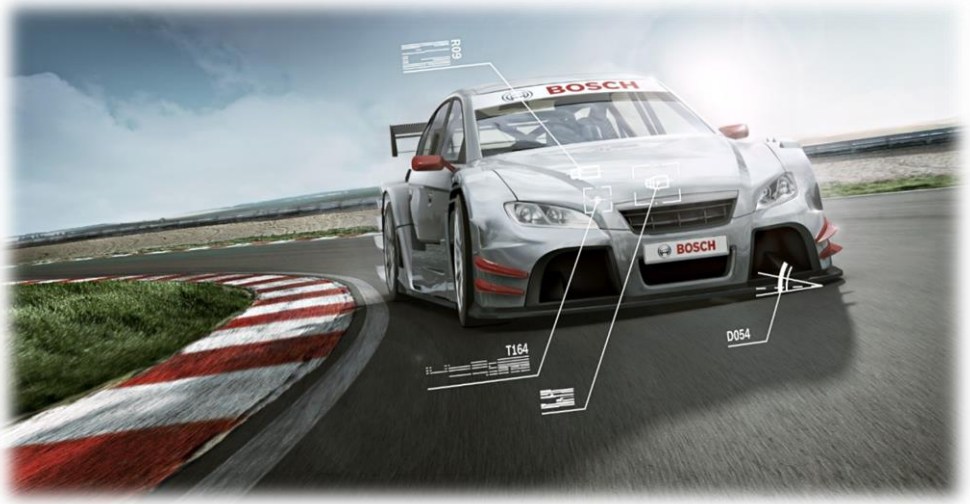
CALIBRATION FUNDAMENTALS FOR A COMPETITIVE ADVANTAGE

BOSCH

Agenda

1. Presentation
2. Test Equipment
3. Basic Calibration Development Procedure
4. Fuel Calibration
5. Fuel System Components
6. Conclusion



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Presentation
Étienne St-Laurent

- ETS Formula SAE 2009-2015
  - Engine Calibration
  - Systems Engineering: Intake, Exhaust, Fuel, Muffler, Cam, Cooling, Transmission
  - Engine Block Design
- Bosch Motorsport MSD1/NA 2016 - Present
  - Engine Control Software and Application
    - Cadillac ATS-V.R GT3
    - Camaro ZL1 GT4
  - IMSA Scrutinnering Data Acquisition
  - Various Customers Engine Calibration Support
    - Porsche 928 twin turbo
    - Cadillac 2001 LMP1
    - McLaren Engineering
    - Lamborghini

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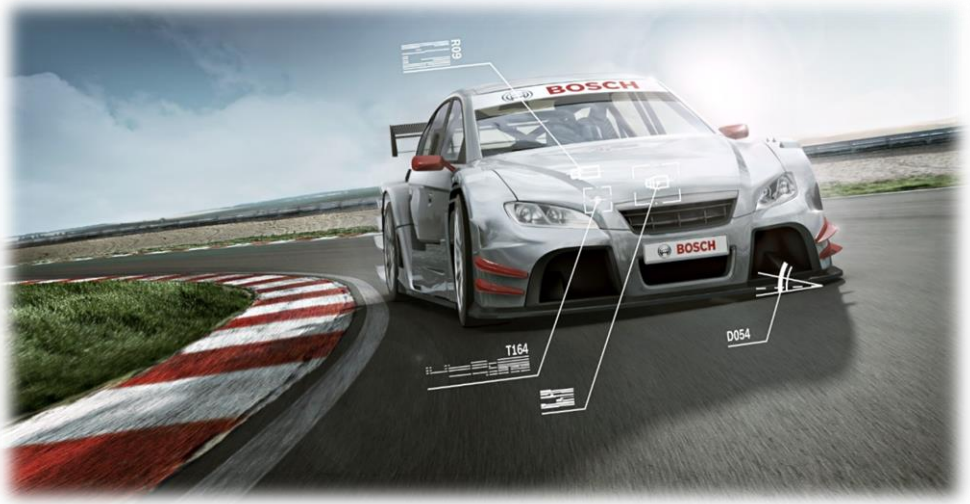

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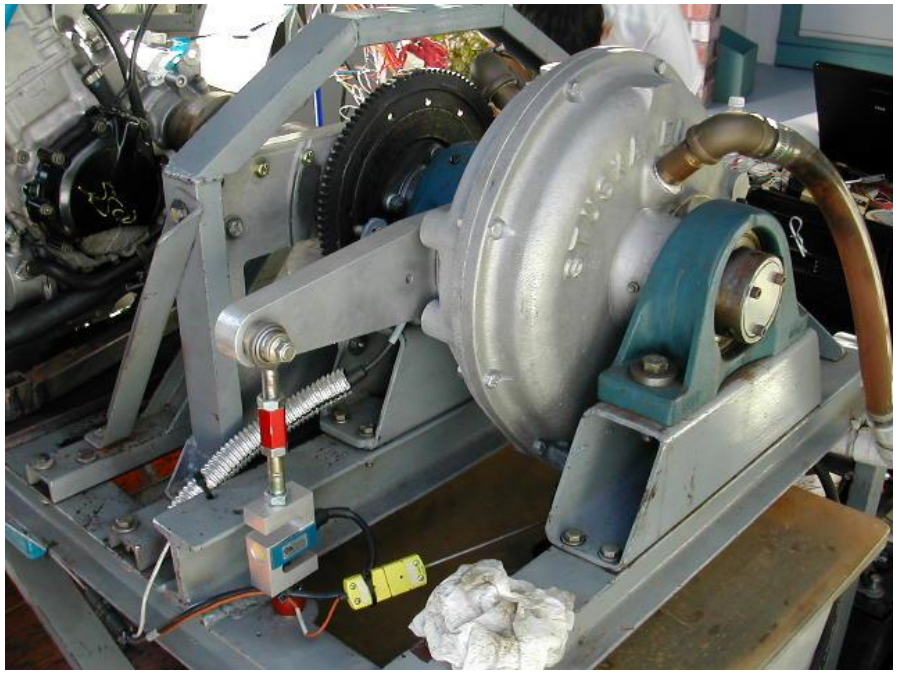
Test Equipment
Test Cell

- Dynamometer:
  - Control engine speed
    - Steady, hold speed
    - Sweep
  - Measure Torque
  - Dynamic test capacity… Doesn't need to be fancy

- Ventilation:
  - Keep you and the engine alive!



Test Equipment
Your car! (and a data acquisition system)

- DAQ system:
  - Logging of essential channels
    - Lambda
    - Engine speed
    - Load (manifold pressure, throttle position or air mass flow)
    - Temperatures: coolant, oil, air
  - Data Analysis
    - Making sense of some of the squiggly lines

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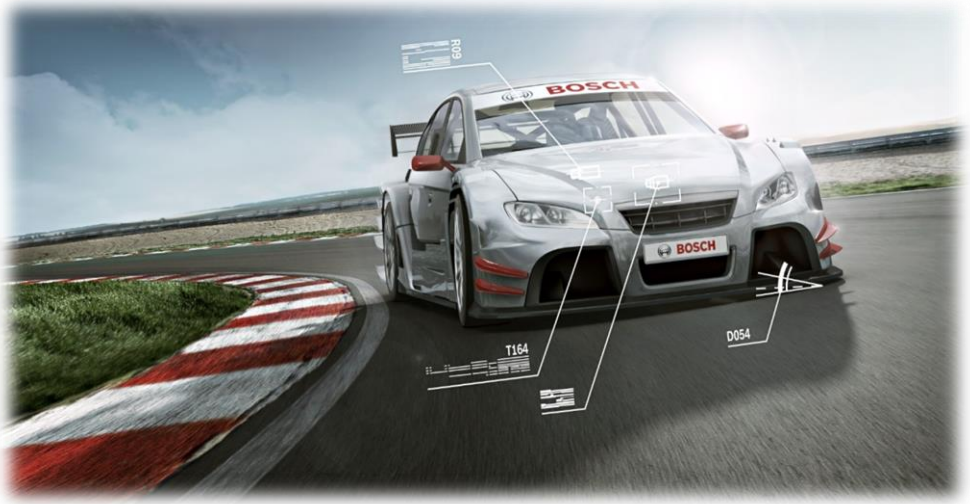

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Calibration Development Procedure
Strategy

- Alpha-N
  - Naturally aspirated engines
  - Big Plenum
  - Single and twin cylinder
  - Better transient response
  - Load calculated based on throttle position

- P-N, Speed density
  - Turbo engines
  - 3-4 + Cylinder engines
  - More precise steady state load calculation
  - Usually preferred over Alpha-N,
  - Load calculated based on plenum pressure (post throttle)

Hardware dependency:
- Engine
- Intake Manifold
- Controller

Try them both! See what happens, document it!

Calibration Development Procedure
Sensors/Actuators

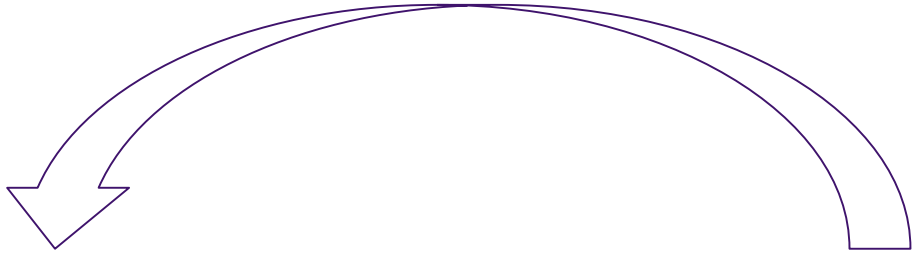
Sensor selection criteria:

- Pressure range
- Temperature range
- Environment
- Signal Output
  - What input is available on your engine controller?
- Input voltage
- Response, for example:
  - Lambda sensor
  - Thermocouples
- Repeatability

Actuation selection criteria:

- Flow
- Power
- Size
- Input Voltage
- Price
- Availability

Calibration Development Procedure
Defining Performance Targets

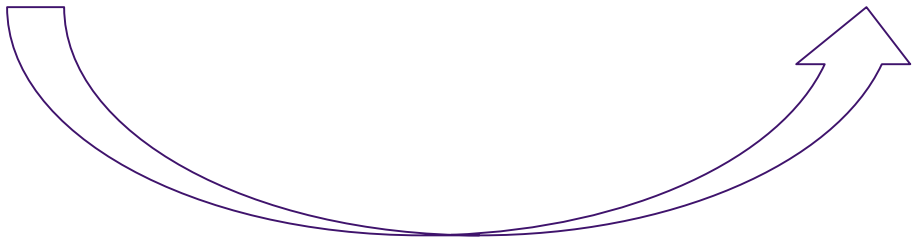


Measurable engine performance target:

- Power/Torque
- Break specific fuel consumption
- Weight
- Response: Driver input -> Torque output
  - Time
  - Repeatability

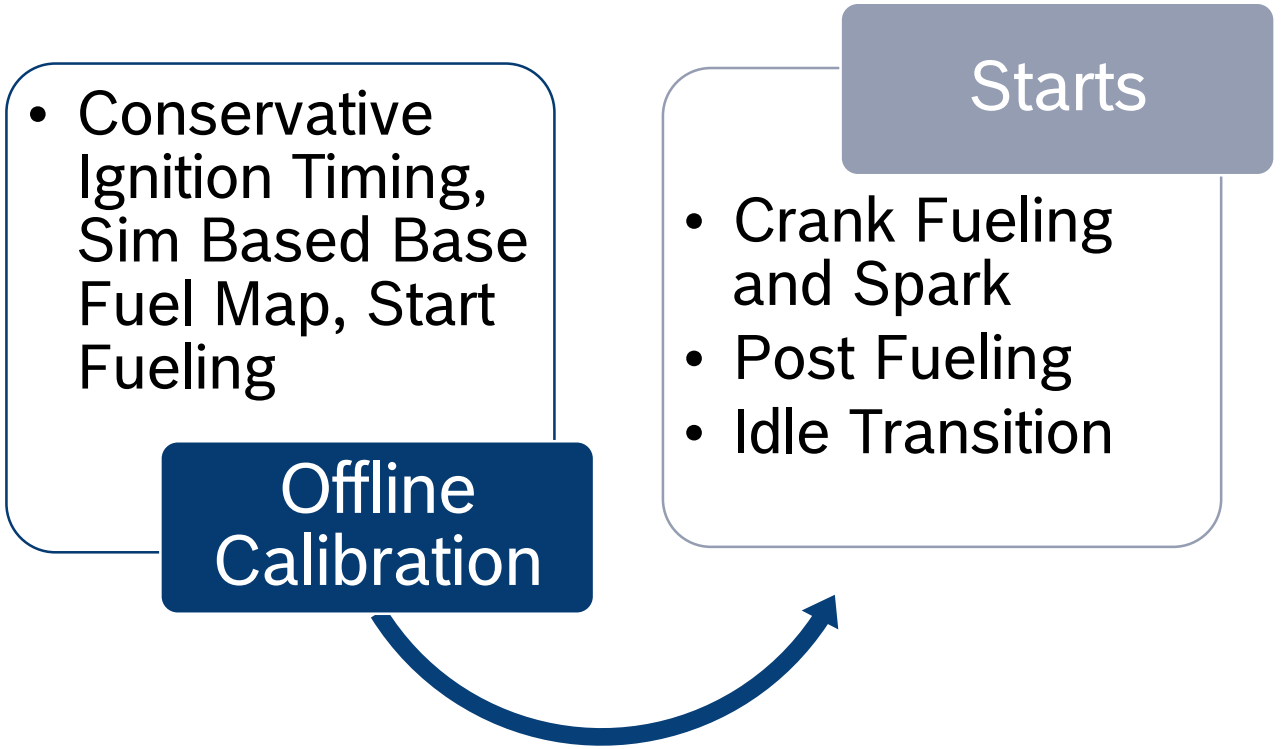
Measurable vehicle performance target:

- Acceleration
- Lap time specific fuel consumption
- Weight
- Drivability (not really measurable…)



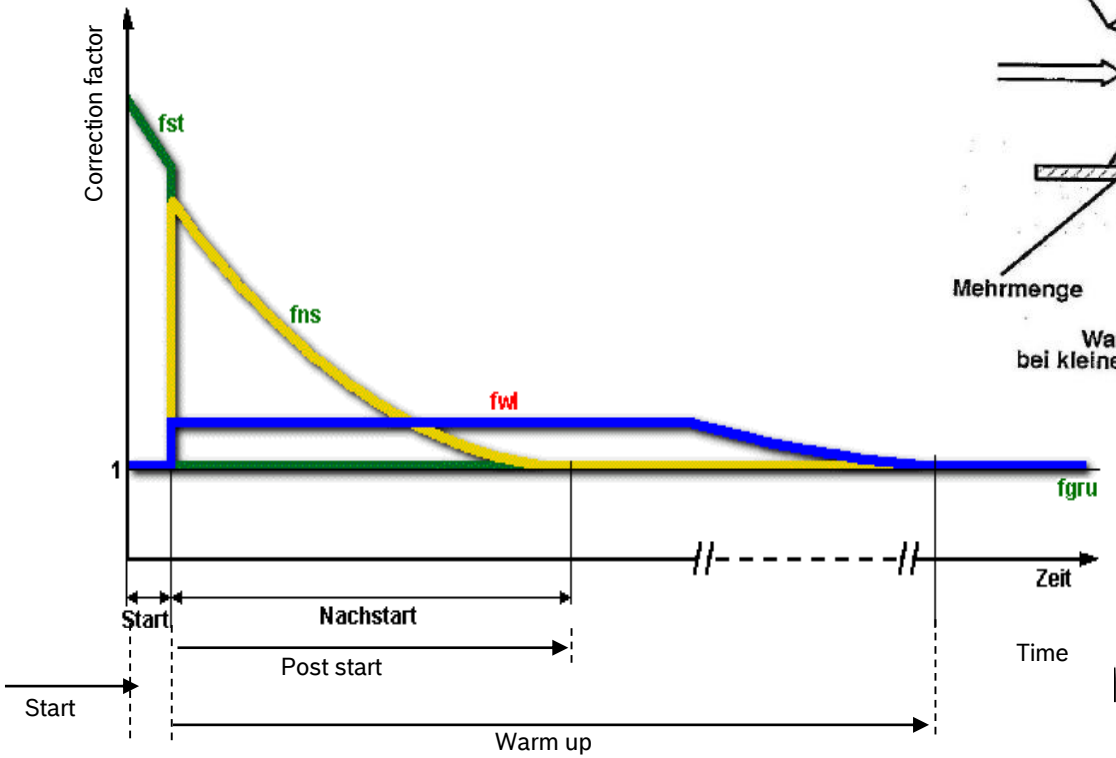
Calibration Development Procedure
Stage 1

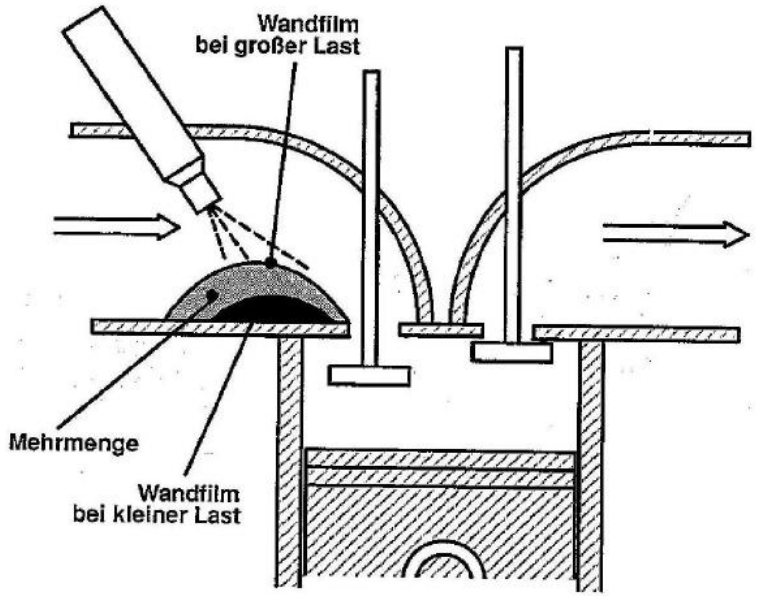
- Do not skip steps!



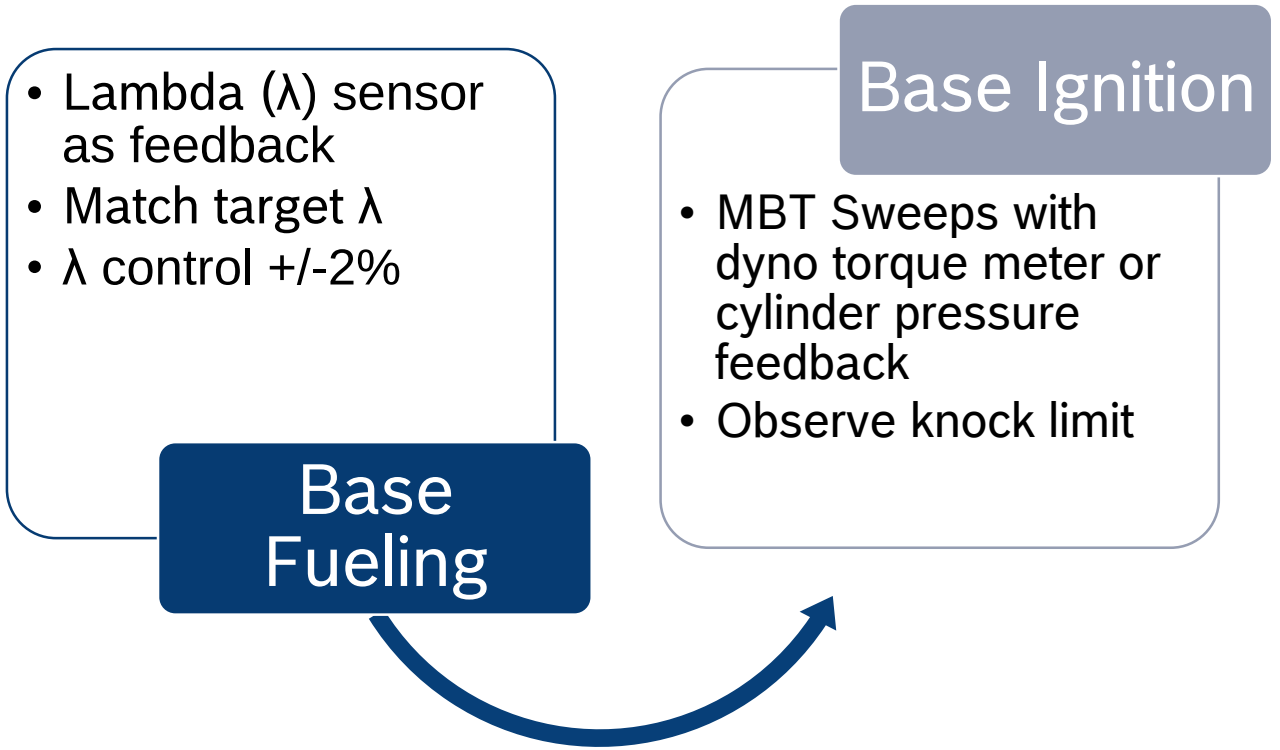
Calibration Development Procedure
Starts

- 3 parts of start
  - Start
  - Post start
  - Warm up





Calibration Development Procedure
Stage 2



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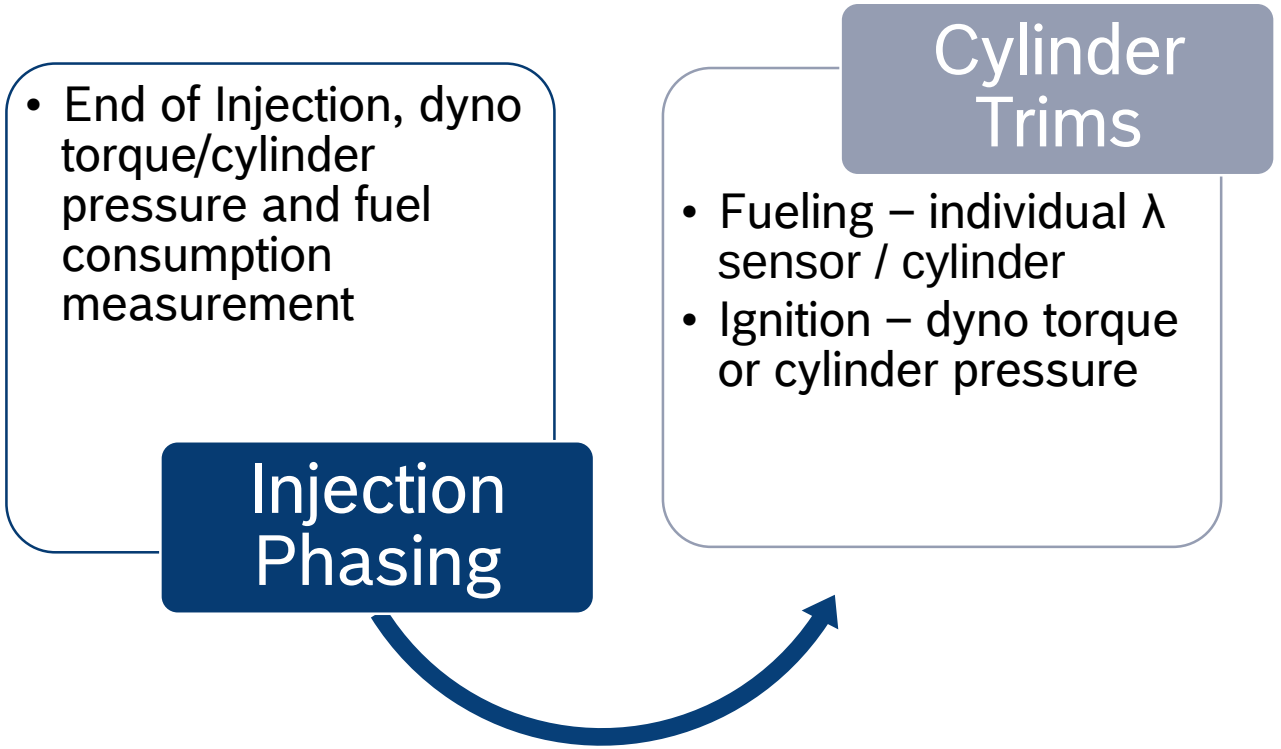
Calibration Development Procedure
Stage 3



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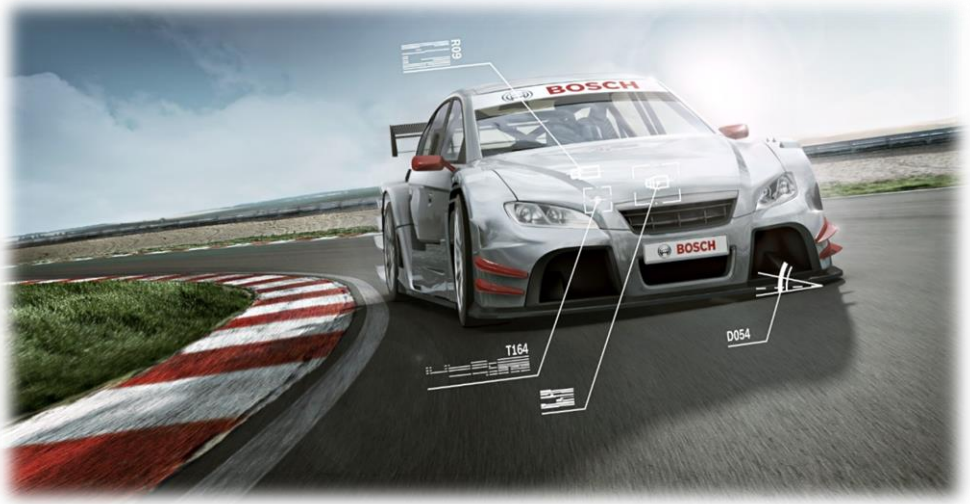

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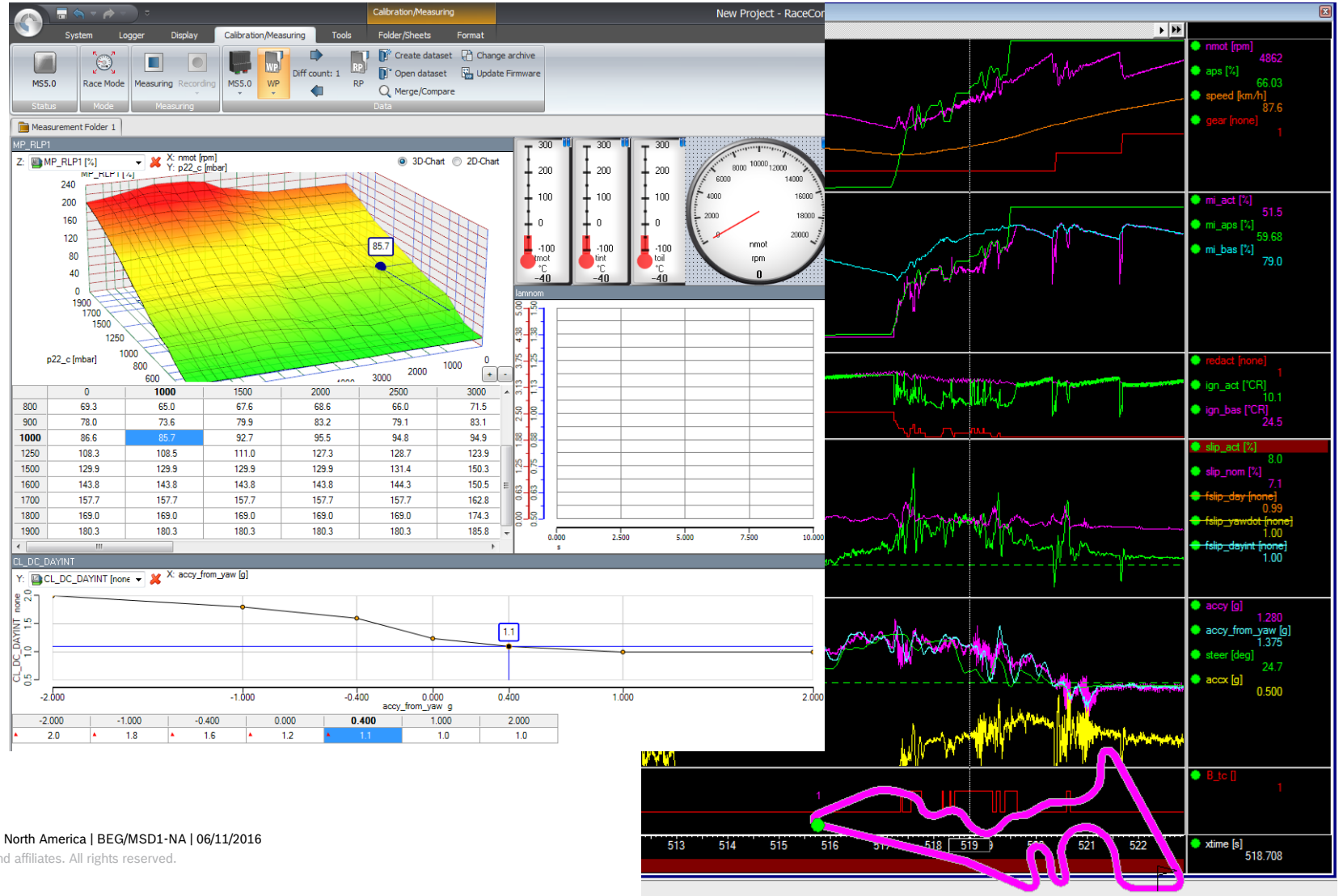
Fuel Calibration



	0	1000	1500	2000	2500	3000
800	69.3	65.0	67.6	68.6	66.0	71.5
900	78.0	73.6	79.9	83.2	79.1	83.1
1000	86.6	85.7	92.7	95.5	94.8	94.9
1250	108.3	108.5	111.0	127.3	128.7	123.9
1500	129.9	129.9	129.9	129.9	131.4	150.3
1600	143.8	143.8	143.8	143.8	144.3	150.5
1700	157.7	157.7	157.7	157.7	157.7	162.8
1800	169.0	169.0	169.0	169.0	169.0	174.3
1900	180.3	180.3	180.3	180.3	180.3	185.8

-2.000	-1.000	-0.400	0.000	**0.400**	1.000	2.000
2.0	1.8	1.6	1.2	1.1	1.0	1.0

Fuel Calibration

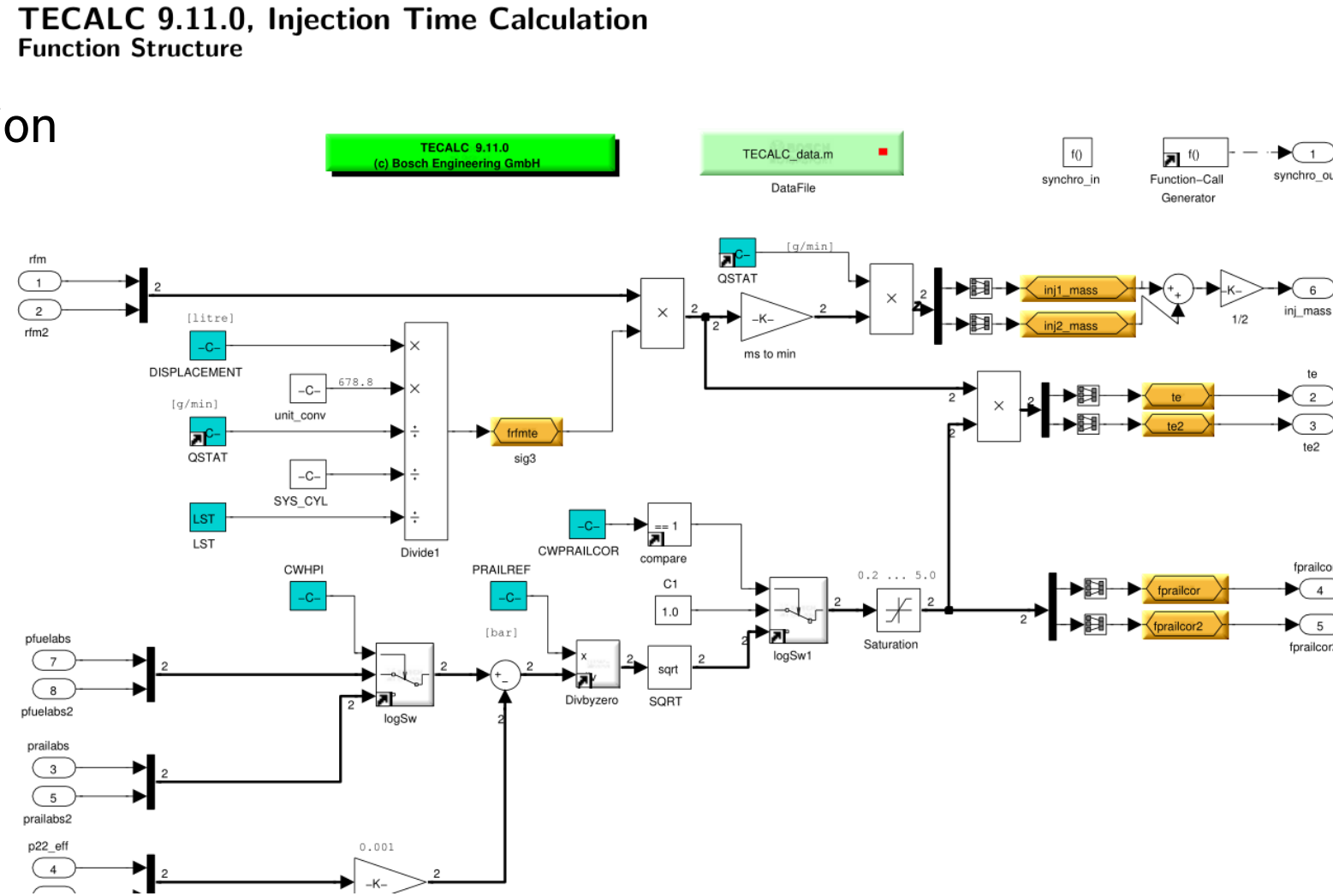
The most important tool!

Lambda measurement

- Sensor accuracy
- Measurement delay
- Per cylinder / bank / engine

Fuel Calibration
Considerations

- Injector Characterization
- Engine load
- Temperatures



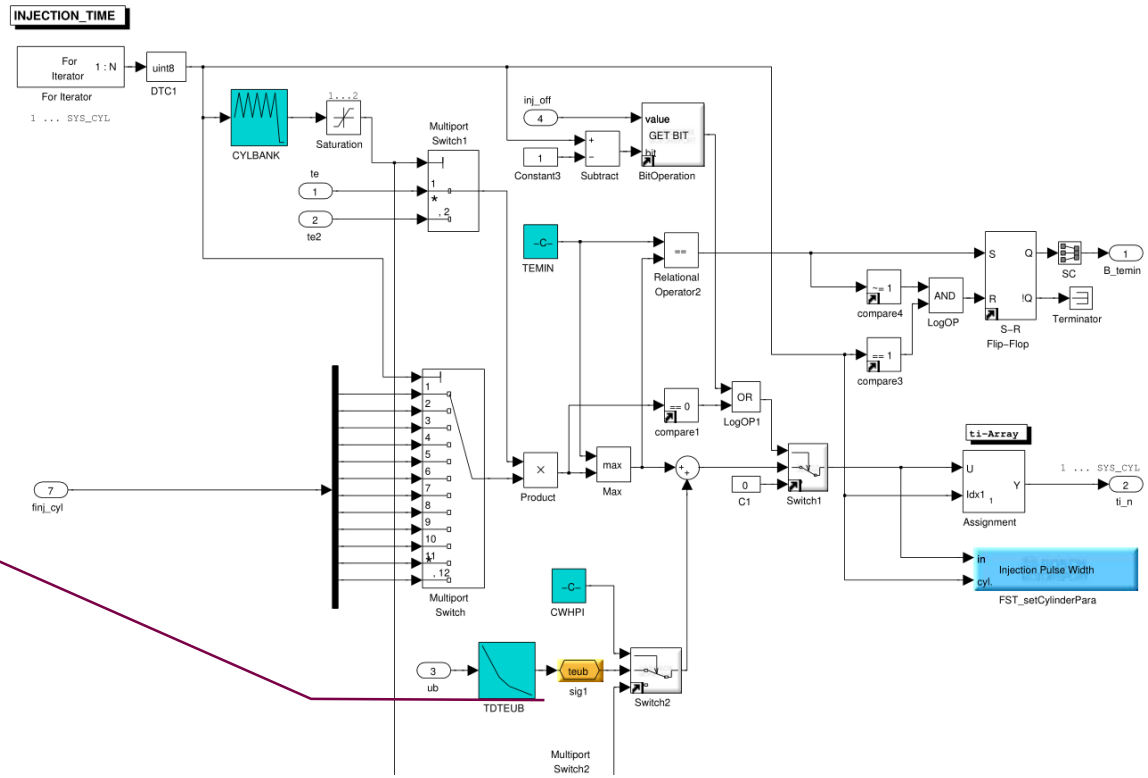
Fuel Calibration

Injector Characterization

- Datasheets or measurement
  - Flow rate
  - Dead time
- Translation to ECU parameters

ID1300 Dynamic Flow Data

Fuel Pressure	Offset (µsec)					Slope
(psid)						(cc/min)
	8 Volts	10 Volts	12 Volts	14 Volts	16 Volts	
43.5	2340	1585	1180	940	750	1345
45	2385	1605	1195	950	760	1365
50	2540	1665	1250	985	790	1445
55	2695	1730	1300	1020	820	1520
60	2850	1810	1350	1055	845	1590
65	3010	1890	1395	1095	875	1655
70	N/A	1980	1445	1135	900	1715
75	N/A	2080	1500	1175	930	1775
80	N/A	N/A	1560	1220	960	1830
85	N/A	N/A	1620	1260	995	1885
90	N/A	N/A	1685	1300	1025	1935

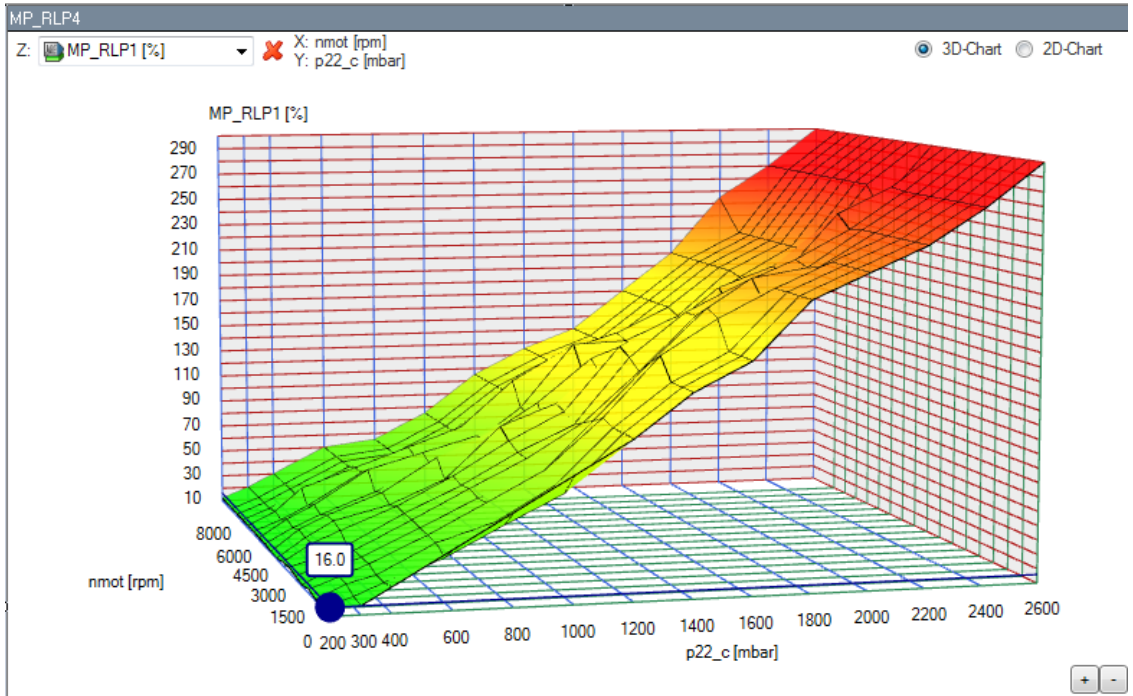


Fuel Calibration
Engine Load

- Steady state or dynamic
- Dynamometer
- On track

Fuel Calibration
Steady State - Dyno

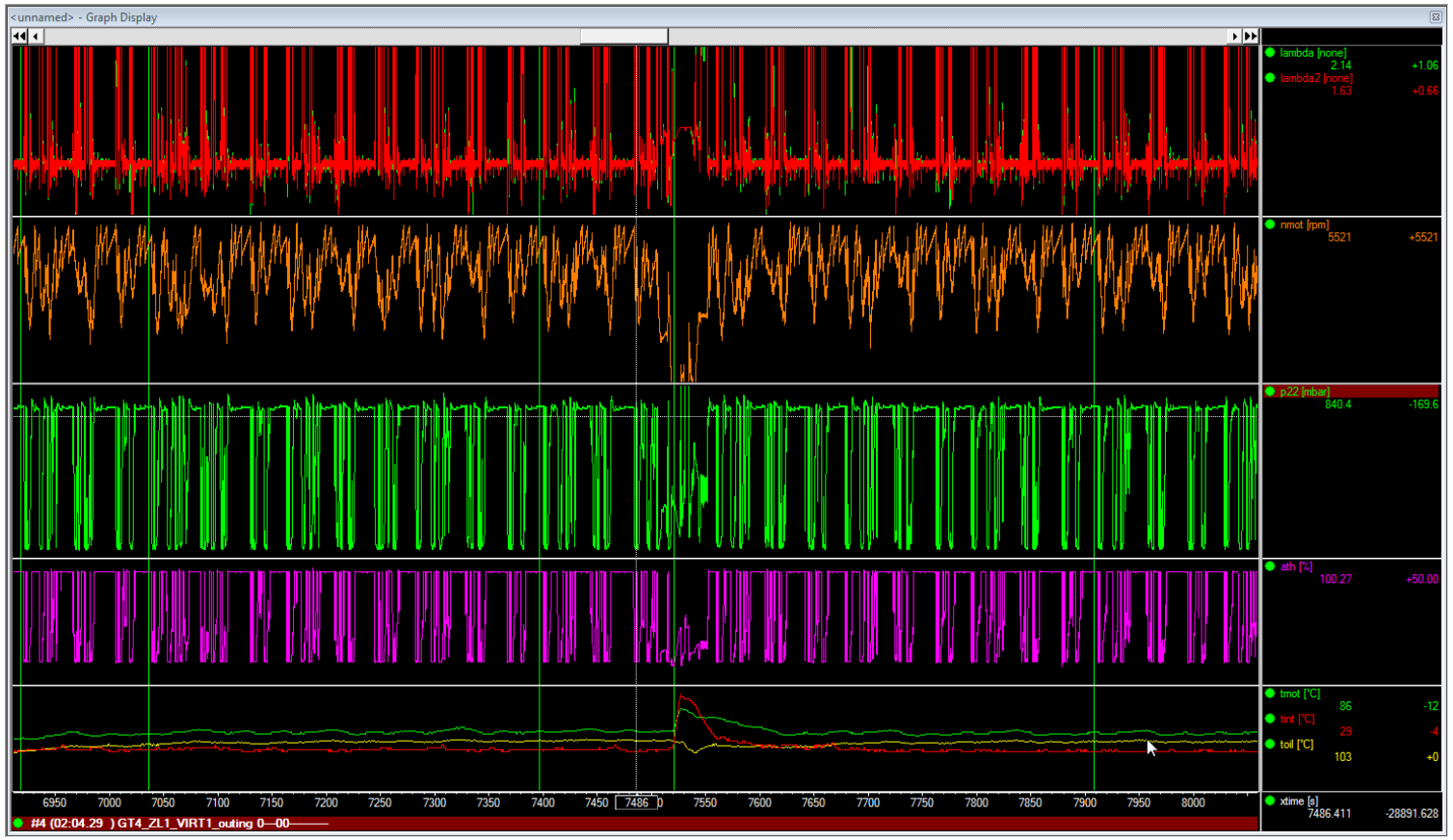
- Systematic calibration of every load site and engine speed site
- Feedback are lambda and torque
- The scaling of the axis is important:
  - Most controllers interpolate linearly between the values
  - Be careful!!!!



	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500	800
200	10.0	10.9	12.9	11.0	12.1	13.6	12.6	10.6	10.8	11.8	11.8	12.0	12.0	12.0	12.0	12
300	17.0	20.5	20.4	21.4	19.6	19.4	24.9	24.6	26.0	22.9	24.8	20.0	22.0	20.0	20.0	20
400	25.4	25.7	28.4	28.3	28.5	27.6	33.4	36.0	35.7	31.8	34.8	30.0	39.1	30.0	30.0	30
600	40.7	45.8	46.6	47.1	48.3	48.5	49.4	46.1	50.8	47.2	59.8	53.6	53.3	50.0	50.0	50
800	61.3	58.5	67.4	66.3	68.8	67.0	69.6	63.3	75.4	66.4	71.0	64.2	67.5	55.0	55.0	55
1000	80.9	81.6	88.5	77.8	88.6	89.0	93.6	100.5	83.8	84.9	82.2	69.7	81.6	75.0	75.0	75
1200	120.0	120.0	123.3	117.5	112.8	107.6	113.8	115.7	90.9	109.7	95.3	99.3	116.3	105.0	105.0	105
1400	150.0	150.0	165.4	157.3	148.1	154.9	159.8	141.1	133.4	141.7	129.3	146.3	138.6	125.0	125.0	125
1600	170.0	170.0	190.0	194.6	186.5	186.1	176.0	166.7	162.3	157.1	144.2	147.9	150.9	140.0	140.0	140
1800	210.0	210.0	210.0	198.4	212.2	205.5	188.7	197.9	175.6	172.9	169.4	165.9	170.0	170.0	170.0	170
2000	227.5	227.5	227.5	221.5	218.8	222.3	209.2	212.6	196.6	192.7	197.4	200.0	200.0	200.0	200.0	200
2200	245.0	245.0	245.0	245.0	245.0	243.3	252.8	235.0	220.7	220.0	220.0	220.0	220.0	220.0	220.0	220
2400	270.0	270.0	270.0	270.0	270.0	270.0	271.6	256.5	270.0	270.0	270.0	270.0	270.0	270.0	270.0	270
2600	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300

Fuel Calibration
Steady State – On track

- Making sense of the squiggly lines…
- Feedback is lambda
- At this point you know what your target lambda is.



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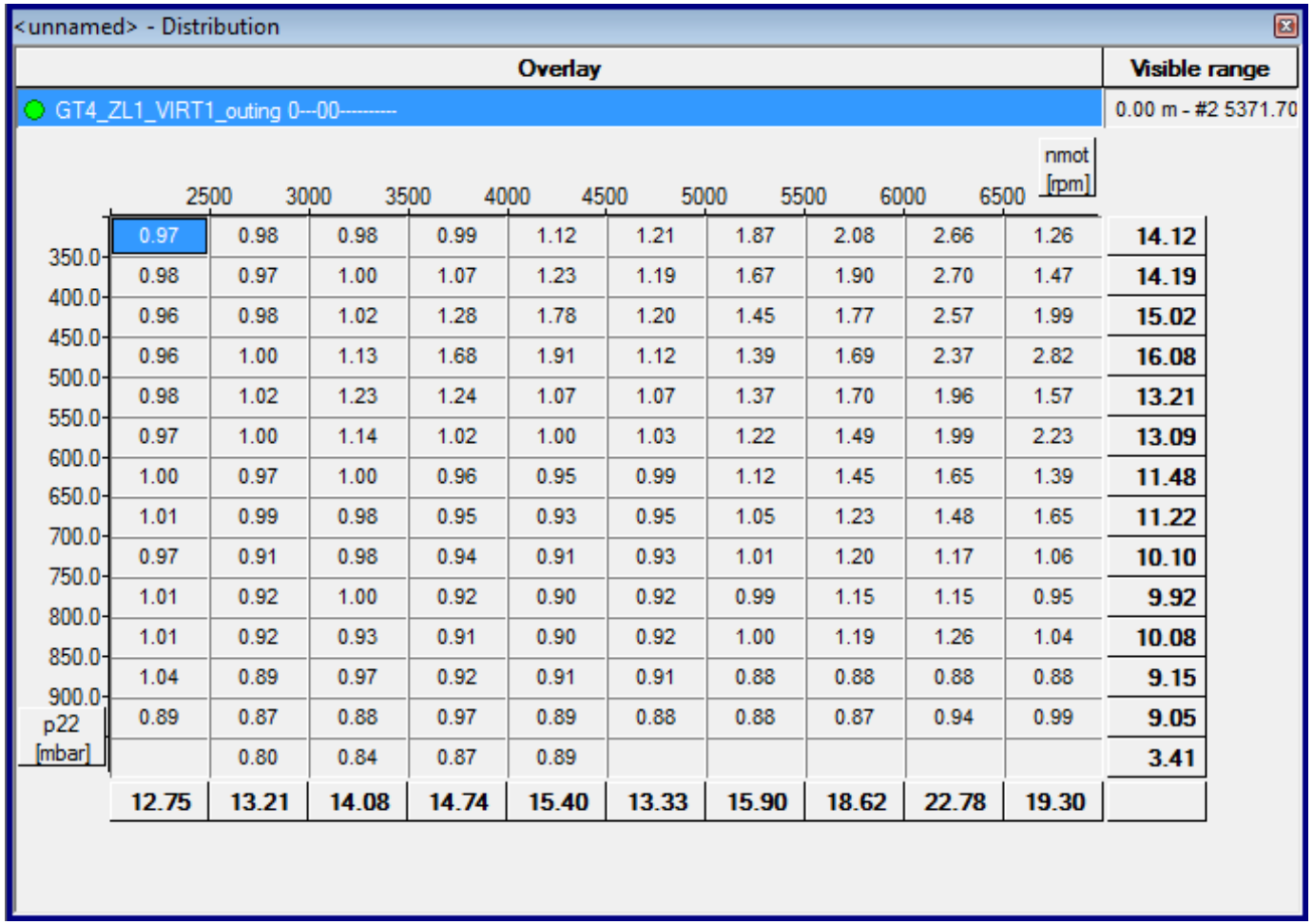
Fuel Calibration
Steady State – On track

- No more squiggly lines!
- Direct answer



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Fuel Calibration
Transients

- Goal
  - Minimize deviation between target and actual lambda under dynamic engine operating conditions

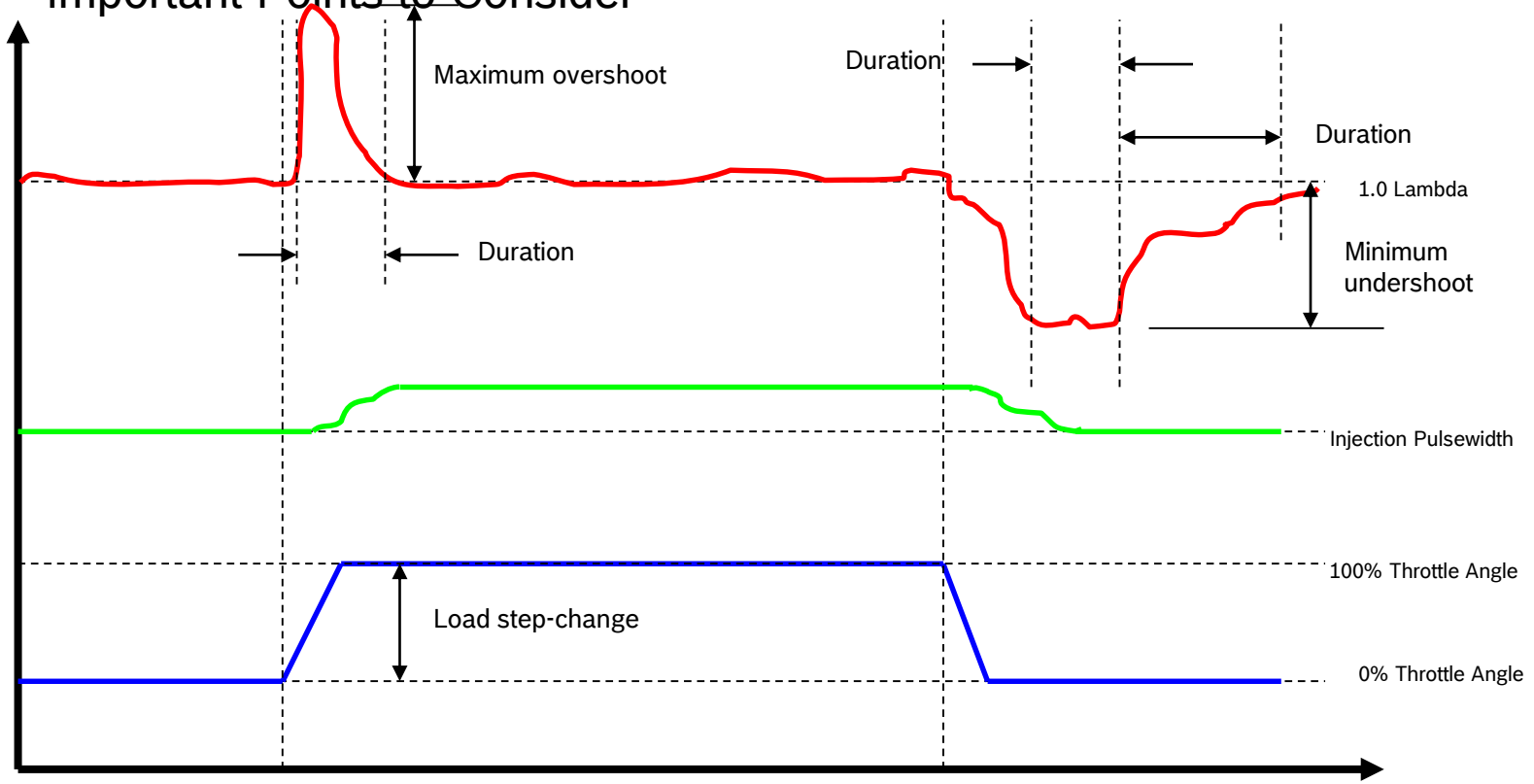
- Target Results
  - Improved driveability/torque delivery
  - Improved dynamic engine response
  - Reduced fuel consumption

Fuel Calibration
Transients

- Calibration process
  - Prerequisites
    - Injector Base Data
    - Disable Closed Loop Control for Lambda
    - Disable Decel Fuel Cut-Off
  - Definition of engine speed test matrix
    - Ex. 2000 – 7000 rpm, 500 rpm increments
  - Definition of load step-change points
    - Ex. Throttle Position based
      - 0-20-0, 0-40-0, 0-60-0, 0-80-0, 0-100-0
      - 20-60-20, 20-80-20, 20-100-20, 40-80-40, 60-100-60
  - Evaluation of positive and negative load step for each test point
  - Population of calibration gains/factors

Fuel Calibration
Transients

- Data Analysis – Important Points to Consider



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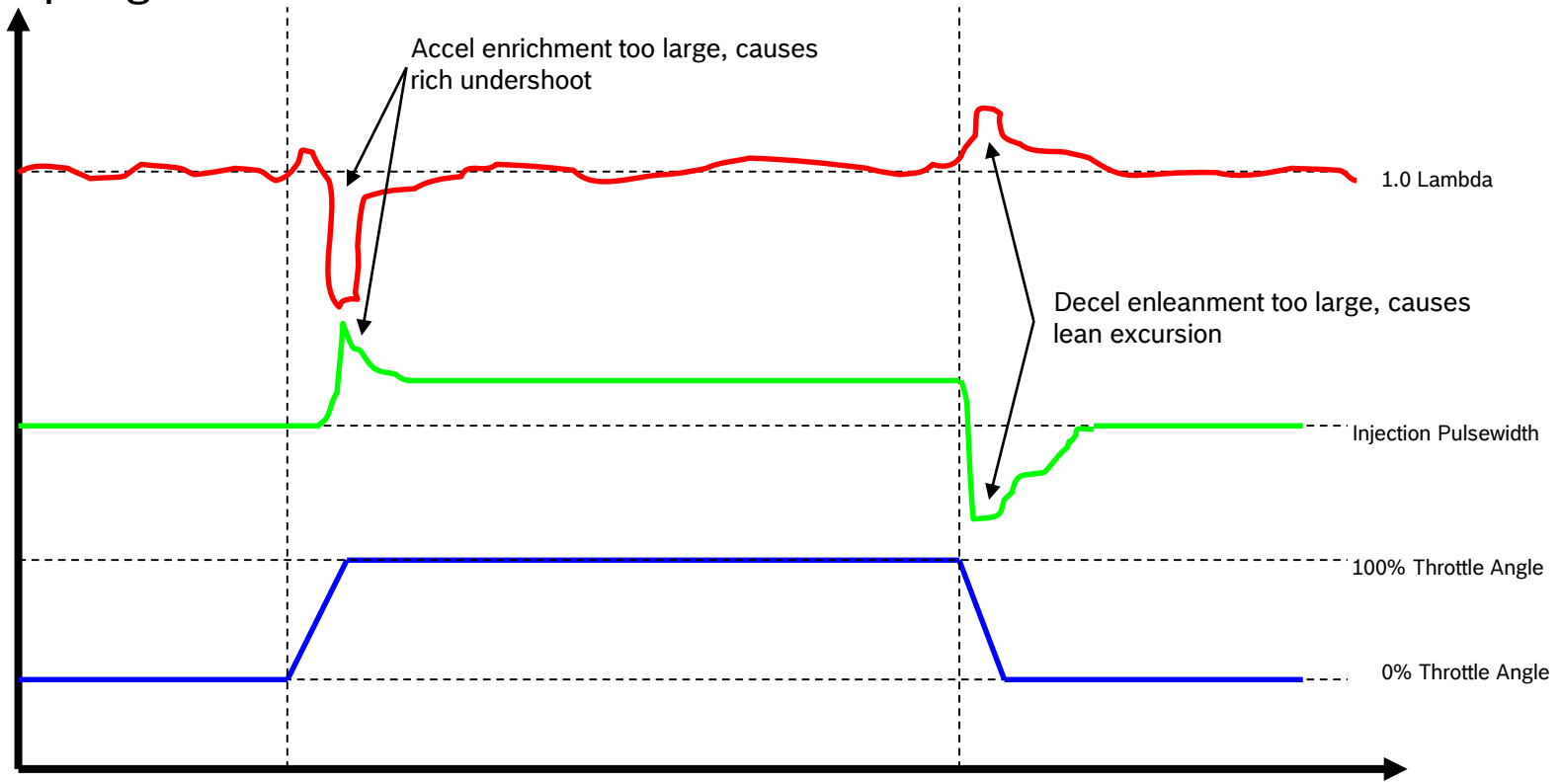
Fuel Calibration
Transients

- Example – improper gains



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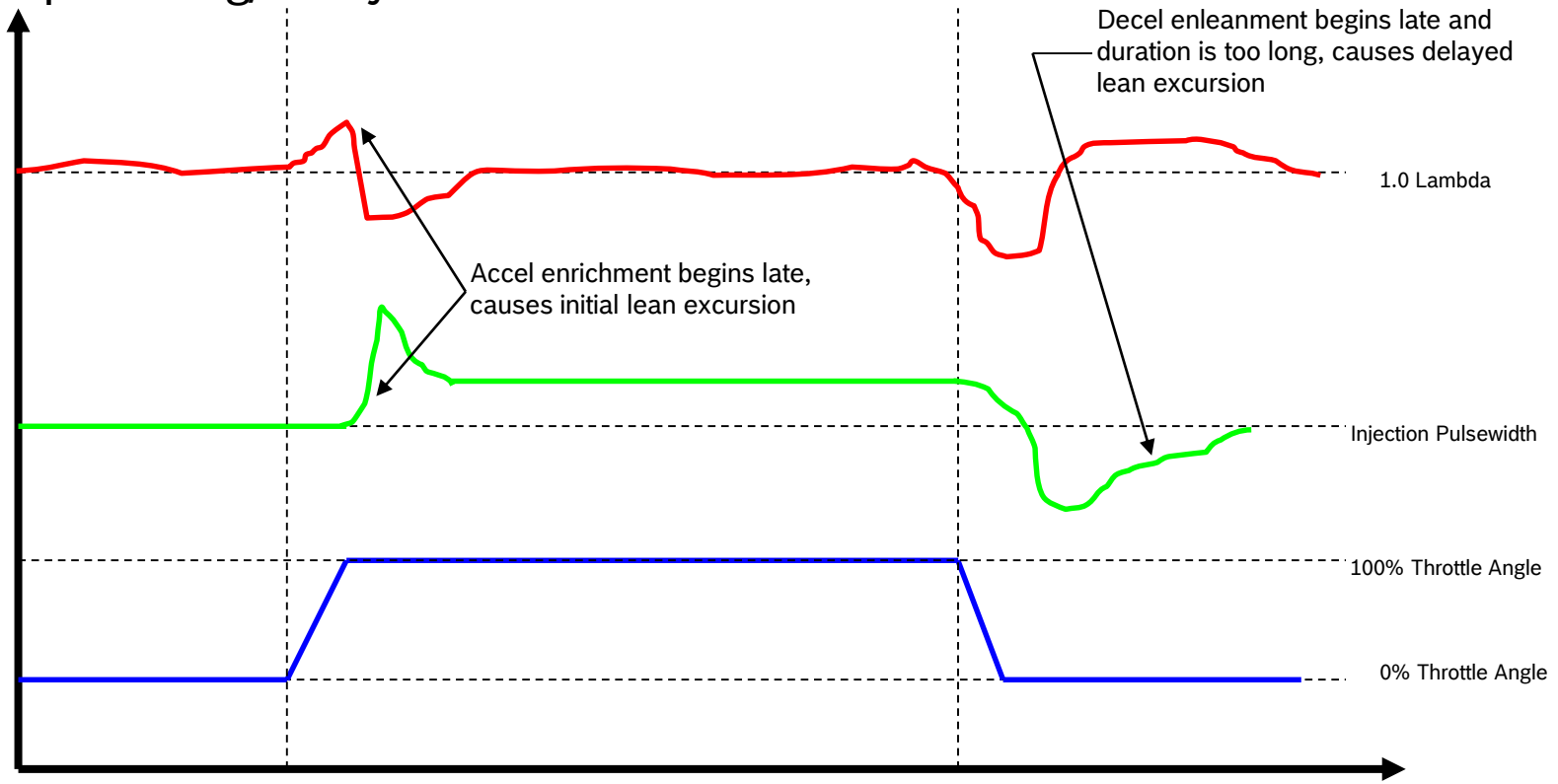
Fuel Calibration
Transients

- Example – improper timing/decay



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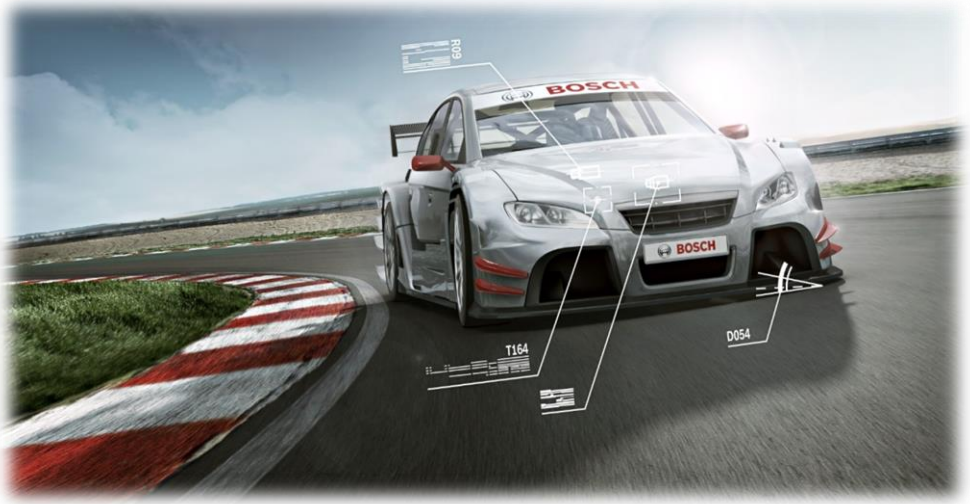

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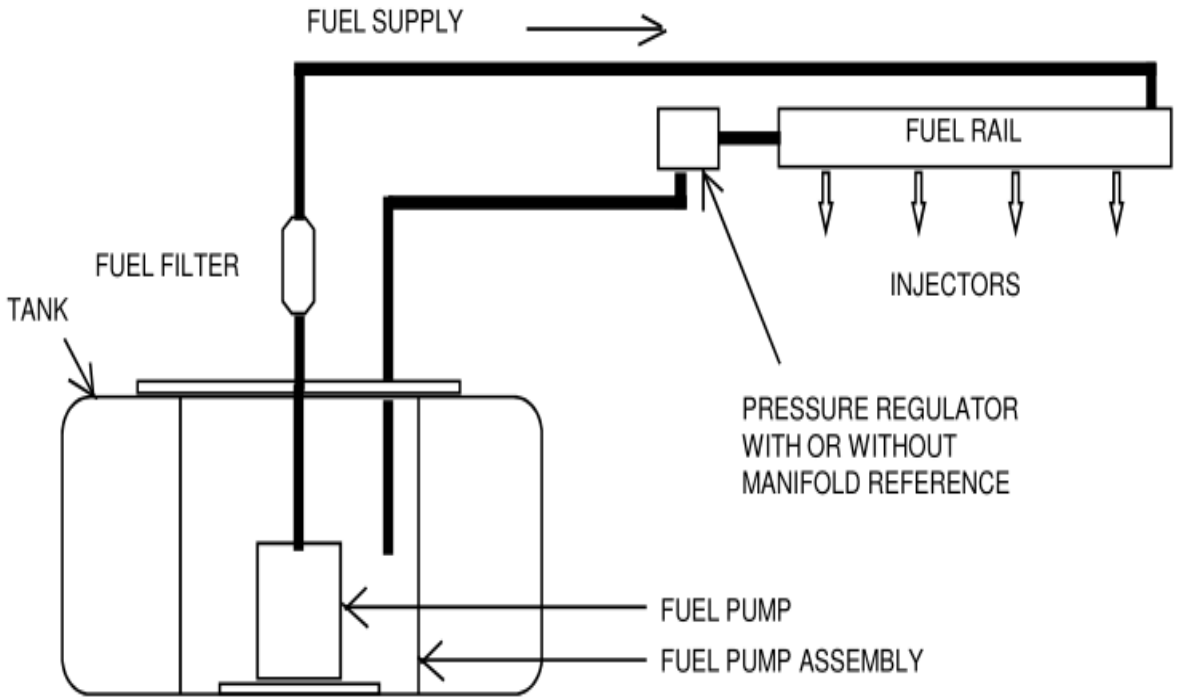
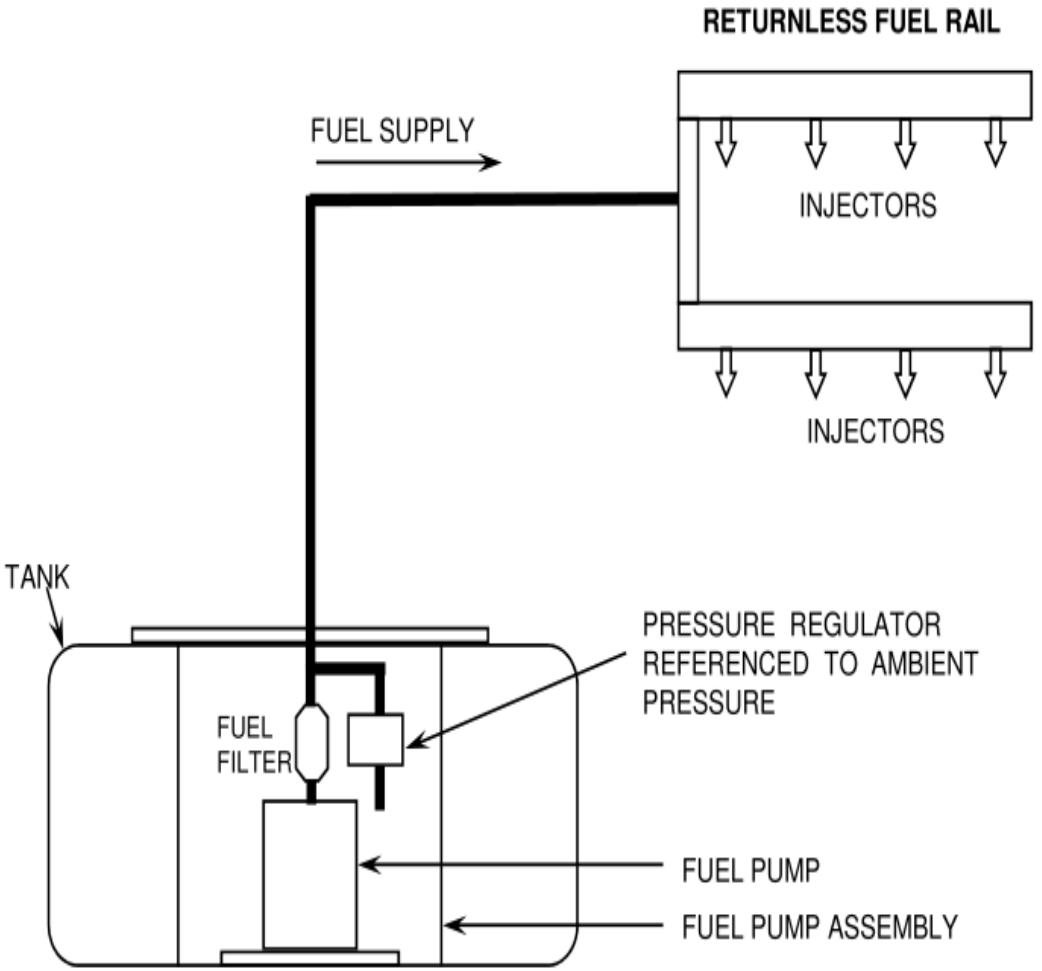
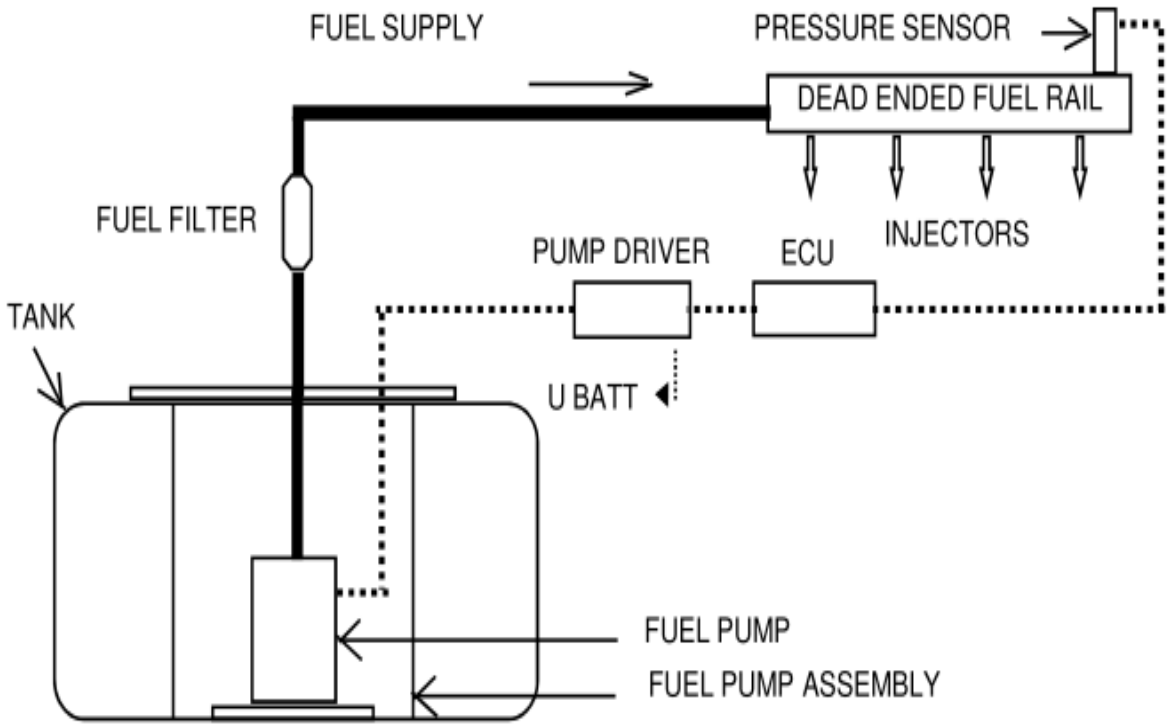
Fuel System Components
Overview – Fuel Return, Mechanical Regulator



Fuel System Components
Overview – Returnless, Mechanical Regulator



Fuel System Components
Overview – Returnless, Regulated Pump Speed



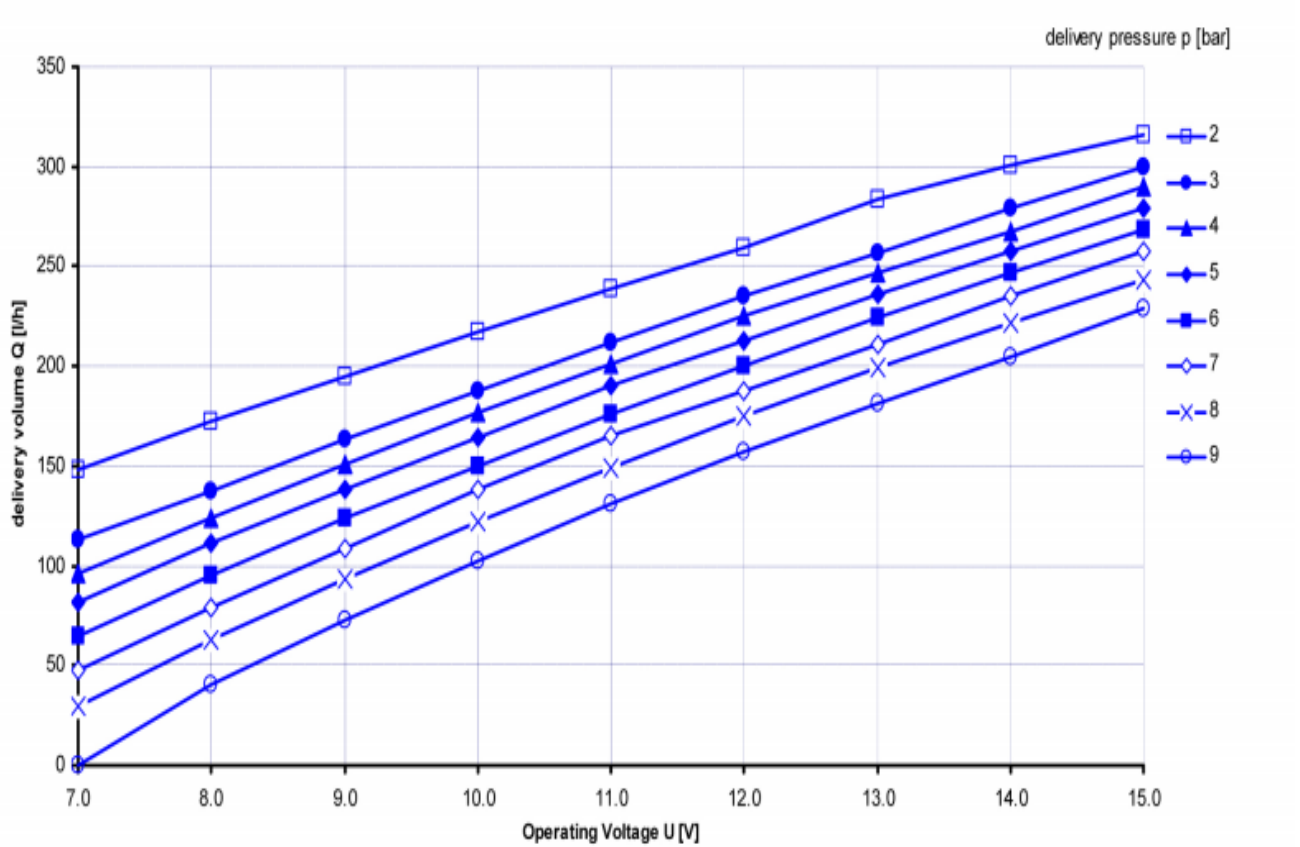
Fuel System Components
Pump

Considerations
- Flow capacity
- Fuel type
- Efficiency
- Control type
- Size / weight / package

Fuel System Components

Pump

As pressure increases flow decreases



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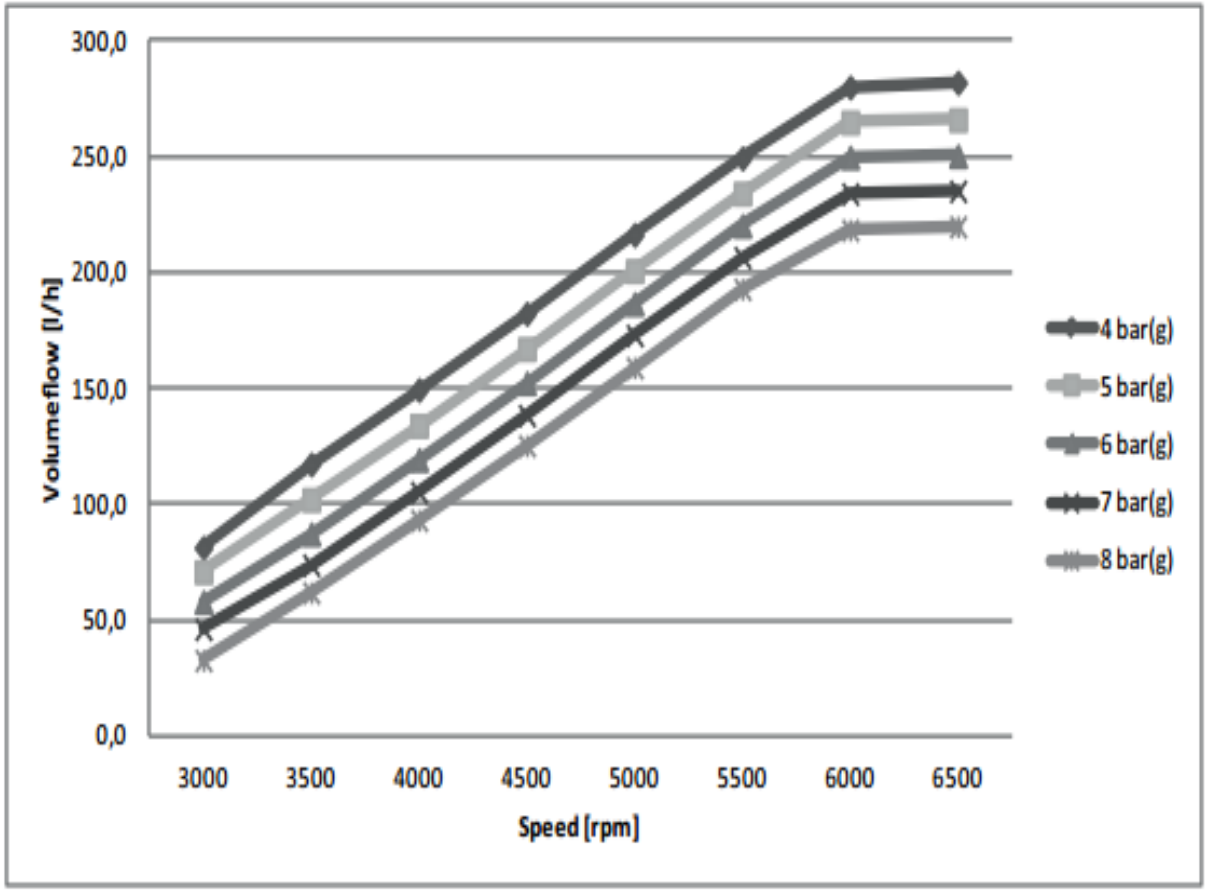
Fuel System Components

Pump

Control opportunities with brushless DC



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Fuel System Components
Pressure Regulator

Considerations

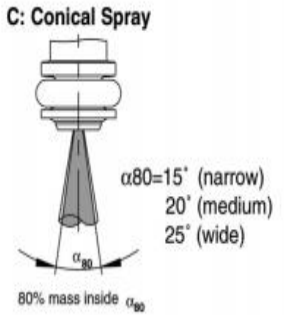
- Reflow
- Fuel type
- Manifold reference

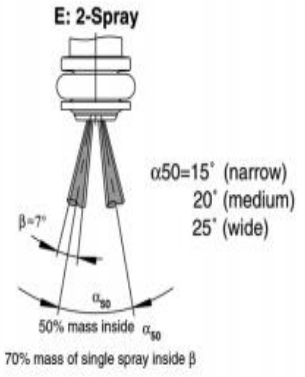
Application	
Pressure range	5 bar
Reflow quantity	15 to 220 l/h
Reference pressure connector	Diam. 5 mm, tube connector
Fuel compatibility	Gasoline, E85, M15
Operating temperature	-40 to 120°C
Storage temperature	-40 to 100°C
Max. vibration	<600 m/s² at 5 to 250 Hz

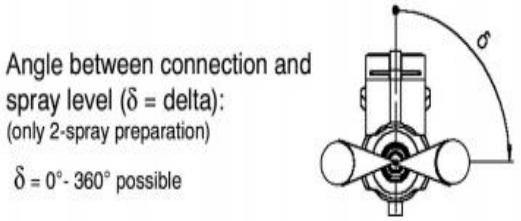
Fuel System Components
Injector

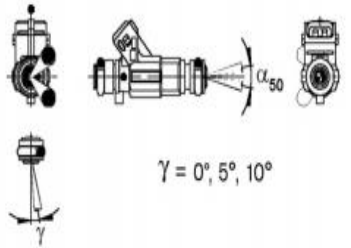
Considerations

- Flow
- Pressure rating
- Manifold location
- Spray pattern
- Fuel type
- Impedance









Fuel System Components

Injector

Flow, Pressure and Time

- Dead time
- Min injection time
- Duty cycle

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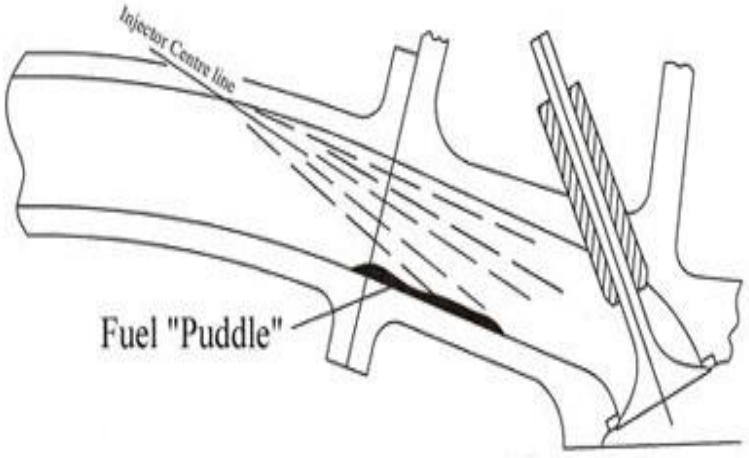
Fuel System Components

Injector

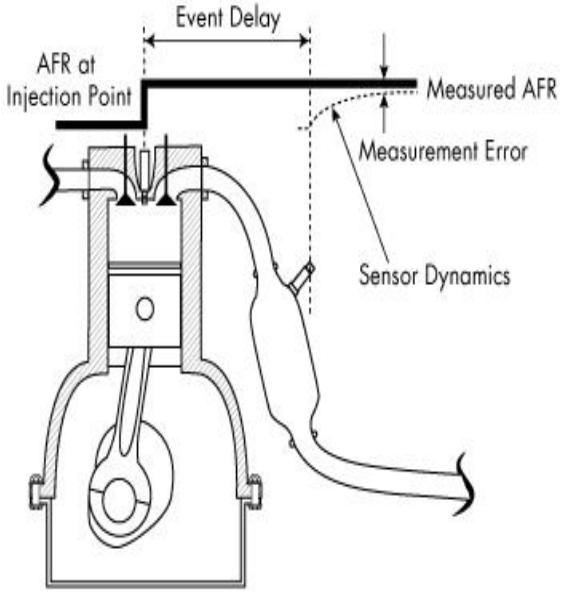
Injector Placement

- Spray pattern
- Upper and lower injectors?



Fuel System Components
Lambda Sensor

Considerations
- Location
- Heat
- Pressure



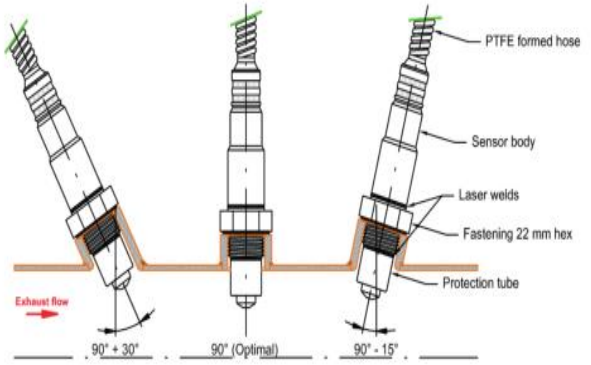
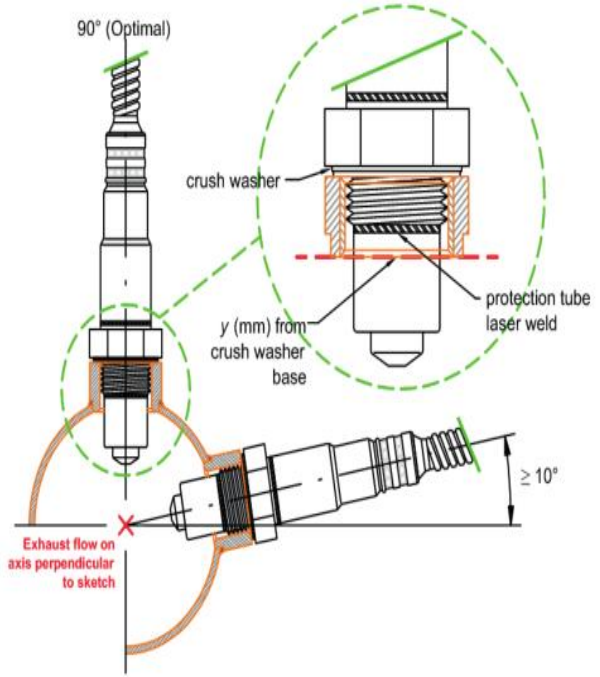
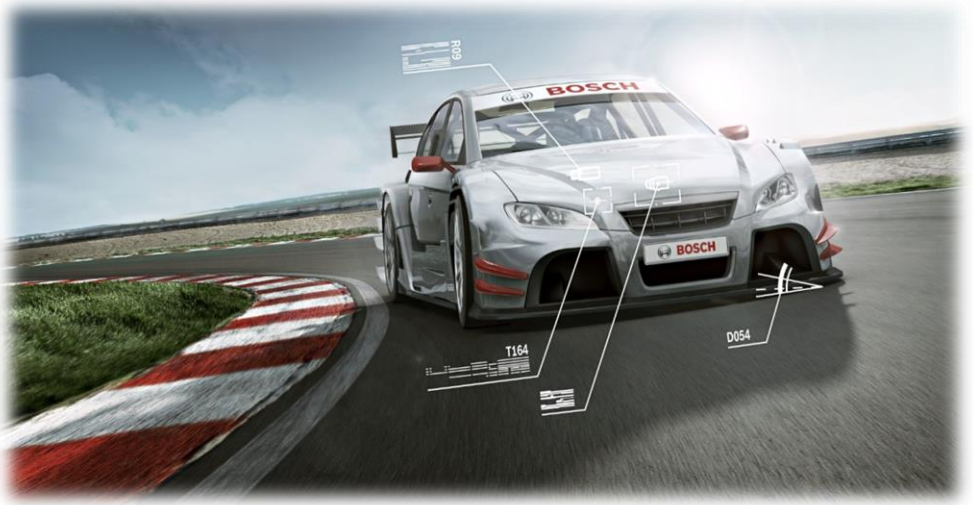


Fig. 5: Lambda Sensor Installation Diagram, Part 1



Agenda

1. Presentation
2. Test Equipment
3. Basic Calibration Development Procedure
4. Fuel Calibration
5. Fuel System Components
6. Conclusion



BOSCH

The Key to FSAE

Set goals
Experiment
Test
Measure
UNDERSTAND

Thank you !

Questions?

Comments?