COMMON RAIL DIESEL CONTROL SYSTEM

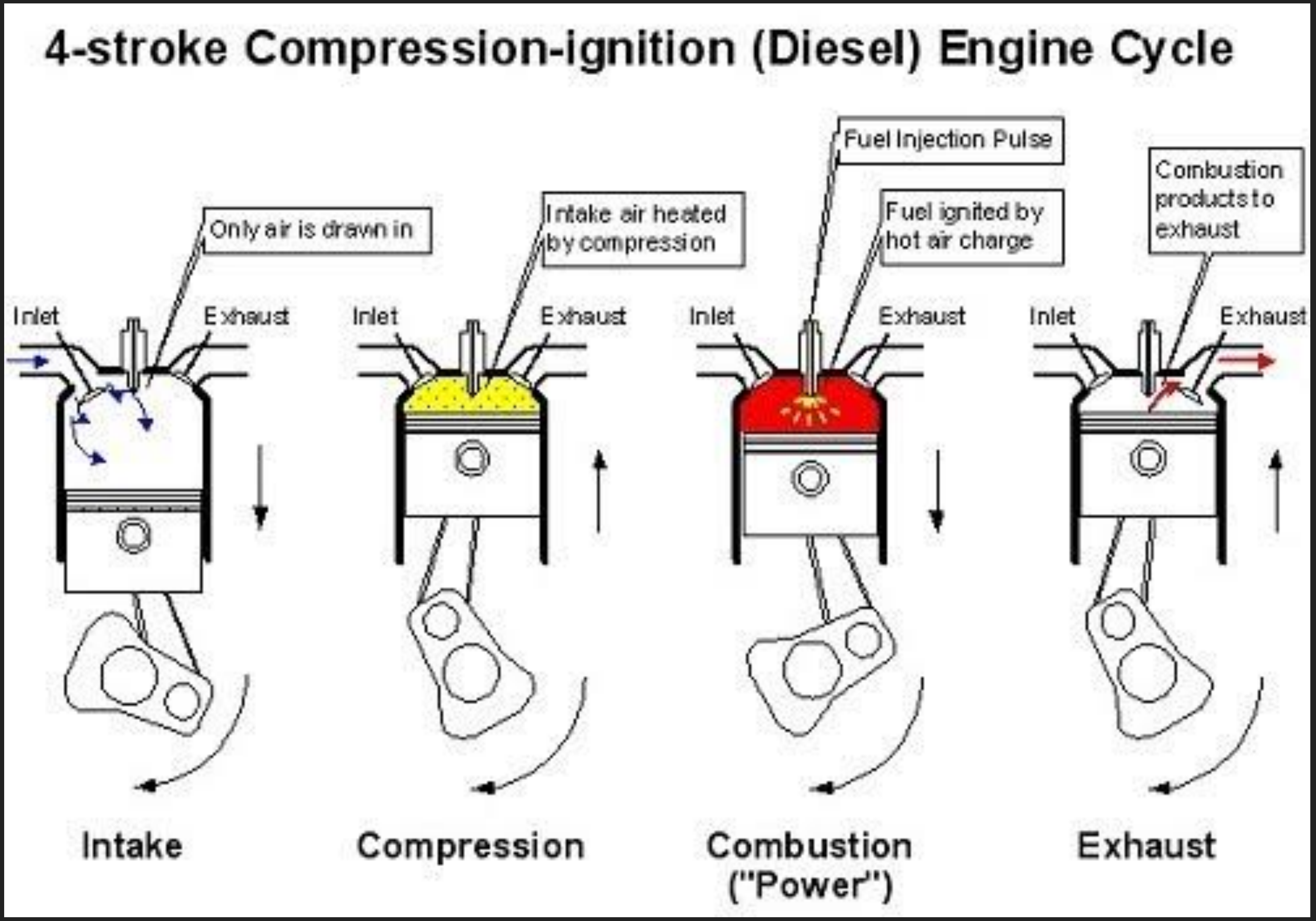
AGENDA

- Diesel Cycle and Engine Background
- Control ECU Hardware
- Control ECU Software
- Injector Driver Hardware/Microcode
- Engine Model Calibration
- Code Walkthrough (Time Permitting)

COMMON RAIL DIESEL

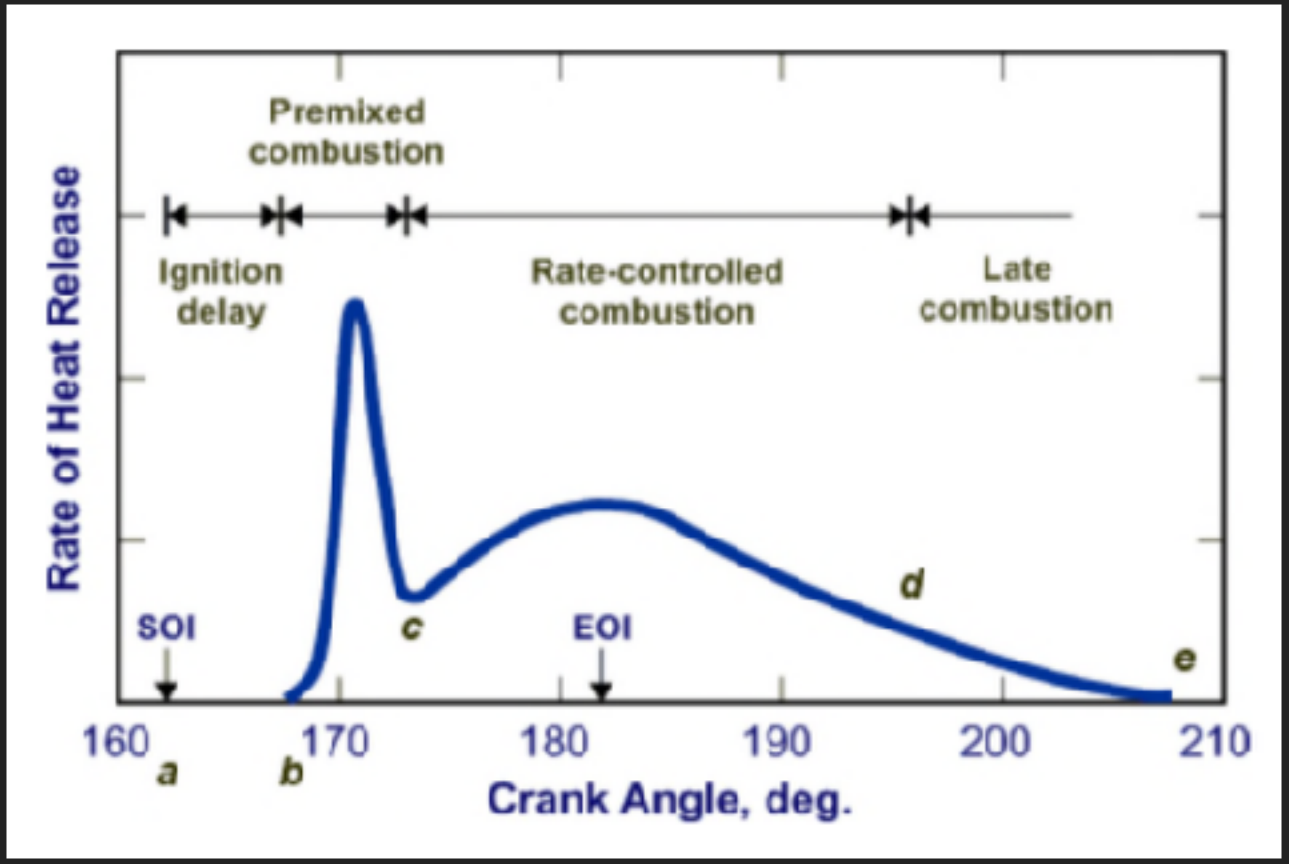
BACKGROUND

DIESEL CYCLE



DIESEL COMBUSTION

- Combustion initiated as fuel delivered and mixed
- Rapid burn during premixed phase results in 'Diesel Clatter'
- Precise injection rate shaping can reduce clatter



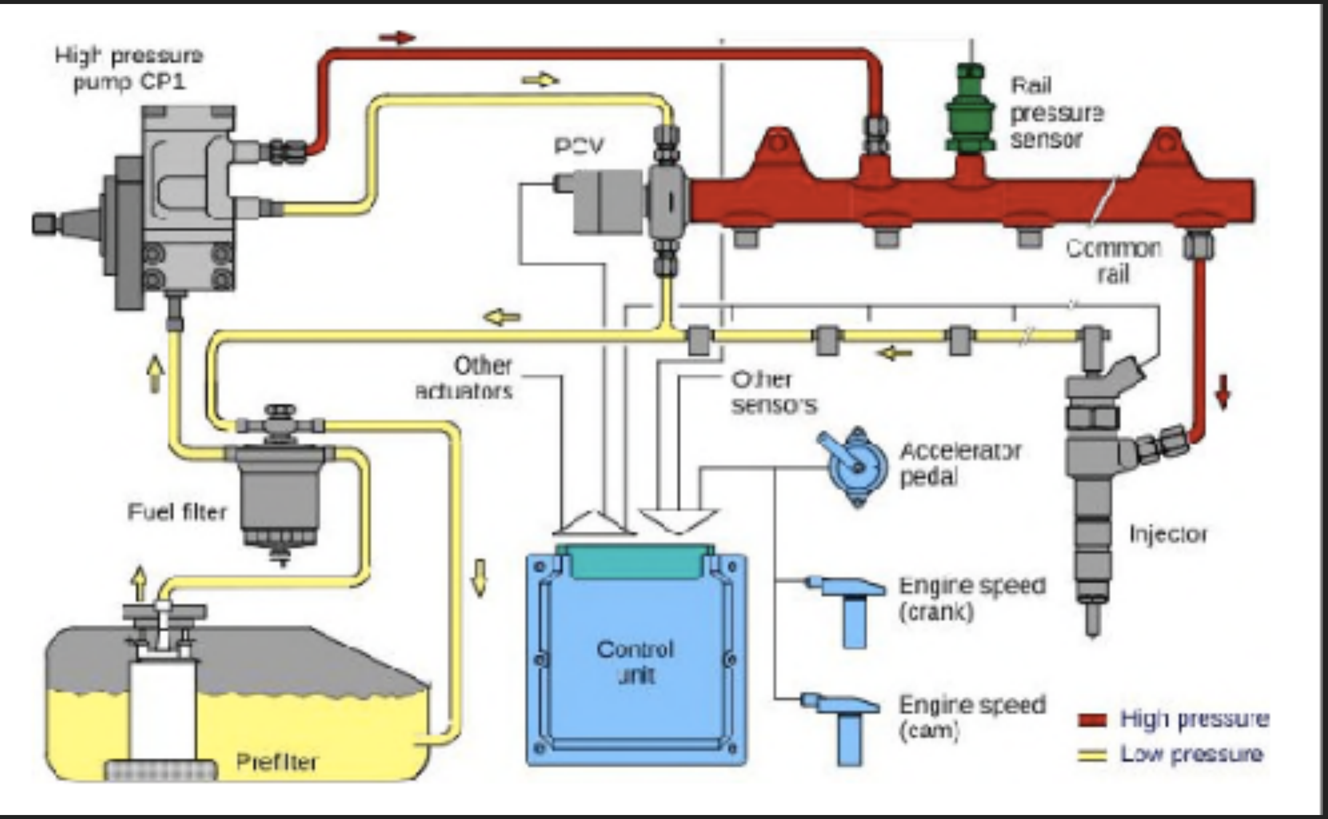
ENGINE - MERCEDES-BENZ OM660

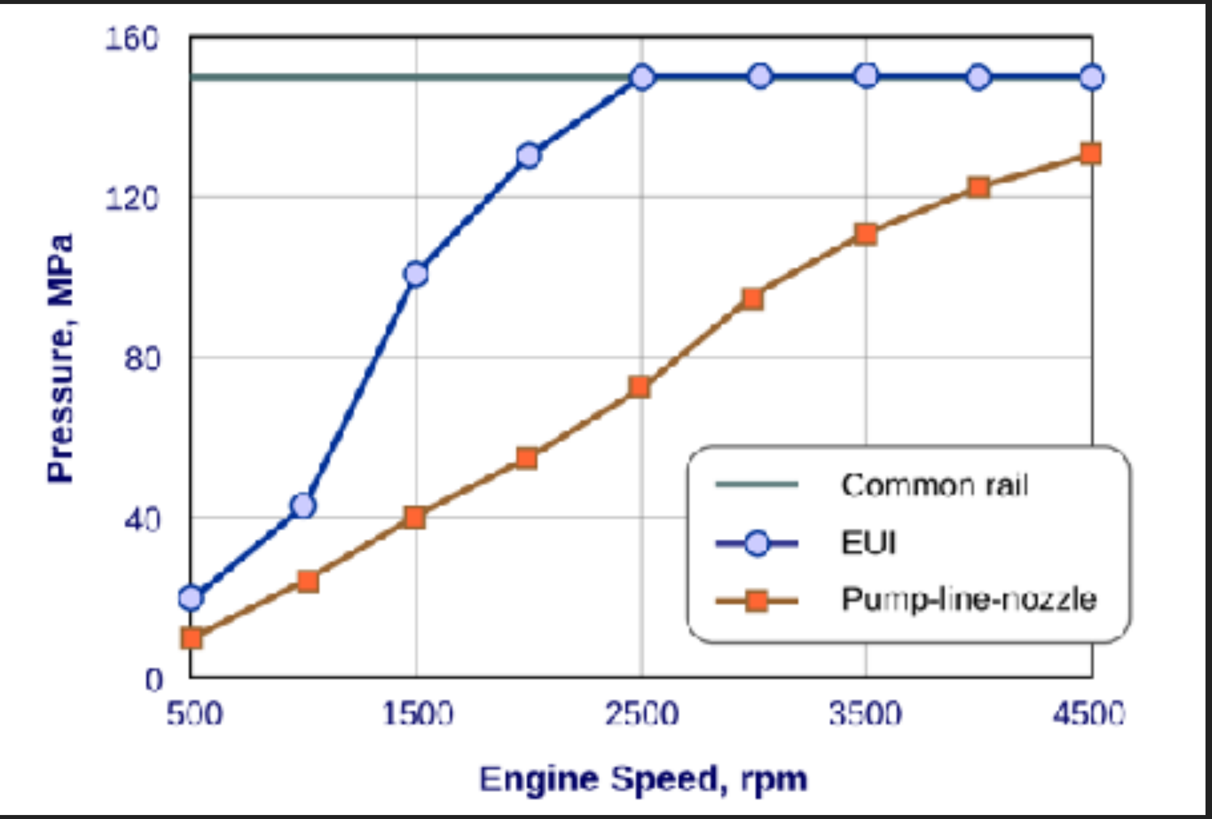
Model	OM660
Displaced volume	799cc
Stroke	79mm
Bore	65.5mm
Compression ratio	18.0:1
Number of cylinders	3 in-line
Dry weight	190lb
Combustion chamber	Direct injected
Valvetrain	Chain-driven OHV
Induction System	Turbocharged
Rated Power	33kW @3800rpm
Rated Torque	100Nm @2000rpm
Fuel System	Common Rail
Fuel Injector Type	CRS1
Fuel Pump Type	CP1
Maximum Fuel Pressure	1400 Bar
Fuel System Supplier	Bosch

smart

COMMON RAIL DIRECT INJECTION

- Full-authority electronic control of all injection parameters
- Full injection pressure at any engine speed
- Injection rate shaping via pilot injection(s)



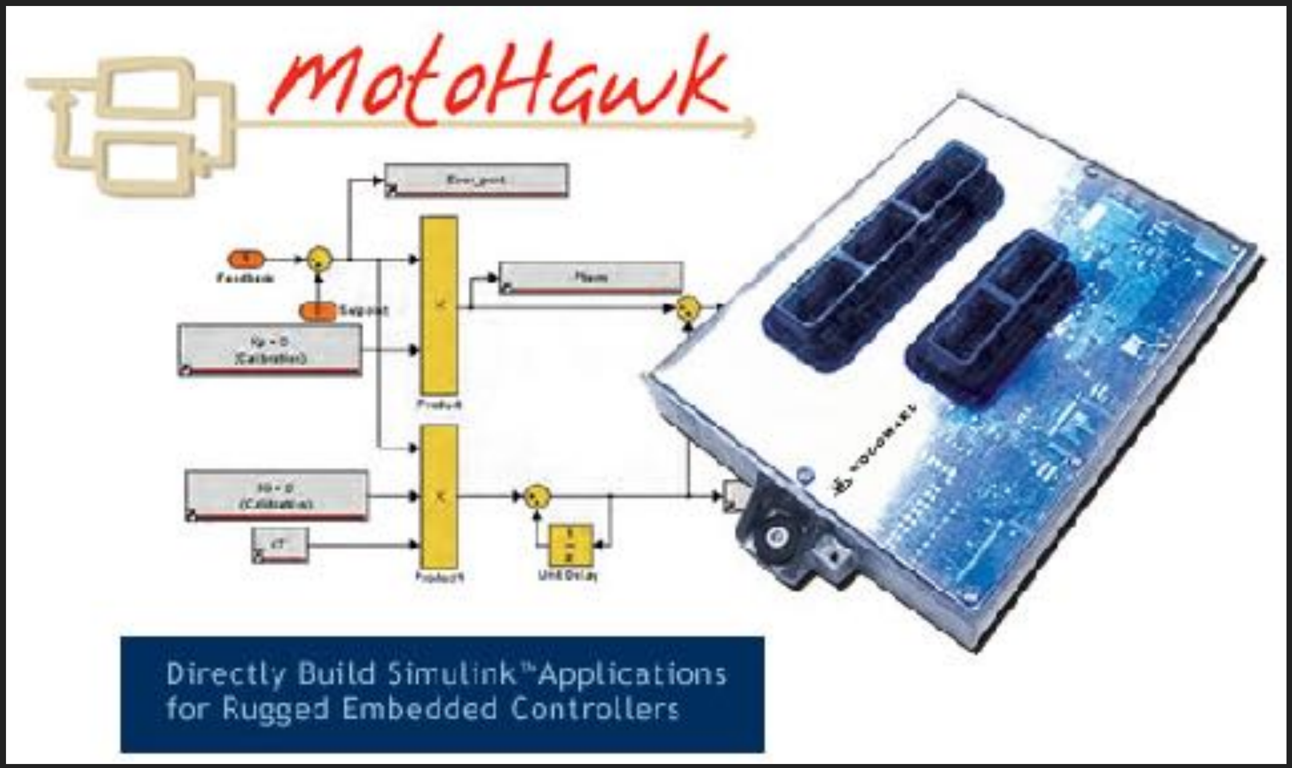


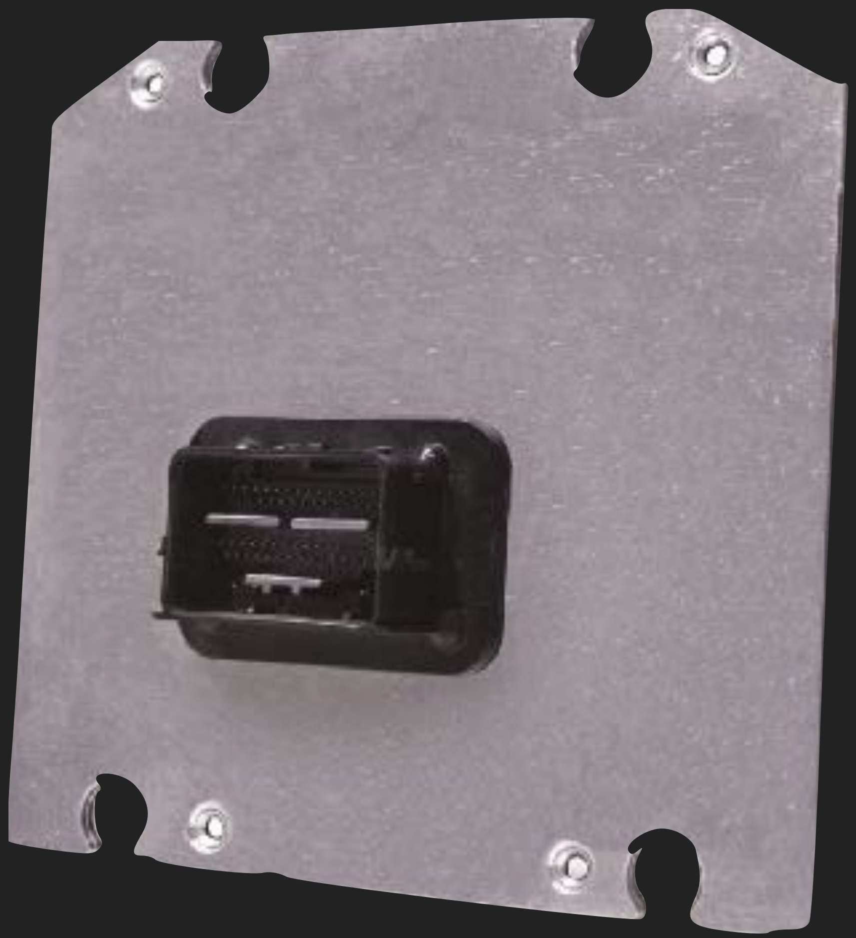
COMMON RAIL DIESEL

CONTROL HARDWARE

WOODWARD MOTOHAWK CONTROL SYSTEM

- Control development platform for rapid prototyping and low volume production
- Off-the-shelf hardware modules and Simulink development environment





WOODWARD MOTOHAWK CONTROL SYSTEM

Model	SECM70 - 1565
Processor	ST SPC563M (PowerPC Book E + SPE/EFPU)
Flash	1.5Mb
RAM	94Kb
EEProm	16Kb (Serial)
Inputs	13 Analog 2 EGO (1 Wide Range / 1 Narrow Range) 2 Knock DSP 4 Switch 3 Frequency/Encoder (2 Variable Reluctance)
Outputs	9 Low Side Drive 4 Relay Drive 4 Peak & Hold Injector 2 Saturating Injector 6 5v TTL Trigger 1 H-Bridge
Communications	2x CAN 2.0B

WOODWARD MOTOHAWK CONTROL SYSTEM

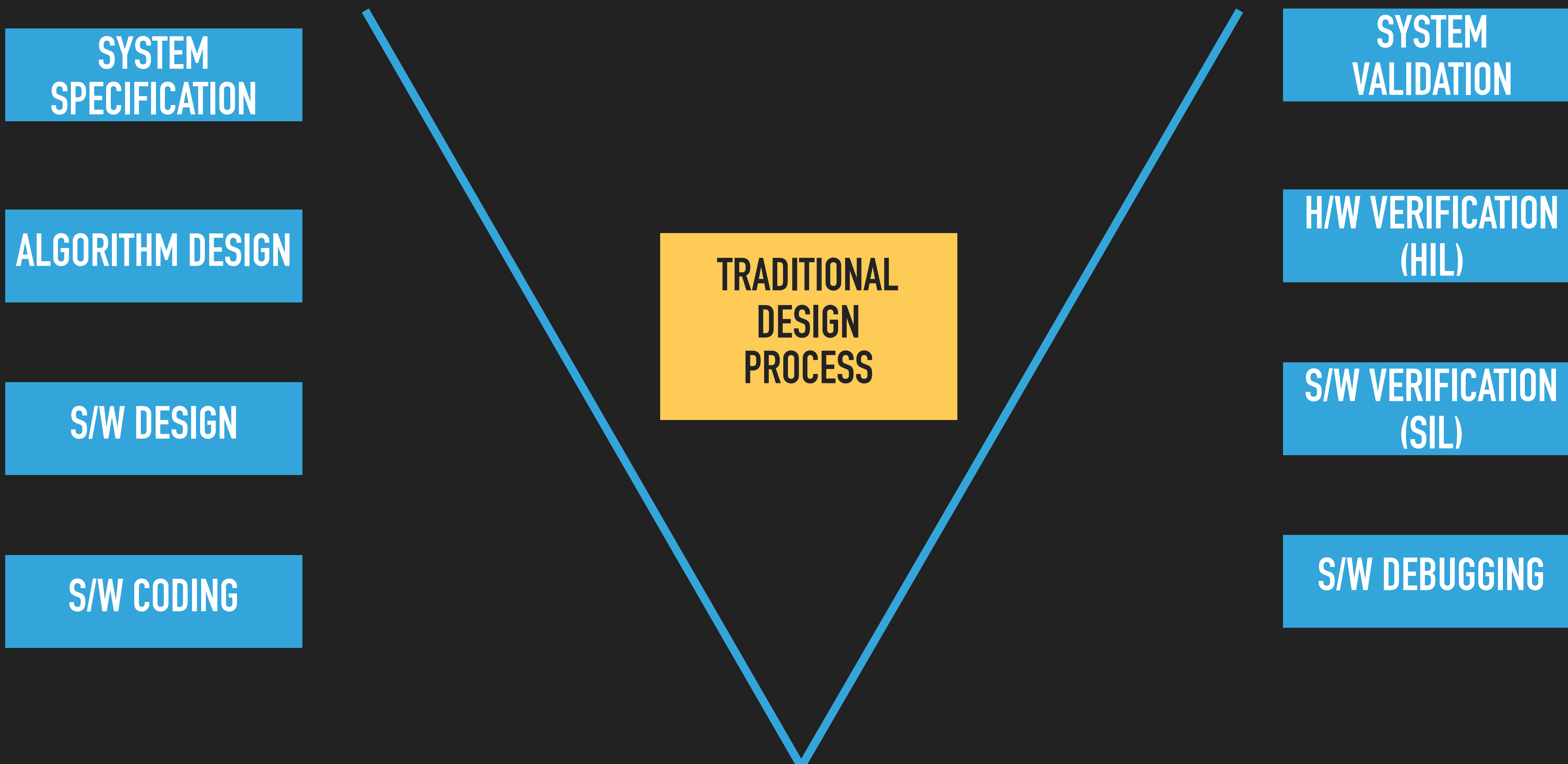
Tear-down of Woodward ECM48 module for reference

(No SECM70 modules have been harmed yet)

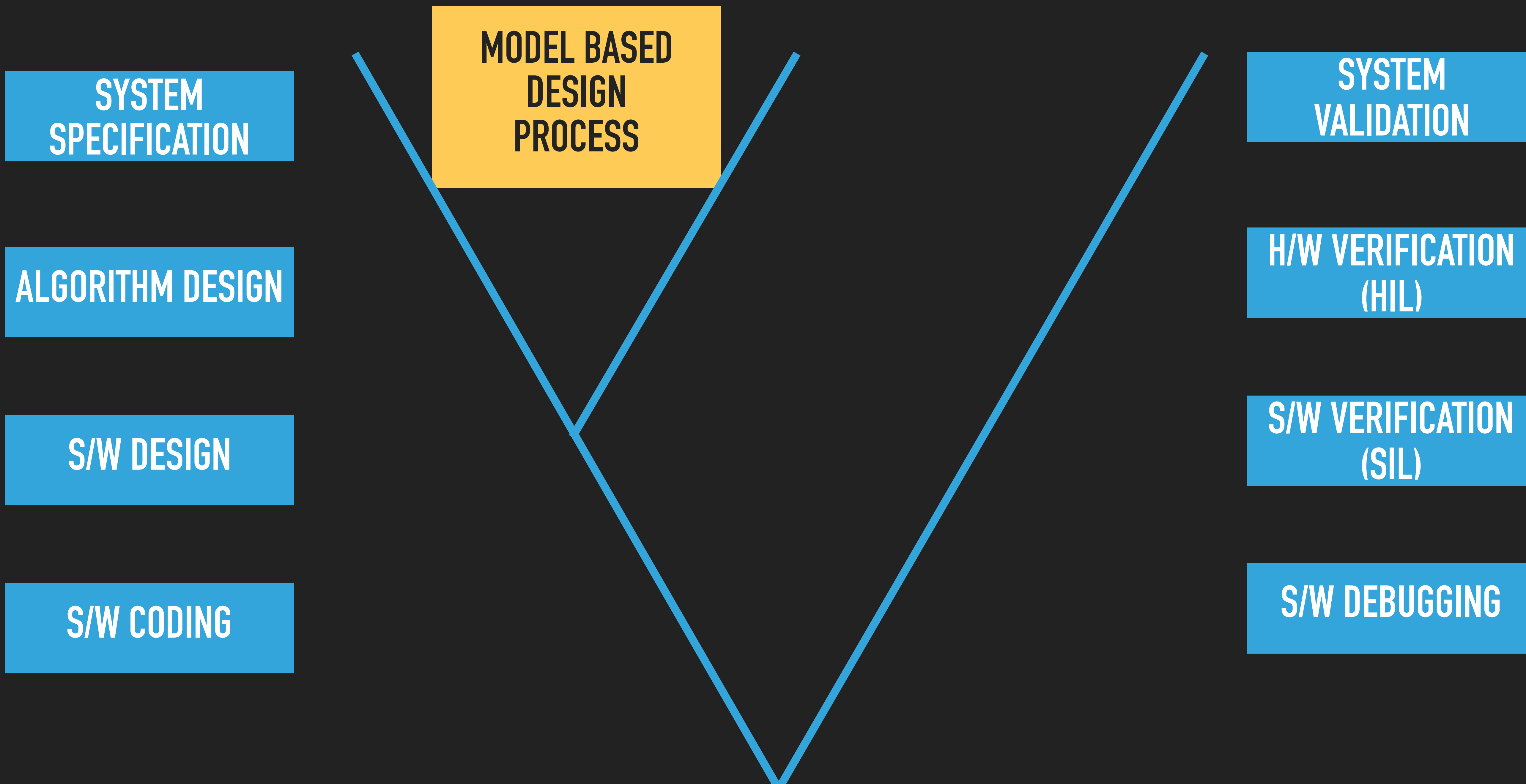
COMMON RAIL DIESEL

CONTROL MODEL DESIGN

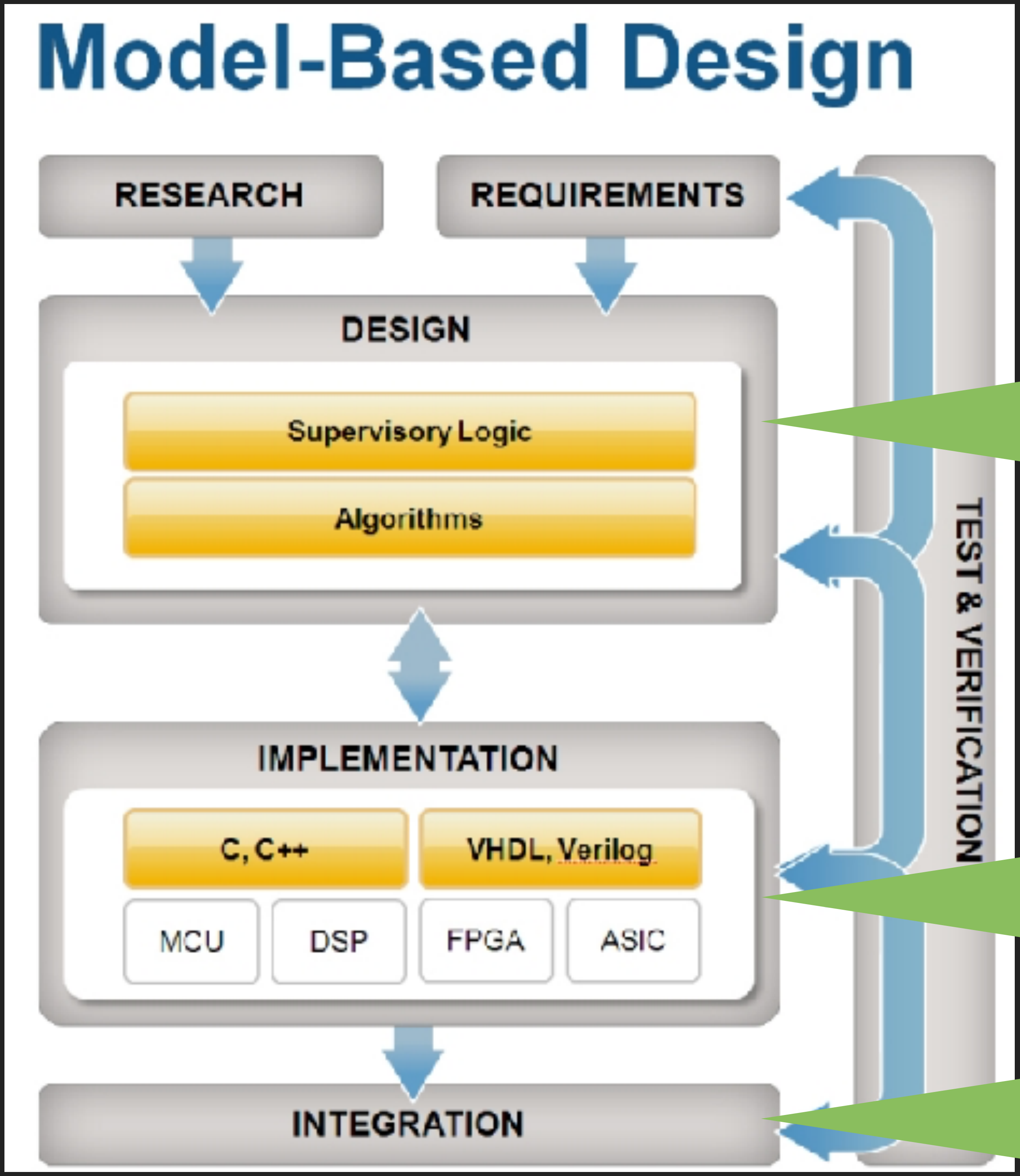
MODEL BASED DESIGN PROCESS



MODEL BASED DESIGN PROCESS



MODEL BASED DESIGN PROCESS



SIMULINK

- EASY TO UNDERSTAND FOR ALL DISCIPLINES
- CO-SIMULATION WITH PLANT MODELS
- VALIDATION AND TEST THROUGH SIMULATION

RTW EMBEDDED CODER

- AUTO-GENERATE C FROM SIMULINK MODEL

MOTOHAWK

- LOW LEVEL SOFTWARE/HARDWARE INTEGRATION

SYSTEM MODULES

SENSORS	ETRQ ENGINE TORQUE MANAGEMENT	CM COMBUSTION MANAGER
TM THERMAL MANAGER	GF GAS FLOWS	FIE FUEL INJECTION EQUIPMENT

SENSORS

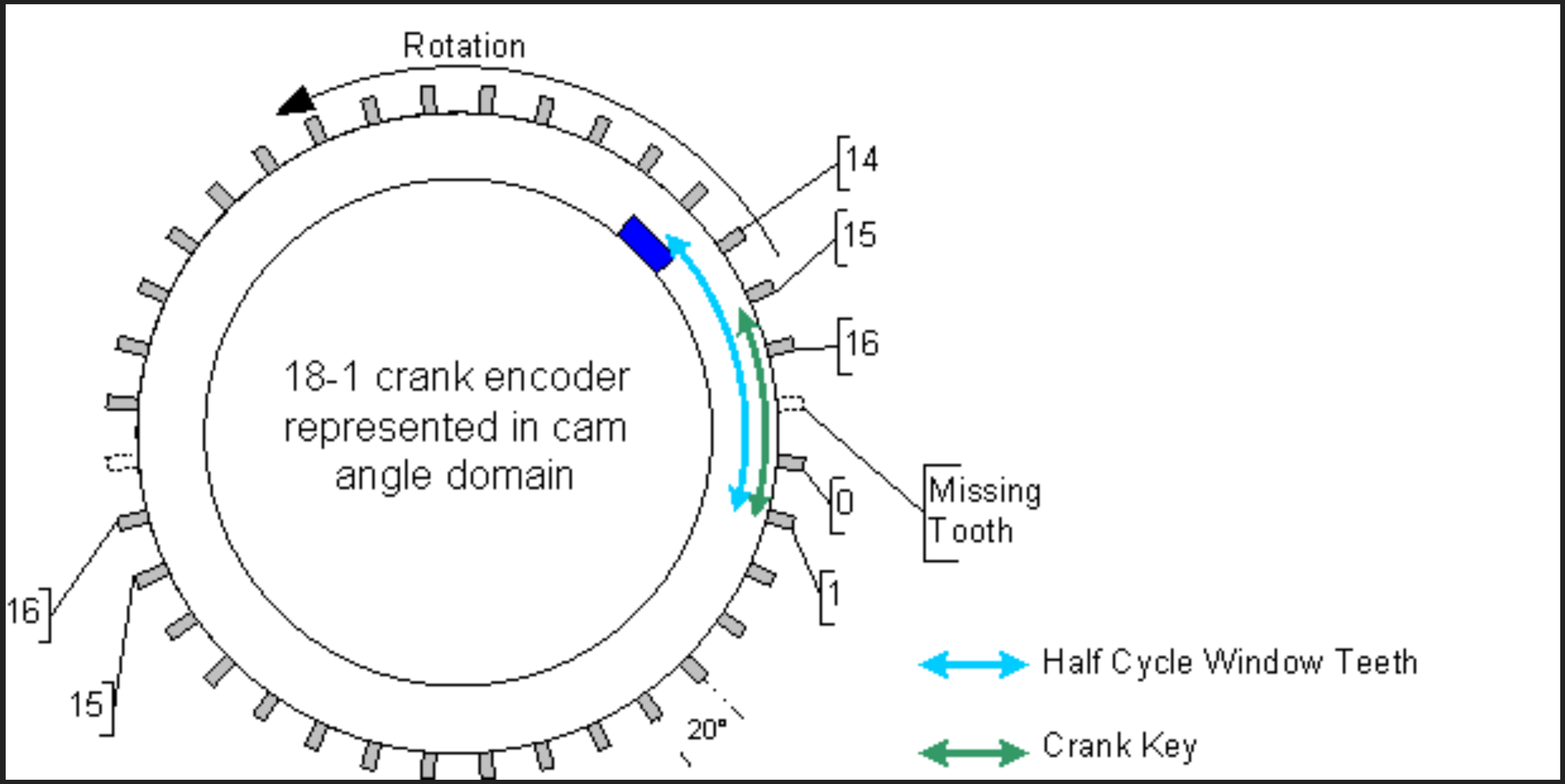
MAP MANIFOLD ABSOLUTE PRESSURE	CRFP COMMON RAIL FUEL PRESSURE	EOP ENGINE OIL PRESSURE	IAT INLET AIR TEMPERATURE
ACT AIR CHARGE TEMPERATURE	ECT ENGINE COOLANT TEMPERATURE	EOT ENGINE OIL TEMPERATURE	MAF INLET AIR MASS FLOW
PVS PEDAL VOLTAGE SENSE (REDUNDANT)	CRANK / CAM ENCODER	VBATT BATTERY VOLTAGE	VSS VEHICLE SPEED SIGNAL

SENSORS

- Sensor scaling, filtering, and fault detection
- Default value substitution in the case of faults
- Redundant sensor cross-validation and failure handling

SENSORS – ENGINE SYNCHRONIZATION

- Crank has 60-2 trigger wheel with variable reluctance sensor
- Cam has 1 tooth with Hall-effect sensor
- ECU synchronizes to both and generates a 1/16th degree angle clock



GAS FLOWS – CHARGE MASS MODEL

- Ideal Gas Law

$$PV = nRT$$

- Solved for Charge Mass

$$\frac{P_{man} V_{disp} \eta_{vol} M_{air}}{T_{man} R_{air}} = m_{charge}$$

$P_{man} = Manifold\ Pressure$

$V_{disp} = Engine\ Displacement$

$\eta_{vol} = Volumetric\ Efficiency$

$R_{air} = Gas\ Constant$

$M_{air} = Molecular\ Weight\ (Air)$

$m_{charge} = Charge\ Mass$

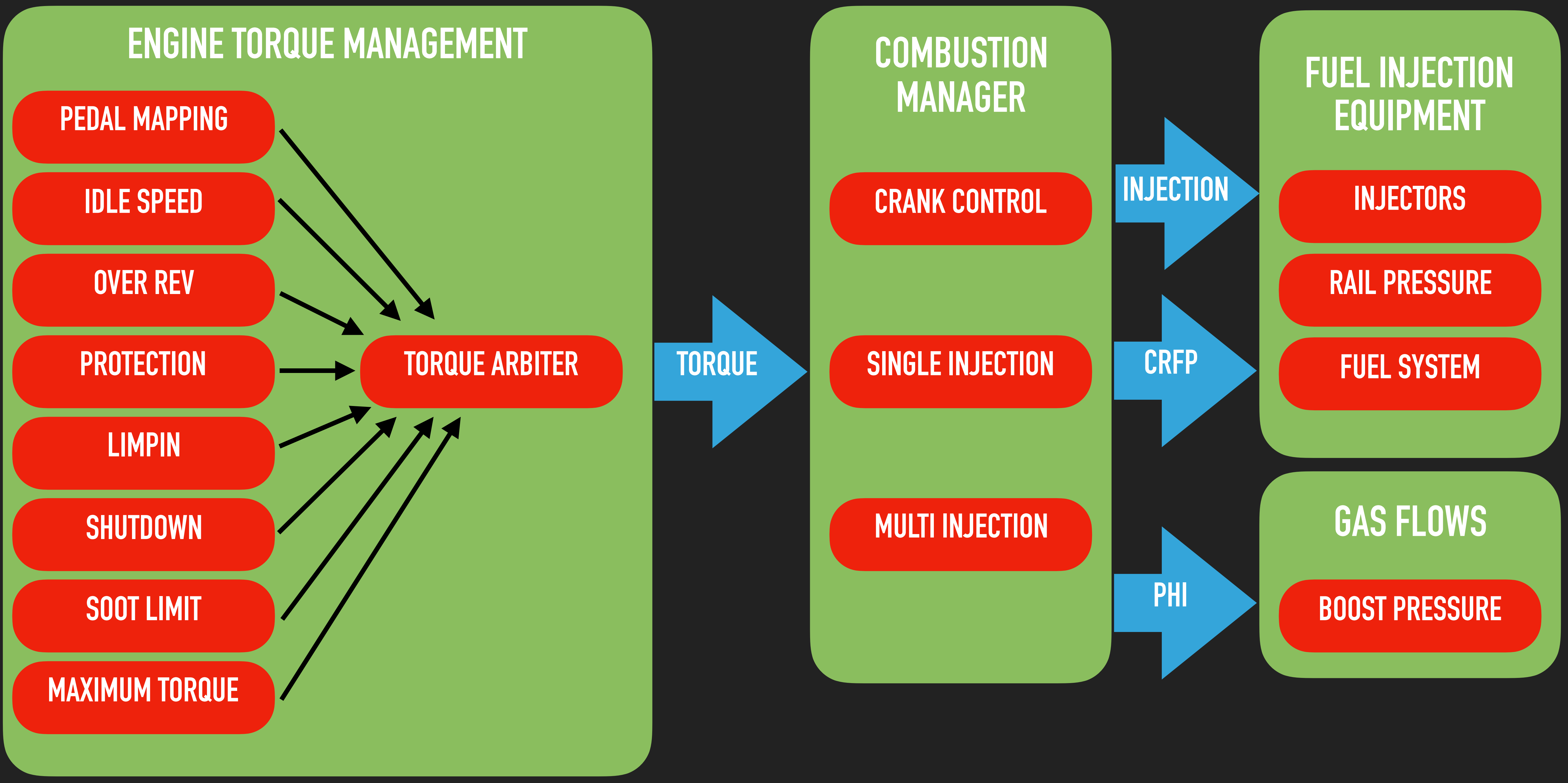
$T_{man} = Charge\ Temperature$

GAS FLOWS – BOOST PRESSURE CONTROL

- Determines duty cycle of waste gate actuator required to reach target boost level
- Duty cycle calculation is derived from the ratio of the target boost gauge pressure to the waste gate spring pressure

$$DC_{wg} = \frac{P_{spring}}{P_{obj} - P_{baro}}$$

TORQUE CONTROL PATH



ENGINE TORQUE MANAGEMENT

- Engine Torque Arbiter (Pre-Pedal)
  - Determines minimum and maximum engine torque requests to be used for pedal scaling
- Pedal Mapping
  - Determine desired pedal torque fraction based on pedal map
    - Pedal maps are surfaces from pedal position and N/V ratio
  - Scale pedal request from minimum to maximum
- Engine Torque Arbiter (Final)
  - Determine actual torque request considering all torque requests
  - Determine ID of torque requester currently active

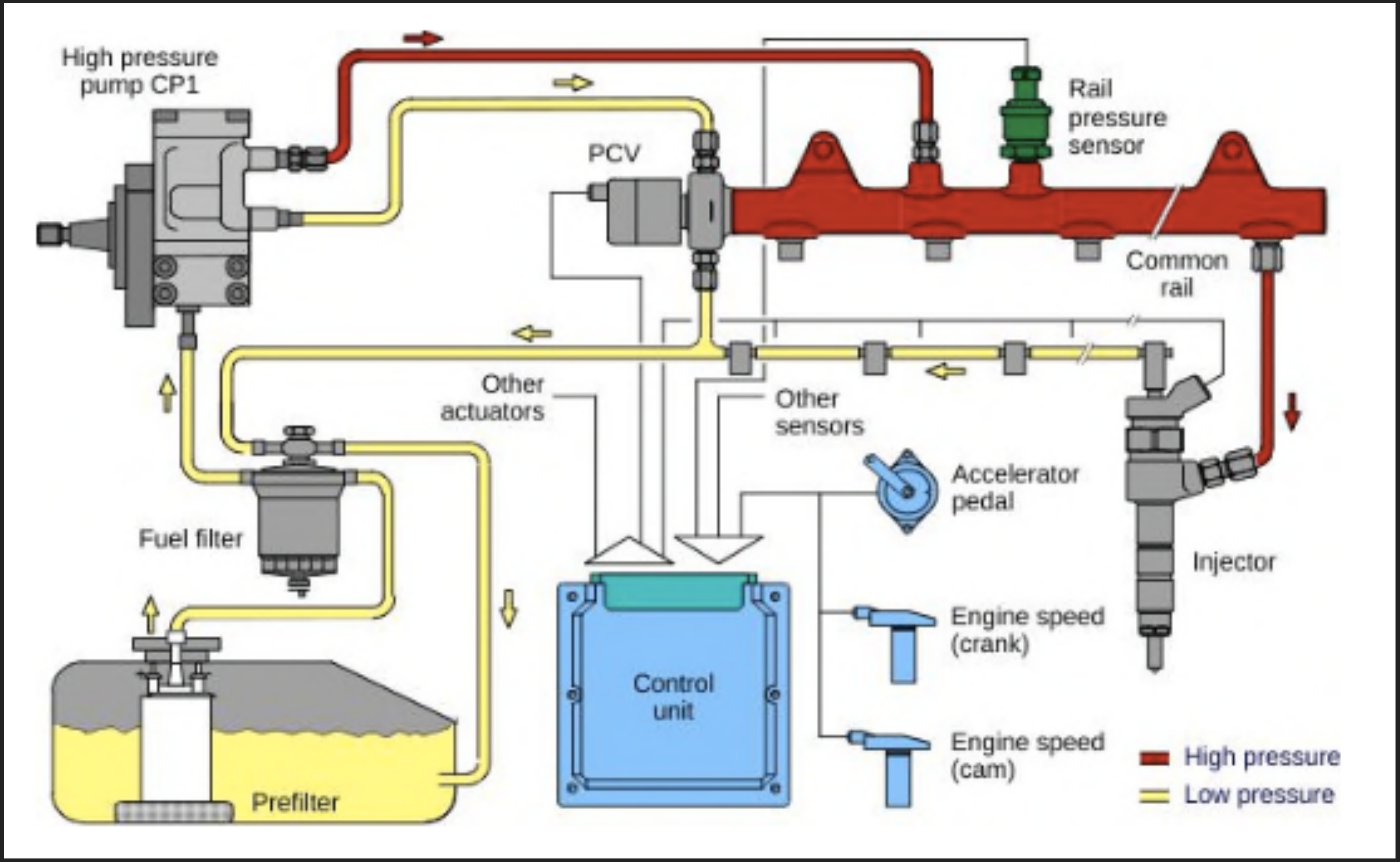
COMBUSTION MANAGEMENT - PHI ɸ OBJECTIVES

- Phi Objective in Cylinder
  - Used in air model inversion for boost objective
  - Used to solve maximum boost soot limit
- Phi Max in Exhaust
  - Used in air model inversion for boost objective
- Phi Max for Soot
  - Used to limit immediate torque based on current air mass

COMBUSTION MANAGEMENT – MULTIPLE INJECTION CONTROL

- Provides calibration maps for up to three torque producing injections (Pilot, Main, After) and other combustion parameters (CRFPObj) which are determined by the torque request
- Maps are determined during dyno calibration, and are a result of manually balancing the following considerations:
  - Combustion efficiency (fuel consumption and CO2)
  - Combustion noise, Diesel ‘clatter’
  - Exhaust emissions - THC (Total Hydrocarbons), CO (Carbon Monoxide), NOx (Nitric Oxides)

FUEL INJECTION EQUIPMENT – HARDWARE



FUEL INJECTION EQUIPMENT – INJECTOR CONTROL

- Injector characteristic maps determined by injector bench testing (Quantity vs Pulse Width)
- Injection drop-dead angle calculation (maximum angle to allow injection)
- Offset all angles from cylinder top-dead-center
- Schedule angular events using Multiple PSP (Periodic Synchronous Pulse) behavior

FUEL INJECTION EQUIPMENT – PRESSURE CONTROL VALVE

- Voltage based control calculation
- Open-loop PCV voltage from target rail pressure
- Closed-loop PCV voltage using P-I control
- Duty cycle calculated from battery voltage
- Open/Short and current faults

FUEL INJECTION EQUIPMENT – VOLUME CONTROL VALVE

- VCV on CP1 high pressure pump disables one piston
- VCV on newer pumps are current-controlled, and meter the inlet flow into the pump (which is more efficient)
- VCV control enables VCV operation based on voltage, RPM, temperature limits
- VCV switches below threshold torque from lookup table, with hysteresis
- Open/Short faults

FUEL INJECTION EQUIPMENT – LIFT PUMP

- Lift pump is mounted in-tank to provide fuel to the engine
- The lift pump driven via a relay when either:
  - The engine is running
  - For 10 seconds after key is turned on
  - The pedal is pressed (for service)

FUEL INJECTION EQUIPMENT – DIAGNOSTICS

- Rail Pressure Undershoot/Overshoot
  - Detects when there is steady state negative or positive in rail pressure to objective
  - Calibrations for minimum error, and time durations required to post fault
  - Fault codes used to diagnose fuel system faults

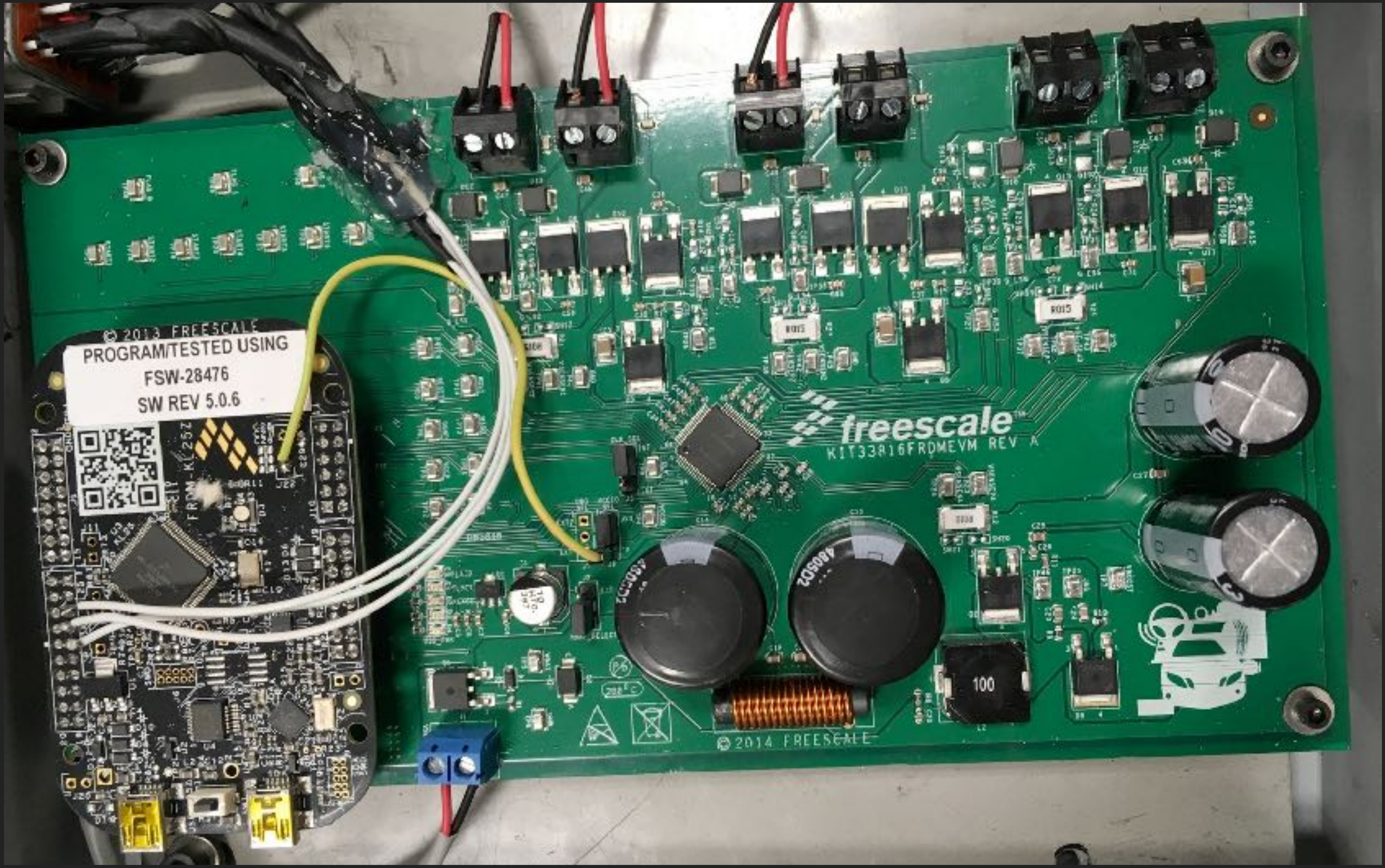
THERMAL MANAGER

- Provides control of thermal devices in the powertrain
  - Glow plugs (via relay)
  - Radiator Fan
- Thermal devices are all controlled independently, based on temperature and run-time thresholds

COMMON RAIL DIESEL

INJECTOR DRIVER

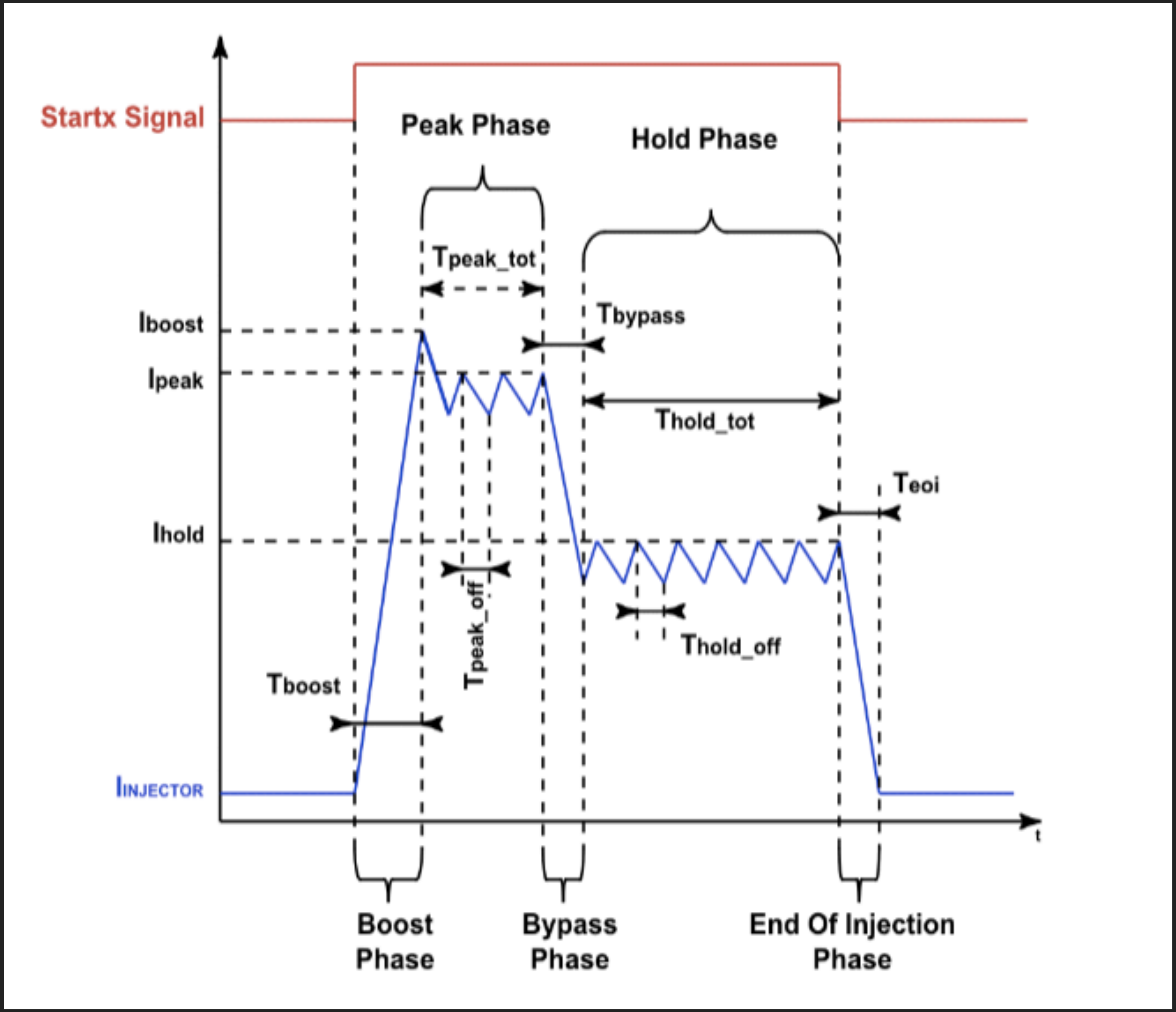
INJECTOR DRIVER



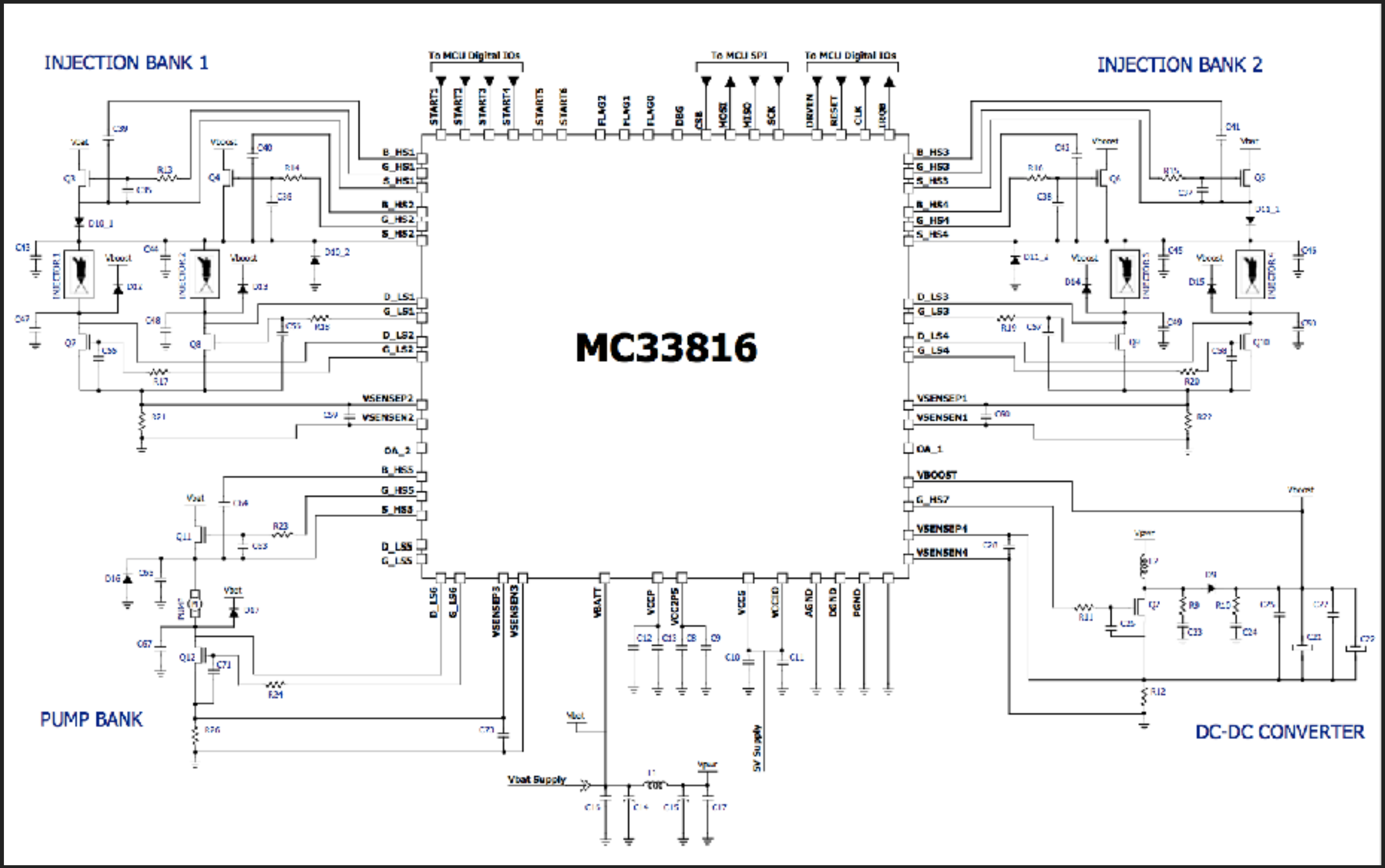
INJECTOR DRIVER CIRCUIT

- NXP MC33816 precision solenoid driver IC
- 33816FRDMEVM dev board used, modified to load MC33816 and configure current profiles autonomously
- Injection waveform configured for three stages:
  - 48v boost to 19a
  - 19a regulated for peak duration
  - 11a regulated for remainder of injection

INJECTOR DRIVER CIRCUIT



INJECTOR DRIVER CIRCUIT



INJECTOR DRIVER

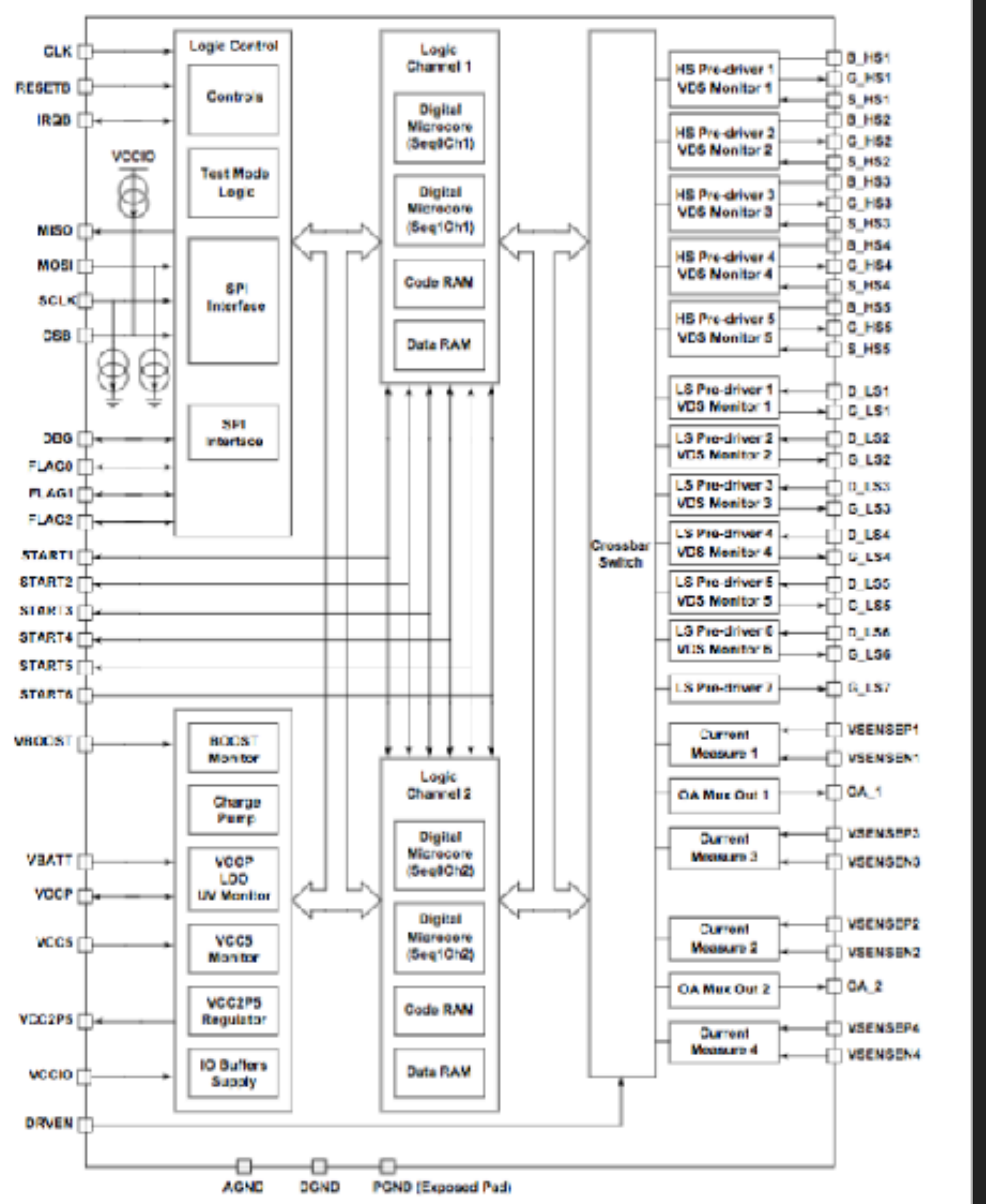


Figure 2. 33816 simplified internal block diagram

INJECTOR DRIVER

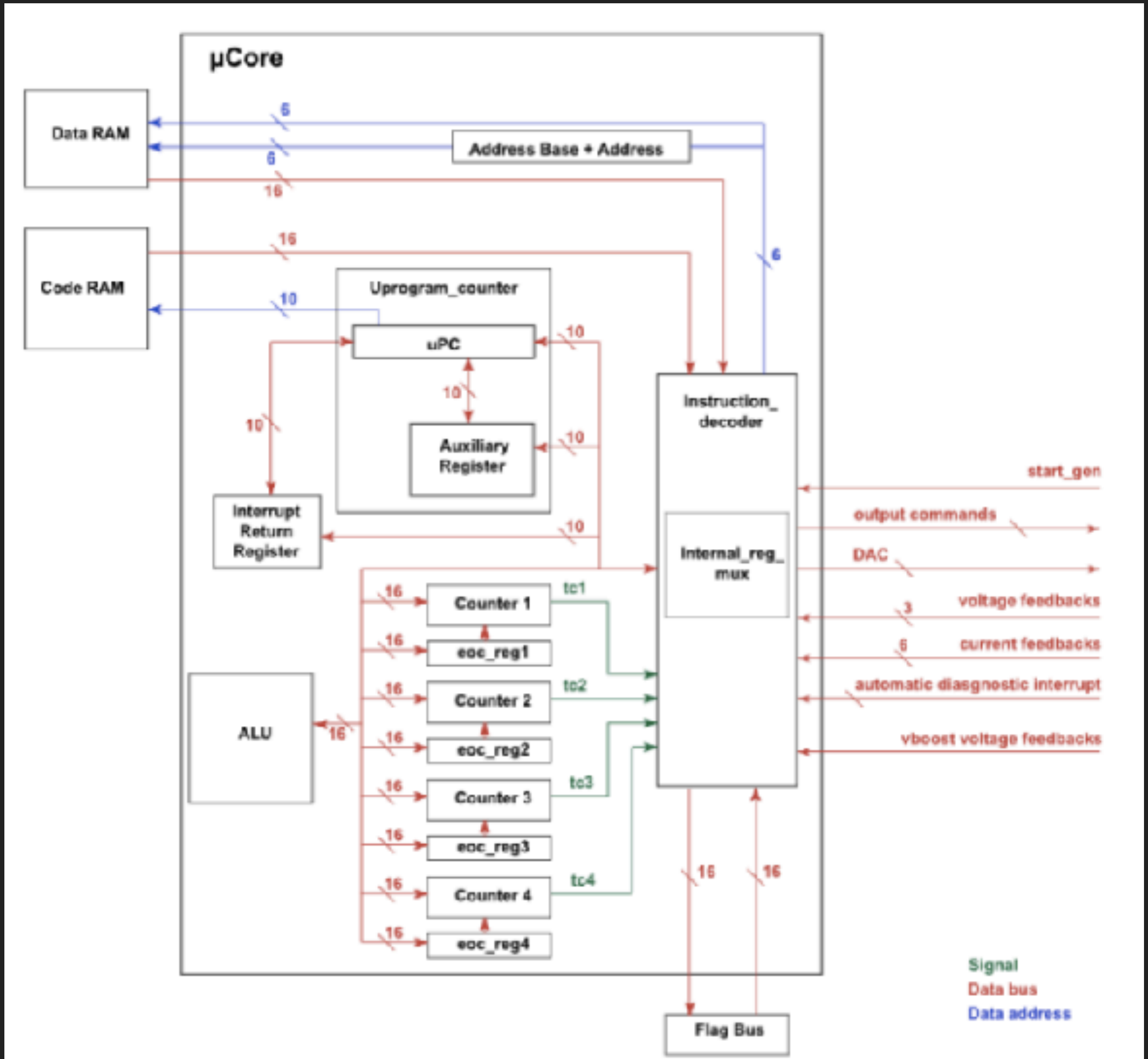


Figure 42. Microcore block diagram

INJECTOR DRIVER CIRCUIT

9.7.3.5 Wait table

The *wait* instruction uses a 'wait table' to configure its behavior. The wait table is composed of five entries. Each entry contains:

- An enable flag (one bit). This flag is set by the wait instruction to select if the condition code specified in the entry is enabled.
- A condition code. (6-bit) This code specifies the condition to be tested.
- A destination address (10-bit). This address specifies the address of the Code RAM to which the program execution should jump if the wait condition is satisfied. Regardless of the addressing mode (DM or EM), the address stored in the wait table is always the physical address of the destination.

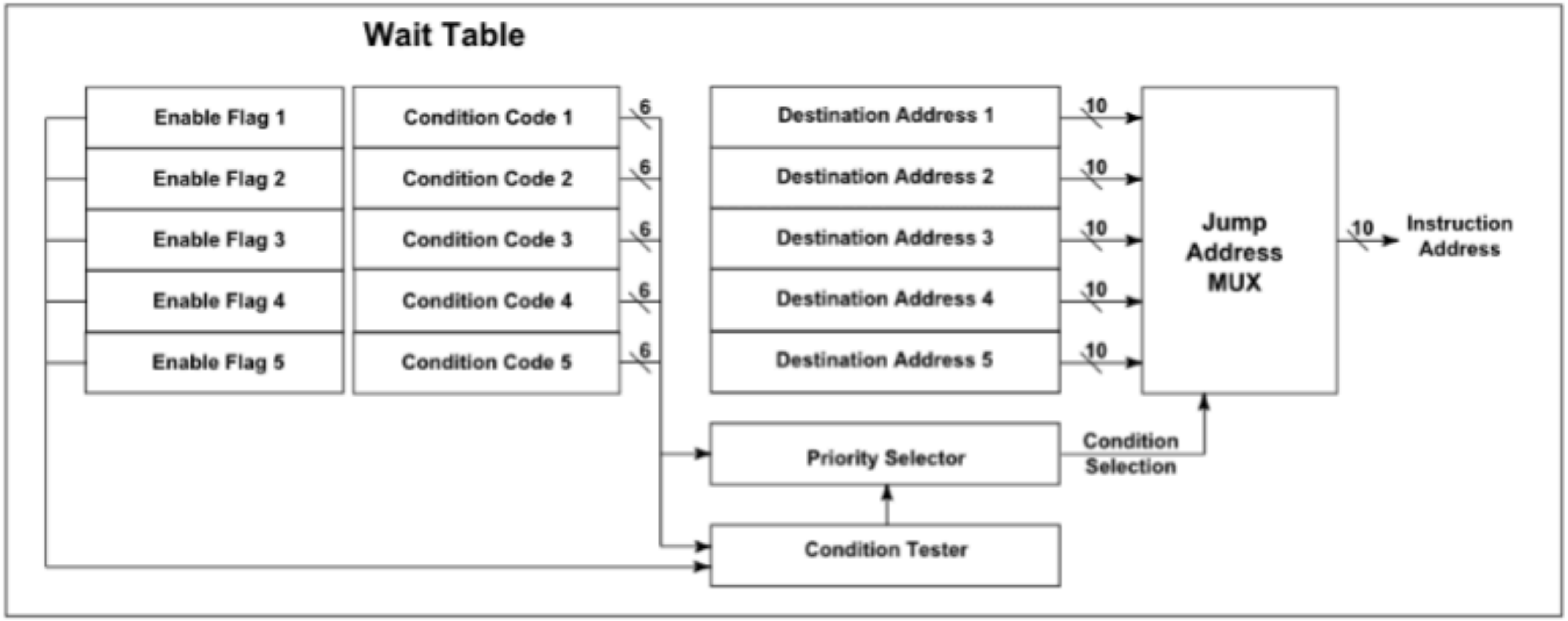


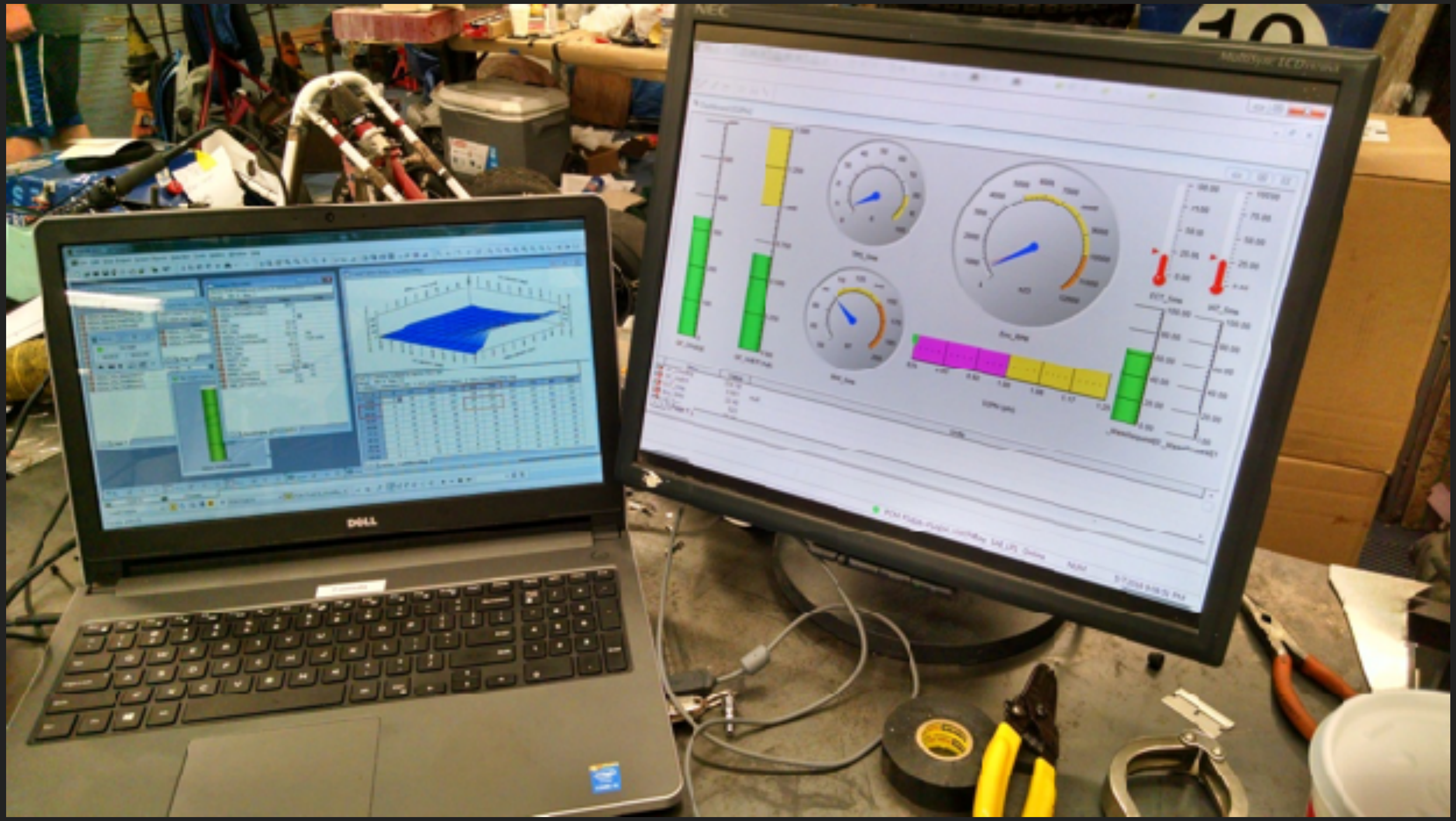
Figure 43. Wait table management diagram

COMMON RAIL DIESEL

CALIBRATION

CALIBRATION PROCESS - METHODS

- CCP (CAN Calibration Protocol) access to ECU
- CCP allows tool to read and write memory by address



CALIBRATION PROCESS - BENCH

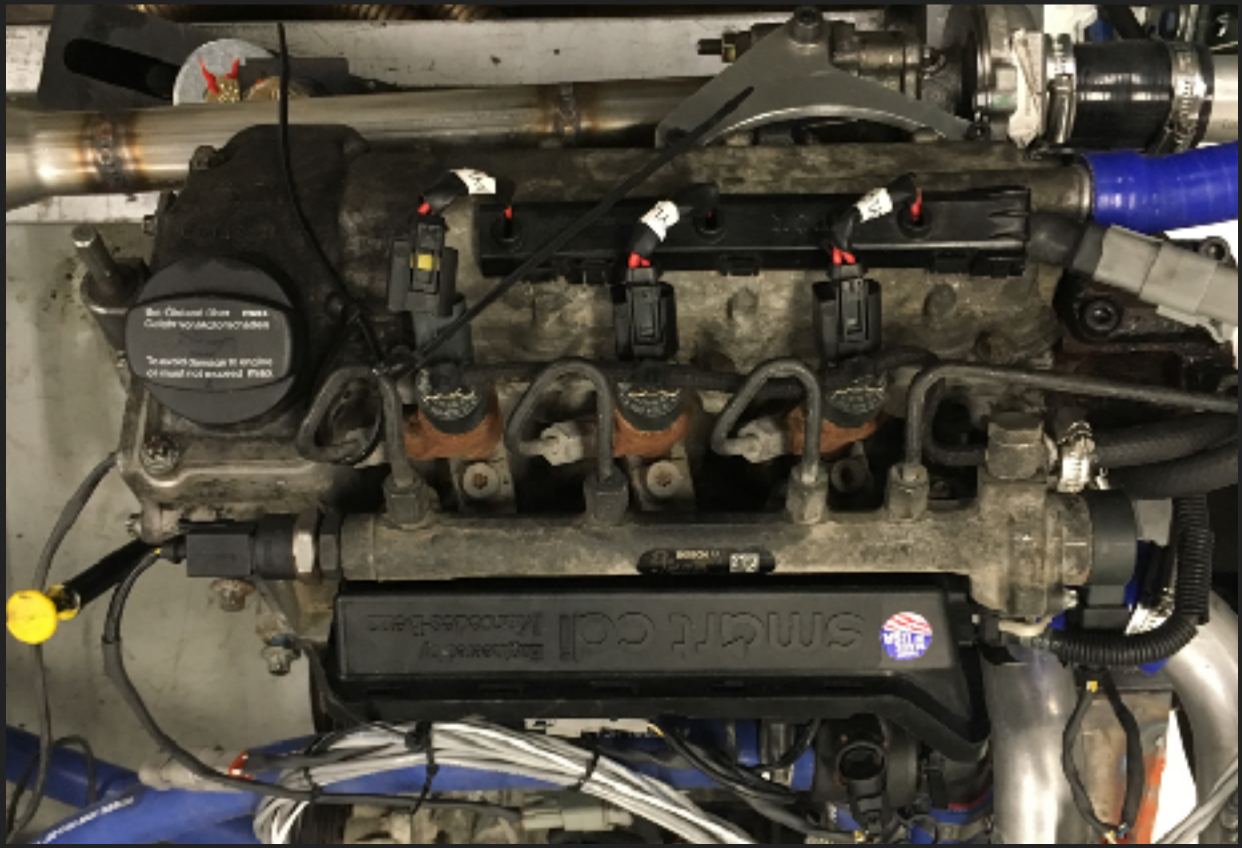
1. Sensor scaling, filtering, and default value calibrations set based on sensor data sheets and usage patterns

2. Engine physical data (i.e. displaced volume) entered according to engine parameters

3. Engine combustion and torque control parameters set to best guesses or zeroed

CALIBRATION PROCESS - DYNO

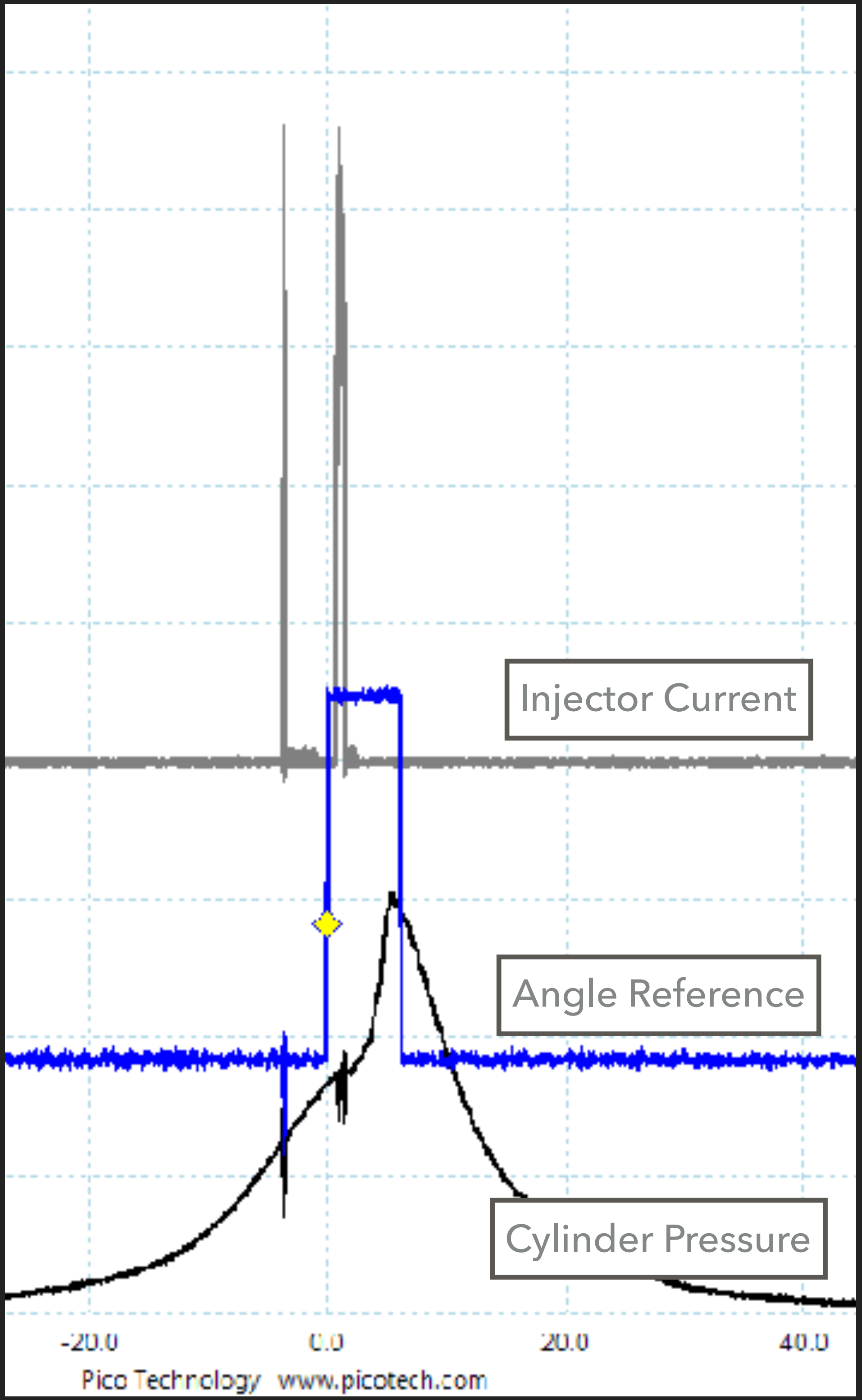
- AC Dynamometer used
- Engine run at variety of speed and load combinations
- Cylinder pressure indicating using Optrand high speed pressure sensor and PicoScope



CALIBRATION PROCESS - DYNO

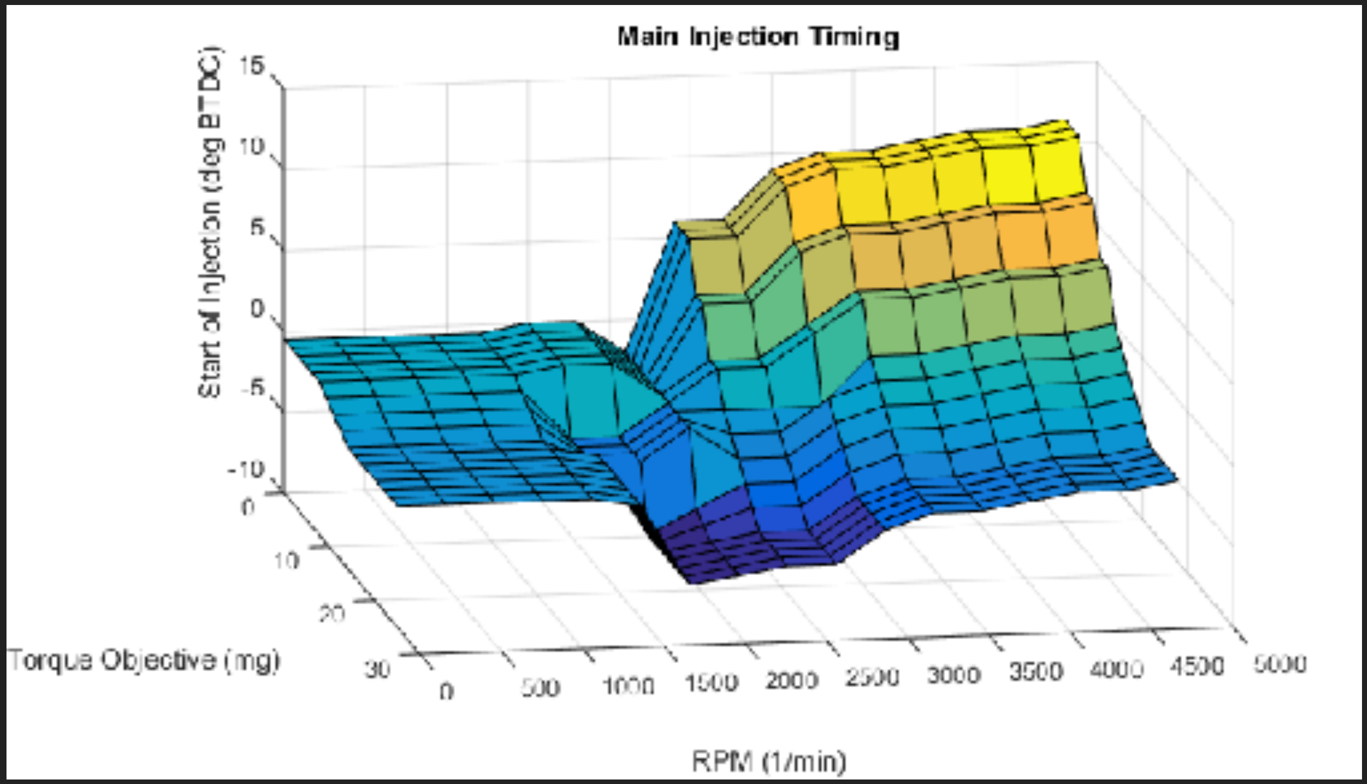
1. Single injection advance and rail pressure mapped for baseline combustion calibration, using dyno torque measurement
2. Volumetric Efficiency mapped using wide range O2 sensor
3. Multi Injection roughed in using single injection calibrations
4. Multi Injection advance and pilot mapped for final combustion calibration, using torque and emissions measurements
5. Soot limit mapped using soot visibility - no soot measurement available
6. Maximum Torque mapped based on power curve targets
7. Start injection advance is mapped

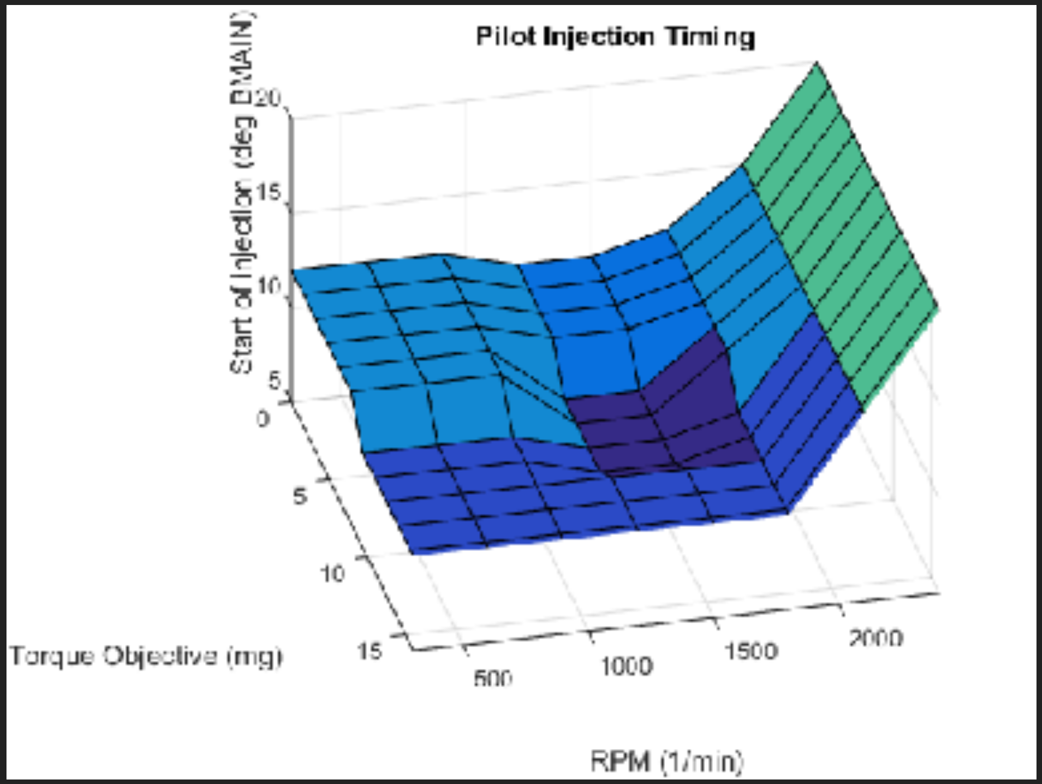
CALIBRATION PROCESS – DYNO



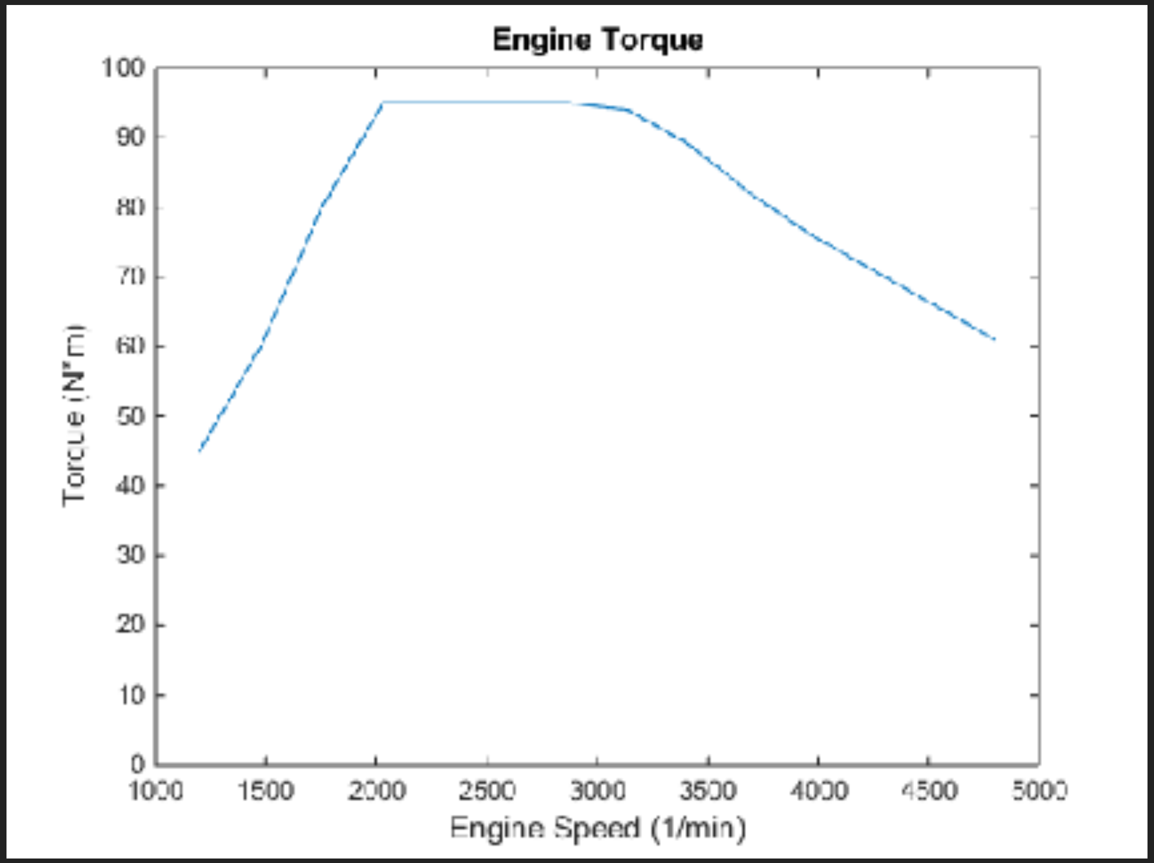
- PicoScope USB oscilloscope used to monitor injection events and cylinder pressure
- ECU outputs 'AngleRef' reference trigger starting at TDC and ending 15deg ATDC
- Ideal LPP (Location of Peak Pressure) should be around 15deg ATDC for ideal combustion, as confirmed by torque measurements

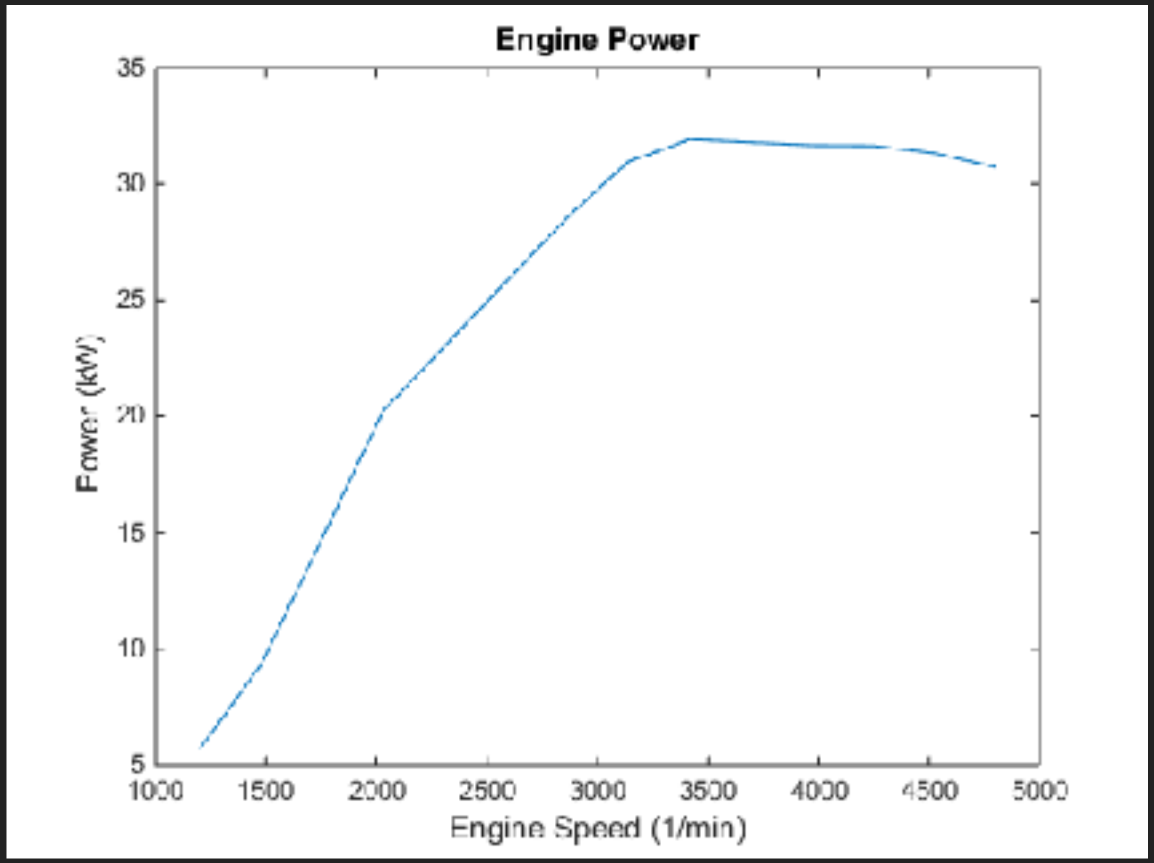
CALIBRATION PROCESS - DYNO





CALIBRATION PROCESS - DYNO





Torque curve matched to published OM660 (97 Nm, 32Kw)

CALIBRATION PROCESS - VEHICLE

1. Start injection quantity is mapped (cannot be done on dyno due to AC dyno inertia and speed control)

2. Vehicle is driven to fine-tune pedal mapping and CVT tuning together

3. Thermal calibrations are performed using the vehicle cooling loop

COMMON RAIL DIESEL

QUESTIONS?