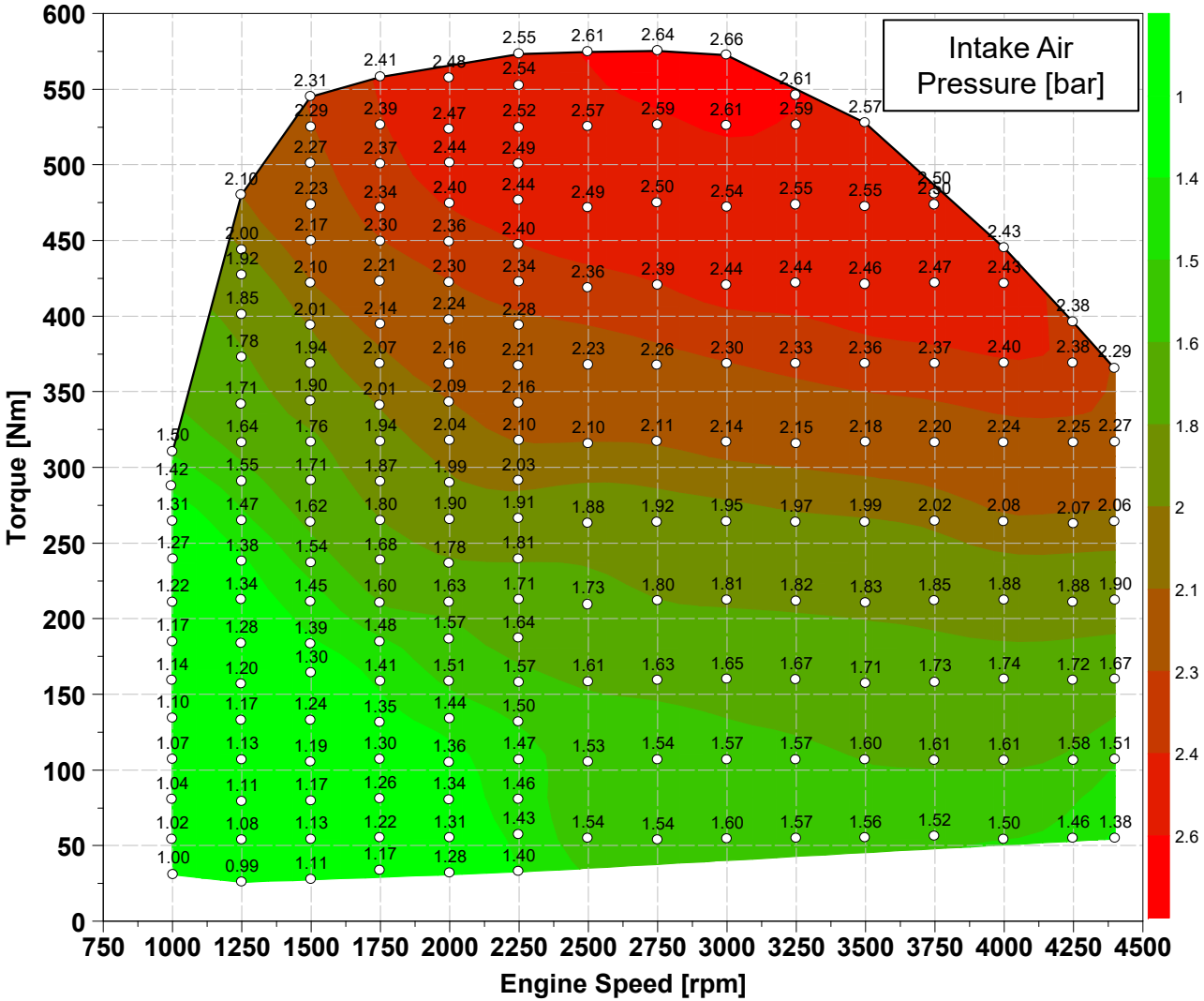
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Intake air temperature decreases with speed and was higher from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm due to the higher EGR percentages in this area of the map.

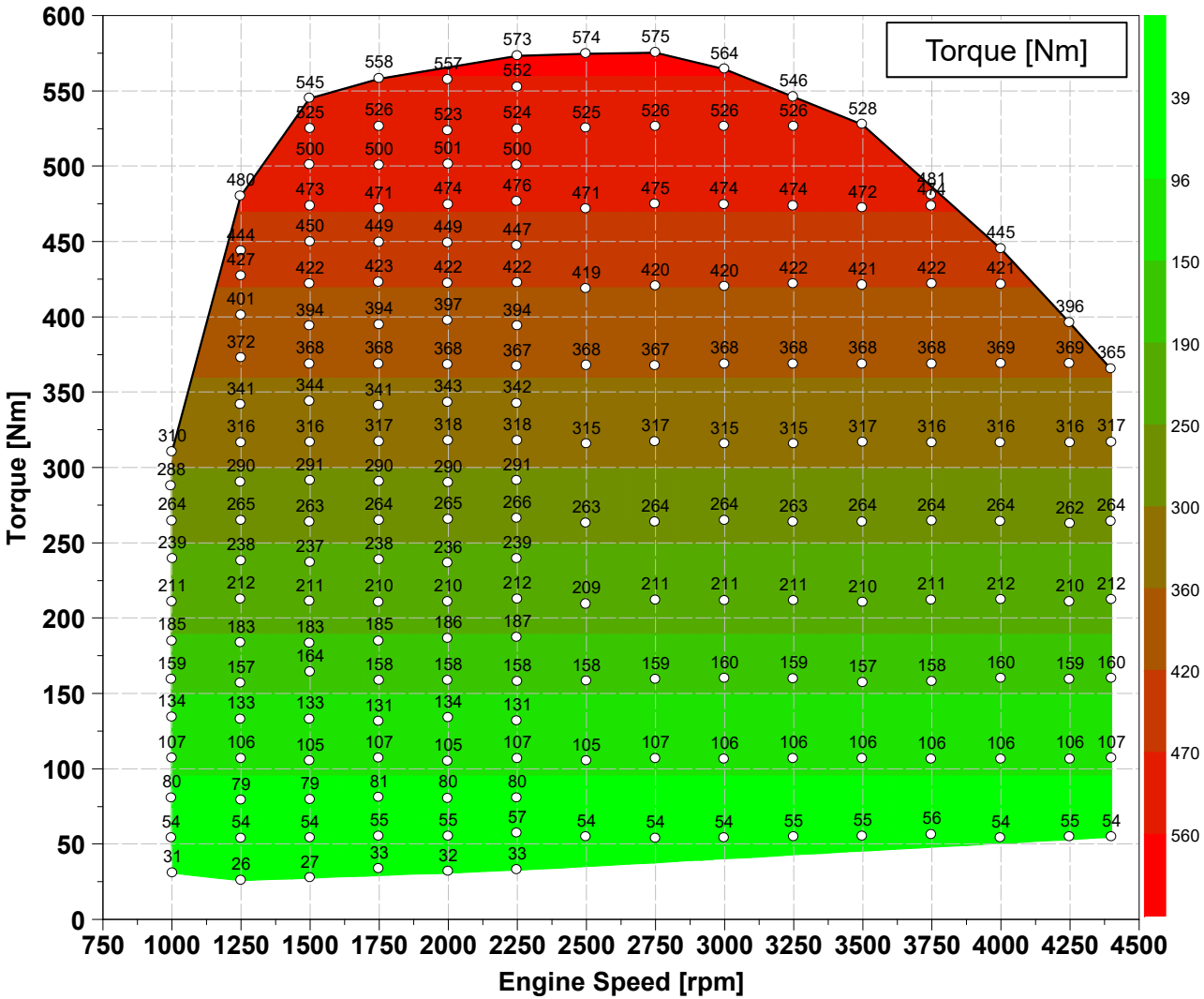
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- Intake air pressure increases with speed and load.

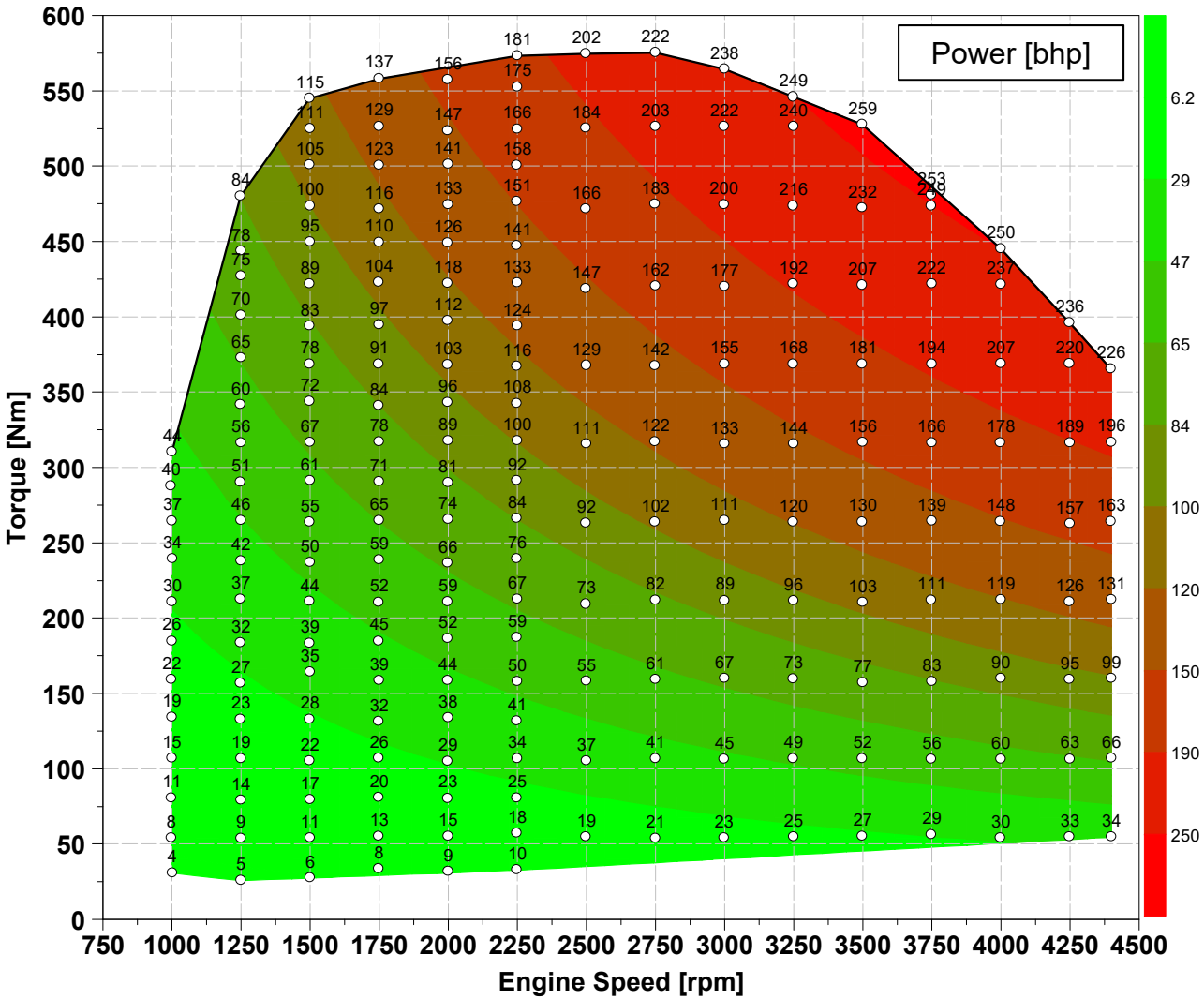
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The engine is rated to produce 560 Nm of torque at full load. At full load during testing the engine was capable of reaching 570 Nm on average.

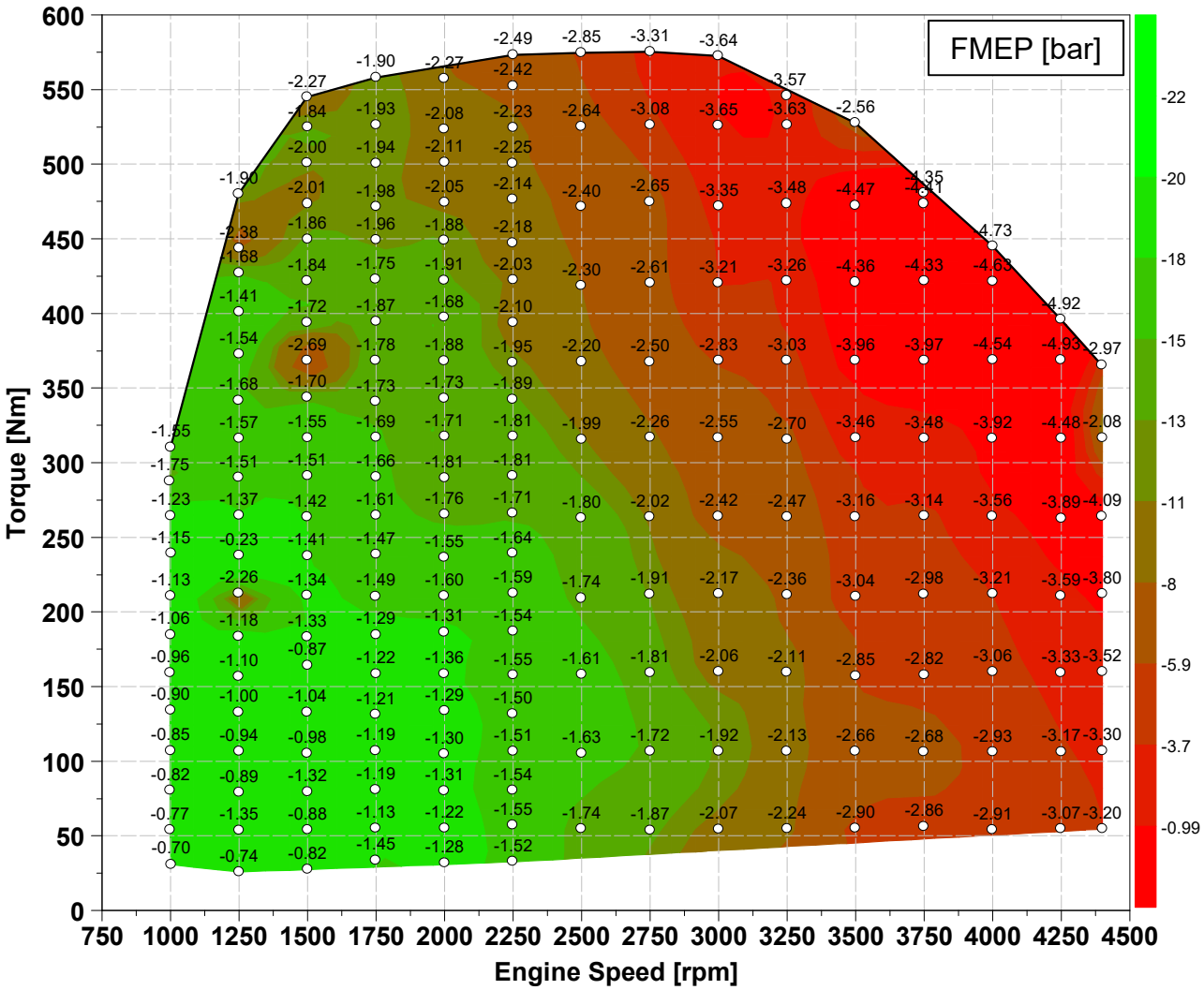
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The engine is rated to produce 255 bhp of torque at full load. The engine was capable of reaching peak power from 3500 rpm to 4000 rpm.

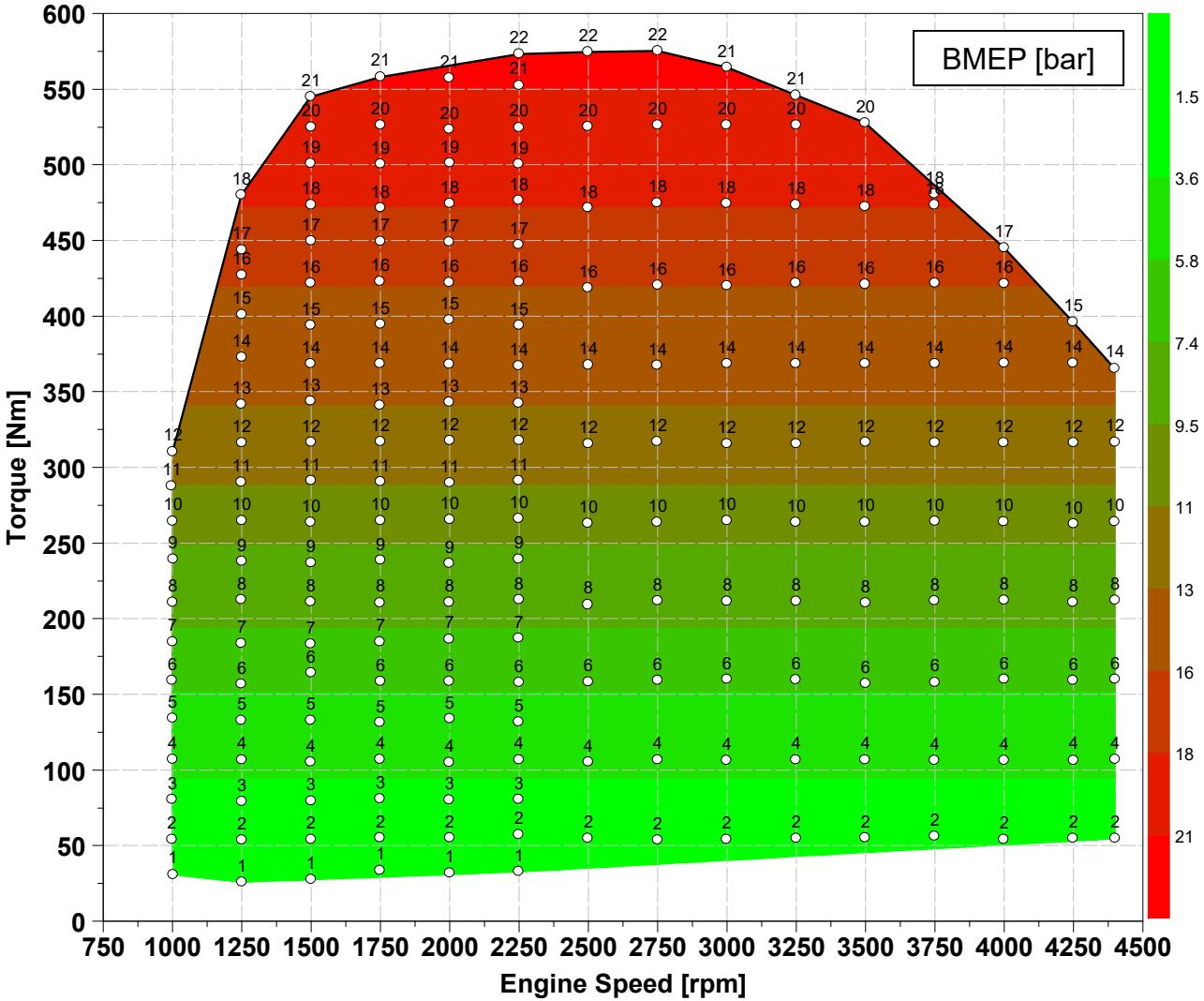
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The FMEP began to decrease as there were increases in speed.
- The highest FMEP values of were within the 1000 rpm to 2250 rpm speed range approximately around -1 bar.

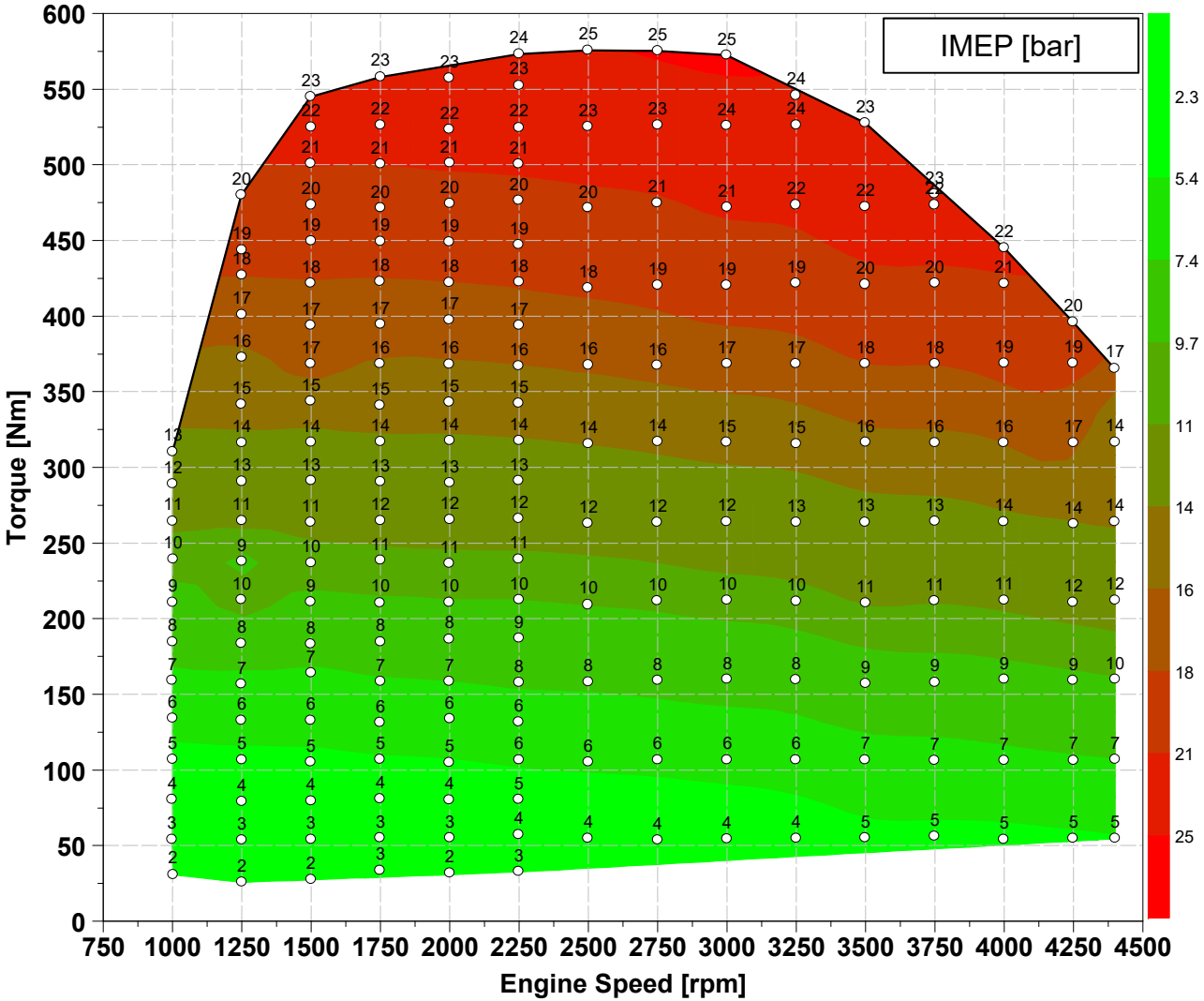
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The engine produced peak BMEP of approximately 22 bar in the full range of the engine map.

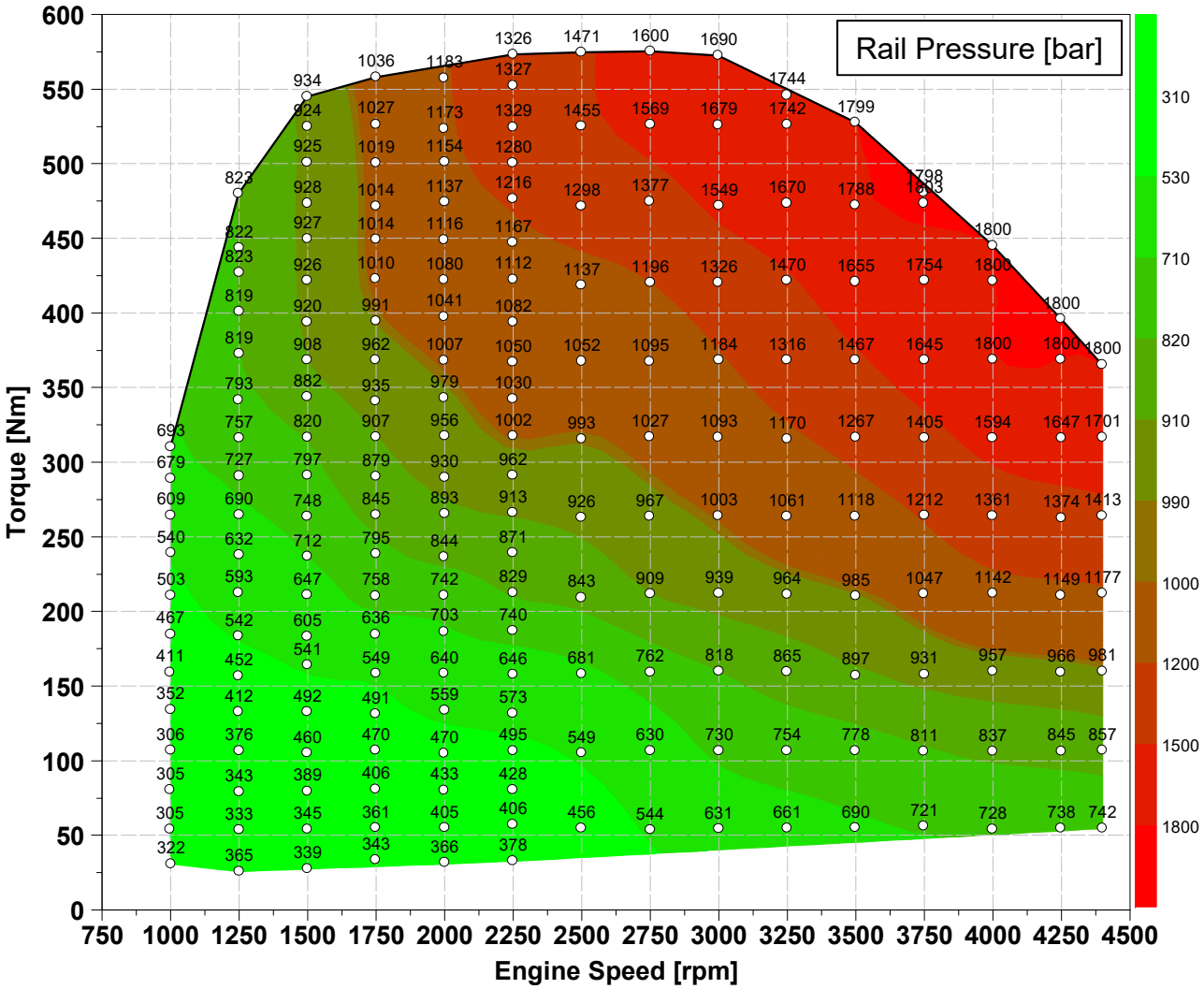
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The engine produced peak BMEP of approximately 25 bar in the full range of the engine map.

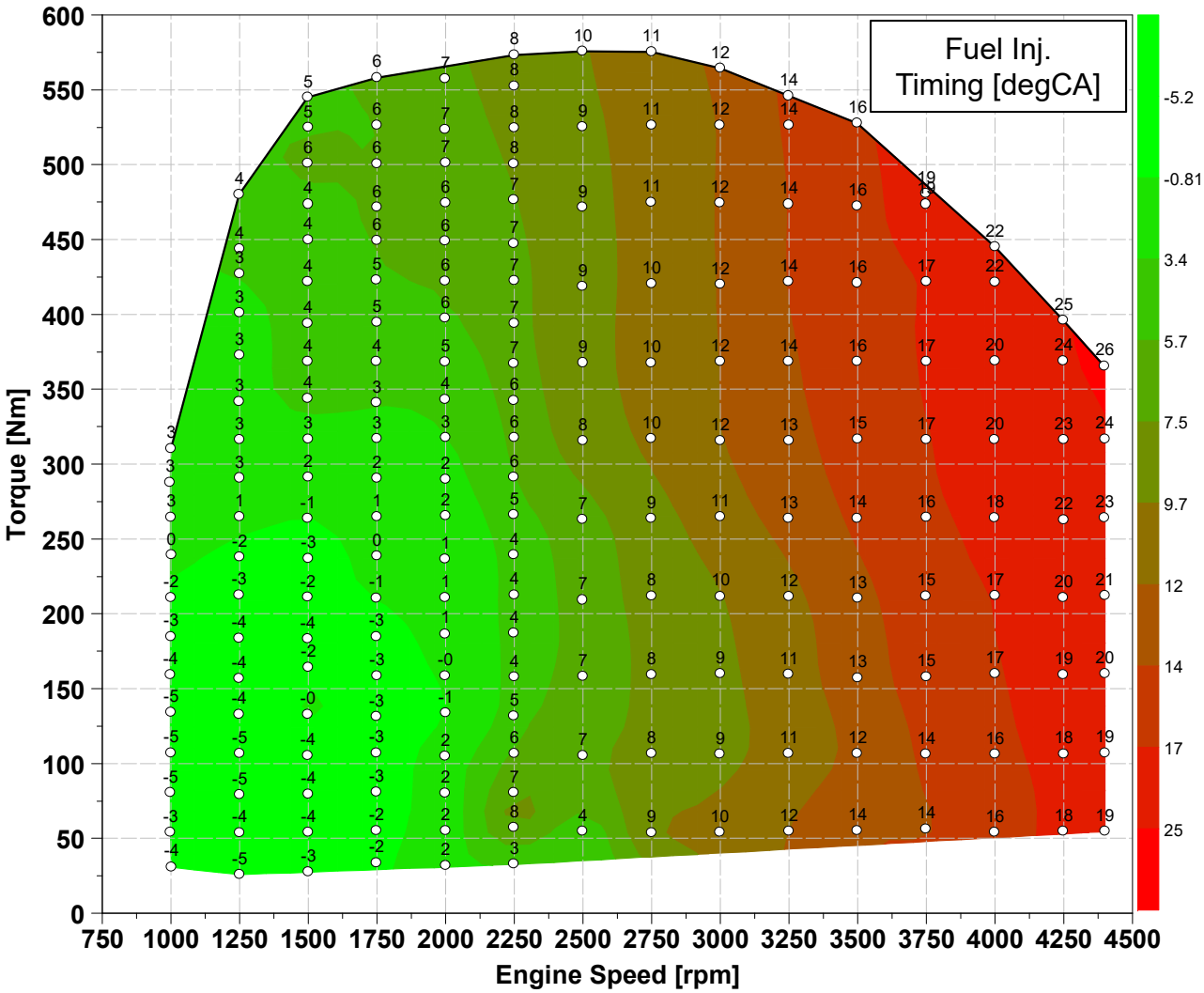
FEV Benchmarking
BMW X5d 35d: Engine Mapping



Comment

- The fuel rail pressure is in the range of 300 – 600 bar.
- The fuel rail pressure increases proportionately to the increase in power on the engine map.

FEV Benchmarking
BMW X5d 35d: Engine Mapping



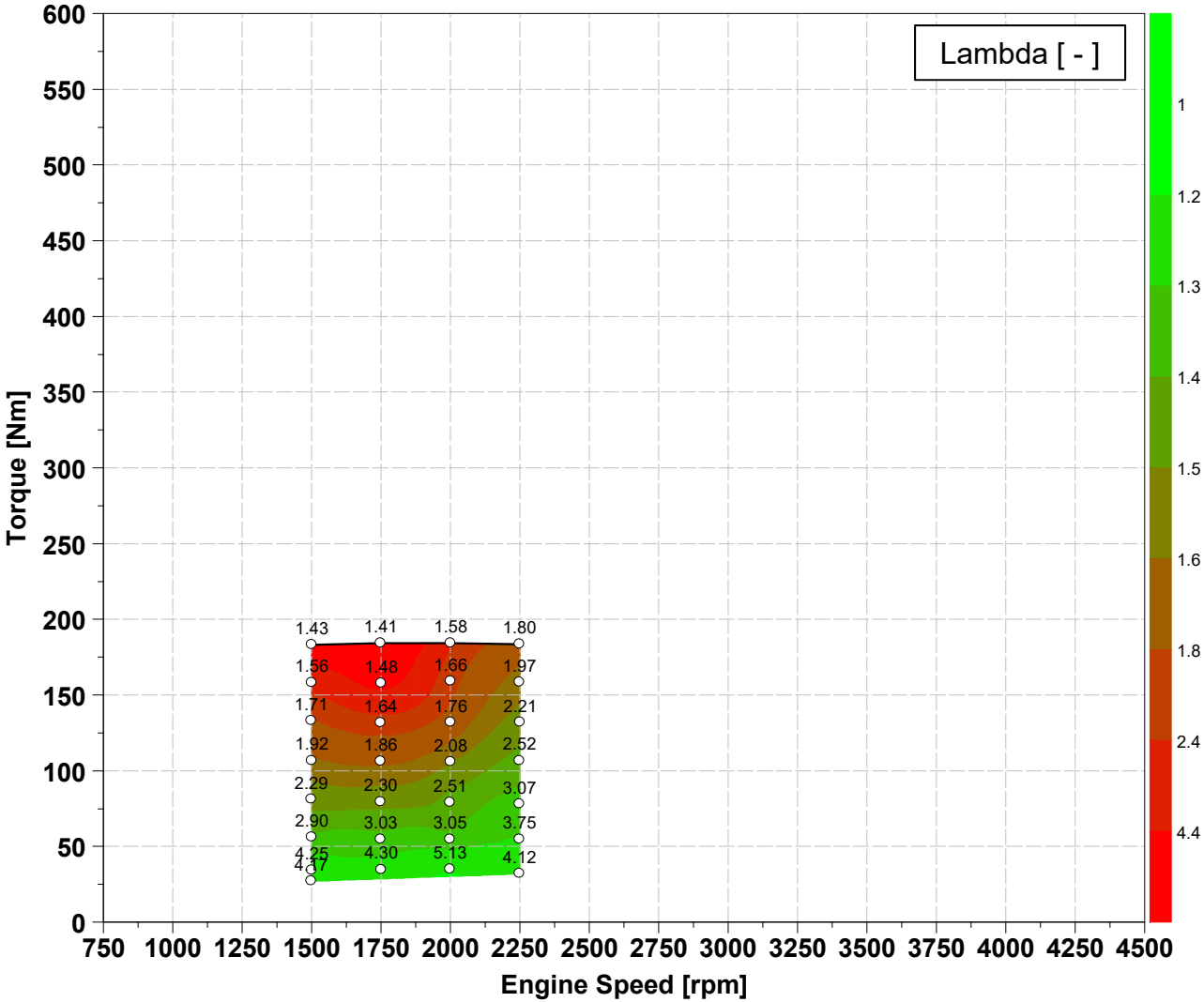
Comment

- The engine fuel injection timing was delayed with increase in speed.

Agenda

- Introduction
- Vehicle Break In
- DPF Regeneration Interval Investigation
- Engine Mapping
- EGR Mapping
- Urea Course Engine Mapping
- Continuous Data
- ASCMO Simulations
- Conclusion

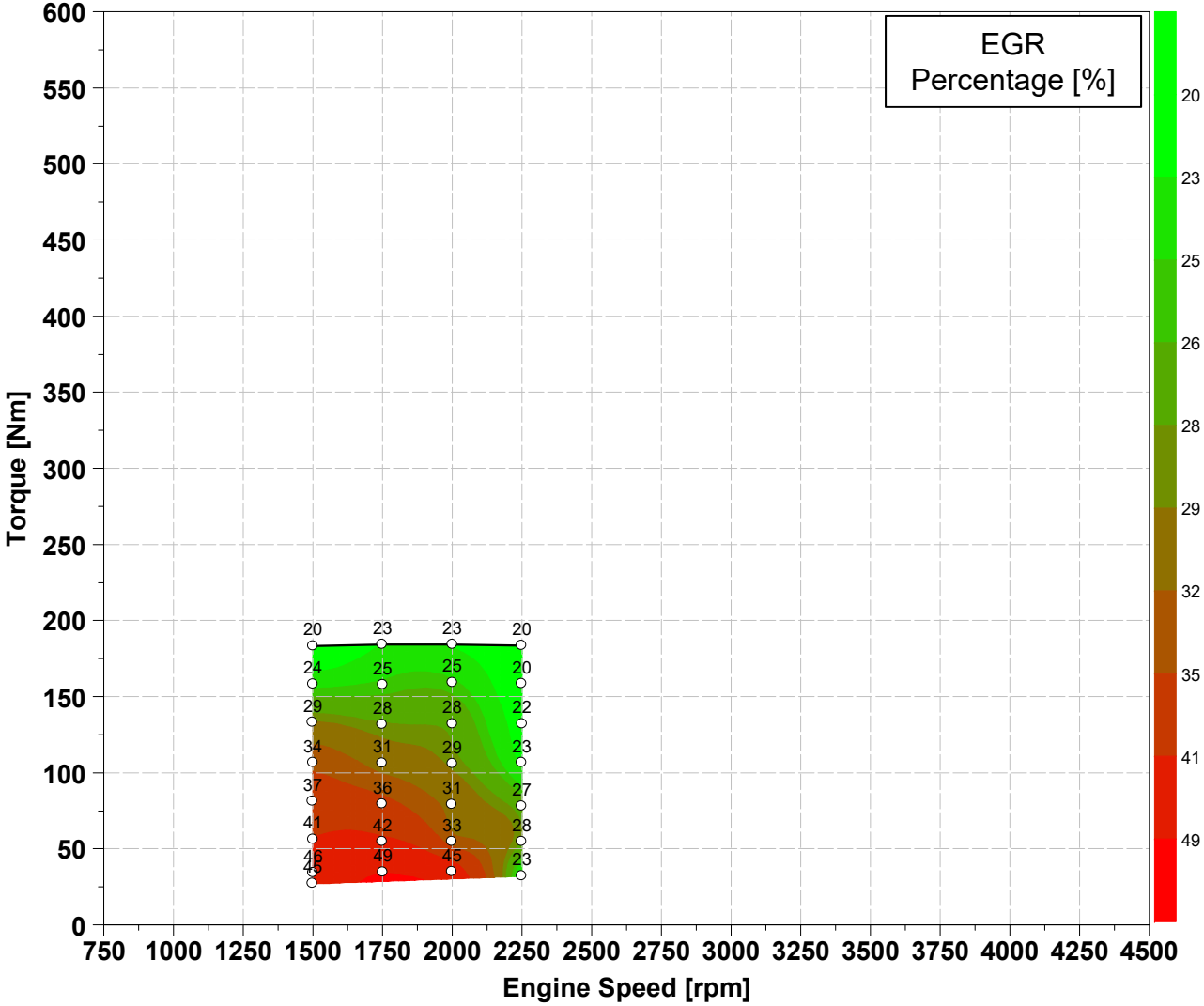
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- Lambda values ranged from 1.30 – 4 over the entire map
- At 200 Nm the engine runs at lambda values of approximately 1.5. While at lower loads lambda values reaches 5.

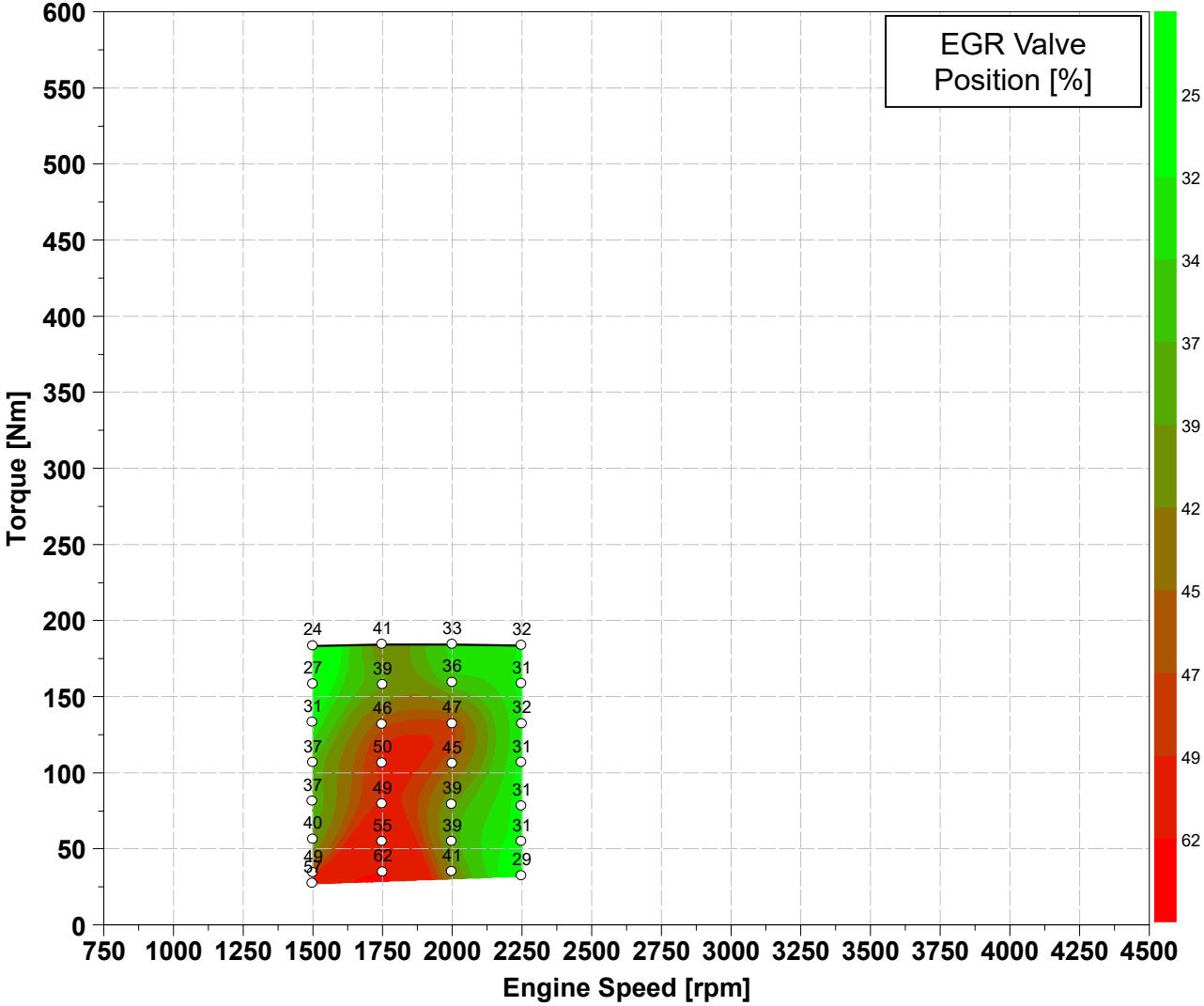
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- EGR percentages were highest at from 1500 rpm and 1750 rpm at low loads approximately 40%.
- On higher speed and load points the EGR percentage decreased to 20%.

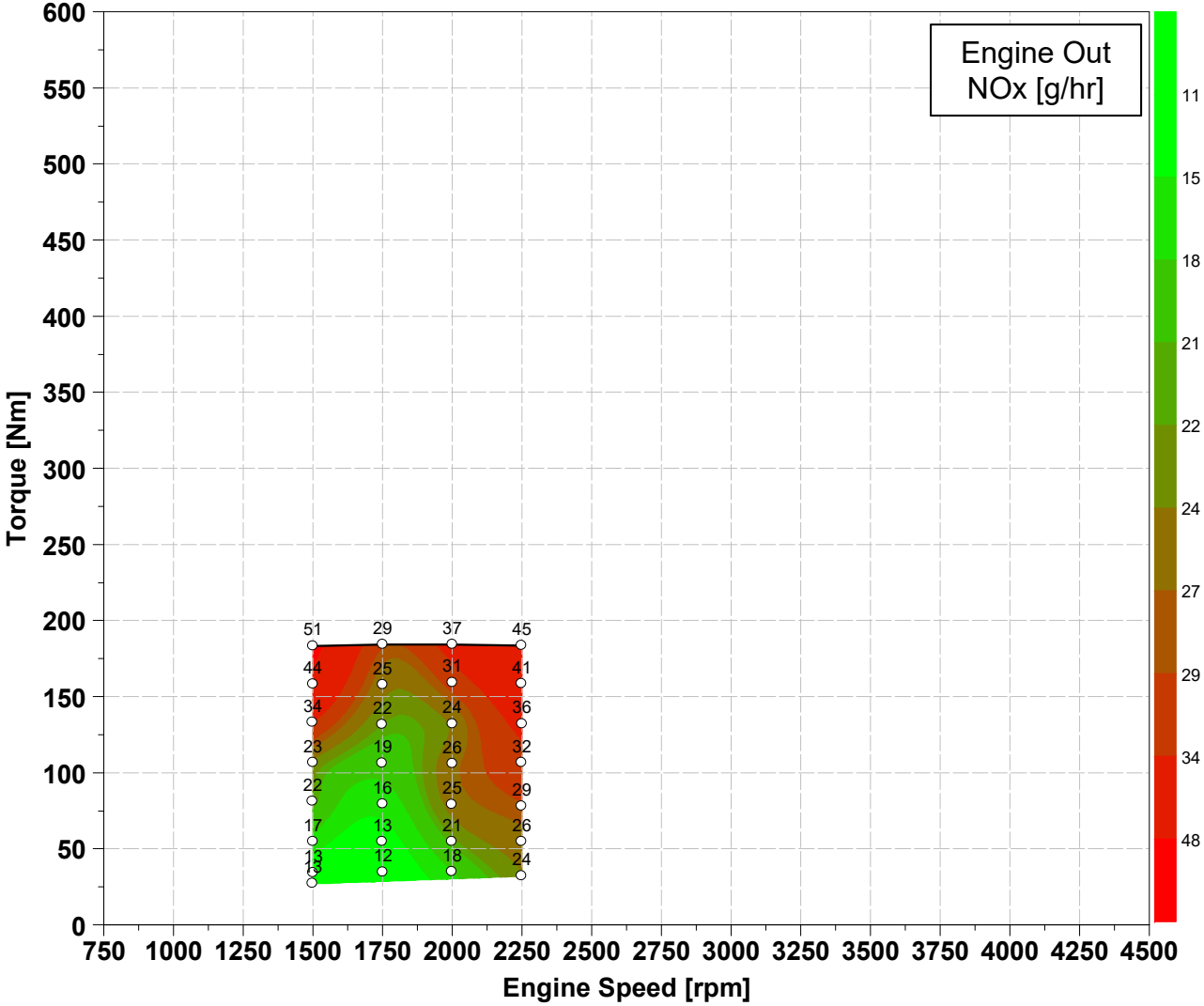
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- EGR valve position was more open at lower load and speed points on the map from 1500 rpm and 1750 rpm at low loads approximately 40%.

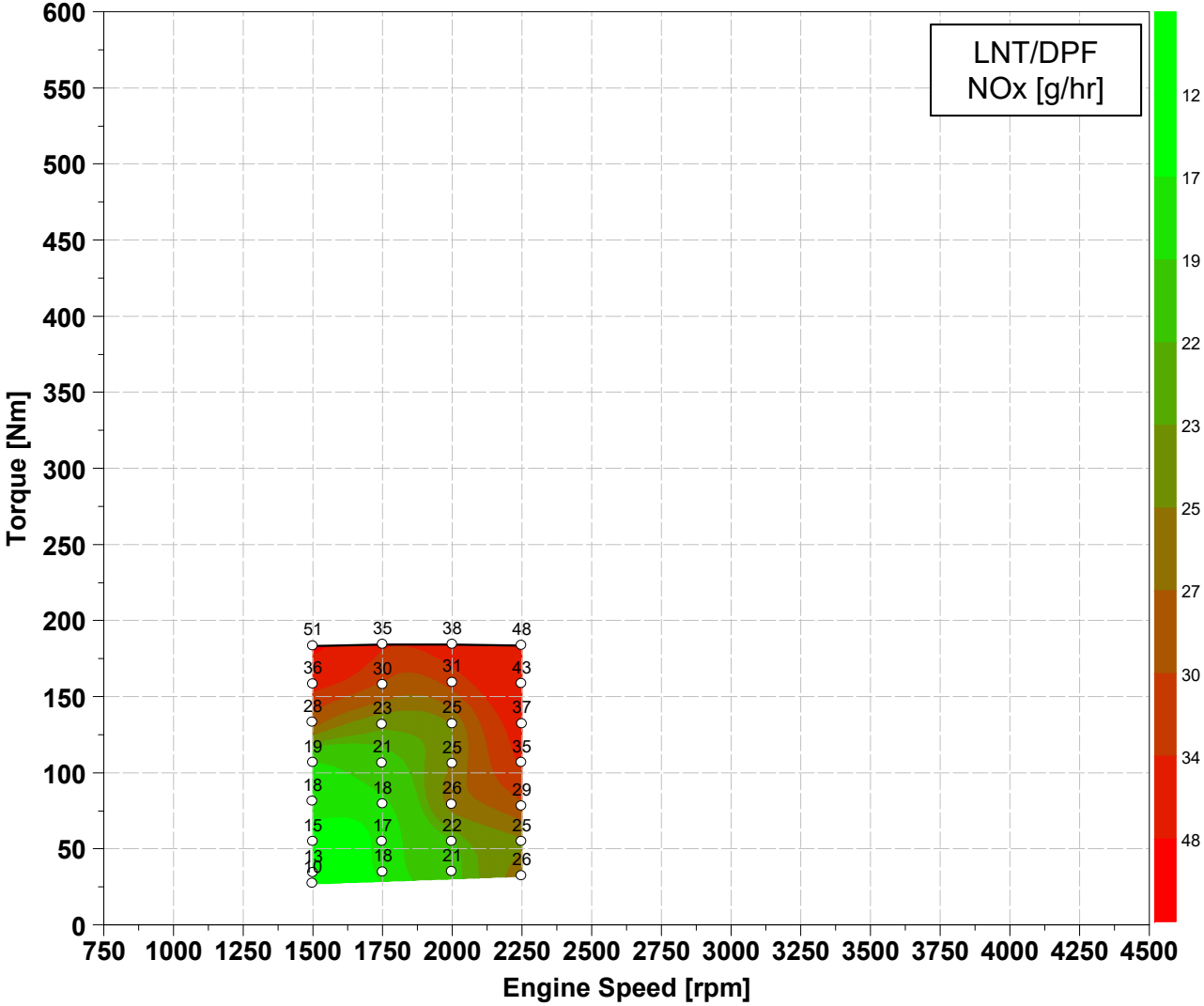
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- Engine out NOx was relatively low from 1500 rpm to 2000 rpm and 25 Nm to 150 Nm on the map below approximately 25 g/hr.
- Outside of this range the engine out NOx is much higher at 25 g/hr. or more
- The NOx emissions are more impacted by load than speed.

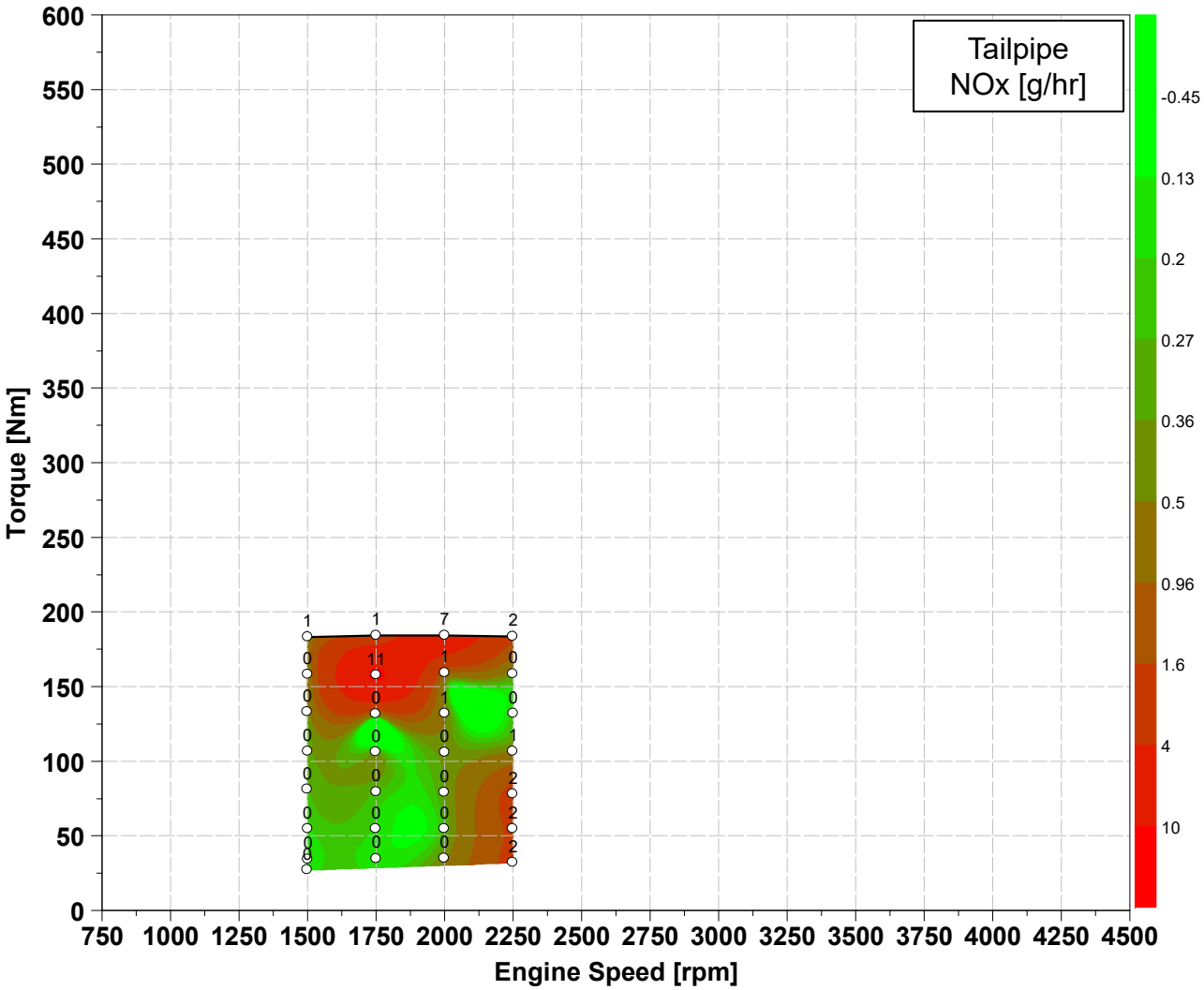
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- The engine out NOx was slightly reduced across the LNT catalyst. With some reduction up to 3 g/hr.

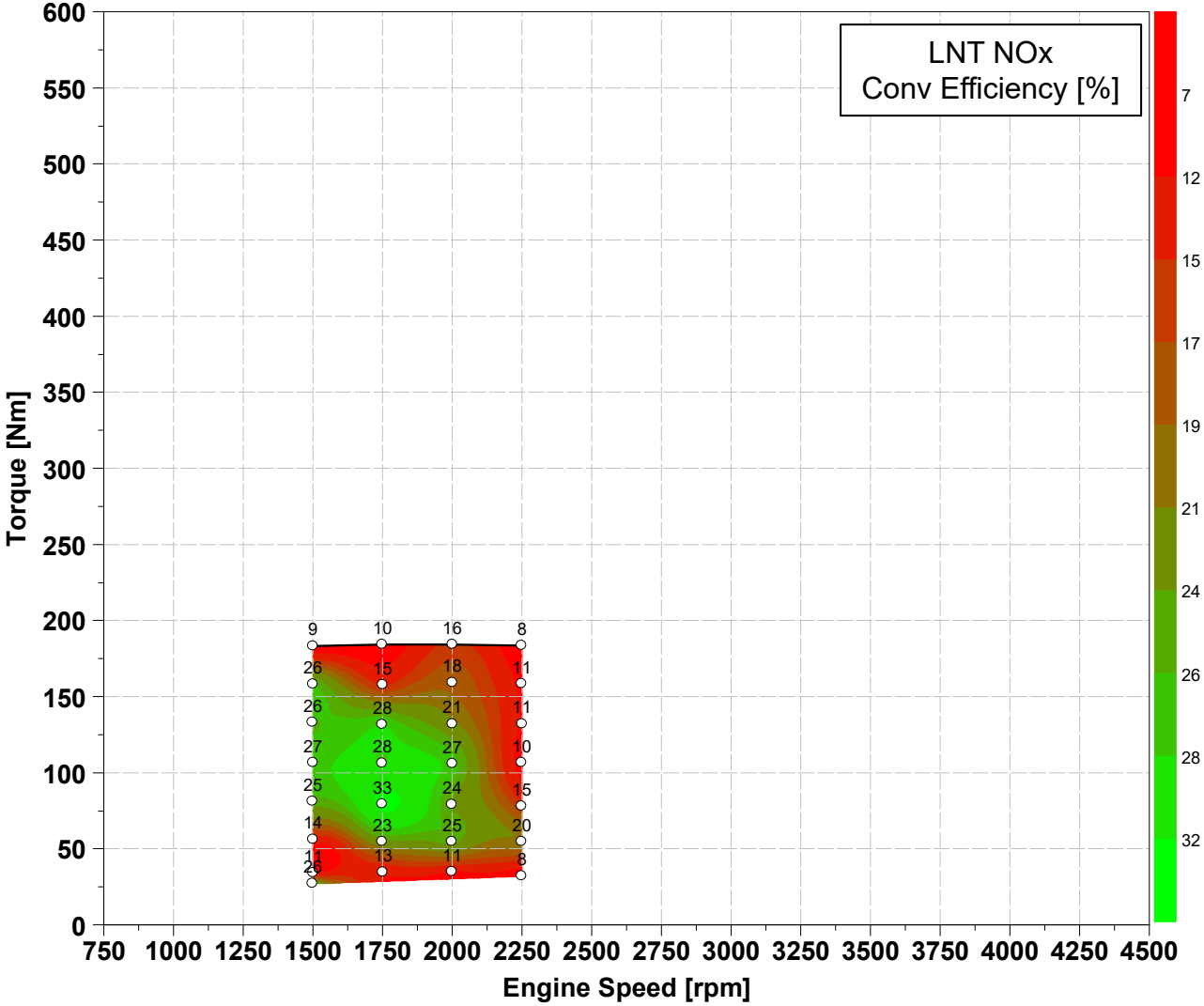
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- The tailpipe NOx was significantly lower compared to engine out, less than 2 g/hr for most areas on the engine map.

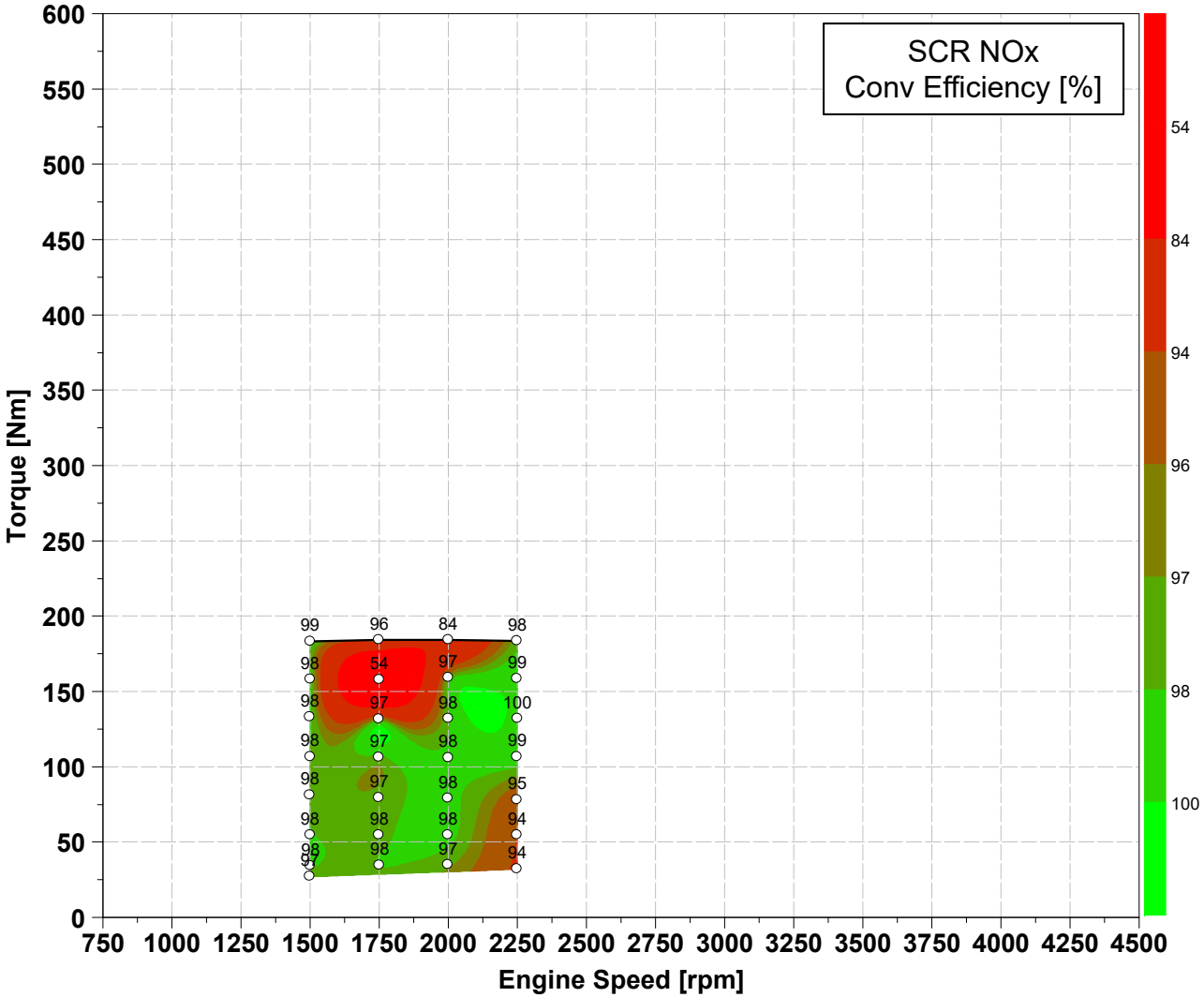
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- The LNT/DPF NOx conversion efficiency was most efficient from 1500 rpm to 2000 rpm and 50 Nm to 150 Nm
- With NOx conversion efficiencies reaching up to 33% at 1750 rpm.

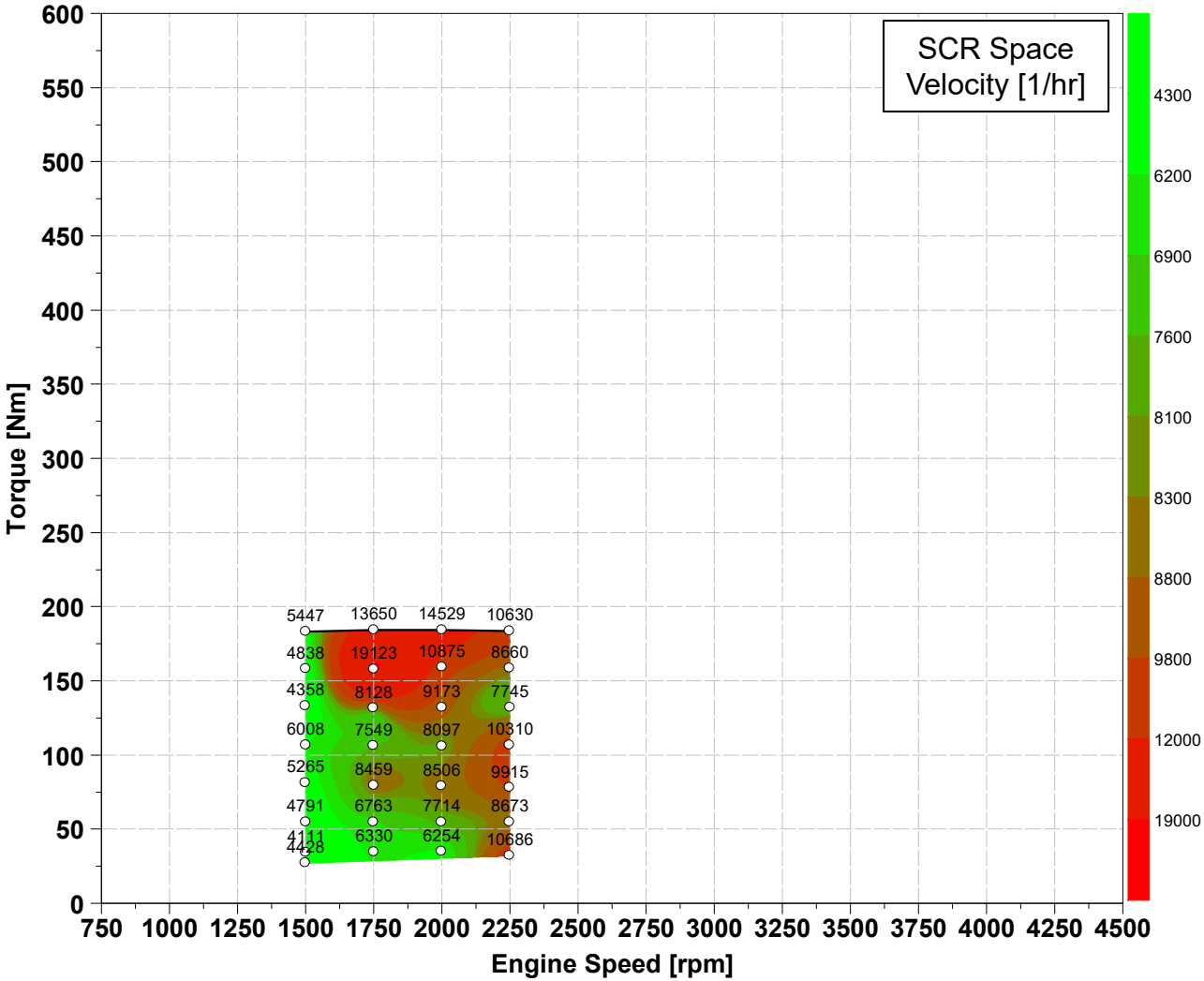
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- The SCR NOx conversion efficiency was consistent across the entire map excluding one point at 1750 rpm and 165 Nm
- With efficiencies reaching to as high as 100%

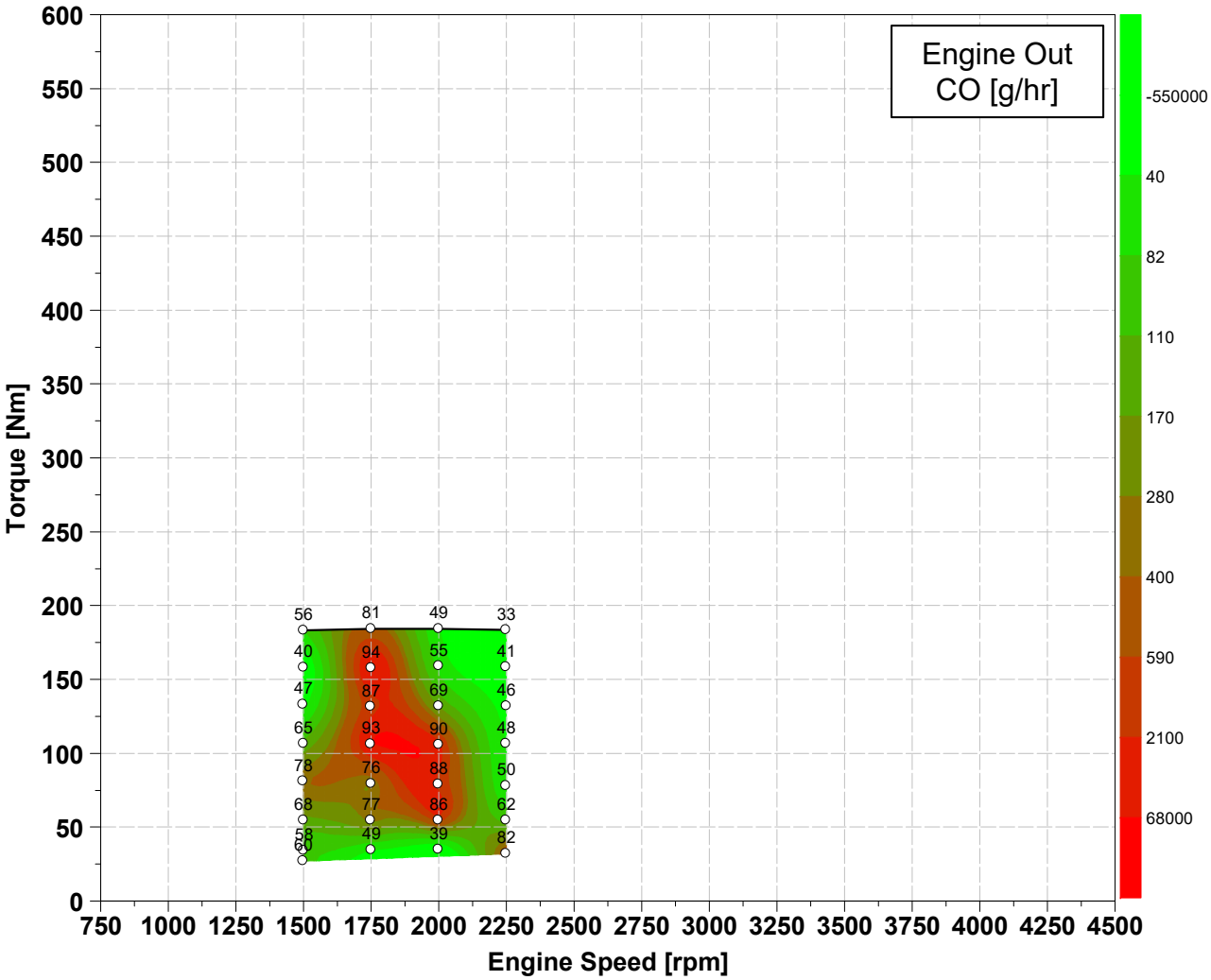
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- The SCR space velocity was lowest from 1500 rpm to 1750 rpm and 25 Nm to 125 Nm
- The space velocity value increased with increases in load.

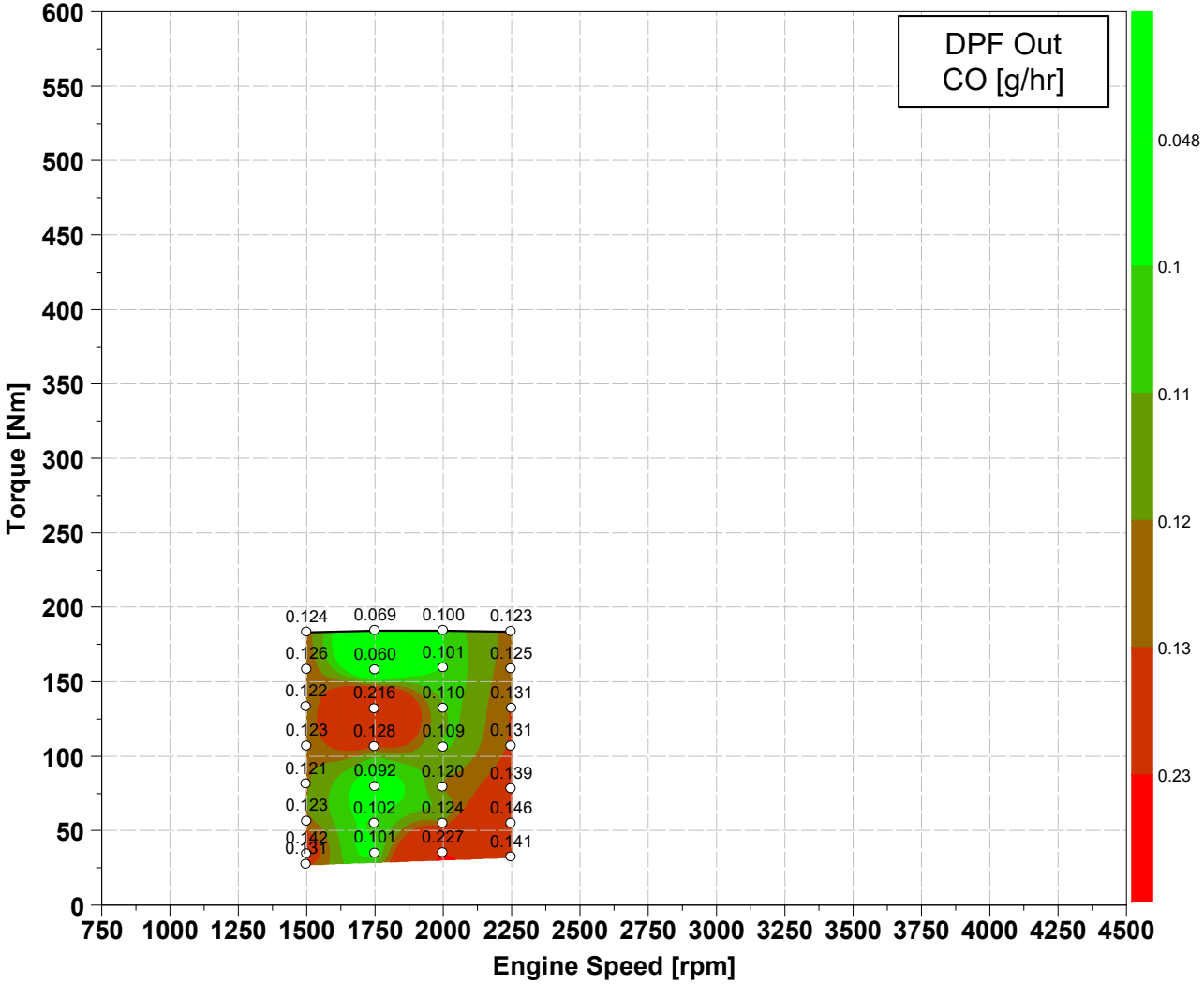
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- Engine out CO was much higher at 1750 rpm and 2000 rpm opposed to the other points on the map.

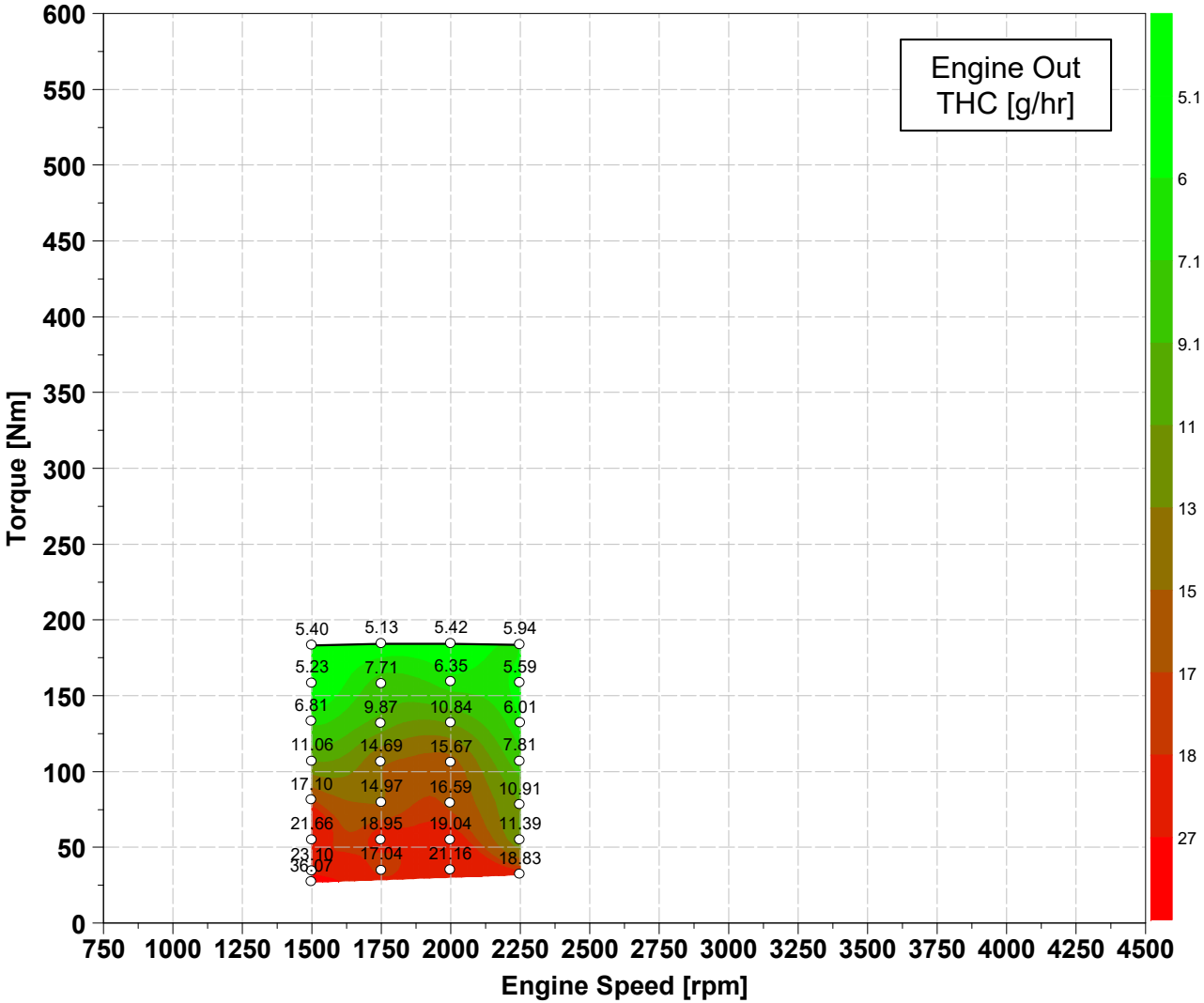
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- The tailpipe CO is much lower, less than 2 g/hr, for most areas on the engine map

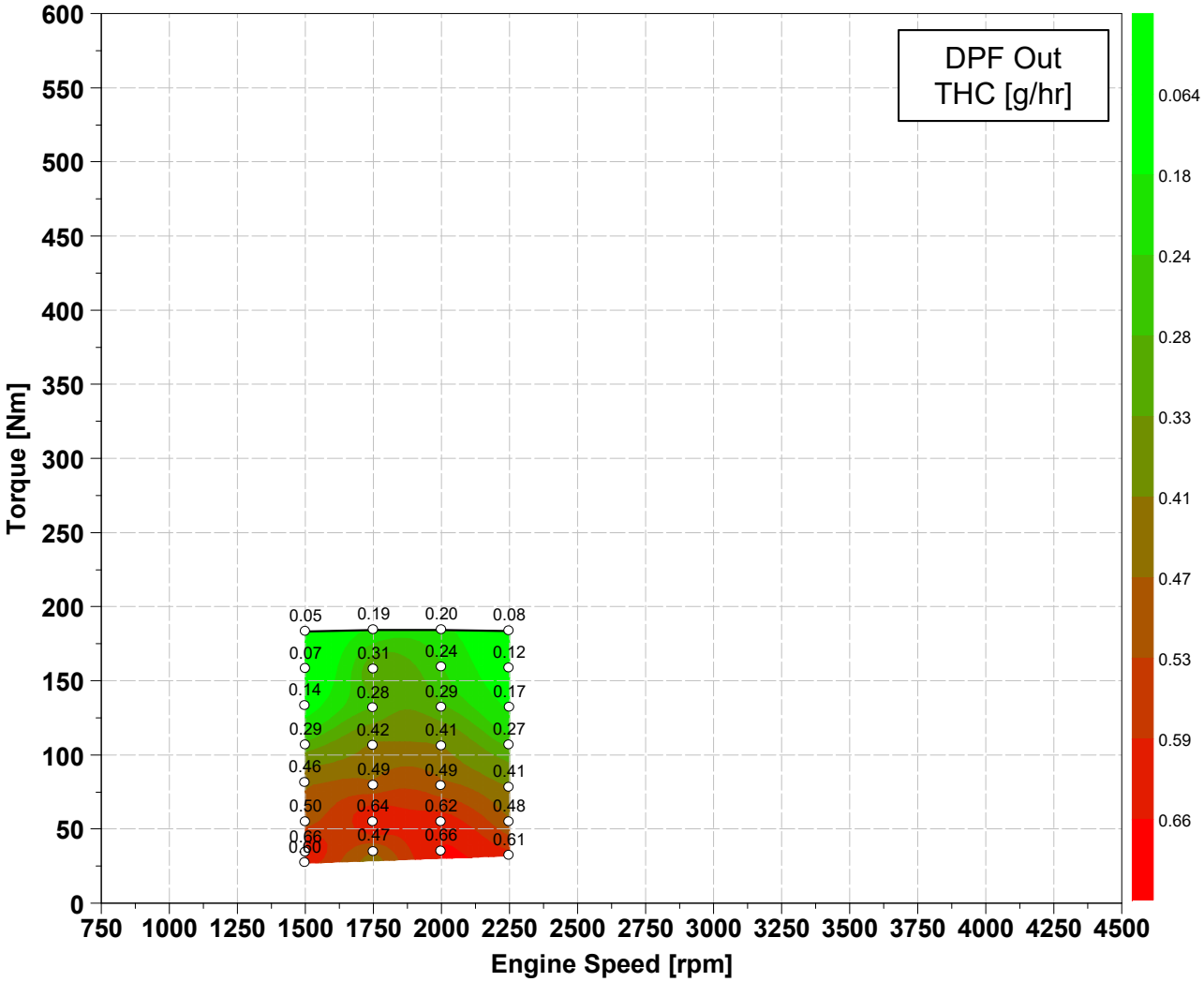
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- The highest THC emissions were from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm and were typically lower at low loads on the engine map.
- THC mass flow was calculated assuming all exhaust THC species were propane.

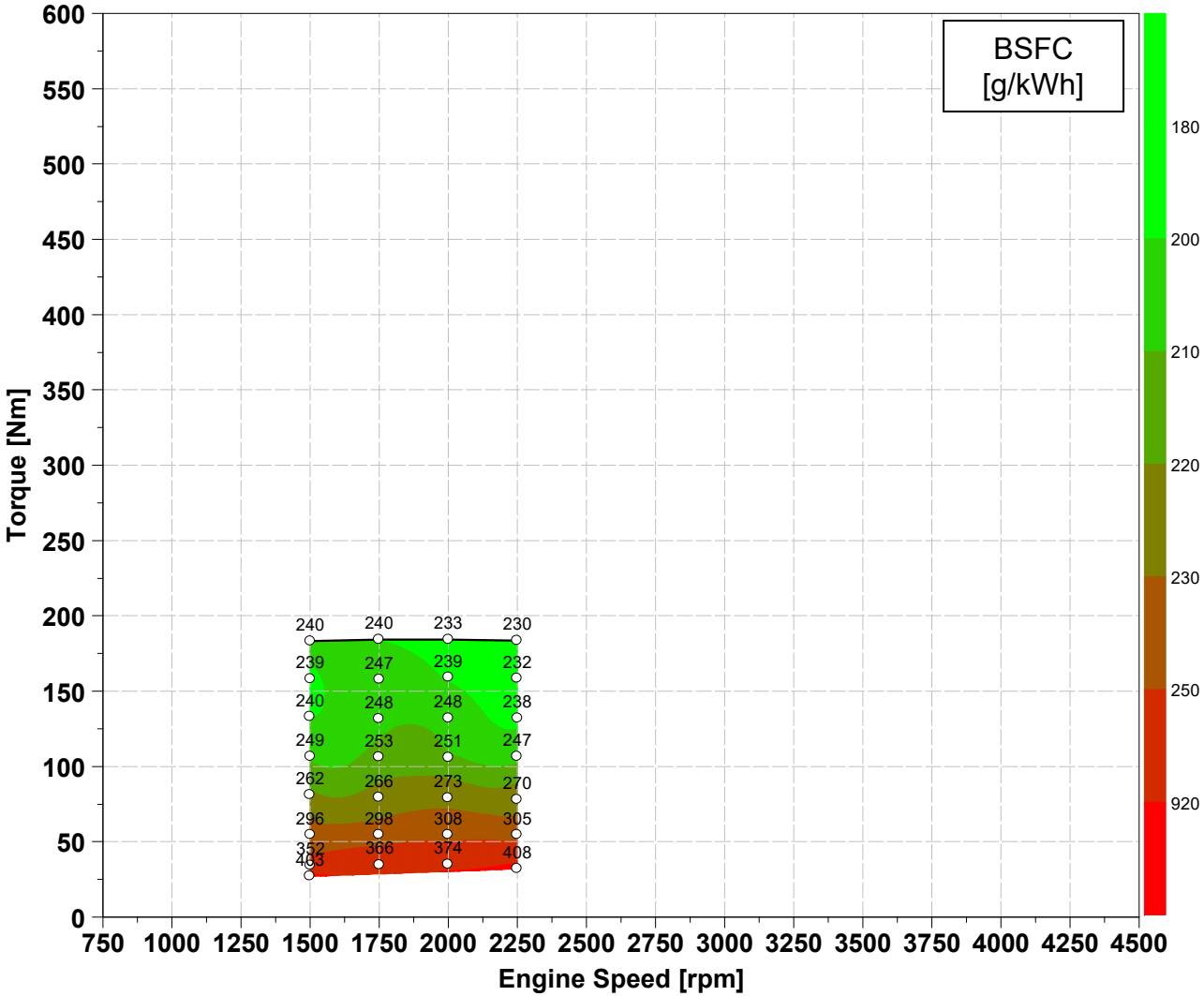
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- The tailpipe THC was less than 1 g/hr throughout the entire engine map.
- THC mass flow was calculated assuming all exhaust THC species were propane.

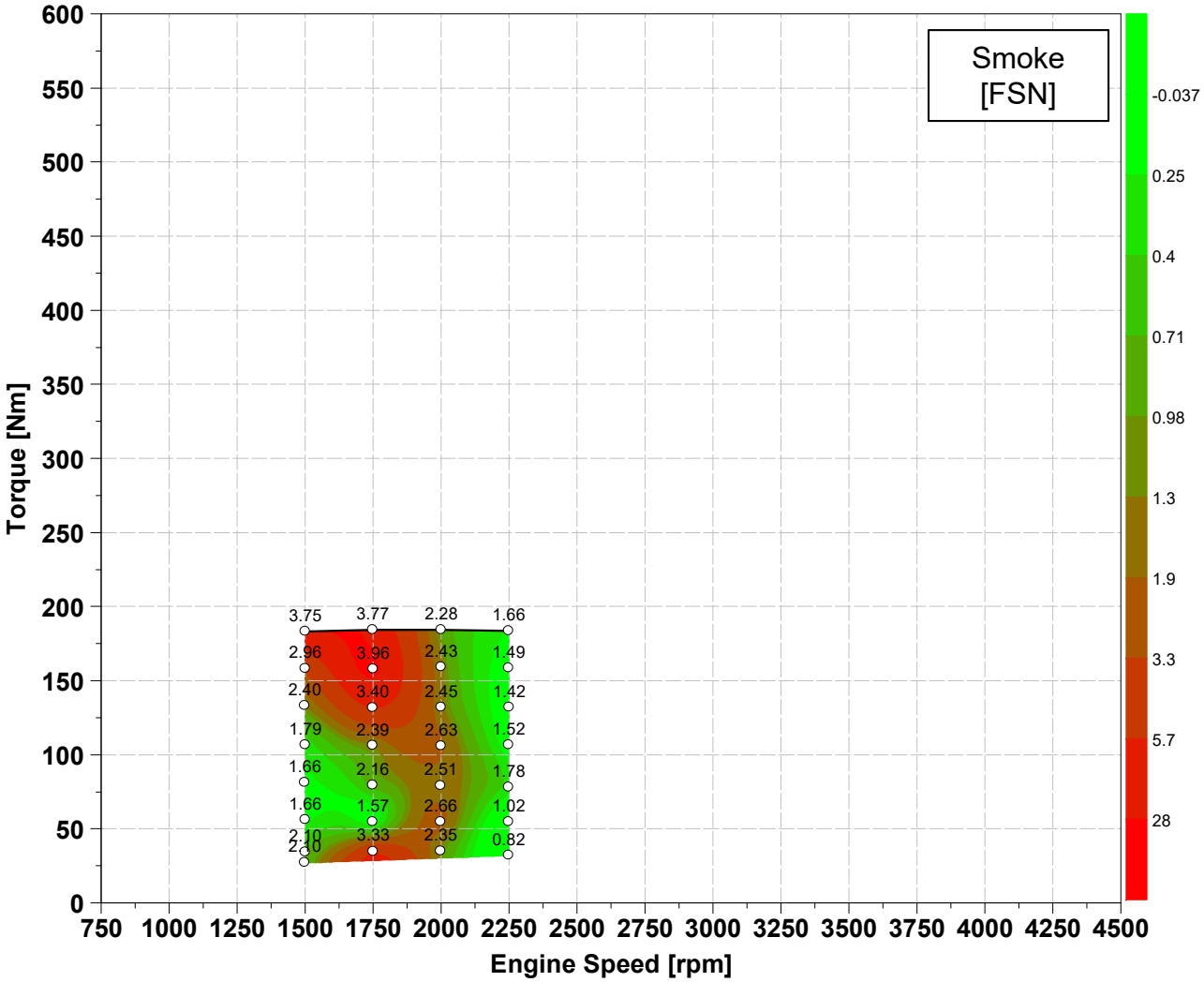
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- The BSFC began to decrease in as there were increases in load.
- Higher BSFC values were measured at low loads with values higher than 300 g/kWh.

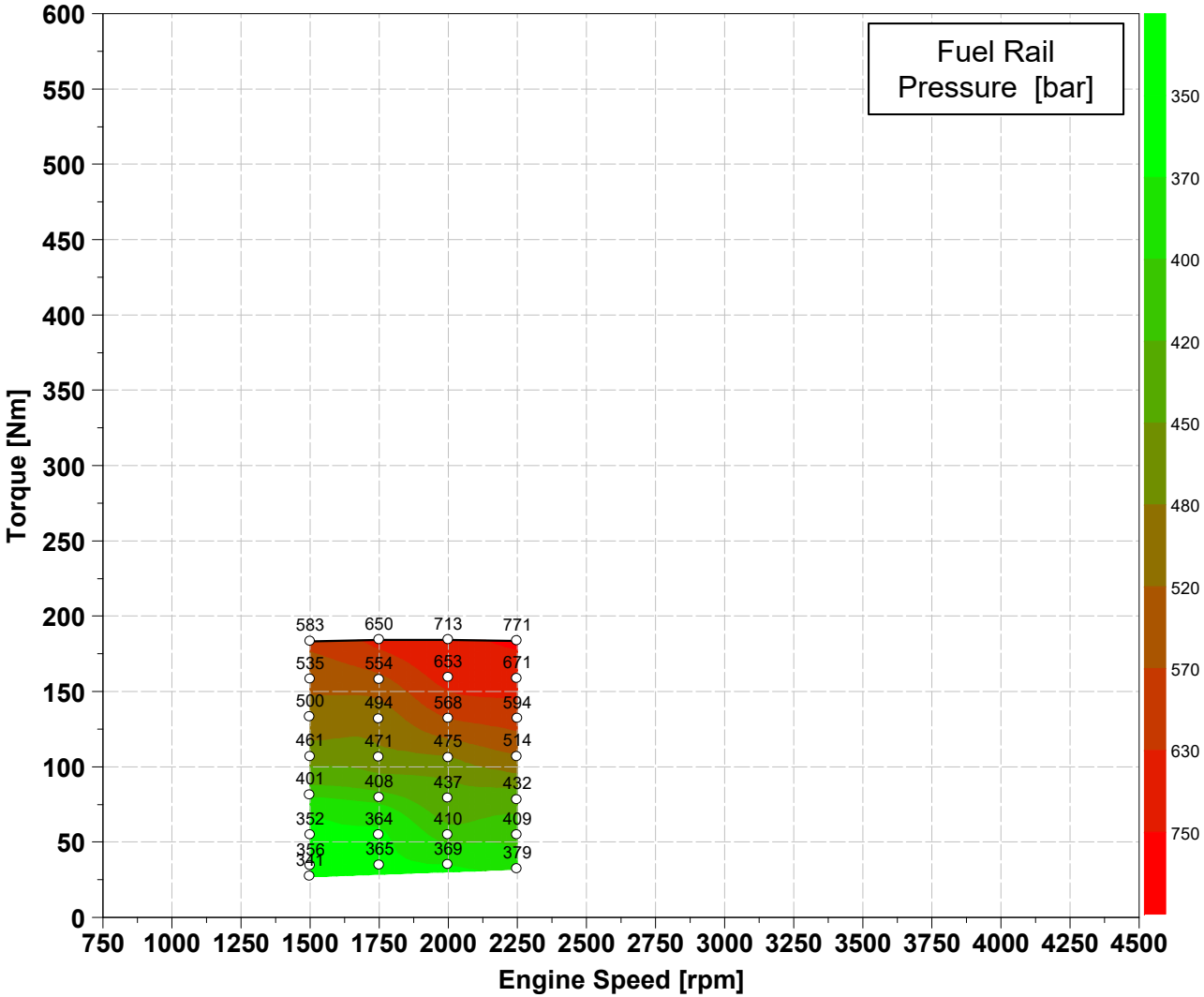
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- The engine out smoke was highest at 1750 rpm and 25 Nm to 165 Nm with FSN values higher than 3.

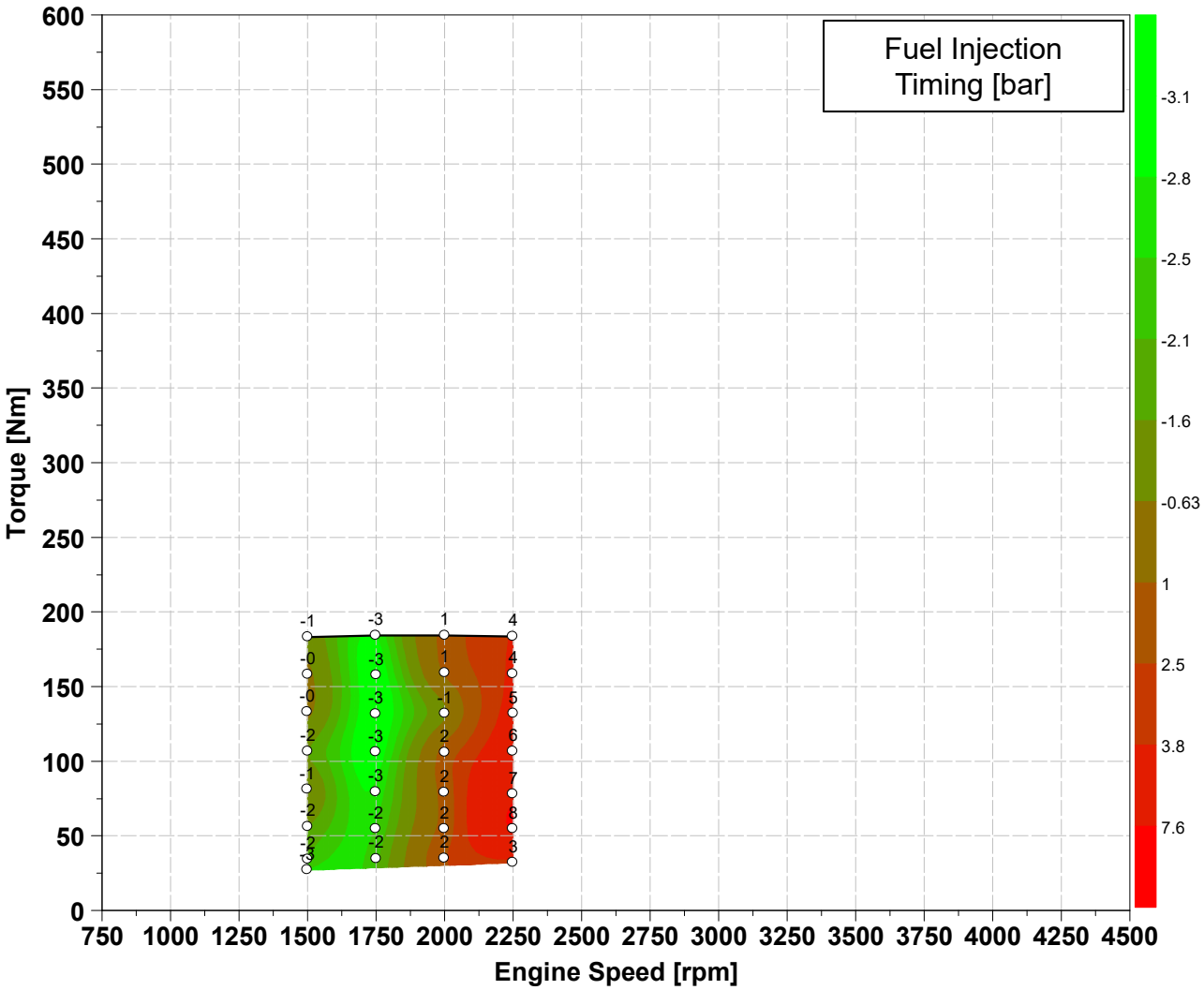
FEV Benchmarking
BMW X5d 35d: EGR Mapping



Comment

- The fuel rail pressure is in the range of 300 – 800 bar
- The fuel rail pressure increases proportionately to the increase in power on the engine map

FEV Benchmarking
BMW X5d 35d: EGR Mapping



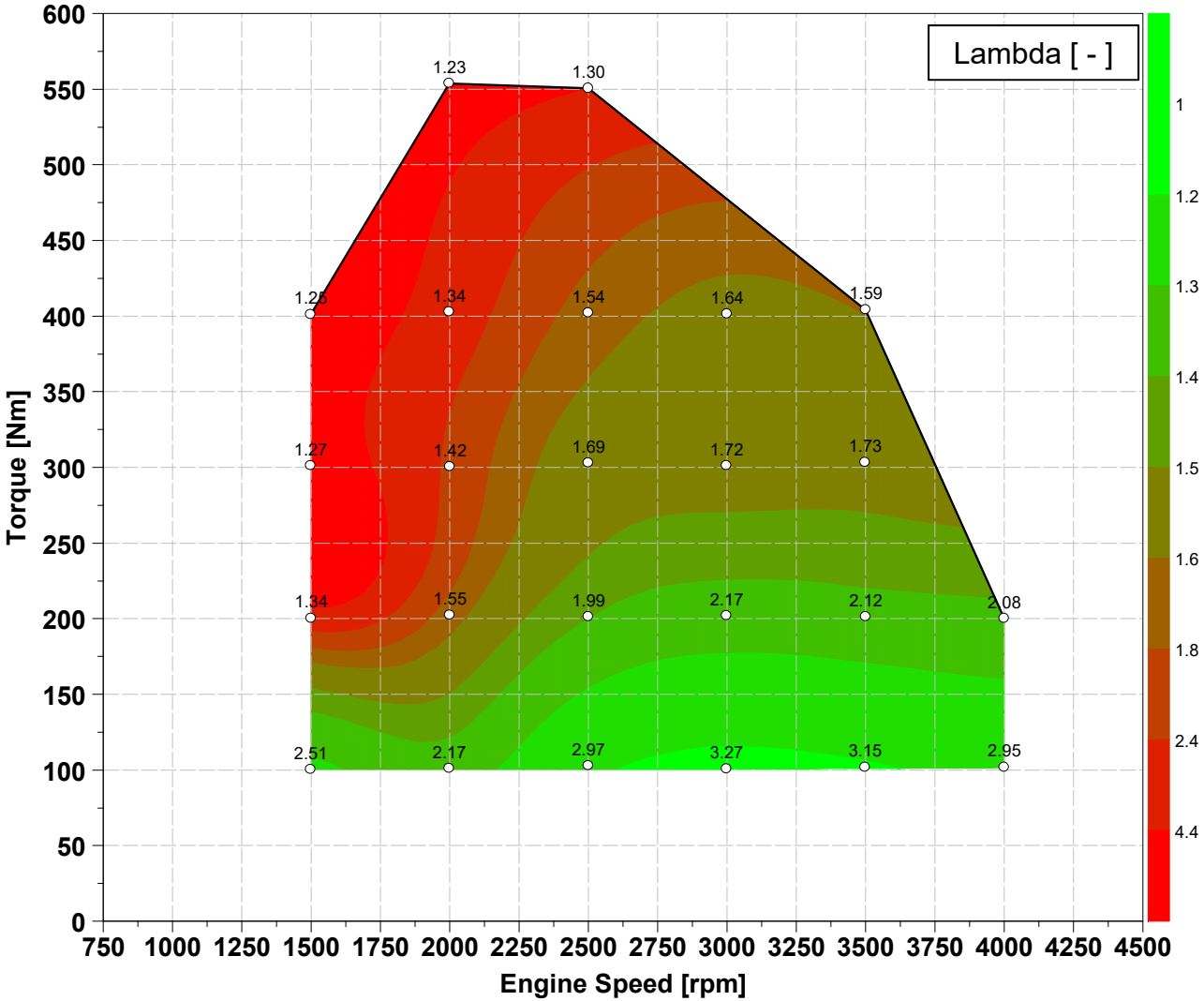
Comment

- The engine fuel injection timing was delayed with increase in speed

Agenda

- Introduction
- Vehicle Break In
- DPF Regeneration Interval Investigation
- Engine Mapping
- EGR Mapping
- Urea Course Engine Mapping
- Continuous Data
- ASCMO Simulations
- Conclusion

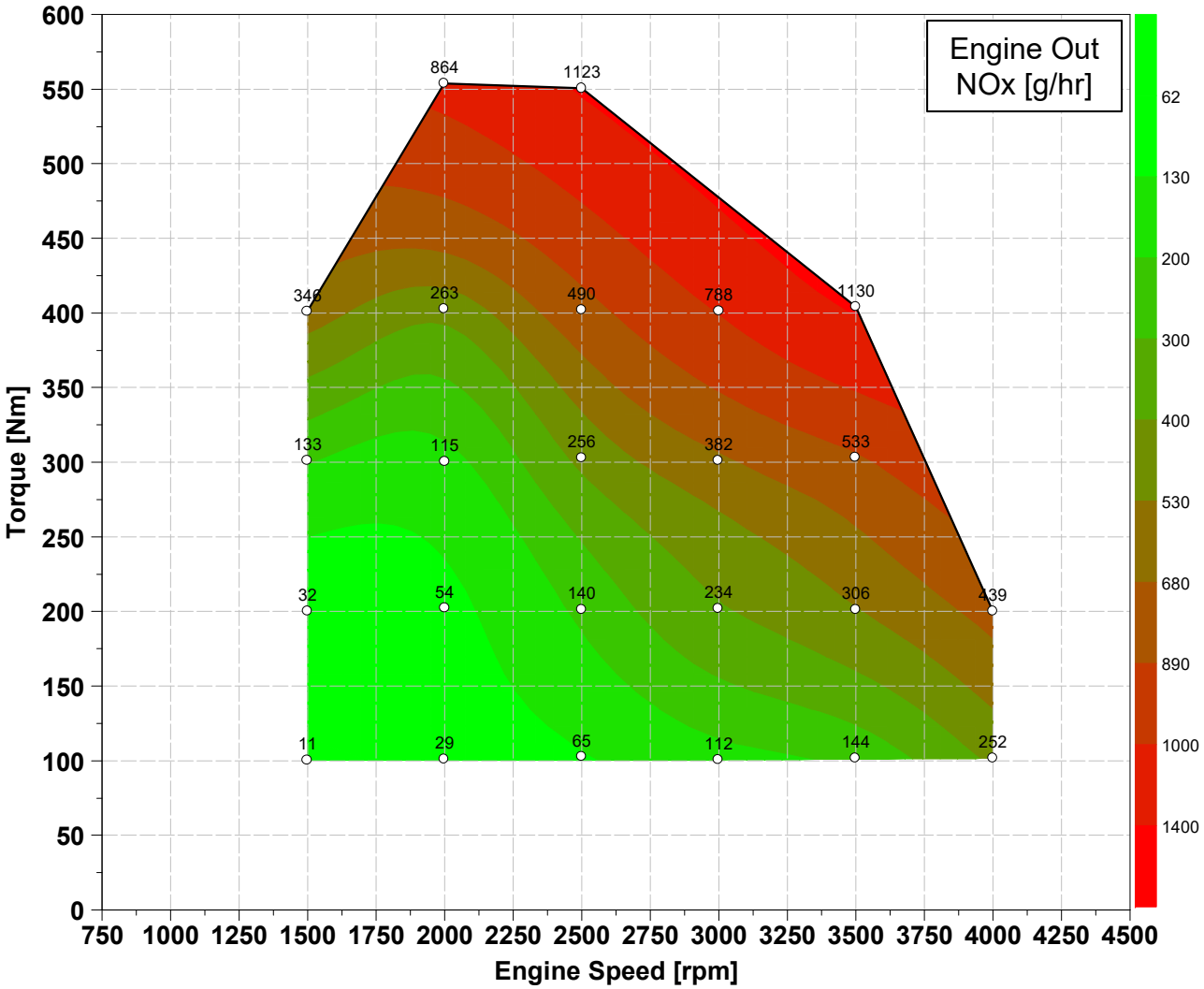
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Lambda values were 1.2 – 3 with leaner values, approximately 3, at low loads.

FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map

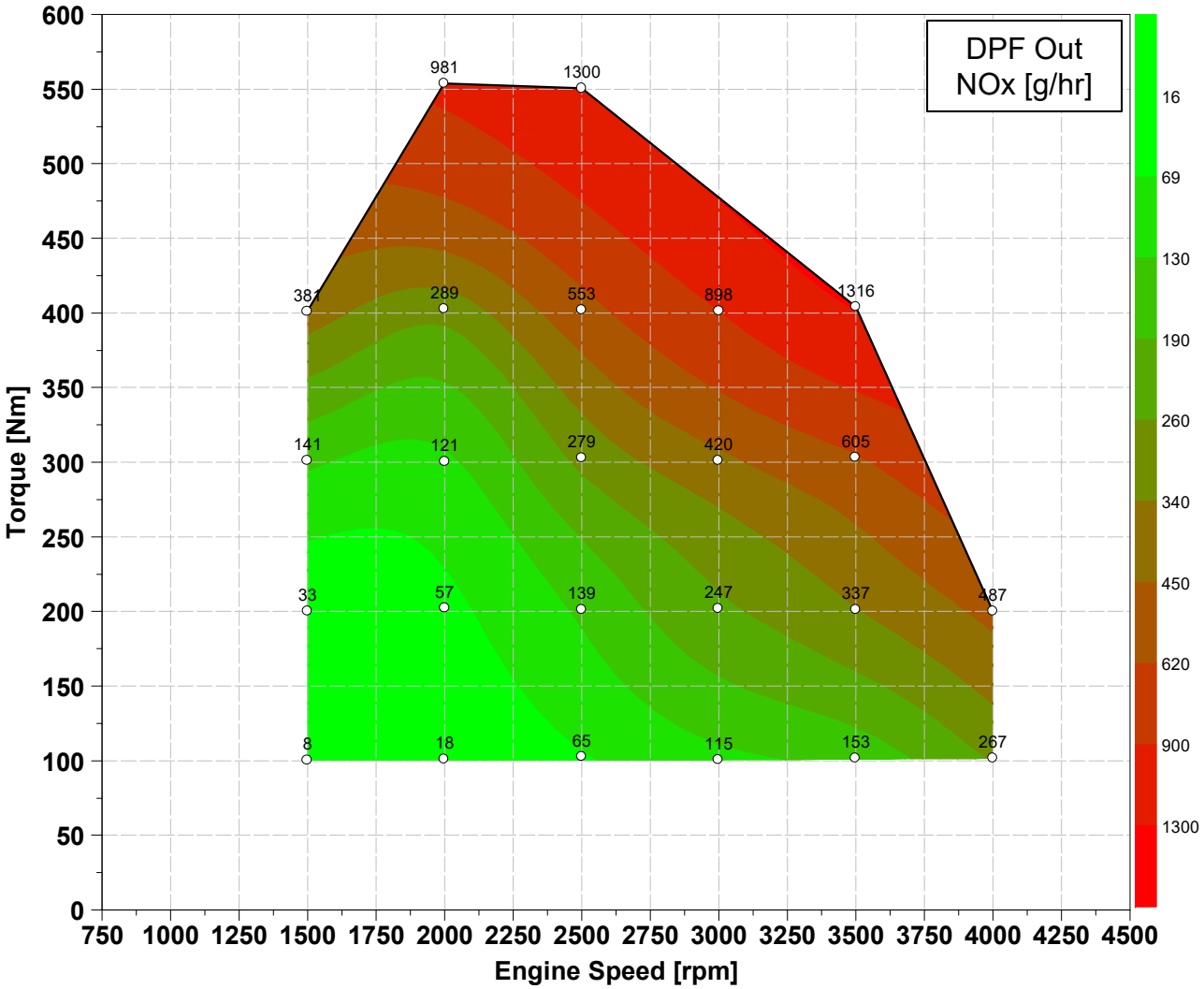


*calculated from E-bench

Comment

- Engine out NOx was relatively low between 1500 rpm and 2000 rpm and 100 Nm to 200 Nm below approximately 55 g/hr.
- Outside of this range the engine out NOx is much higher.
- The NOx emissions are more impacted by load than speed.

FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map

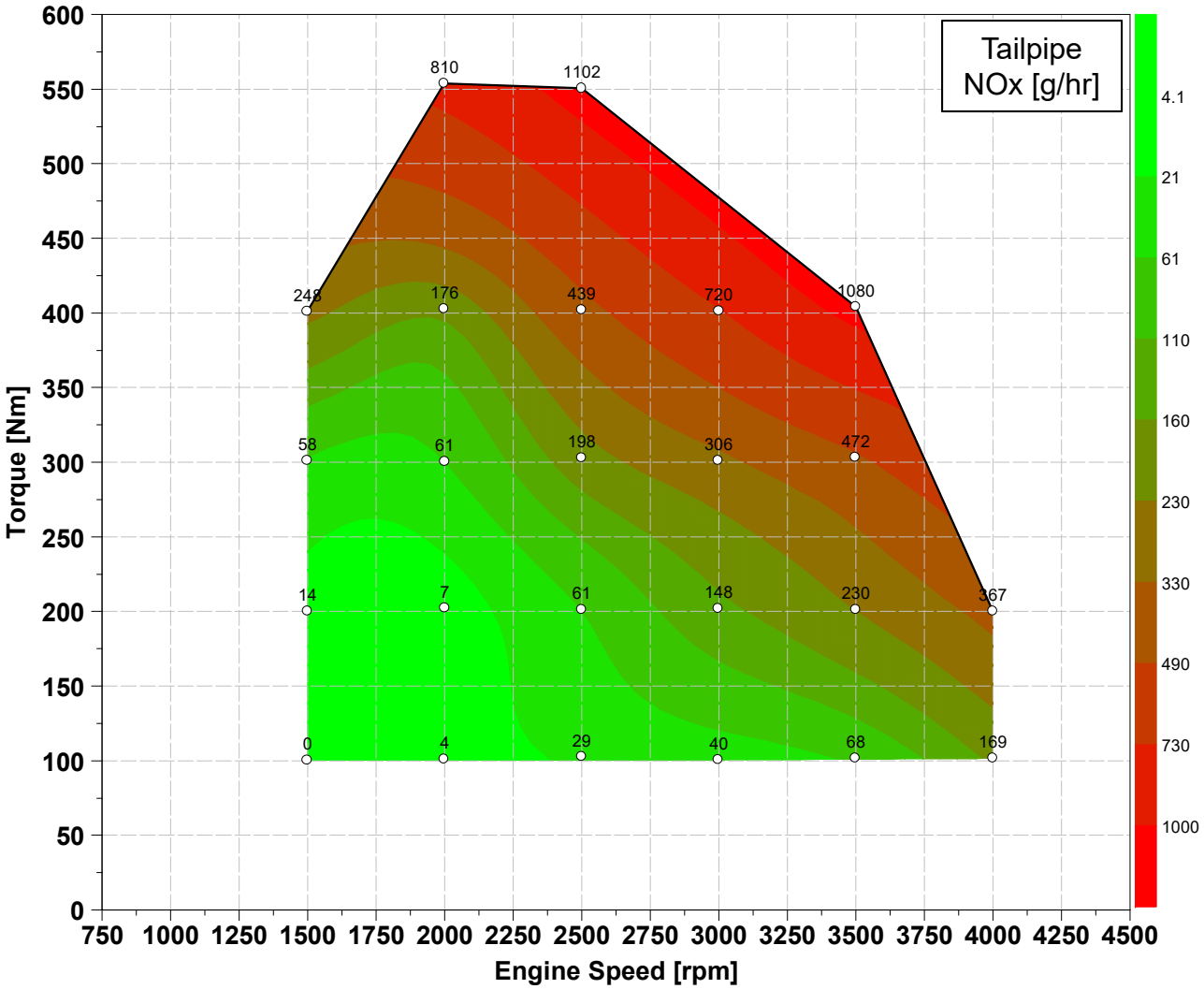


*calculated from on board NOx sensor

Comment

- DPF out NOx was relatively low between 1500 rpm and 2000 rpm and 100 Nm to 200 Nm.
- The NOx emissions are more impacted by load than speed.

FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map

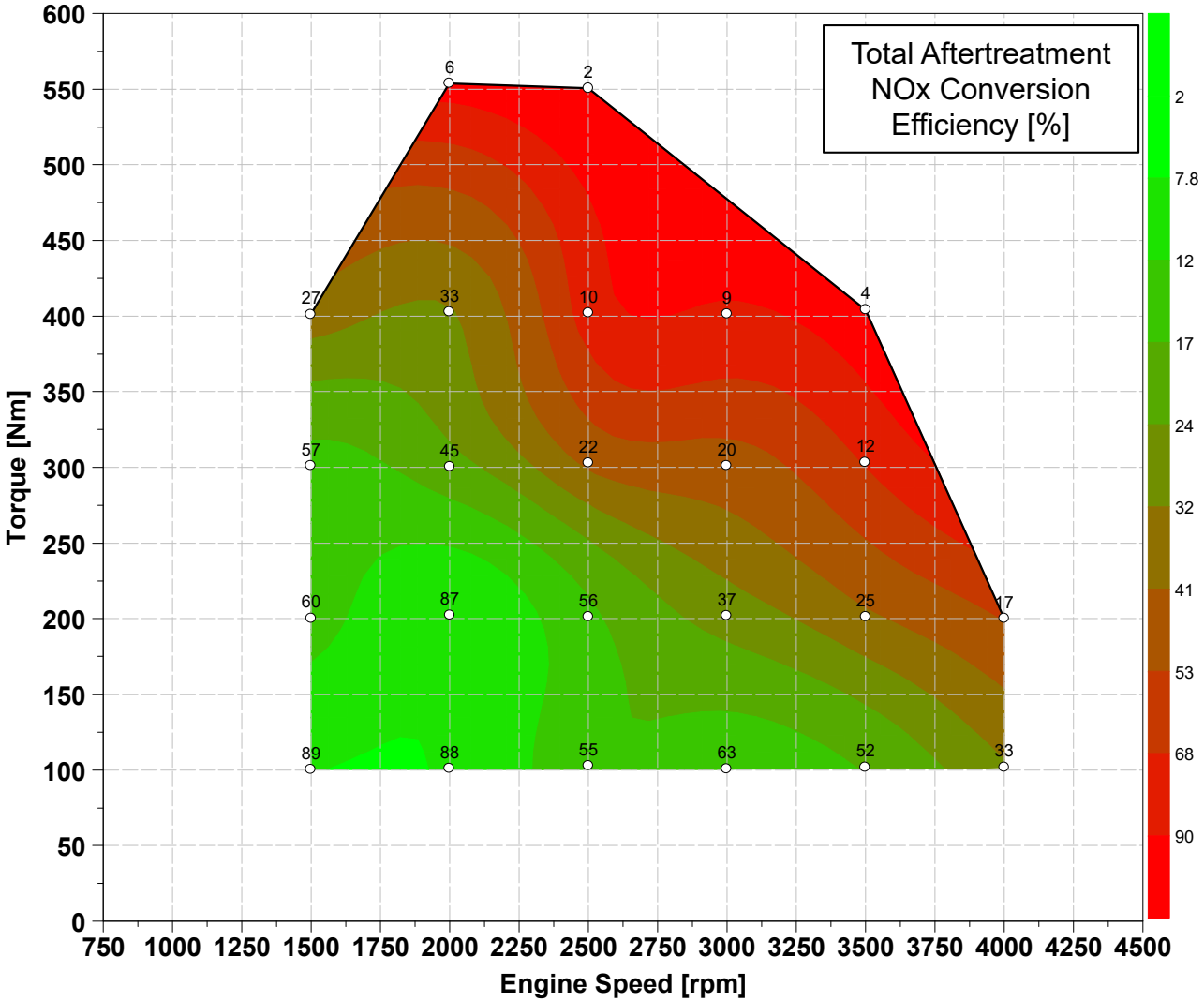


*calculated from E-bench

Comment

- The tailpipe NOx was significantly lower compared to engine out, less than 15 g/hr between 1500 rpm and 2000 rpm and 100 Nm to 200 Nm.

FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map

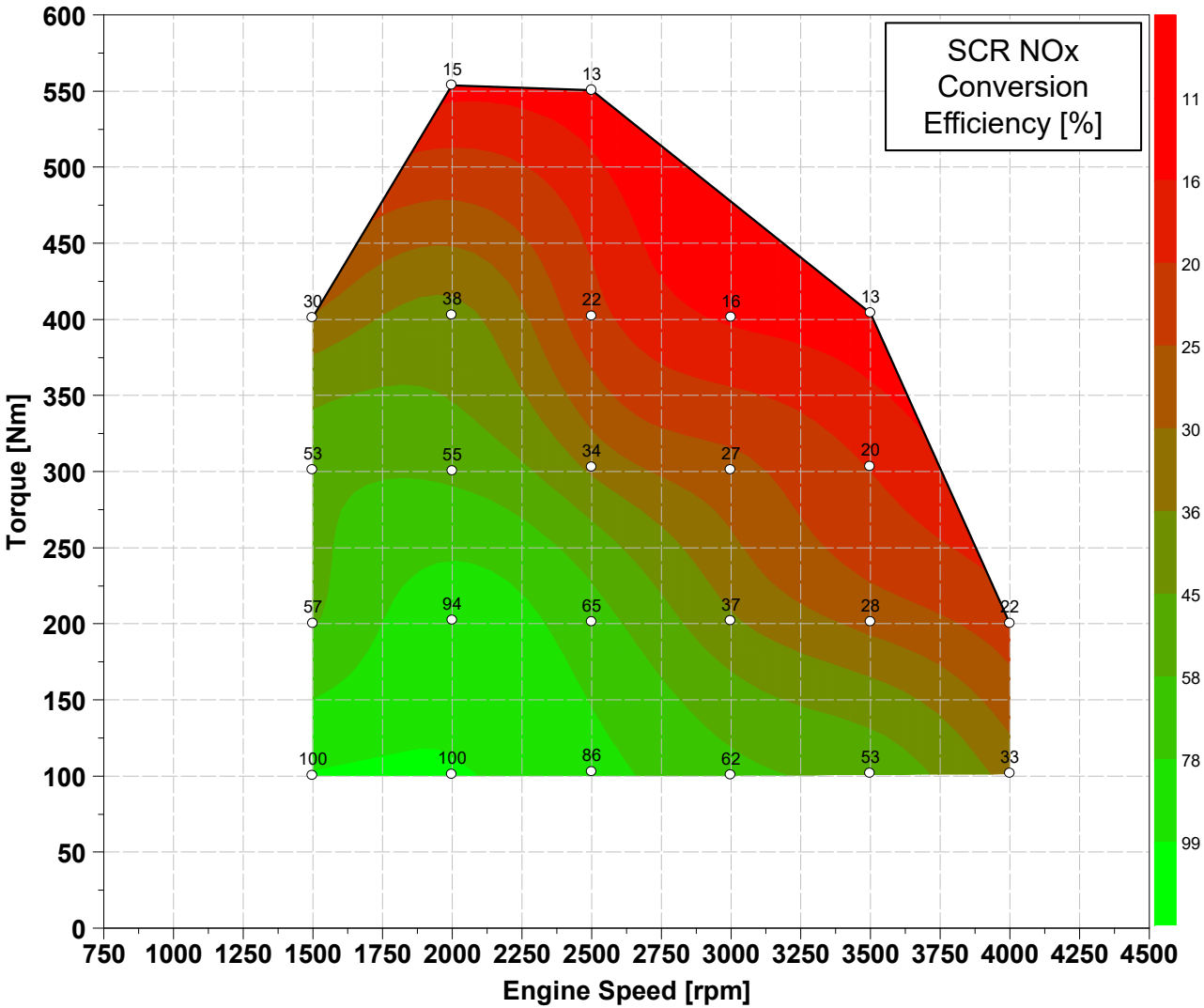


*calculated from E-bench

Comment

- The Total Aftertreatment (includes LNT and SCR) NOx conversion efficiency between 1500 rpm and 2000 rpm and 100 Nm to 200 Nm There were significant decreases in NOx conversion efficiency with increase in load.
- Total Aftertreatment NOx conversion efficiency was determined using an emissions bench at the engine out location and tailpipe, respectively.

FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map

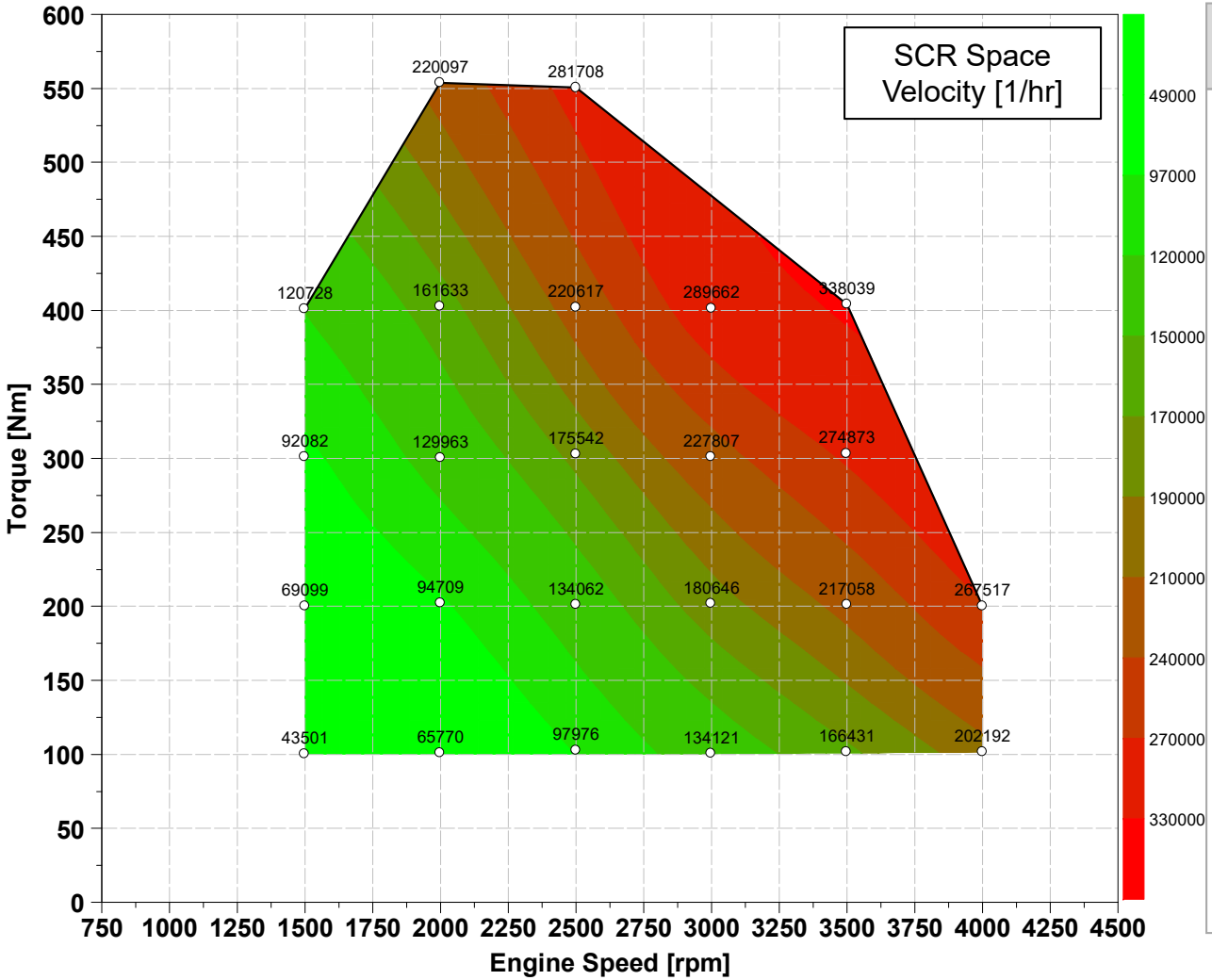


*calculated from on board NOx sensor

Comment

- The SCR NOx conversion efficiency was most efficient in low between 1500 rpm and 2000 rpm and 100 Nm to 200 Nm reaching 100% NOx conversion efficiency at some points.
- High load and speed areas on the map the ATS efficiency was lower than 20%.
- The SCR conversion efficiency was determined using the on board NOx sensors upstream and downstream of the SCR catalyst, respectively.

FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map

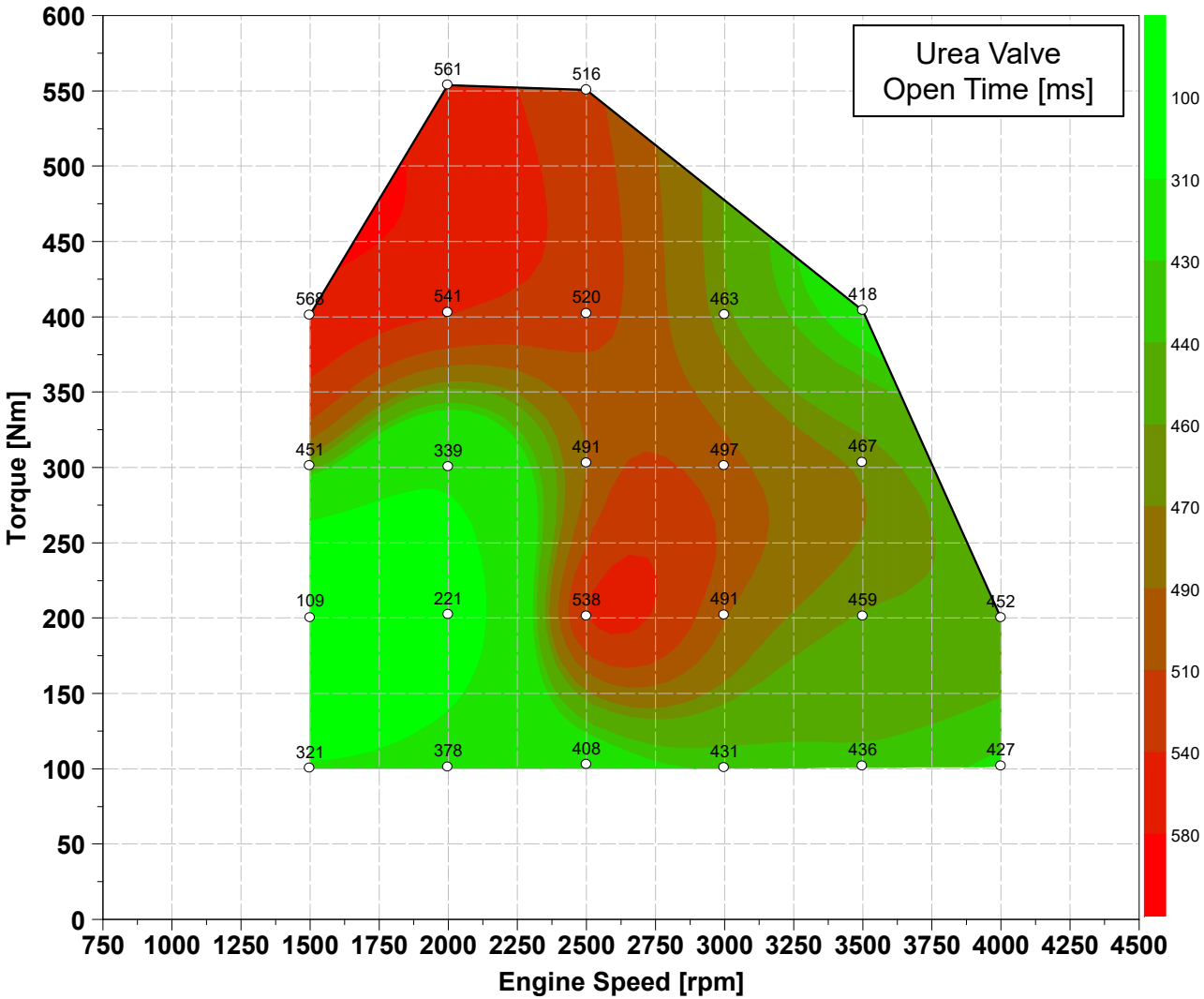


Comment

- The SCR space velocity was lowest from 1000 rpm to 2250 rpm and 25 Nm to 200 Nm.
- The space velocity value increased substantially at full load and peak power at 4000 rpm.

*calculated from on board NOx sensor

FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map

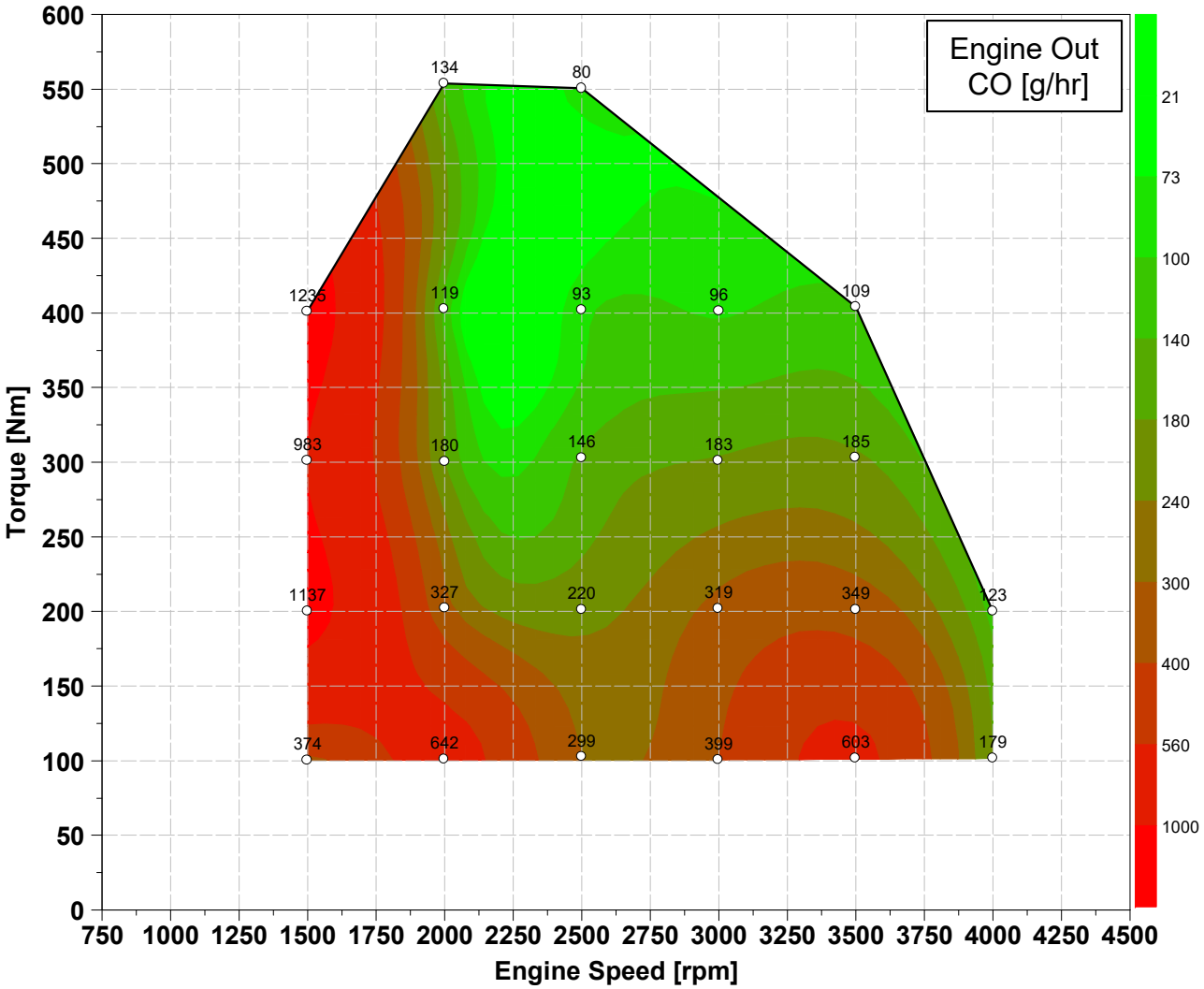


*calculated from on board NOx sensor

Comment

- The figure details how much time the urea dosing valve was open within in a 8,000 ms time frame.

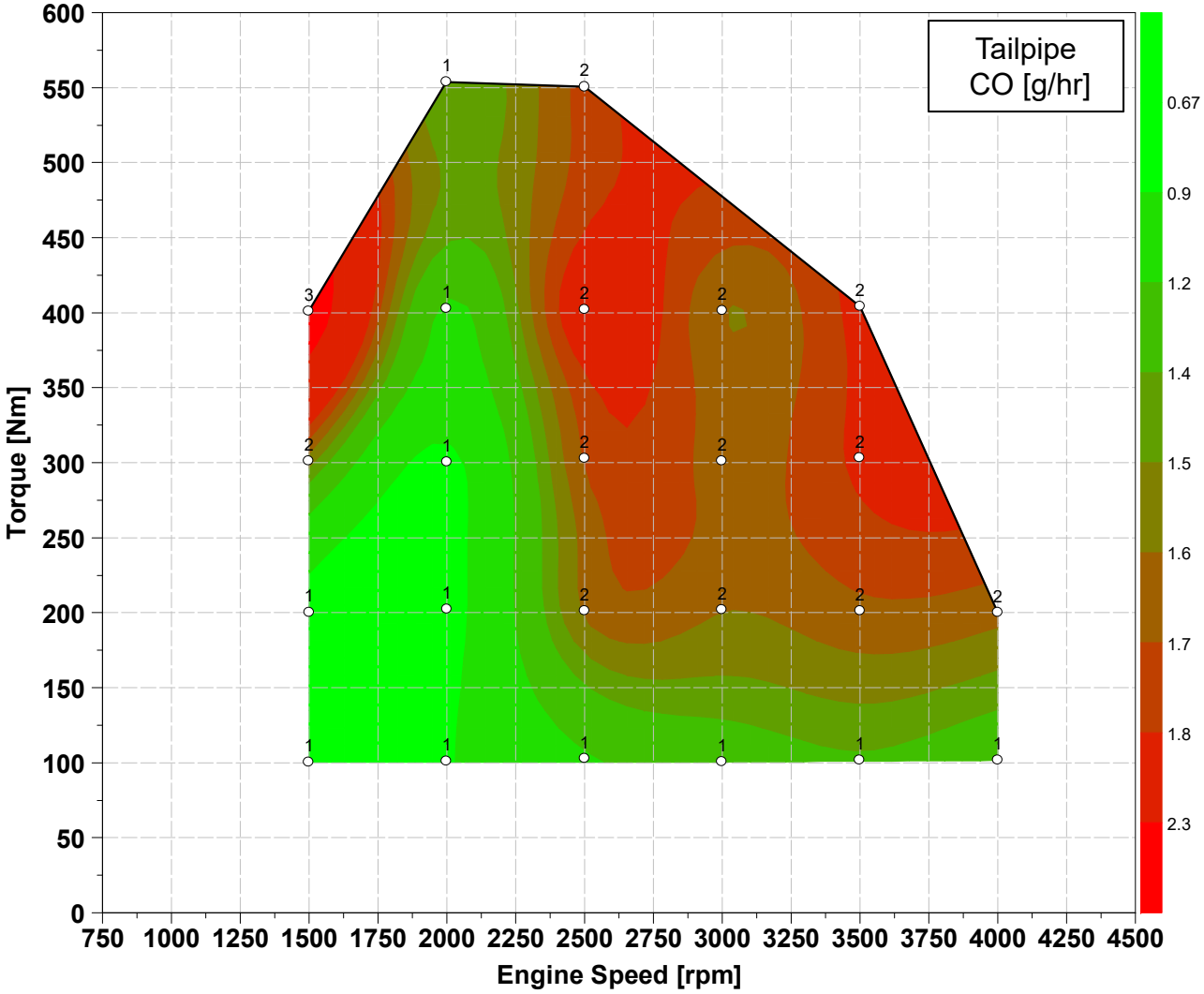
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Engine out CO emissions correlated with exhaust mass flow ass the value decreases with increase in flow.

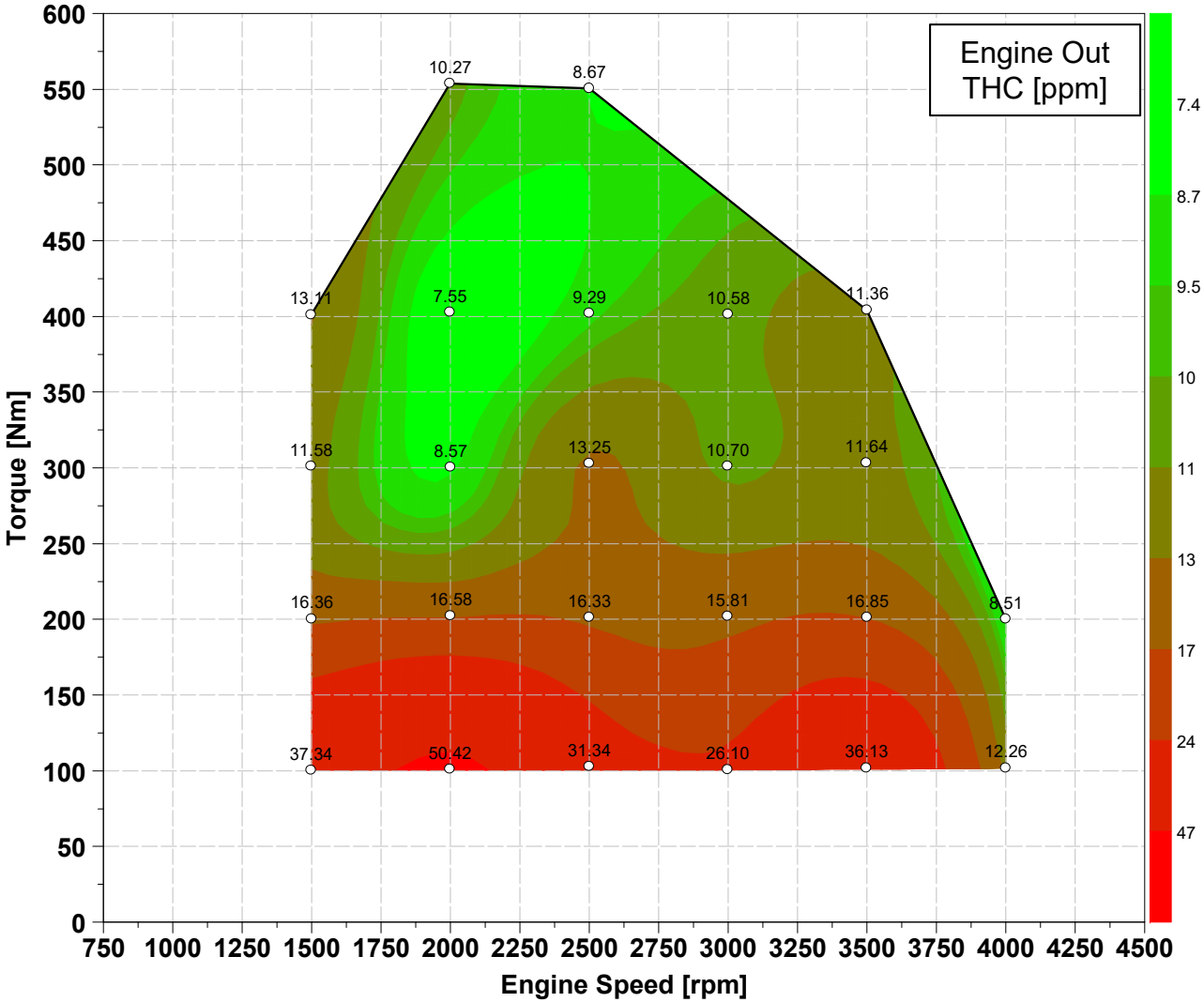
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Tailpipe out CO emissions were significantly lower, with values of 3 g/hr or less.

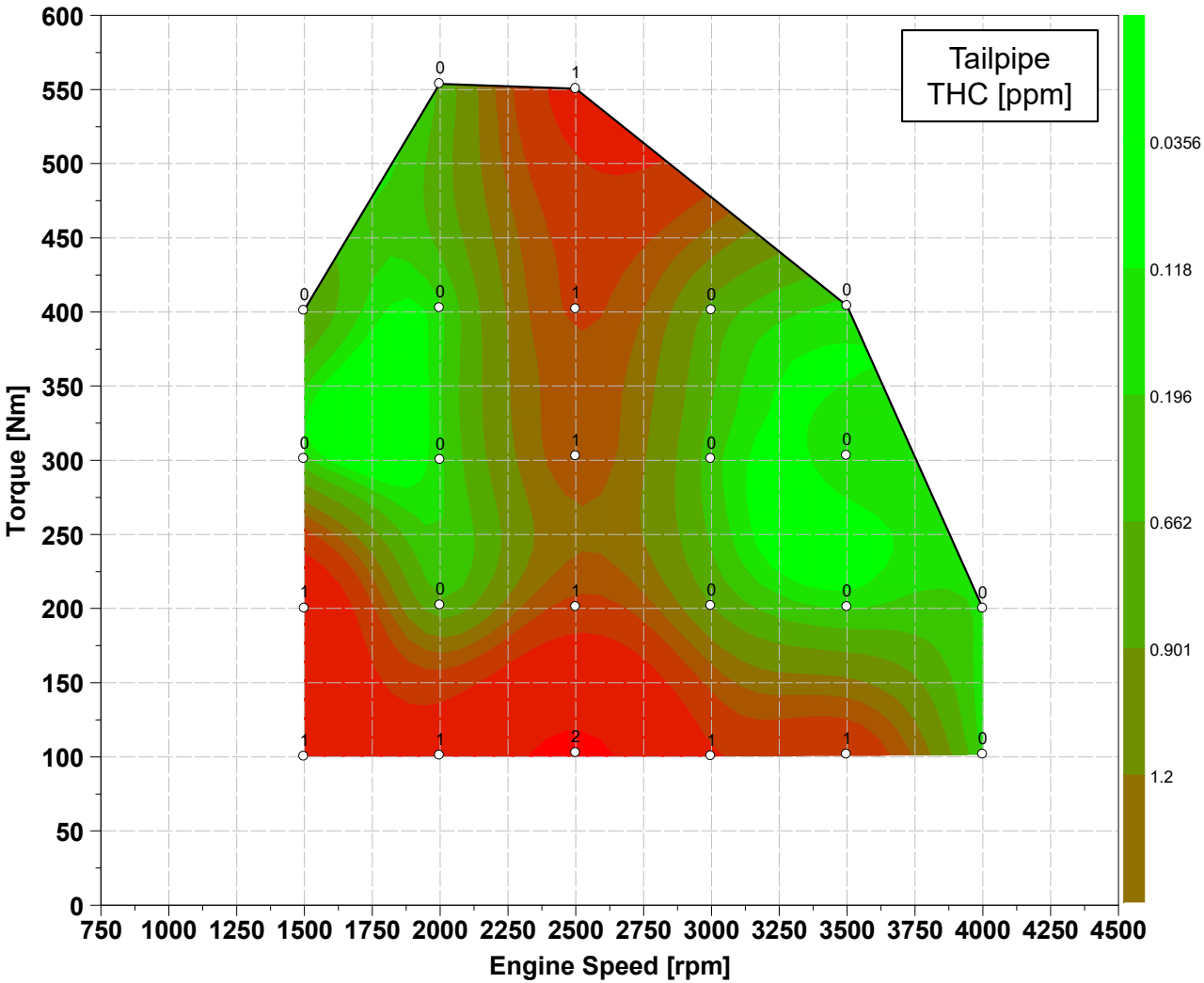
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- The highest THC emissions were at low loads of 100 Nm and began to decrease with increases in load.

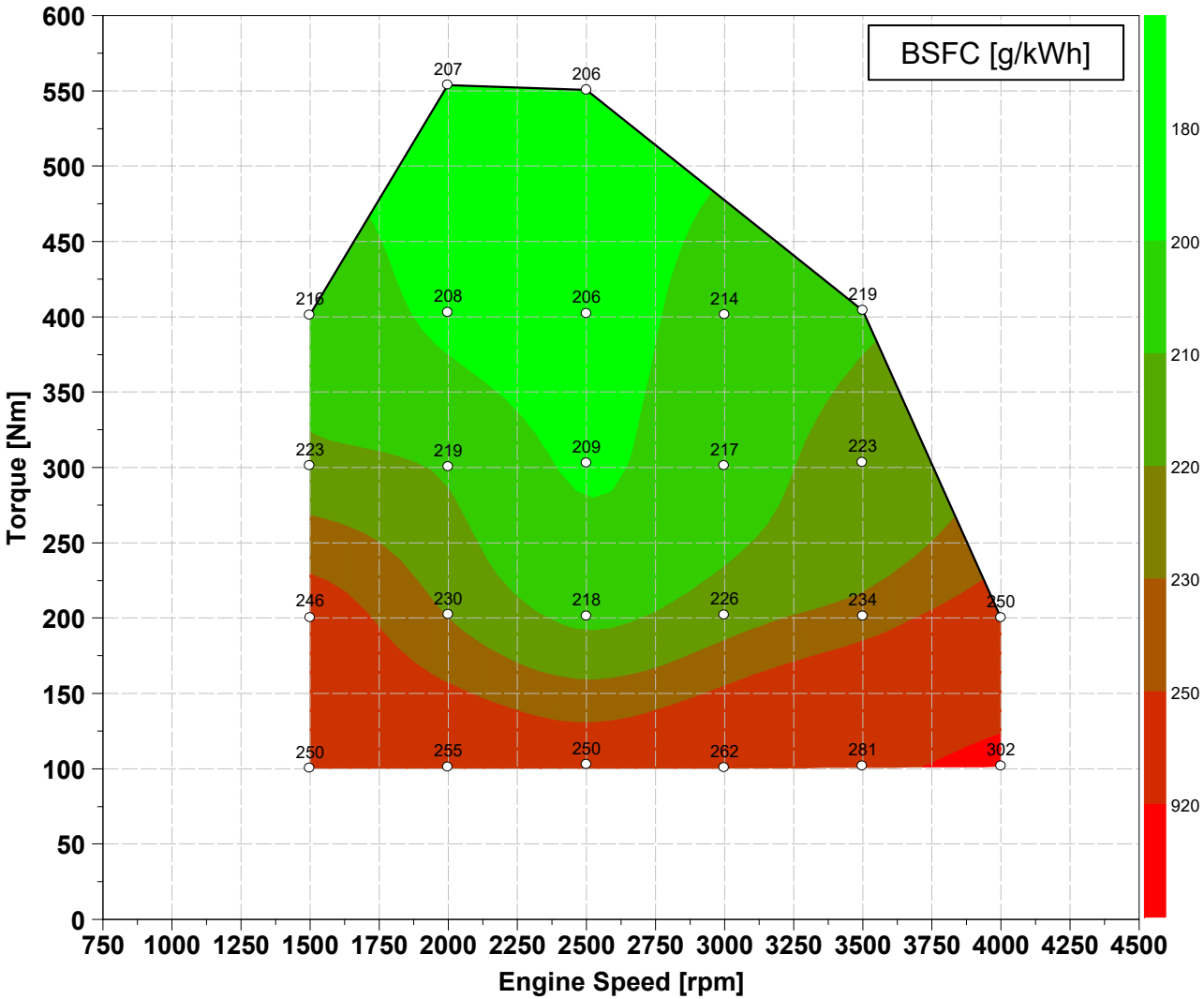
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- The tailpipe THC was less than 5 ppm for most points on the engine map, with the exception of a few outliers.

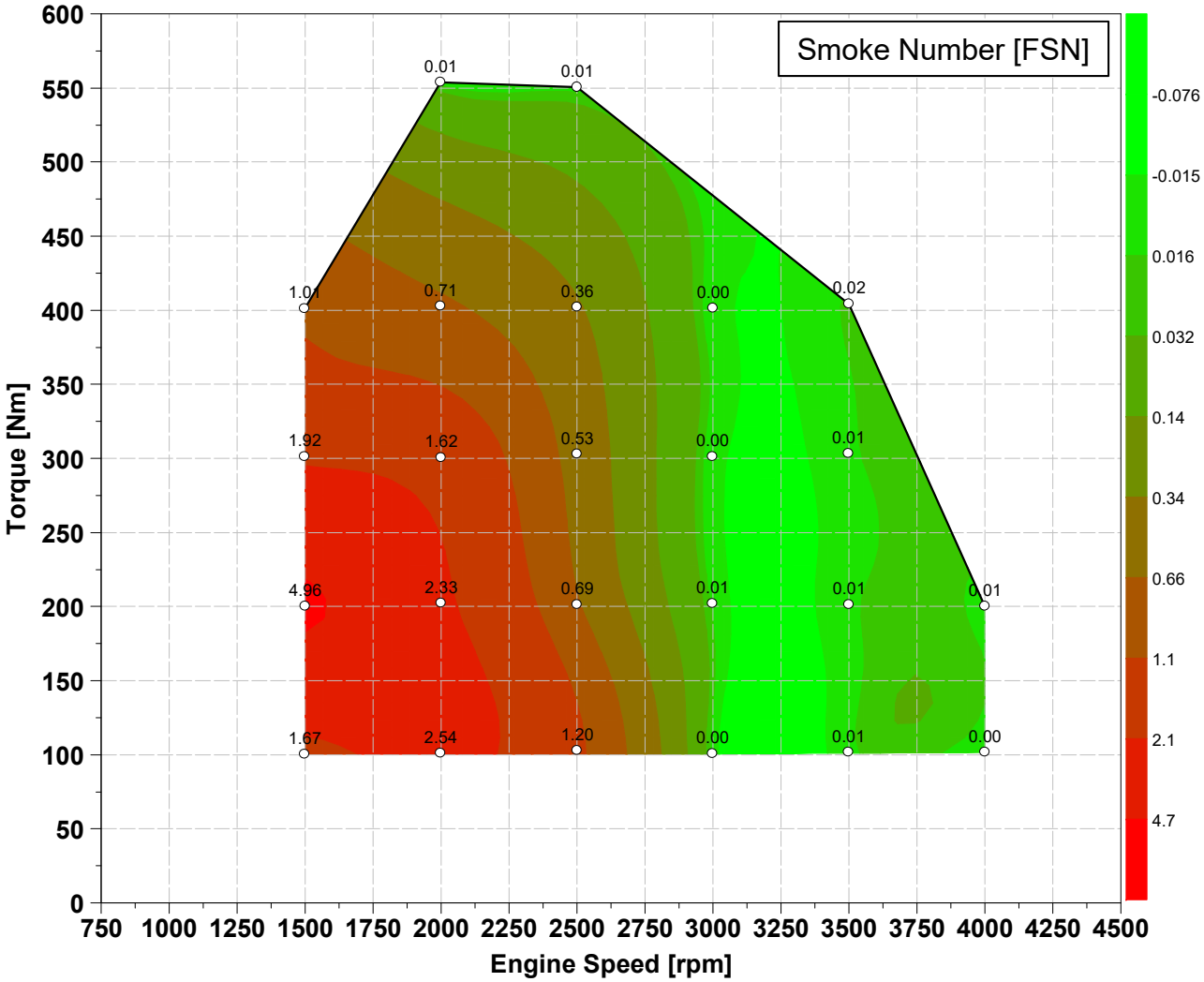
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- The BSFC began to decrease in as there were increases in load.
- The engine operating area consisted of BSFC values of approximately 240 g/kWh or higher.

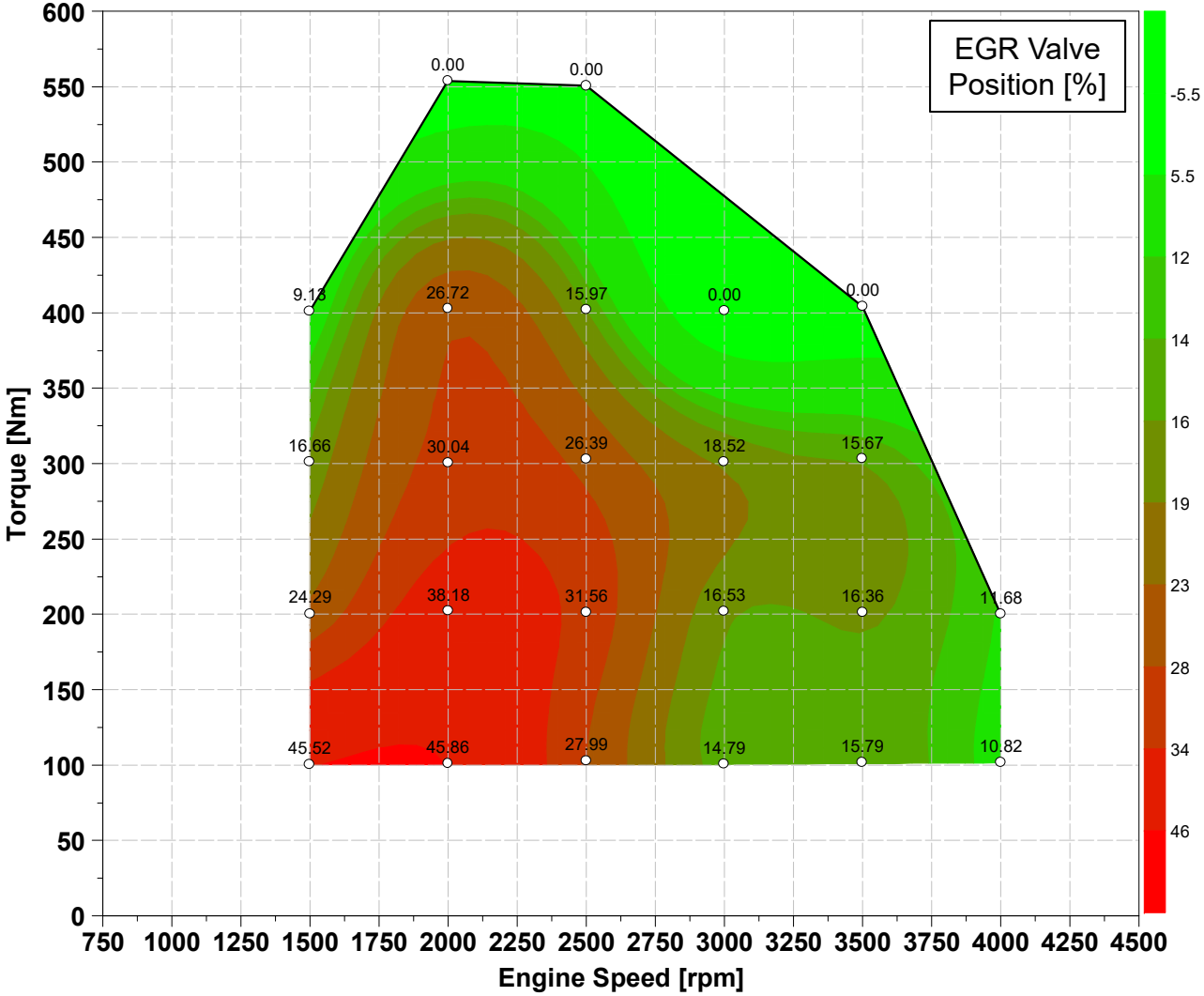
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Engine out smoke was higher in the low load ranges and significantly decrease with increases in sped and load.

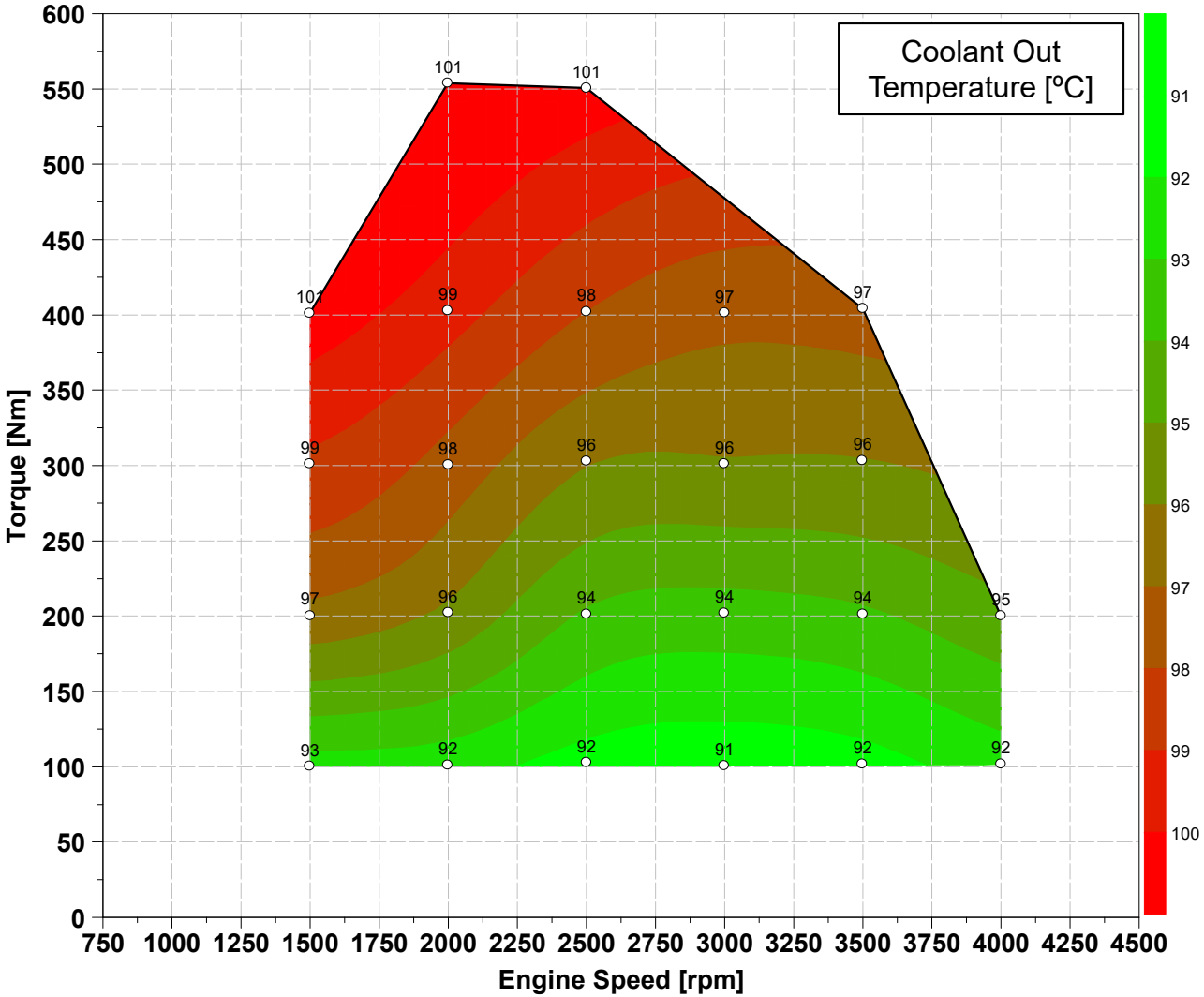
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- The EGR valve was position was open up to 45% within 1500 rpm and 2000 rpm and 100 Nm to 200 Nm and began to decrease with increases in speed and load.

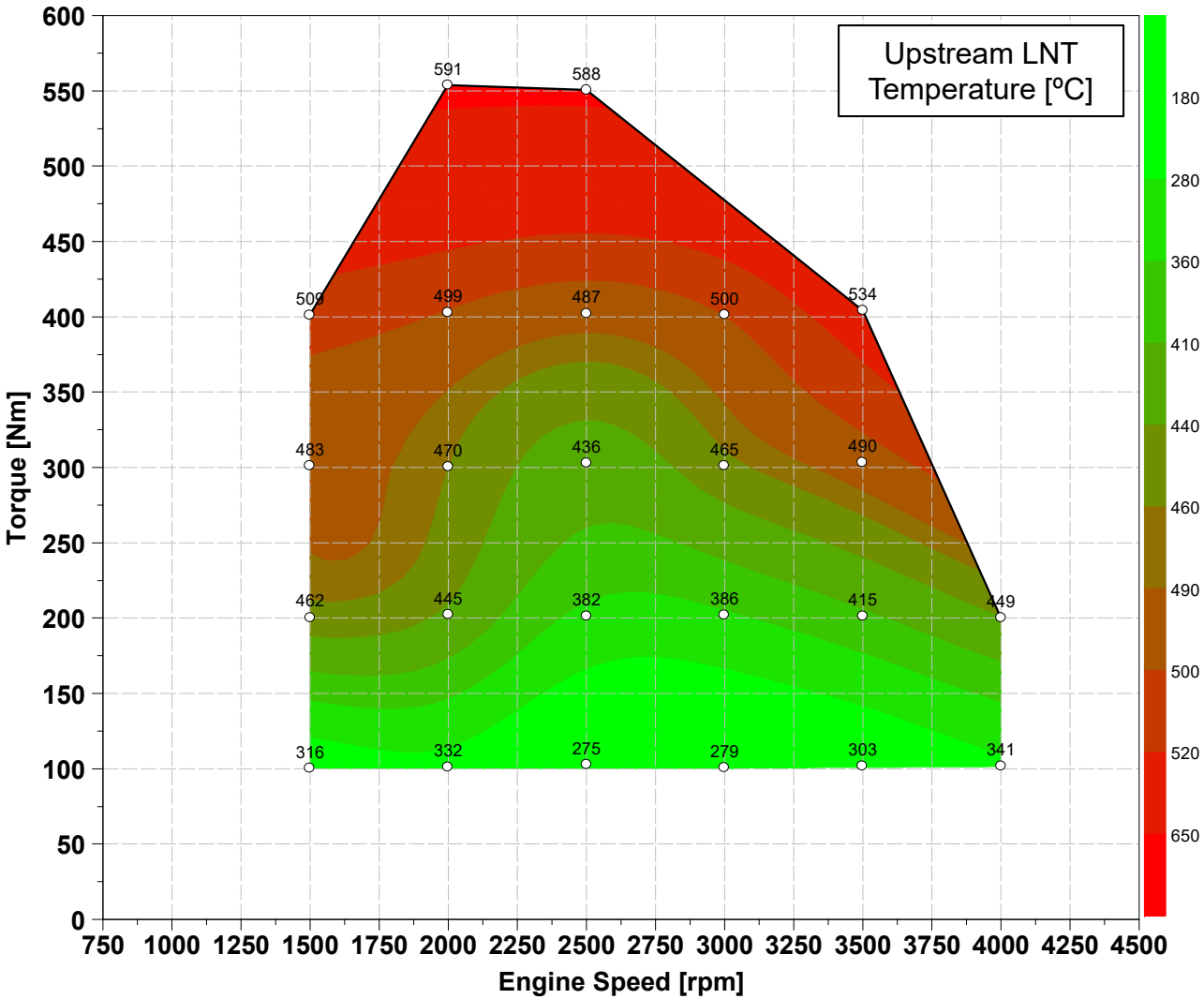
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- The coolant temperature increased with load from 90 ºC to 100 ºC.

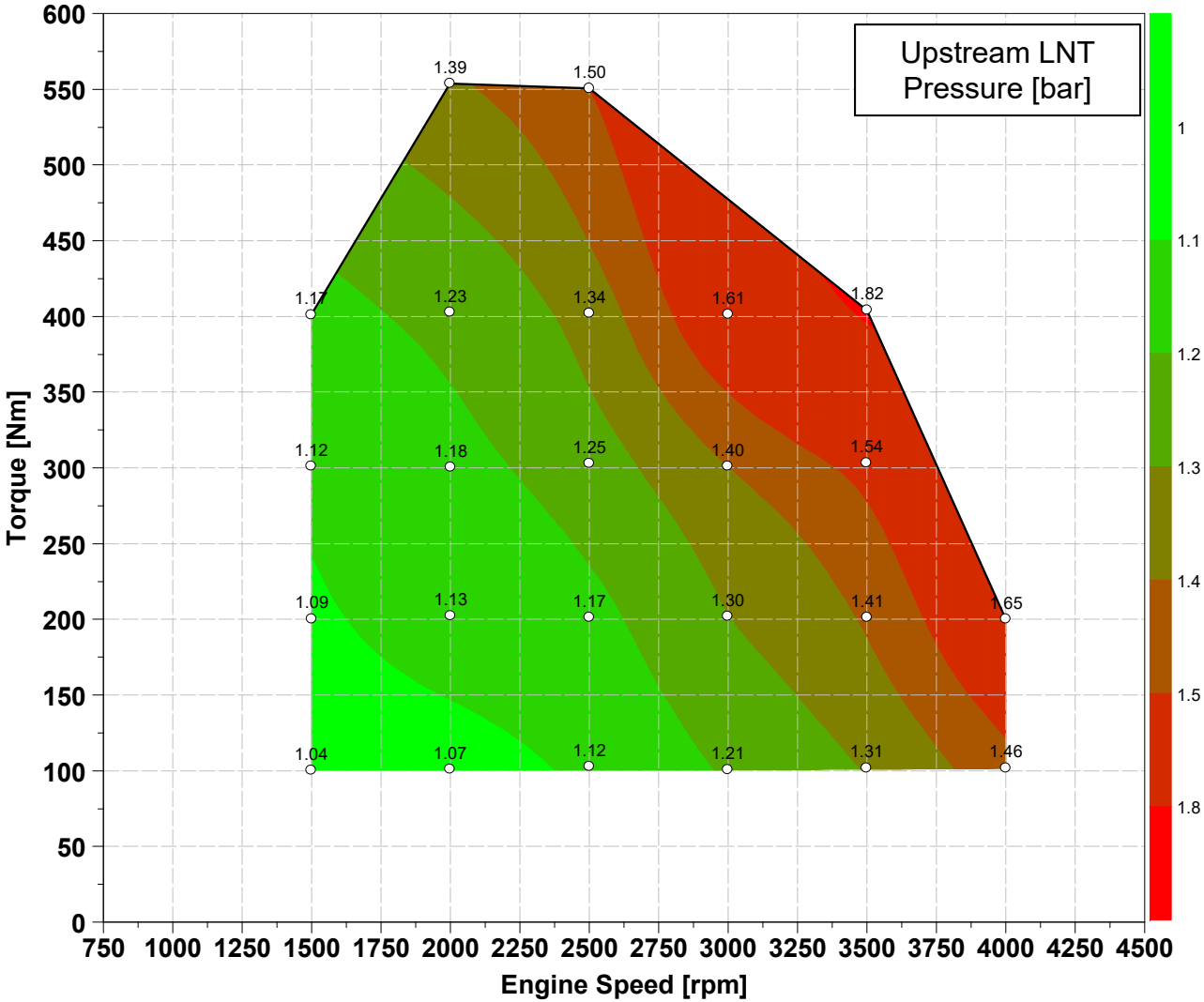
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Exhaust gas temperatures increased with load.

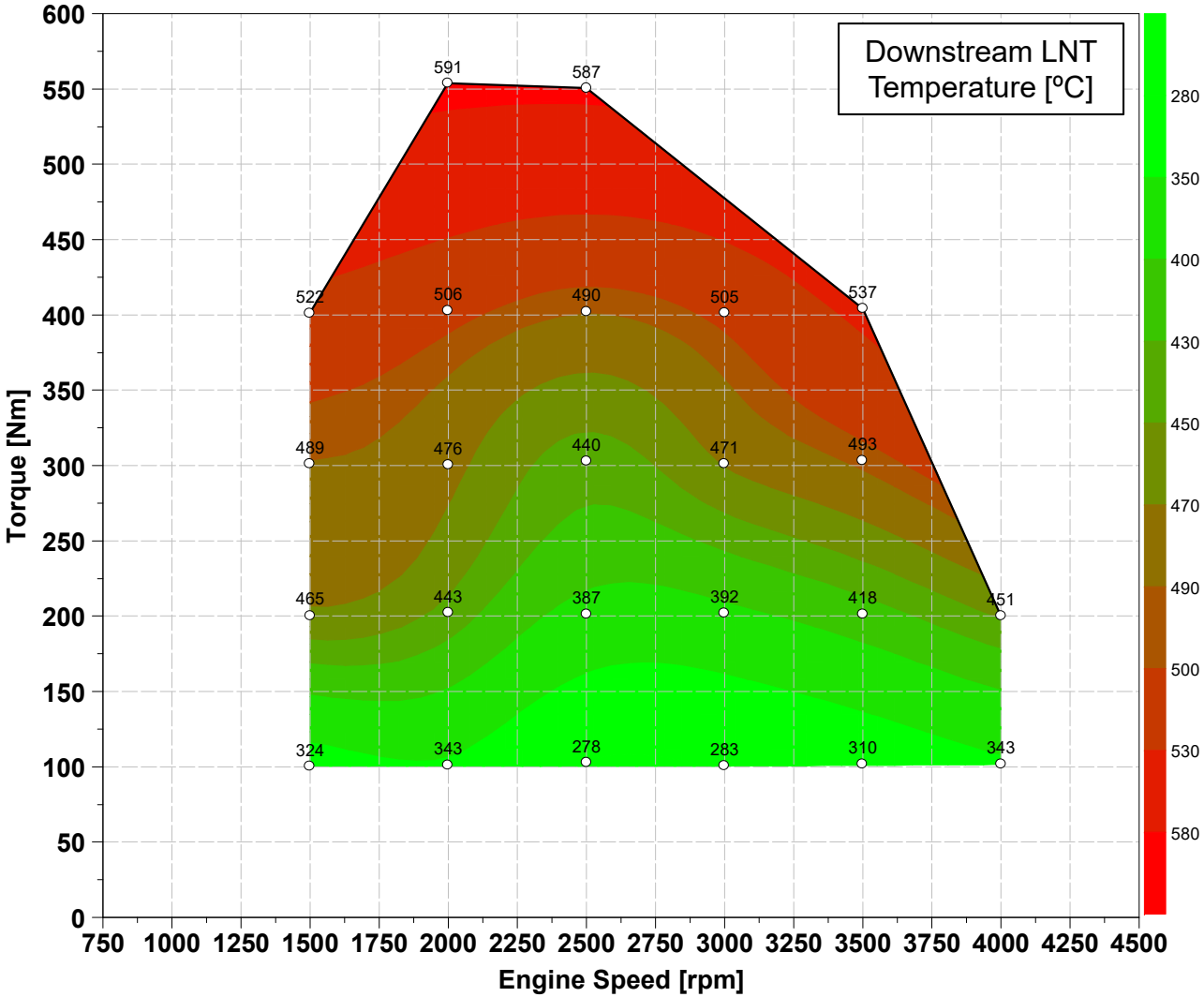
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Exhaust gas pressure at the engine out positions were more speed dependent.

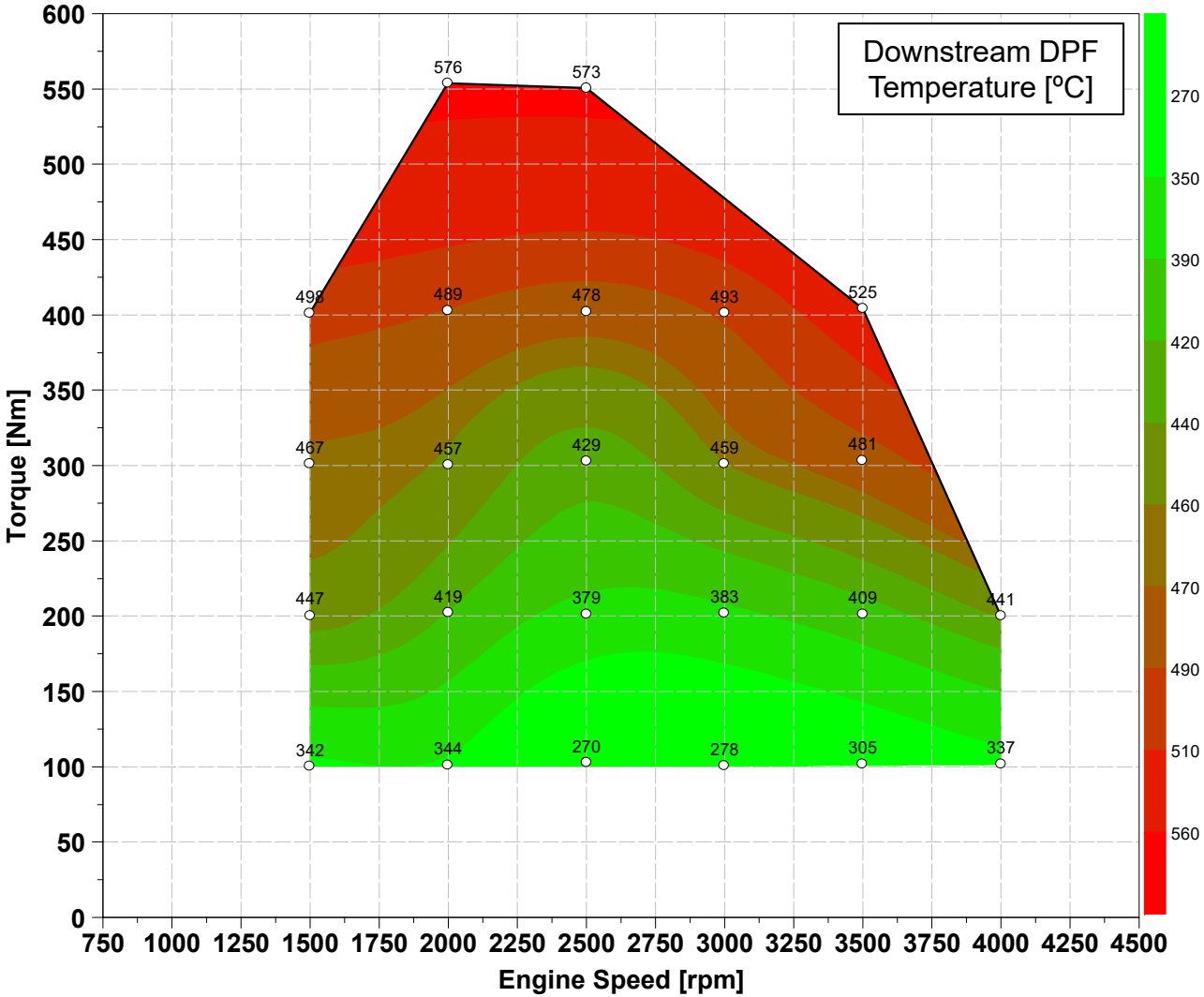
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Exhaust gas temperatures increased with load.

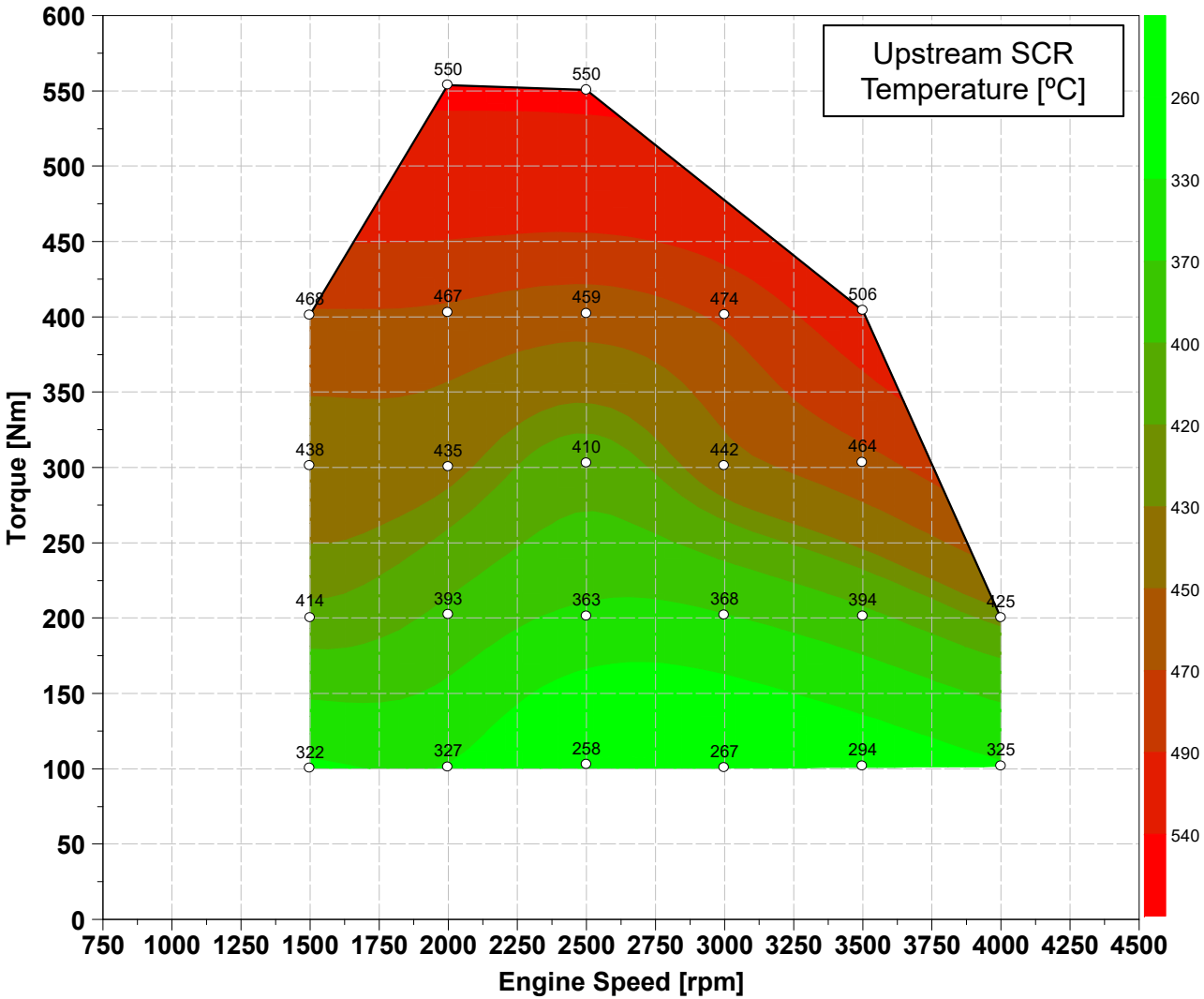
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Exhaust gas temperatures increased with load.

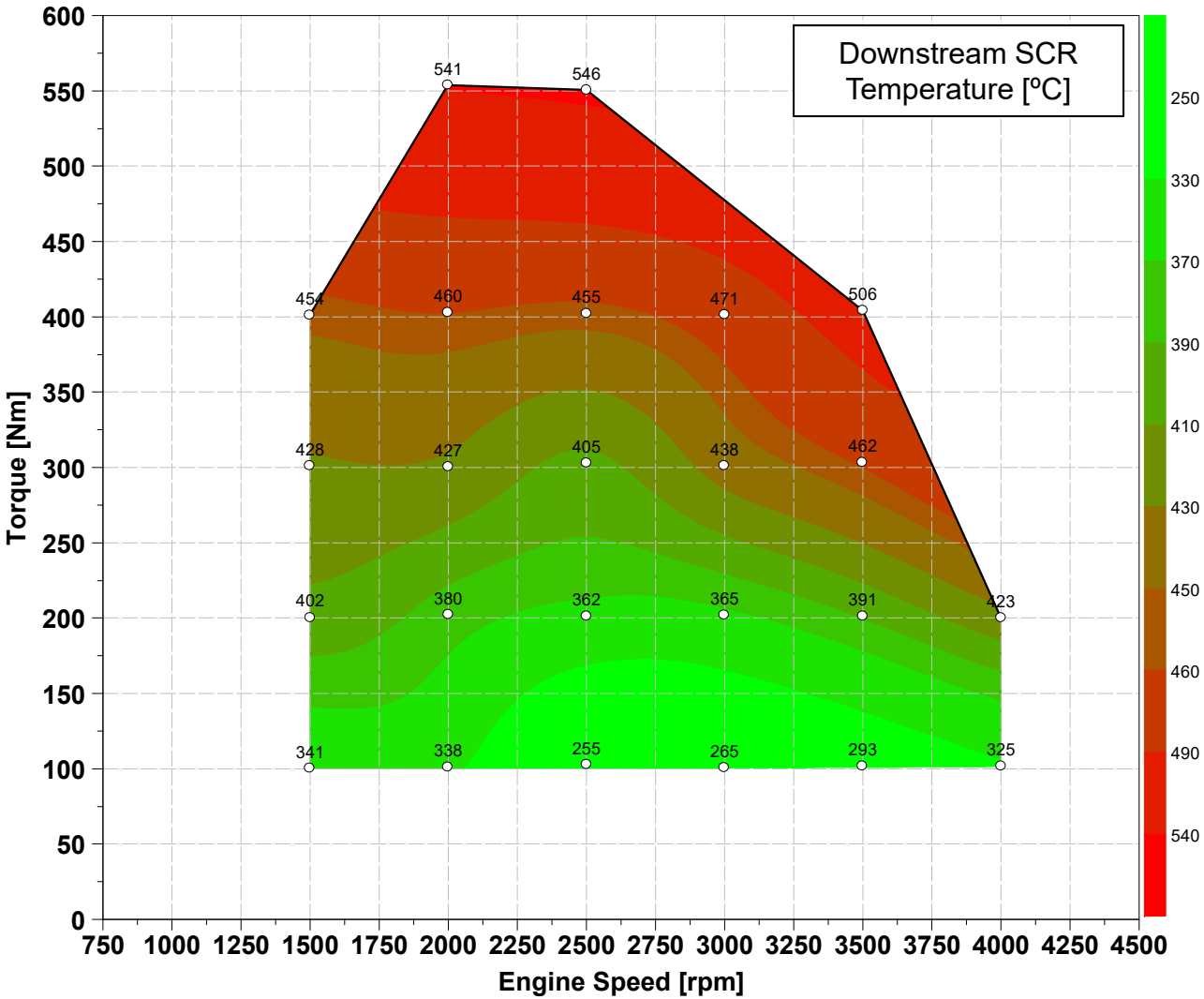
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Exhaust gas temperatures increased with load.

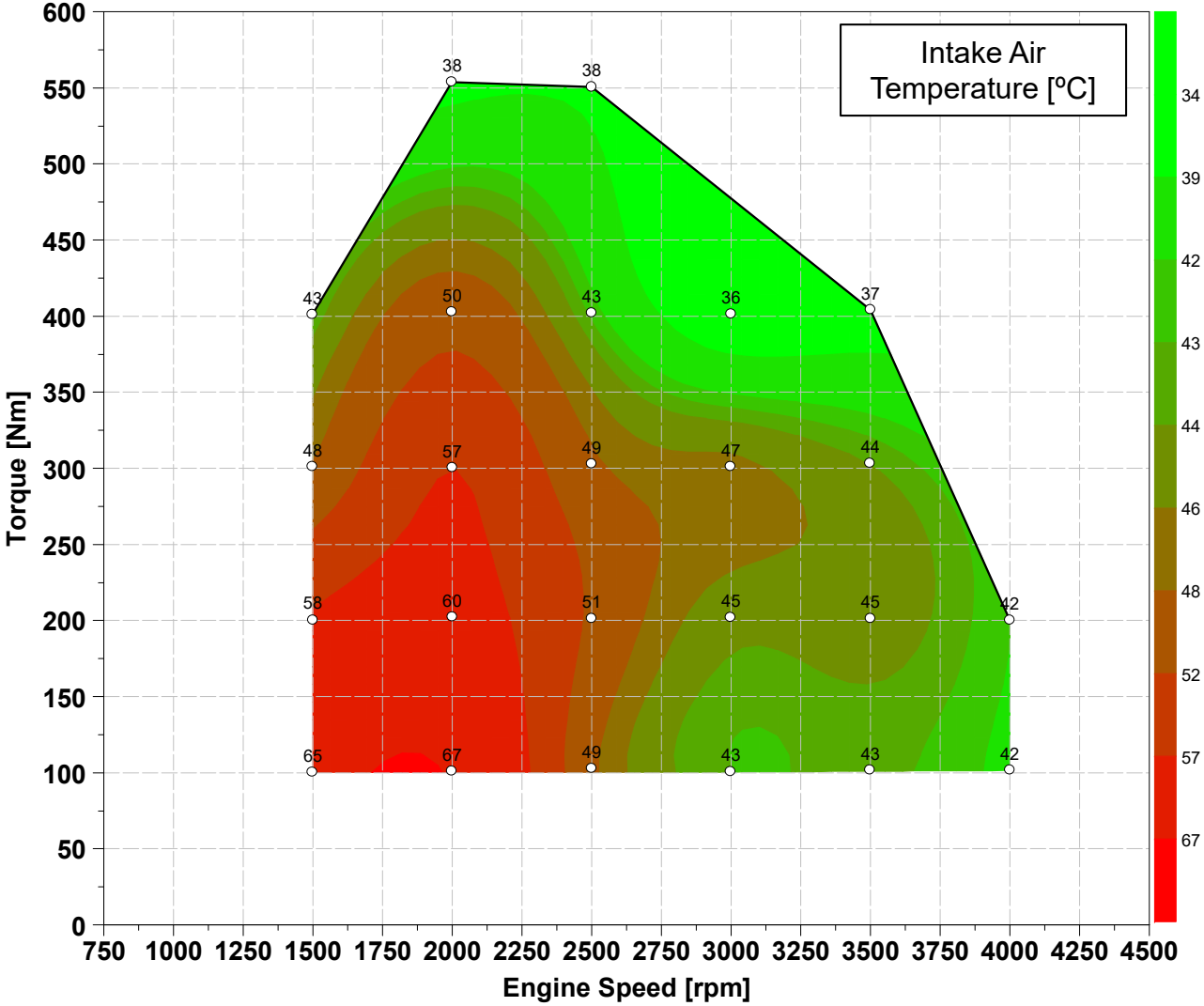
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Exhaust gas temperatures increased with load.

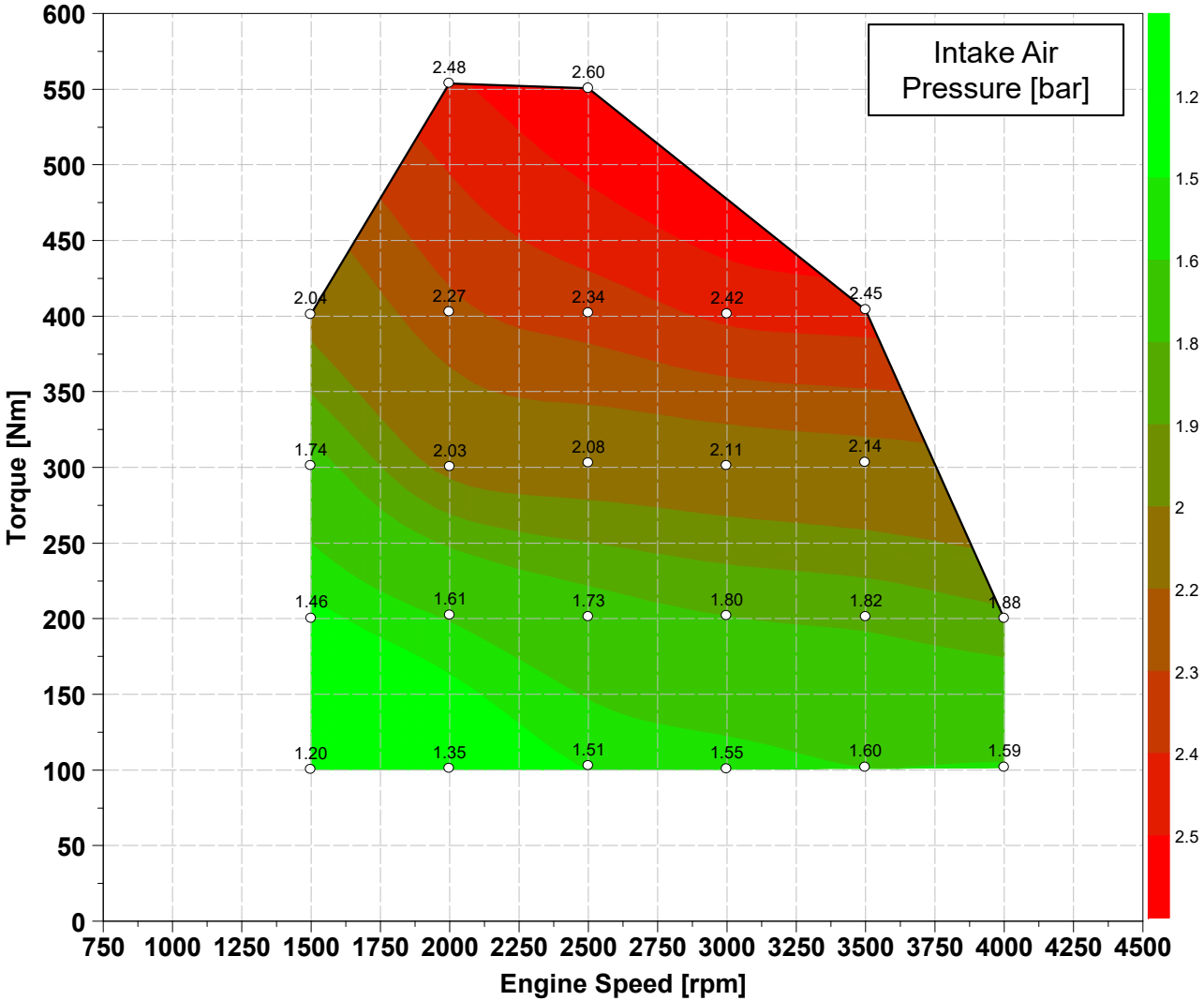
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Intake air temperature decreases with speed and load.
- The temperature began to decrease with less use of EGR at higher speeds and loads.

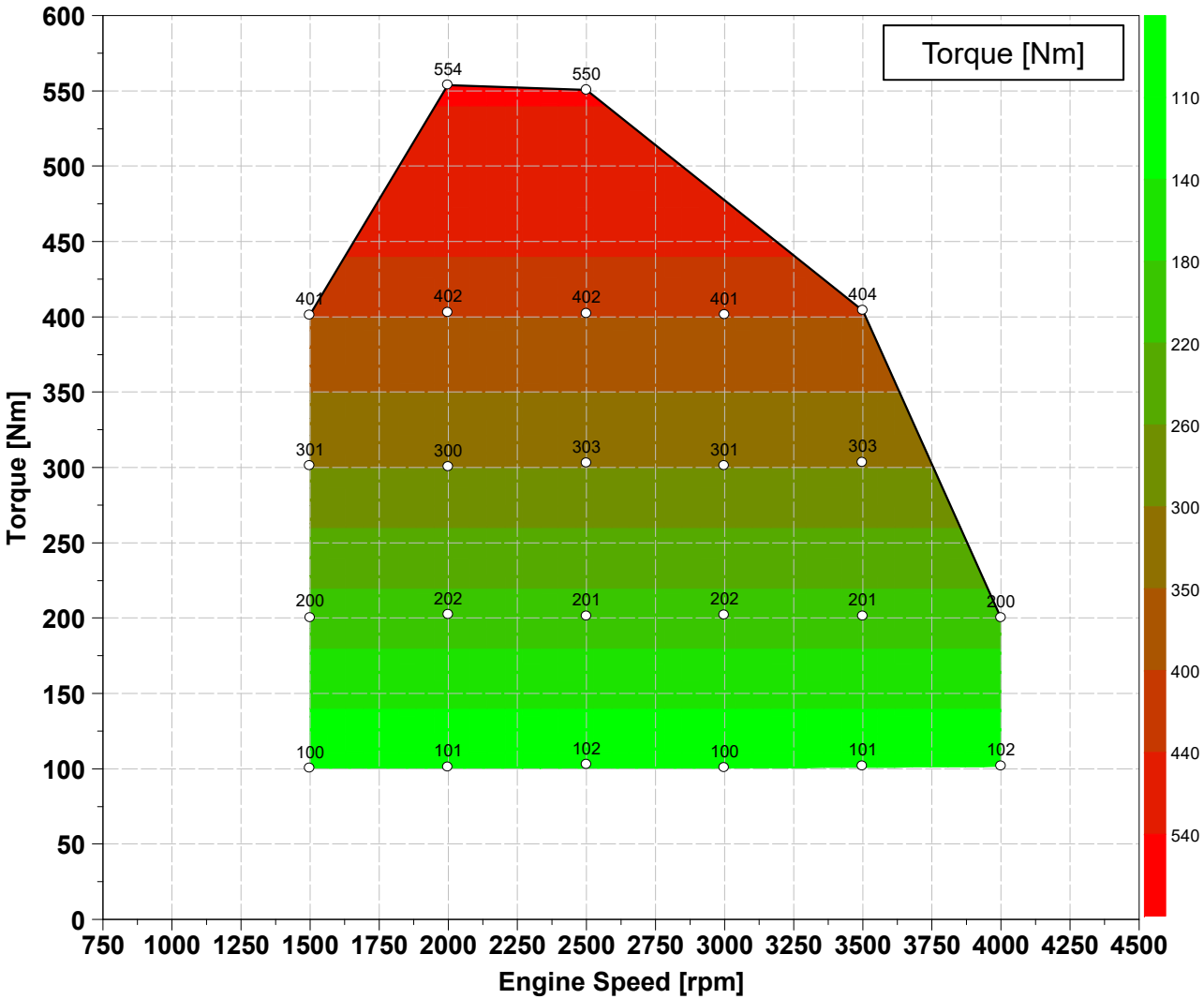
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Intake air pressure increased consistently with load.

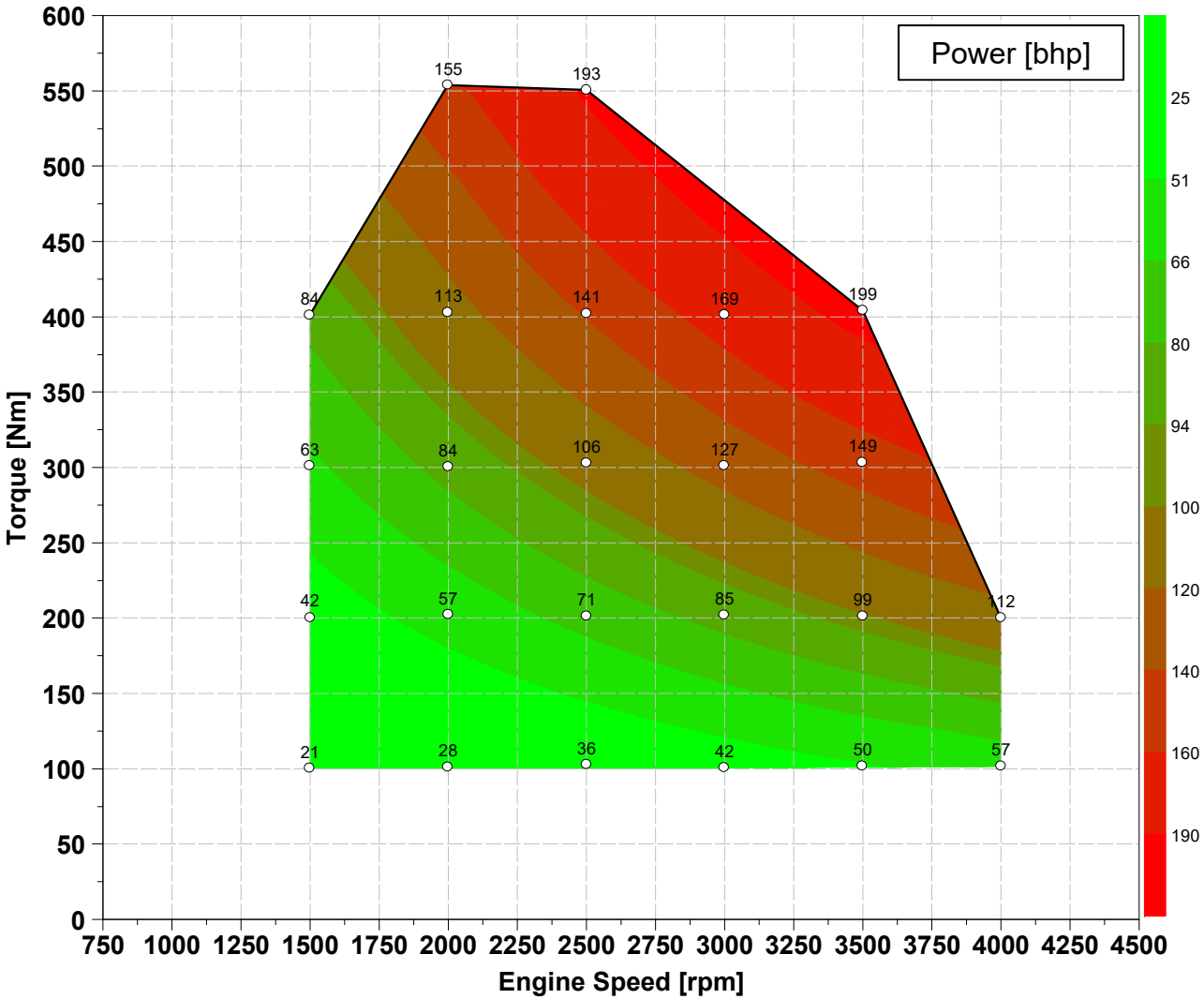
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Peak torque reached during testing was 550 Nm.

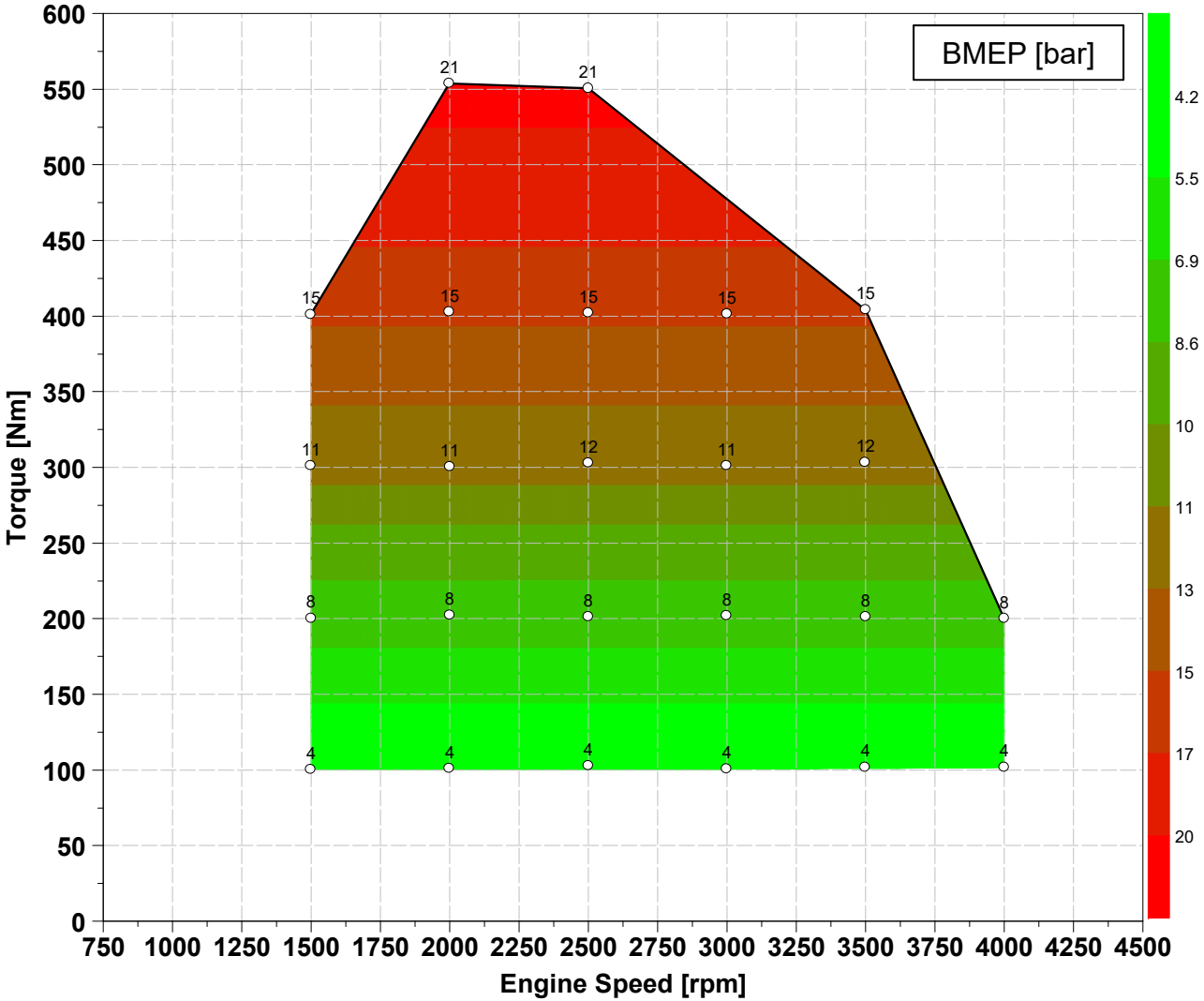
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- Peak torque reached during testing was 200 bhp.

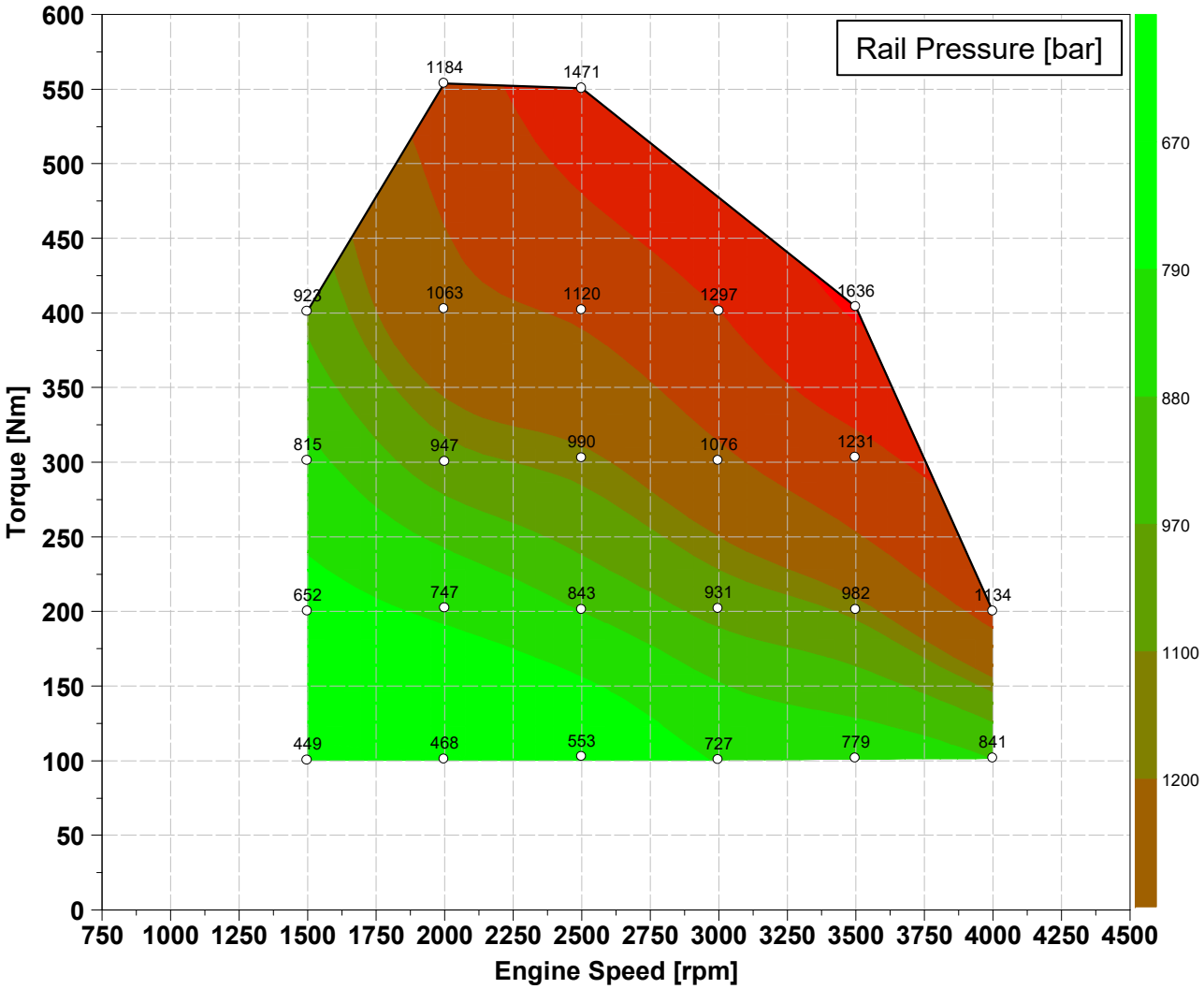
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- The engine produced peak BMEP of approximately 21 bar in the full range of the engine map.

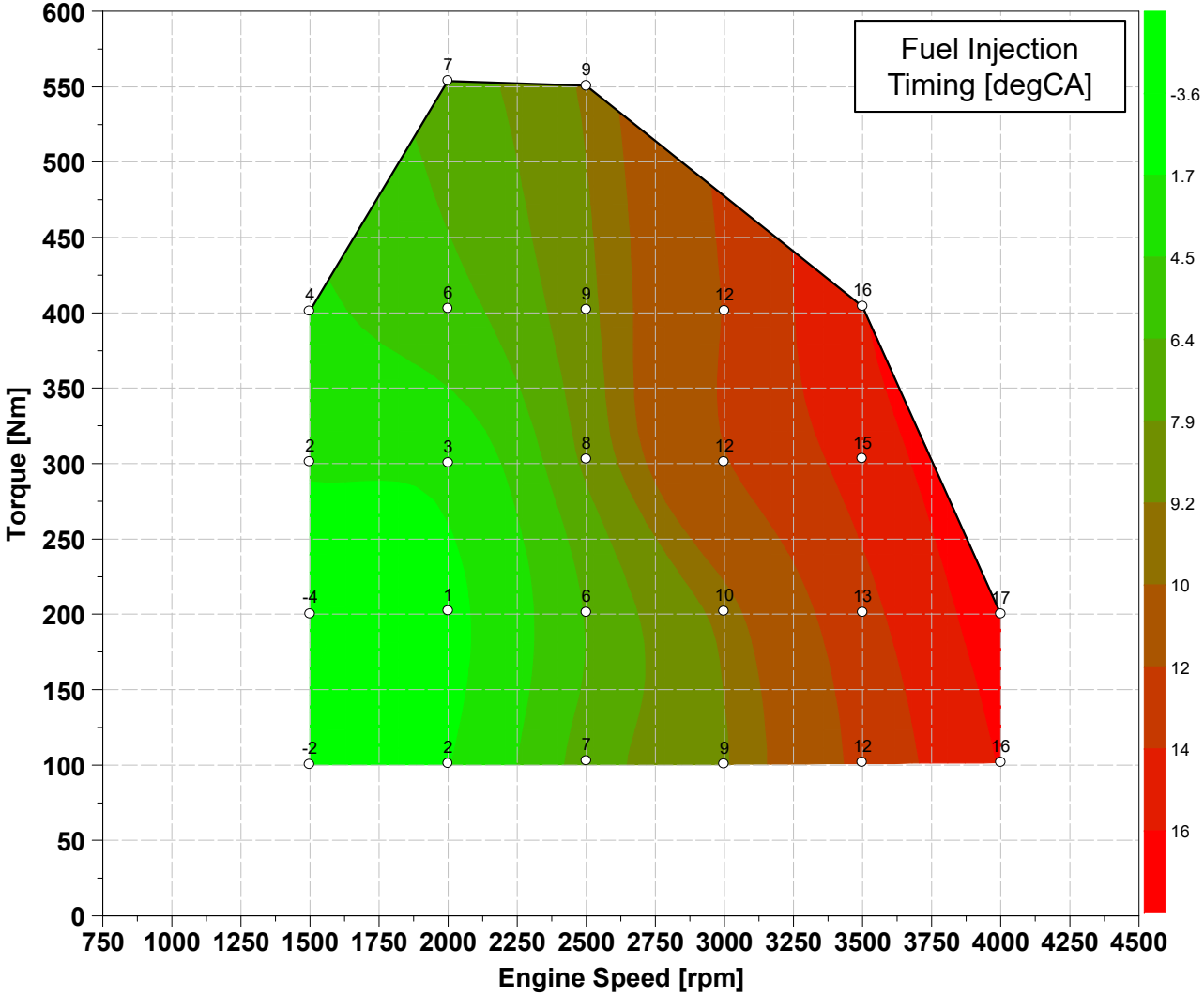
FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- The fuel rail pressure is in the range of 400 – 700 bar within 1500 rpm and 2000 rpm and 100 Nm to 200 Nm.
- The fuel rail pressure increases proportionately to the increase in power on the engine map.

FEV Benchmarking
BMW X5d 35d: Urea Coarse Engine Map



Comment

- The engine fuel injection timing was delayed with increase in speed.

Agenda

- Introduction
- Vehicle Break In
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- EGR Mapping
- Urea Coarse Engine Mapping
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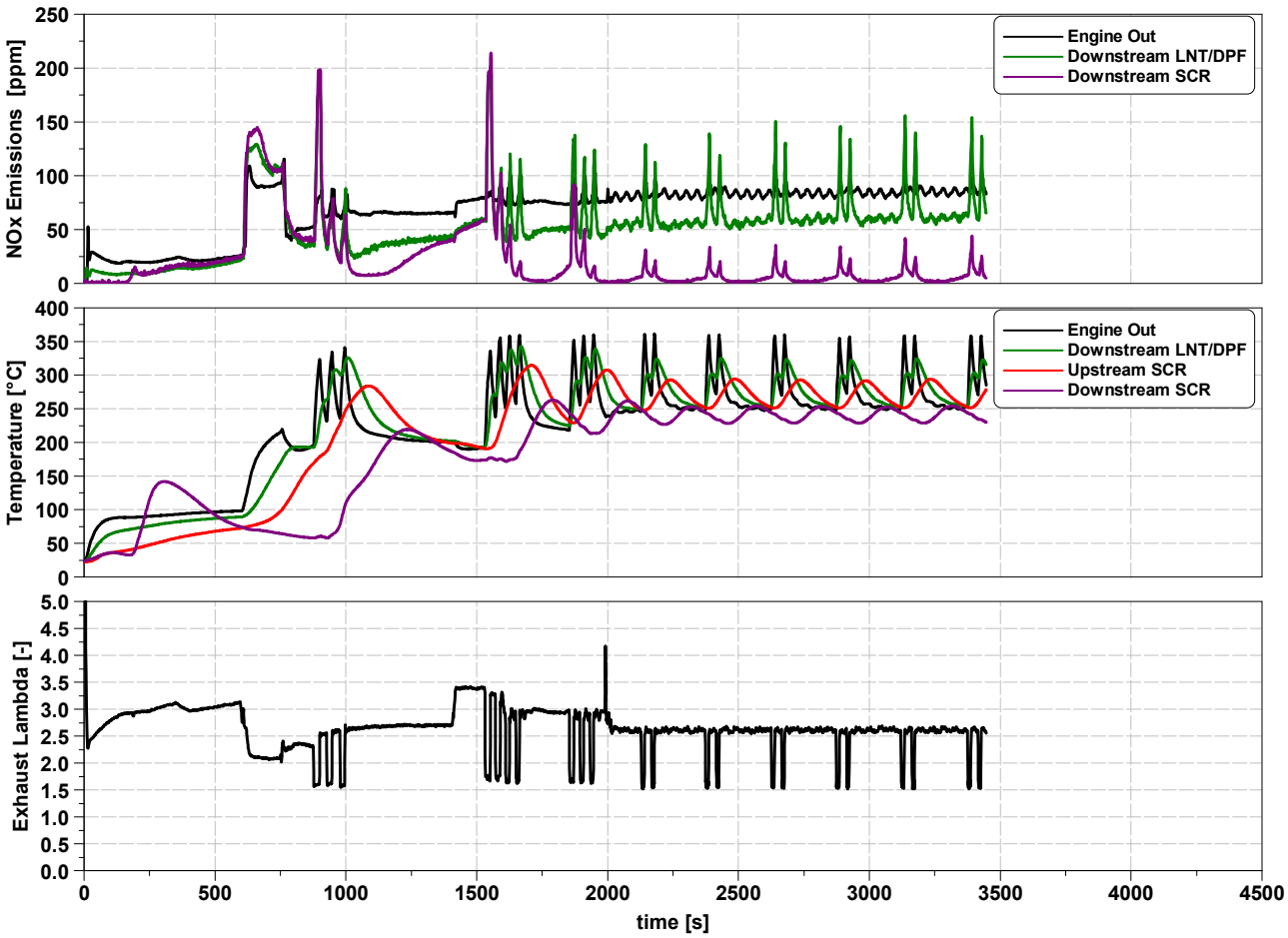
- ASCMO Simulations
- Conclusion

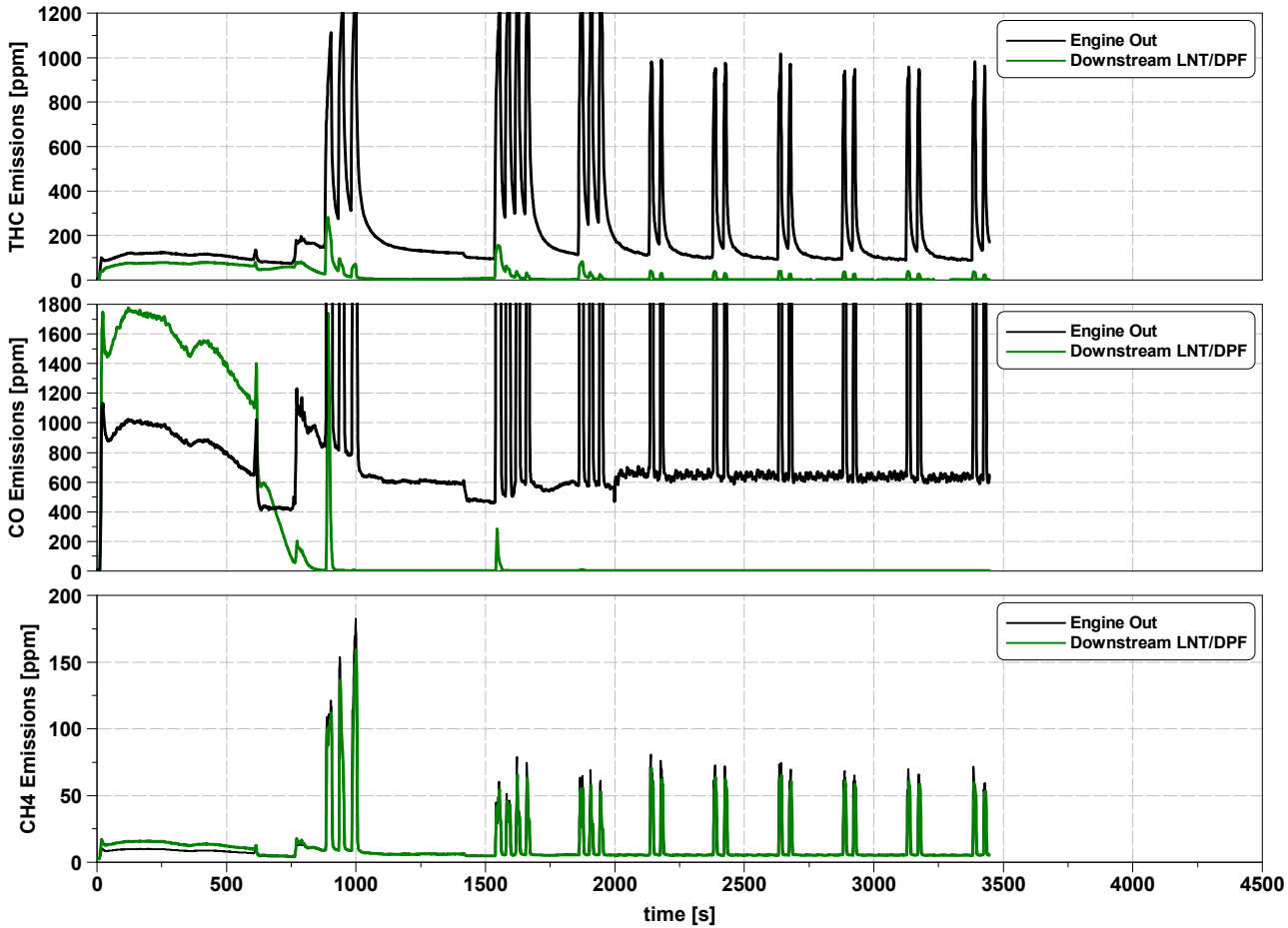
FEV Benchmarking
BMW X5d 35d: Cold Start



Comment

- Continuous data was recorded during a cold start to determine the emissions and warm up strategy of the aftertreatment system,
- At the beginning of the cold start there is no significant NOx conversion across the LNT or SCR catalyst.
- At 1000 seconds into the test there was some NOx conversion across the LNT.
- At 1500 seconds into the test the NOx stored in the SCR catalyst is released and NOx conversion across the catalyst begins.
- Several spikes in exhaust temperature were also measured 1500 seconds into the test.

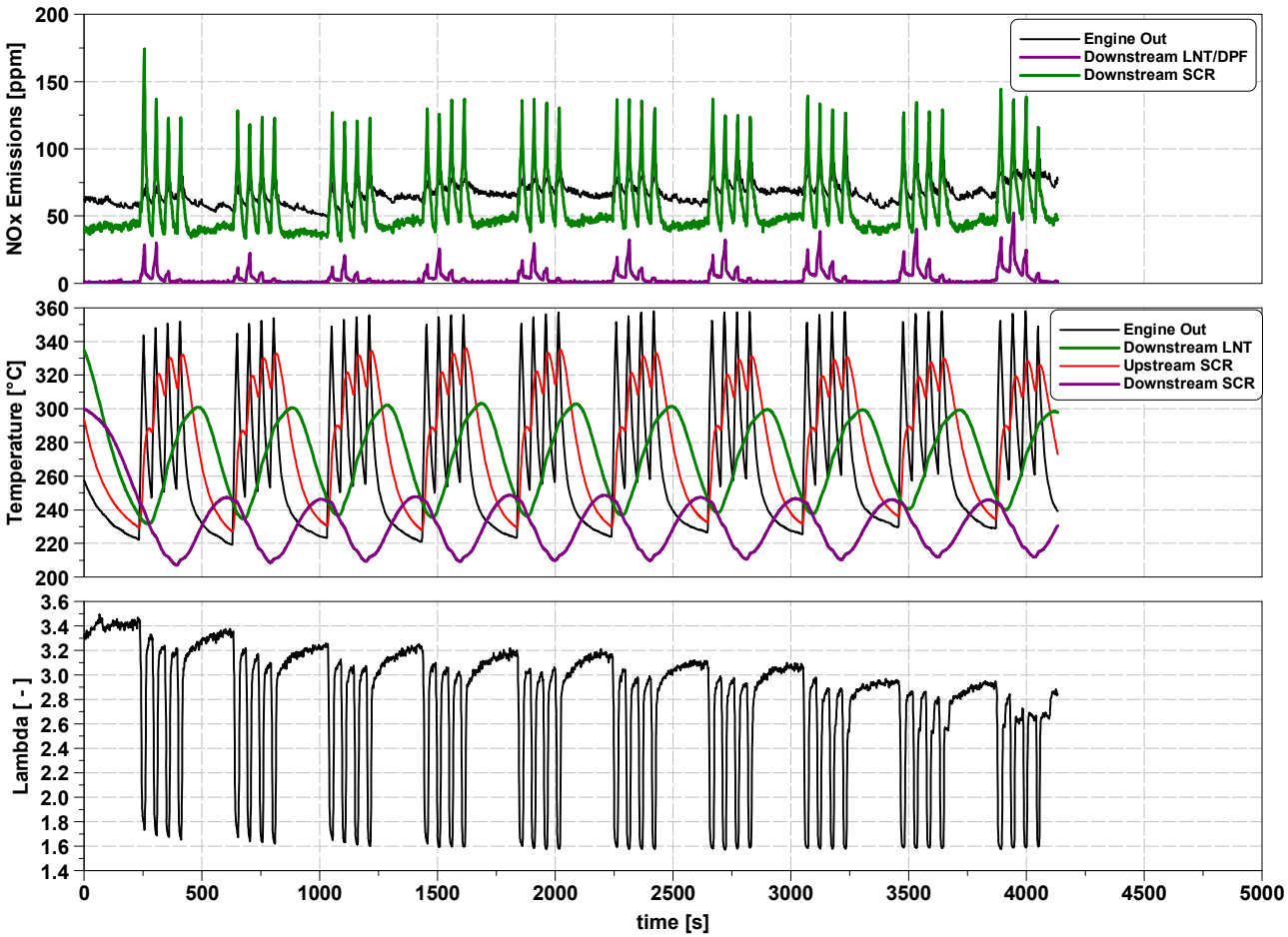
FEV Benchmarking
BMW X5d 35d: Cold Start



Comment

- The conversion of HC and CO emissions across the LNT/DPF catalyst began at 800 seconds into the test.
- The methane emissions produced were not converted.

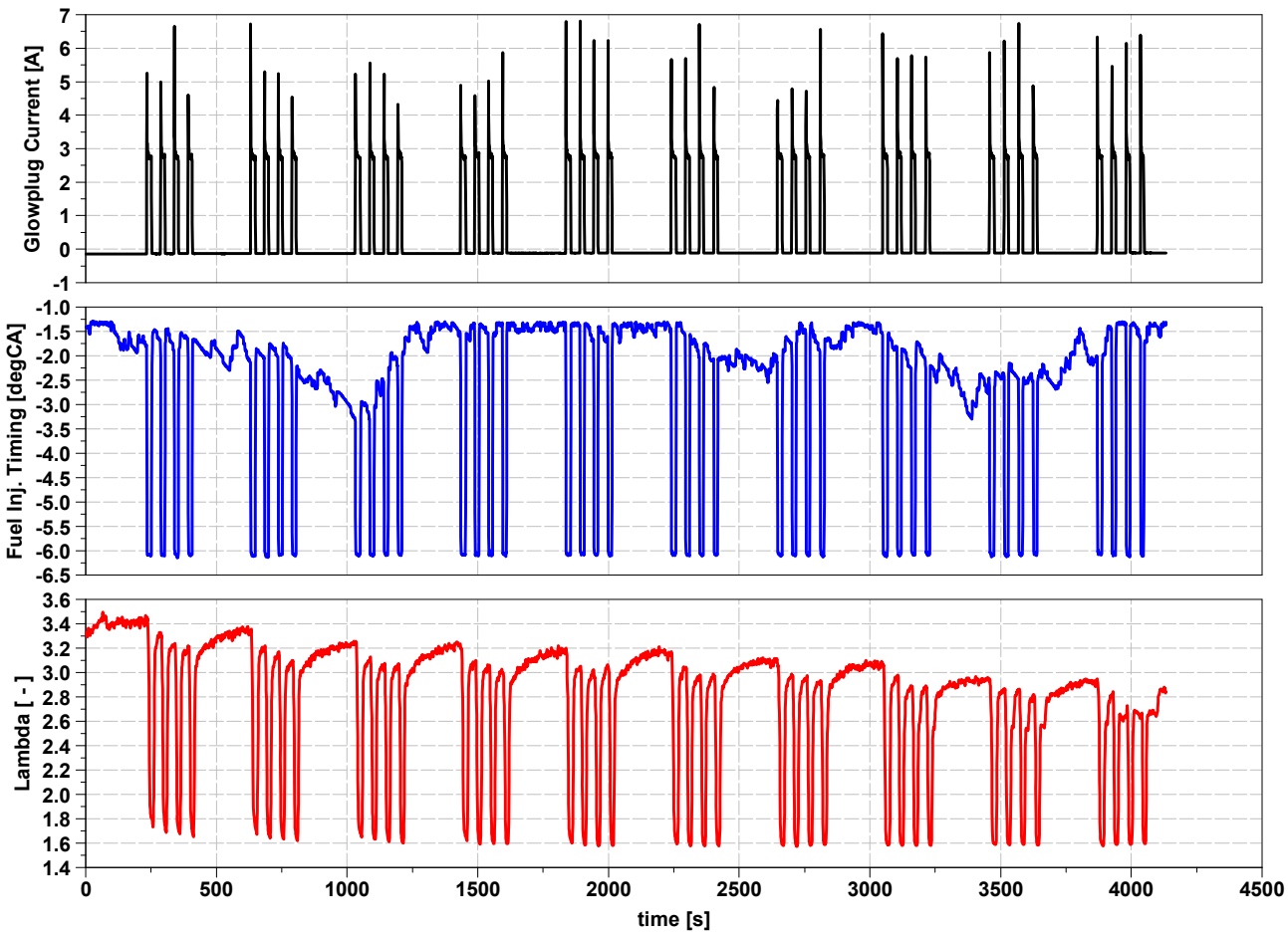
FEV Benchmarking
BMW X5d 35d: Continuous Data



Comment

- Continuous data was taken while the engine was at 1500 rpm and 3 BMEP.

FEV Benchmarking
BMW X5d 35d: Continuous Data



Comment

- It was determined that the engine delayed injection and used the glow plugs in a strategy heat up the aftertreatment in and attempt to keep the SCR catalyst within operating temperature.

Agenda

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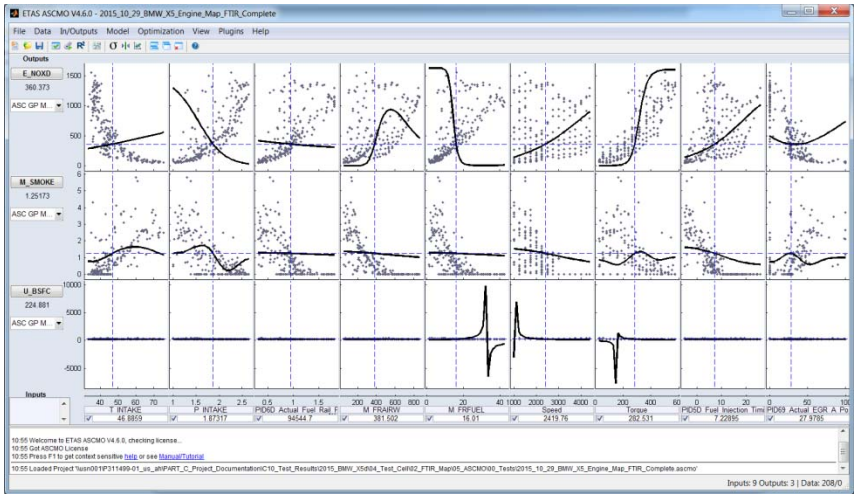
FEV Benchmarking
BMW X5d 35d: Dynamic Engine Modeling

Comment

- The mapped engine data was used in the ETAS ASCMO software in order to create models that can predict data points based off of user inputs.
- The software uses Gaussian algebra and was used to determine data points on the engine map that were not actually measures in the test cell.
- It was discovered that the model was very accurate at predicting some outputs such as NOx, but also very inaccurate at some outputs such as engine out smoke.
- The inaccuracy in some predicted outputs could be due to not having all the appropriate inputs necessary for a predicted output.

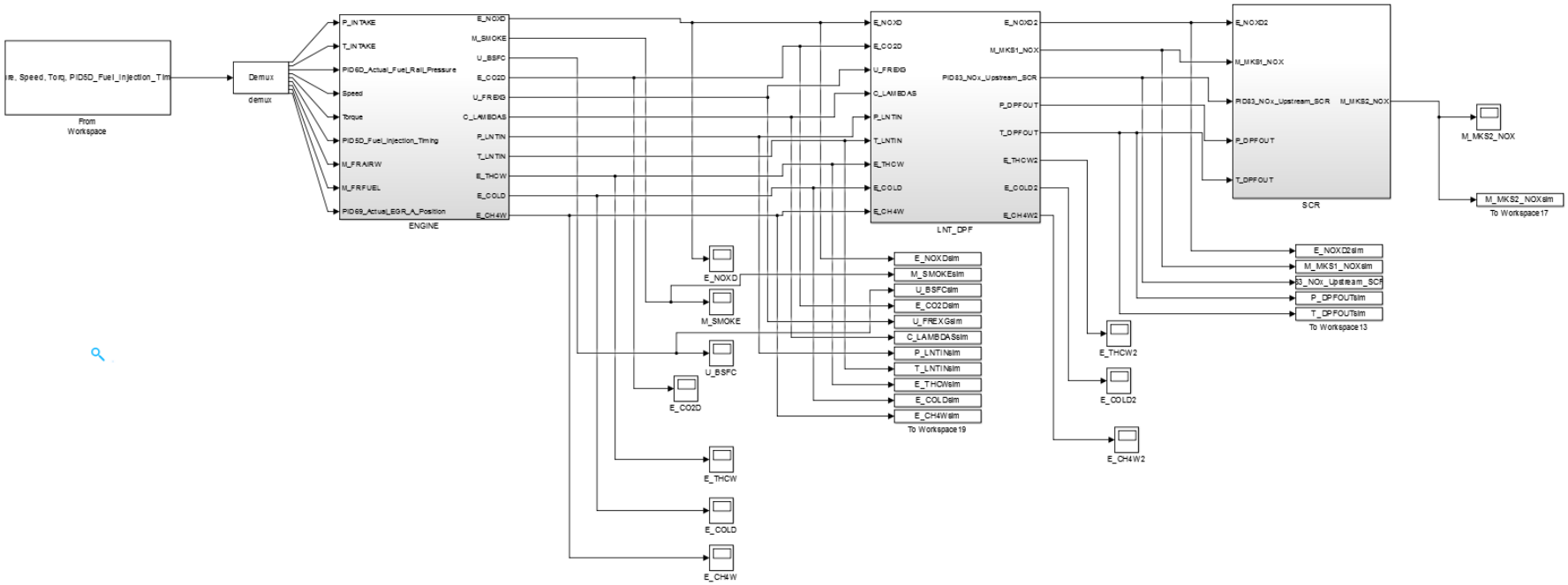


FEV Benchmarking
BMW X5d 35d: Dynamic Engine Modeling

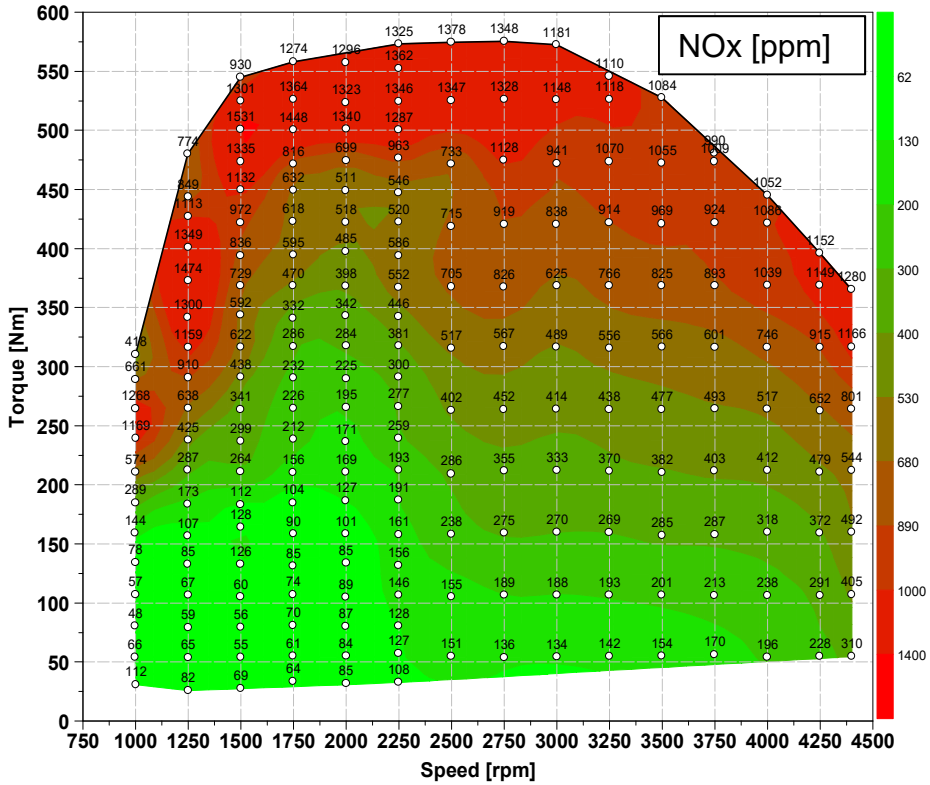
Inputs	Outputs	Outputs
• Intake air temperature	• Engine Out NOx	• Smoke
• Intake air pressure	• LNT/DPF Out NOx	• BSFC
• Rail pressure	• Tailpipe NOx	• Exhaust Mass Flowrate
• Engine speed	• Engine Out CO2	• Lambda
• Torque	• Engine Out THC	• Upstream LNT Pressure
• Start of injection	• Engine Out CO	• Upstream LNT Temperature
• Air mass flow rate	• Engine Out CH4	
• Fuel mass flow rate	• Downstream DPF Pressure	
• EGR valve position	• Downstream DPF Temperature	

FEV Benchmarking
BMW X5d 35d: Dynamic Engine Modeling

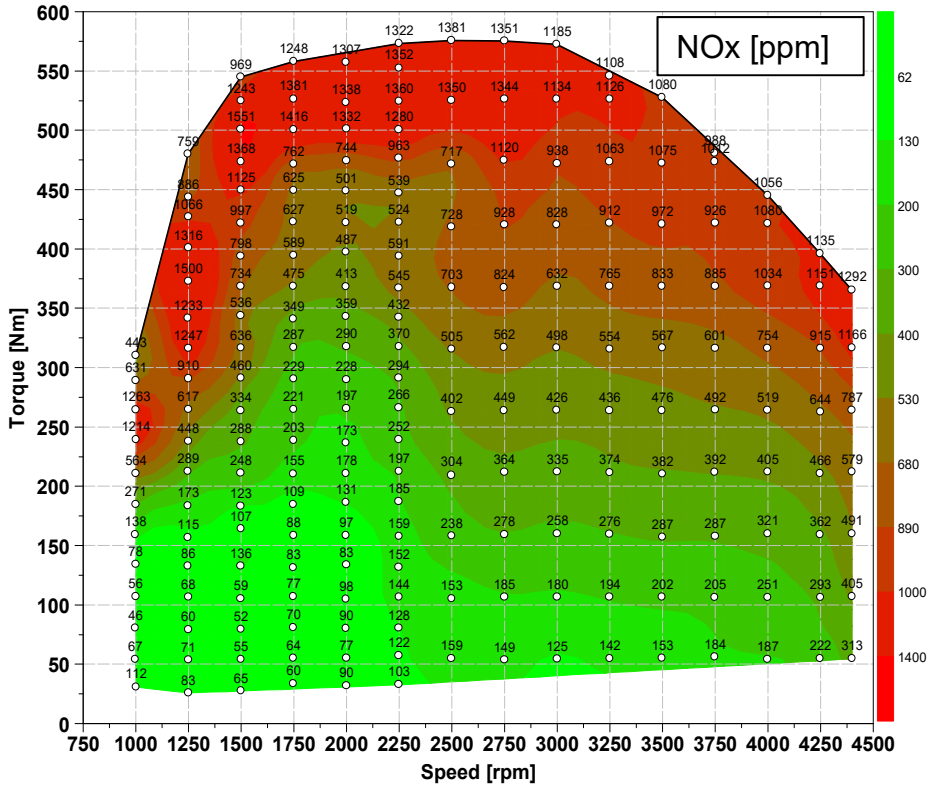
Contract No. EP-C-12-014, Work Assignment 3-11
January 29, 2016



FEV Benchmarking
BMW X5d 35d: Dynamic Engine Modeling

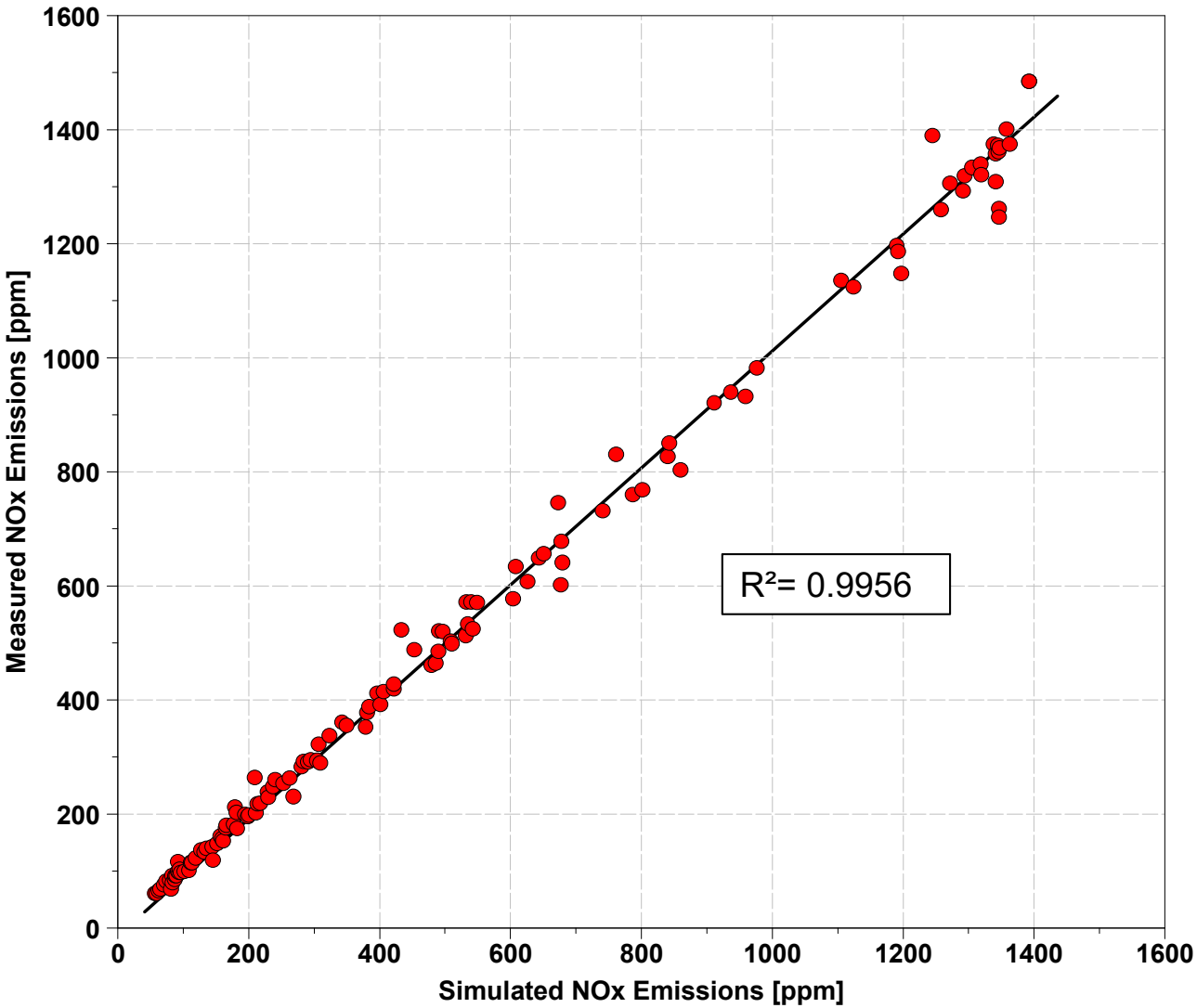


Measured



Predicted

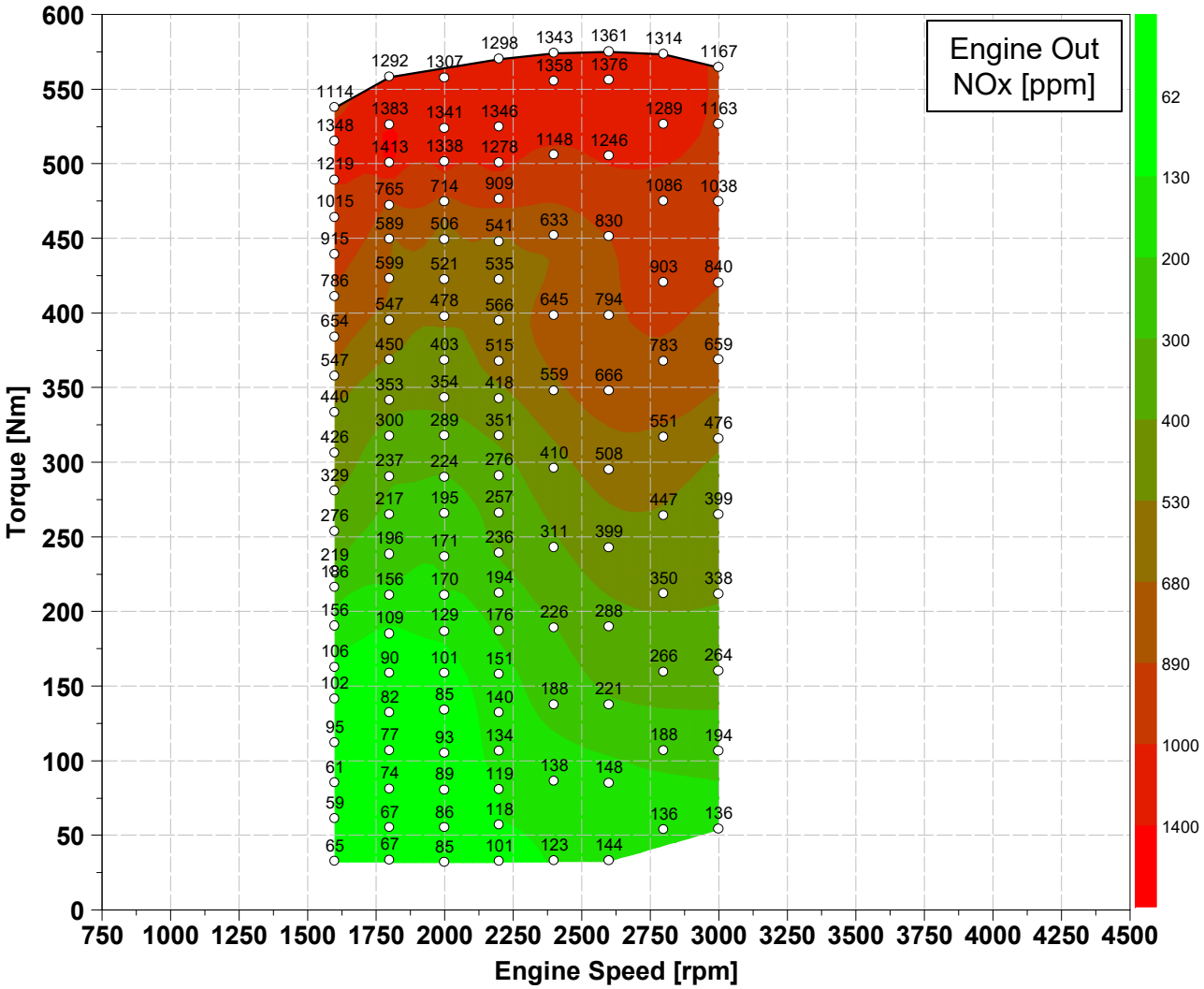
FEV Benchmarking
BMW X5d 35d: Dynamic Engine Modeling



Comment

- The ASCMO model was very accurate at simulating NOx emissions.
- When comparing the actual measured NOx values and comparing them to the simulated NOx values a r-squared value of 0.9956 was achieved.

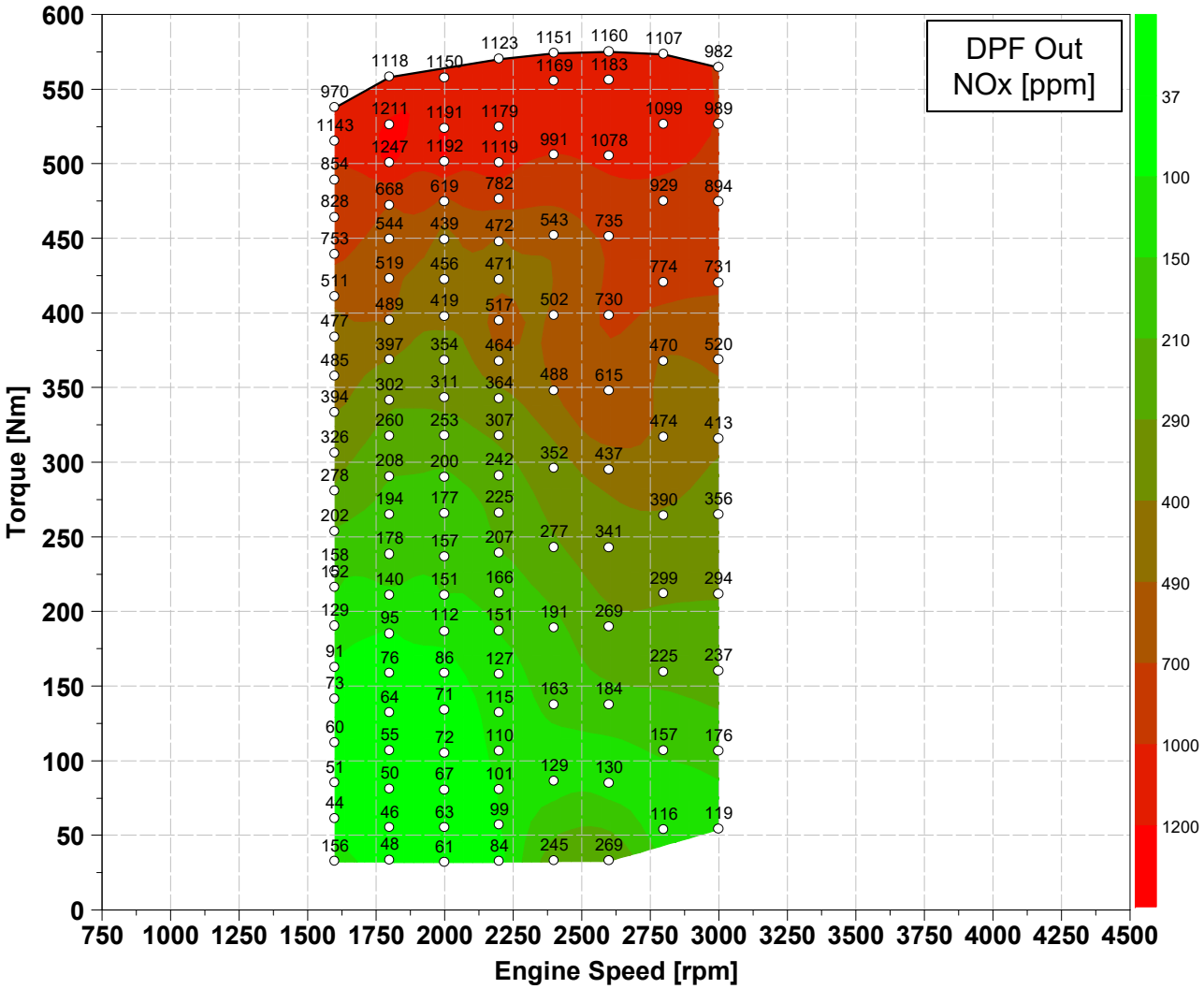
FEV Benchmarking
BMW X5d 35d: Dynamic Engine Modeling



Comment

- The NOx emissions shown were not actually measured, but predicted by interpolating inputs from the actual measured data at different speed points on the engine map.
- The simulated NOx emissions trend has a similar trend from 1600 rpm to 2200 rpm and 40 Nm to 200 Nm.

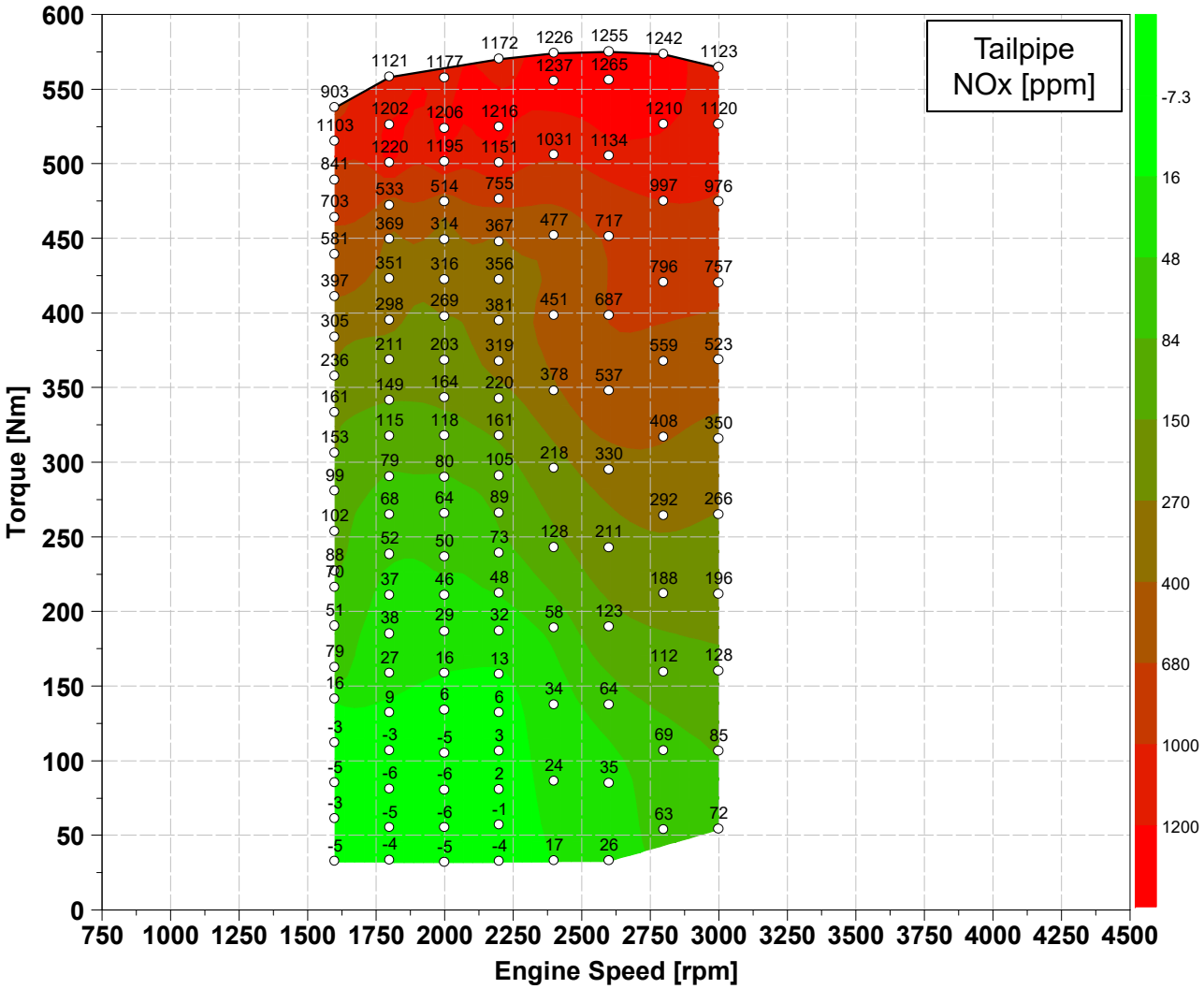
FEV Benchmarking
BMW X5d 35d: Dynamic Engine Modeling



Comment

- The NOx emissions shown were not actually measured, but predicted by interpolating inputs from the actual measured data at different speed points on the engine map.
- The simulated NOx emissions trend has a similar trend from 1600 rpm to 2200 rpm and 40 Nm to 200 Nm.
- The DPF out simulated NOx is based of simulated inputs used in the LNT/DPF model.

FEV Benchmarking
BMW X5d 35d: Dynamic Engine Modeling



Comment

- The NOx emissions shown were not actually measured, but predicted by interpolating inputs from the actual measured data at different speed points on the engine map.
- The simulated NOx emissions trend has a similar trend from 1600 rpm to 2200 rpm and 40 Nm to 200 Nm.
- The tailpipe simulated NOx is based of simulated inputs used in the LNT/DPF model

Agenda

- Introduction
- Vehicle Break In
- DPF Regeneration Interval Investigation
- Engine Mapping
- EGR Mapping
- Urea Course Engine Mapping
- Continuous Data
- ASCMO Simulations
- Conclusions

Conclusions

- The vehicle break in occurred from 800 to 4,000 miles; the BMW X5 35d was within the EPA estimated fuel economy of 23 mpg-city and 31 mpg-highway. Five DPF regenerations occurred during the 3,200 miles of recorded break-in vehicle data.
- The DPF regen interval factor was 0.026 for the vehicle on the FTP75 drive cycle. The LNT NOx conversion was minimal during a DPF regeneration, and during some instances there was no LNT NOx conversion during the DPF regeneration.
- The LNT NOx conversion efficiency was between 10% to 76% across the entire engine map, with the higher NOx conversion efficiency measured in the range of 1000 rpm to 2000 rpm and 25 Nm to 150 Nm.
- The SCR NOx conversion efficiency was between 0% to 100% for the entire engine map, with the higher NOx conversion efficiency of 90% or better within the range of 1000 rpm to 2250 rpm and 25 Nm 200 Nm.
- The total NOx conversion efficiency was between 0% to 100% for the entire engine map, with the higher NOx conversion efficiency of 90% or better within the range of 1000 rpm to 2250 rpm and 25 Nm 200 Nm.

Conclusions

- Carbon monoxide and total hydrocarbon total conversion efficiency for the exhaust aftertreatment system was 95% or better across the entire engine map.
- All emissions species were significantly higher at higher load and speed ranges.
- The full load curve measured on the engine map followed the trend line published by BMW. The engine surpassed the published full load torque value of 560 Nm from 1500 rpm to 3000 rpm at several points reaching to as high as 575 Nm at full load at 2000 rpm.
- EGR percentage was much higher from 1500 rpm to 2000 rpm and 25 Nm to 75 Nm on the coarse EGR engine map.
- The urea valve was active on all parts of the coarse urea map included the high load and speed points.
- During the engine cold start there was no NOx conversion efficiency across the aftertreatment system until 1000 seconds into the test.

Conclusions

- During the cold start and at low load continuous data the engine would run lean, activate the glow plugs, and advance the injection timing in an effort to heat up the aftertreatment system to achieve the highest conversion efficiencies.
- Dynamic engine models were very accurate in predicting pre and post catalyst NOx emissions, but was very inaccurate at predicting smoke, CO, or THC emissions. This can be attributed to the inputs selected to produce the engine and aftertreatment system models.

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