

Comparison of Cold Start Calibrations, Vehicle Hardware and Catalyst Architecture of 4-Cylinder Turbocharged Vehicles

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ABSTRACT

Higher fuel costs and lower greenhouse gas standards, especially CO₂, have compelled vehicle manufacturers to downsize engines while simultaneously using turbochargers on more of their applications. The application of turbochargers improves fuel economy as well as torque and power. However, this also results in lower exhaust temperatures which can challenge the ability of three-way catalysts to achieve low emission levels. This work investigates and compares the catalyst heat-up strategies, hardware, and catalyst architecture of four turbocharged 4-cylinder vehicles: a 2010 VW 2.0L DI, a 2013 Chevy Malibu 2.0L DI, a 2013 Ford Fusion 1.6L DI, and a 2013 Dodge Dart 1.4L Multi-Air. In addition, three emission studies are presented. One study will show a strategy to reduce PGM concentrations in a close-coupled (CC) catalyst. Another study will show how different catalysts respond to deceleration fuel cut offs and the third study will show how HC traps can be effective at reducing HC emissions with complementary air/fuel calibration.

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INTRODUCTION

Figure 1 (1) shows the United States' corporate fleet average fuel economy requirement from 2016 to 2025. Fuel economy for passenger cars must improve from 38 to 55 mpg and light duty trucks from 29 to 40 mpg in this time frame. This is an average improvement of 3%/year. To accomplish these regulations, vehicle manufactures are considering combinations of technologies, such as: downspeeding (high gear transmissions), direct fuel-injection (DI), engine start-stop, various hybrid architectures, gasoline lean-burn engines, and turbocharging (2, 3, 4, 5, 6).

In the same timeframe, California LEV-III emission regulations will begin in 2015 and rollout to 2025. This regulation combines NMOG + NO_x emissions and vehicle manufacturers must have a vehicle fleet average of SULEV30 (30 mg/mile NMOG + NO_x) by 2025 for passenger cars and light duty trucks. Figure 2 (7) shows the fleet average emission regulations for passenger cars and light duty trucks through 2025. In addition, there will also be a supplemental (SFTP) Federal Test Procedure for light and medium duty trucks that do not exist today. Also coming is the Tier 3 emissions regulation by the Environmental Protection Agency (EPA) that is expected to mirror California's LEV-III regulation.

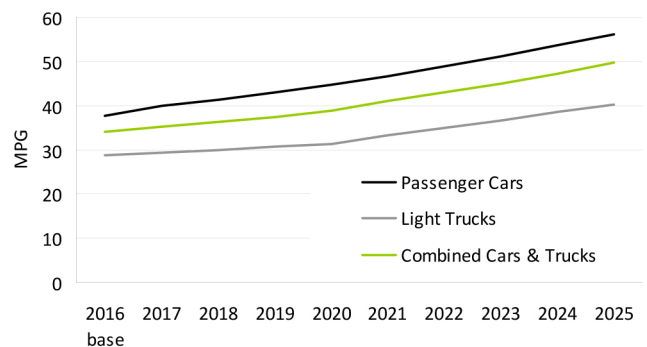


Figure 1. US Federal Fuel Economy Standards for Passenger Cars and Light Duty Trucks

The combination of higher fuel economy standards and stricter emission regulations challenge vehicle manufacturers to provide compliant vehicles that will also satisfy customer expectations. It is the goal of the manufacturer that vehicle power not be sacrificed for the sake of these upcoming regulations. Turbocharged engines will play a significant role by providing higher fuel economy without sacrificing power. Figure 3 (8) shows the growth of light-duty turbocharged applications in the European, North American and Asia Pacific regions over the next seven years. Turbocharged

applications in Asia Pacific will increase at the highest rate, from 9 to 21 million vehicles from 2013 to 2025. At the same time there will be an increase of two million turbocharged vehicles in both Europe and North America. In North America, the increase in turbocharged vehicles is concurrent with increasingly stringent fuel economy and emission standards.

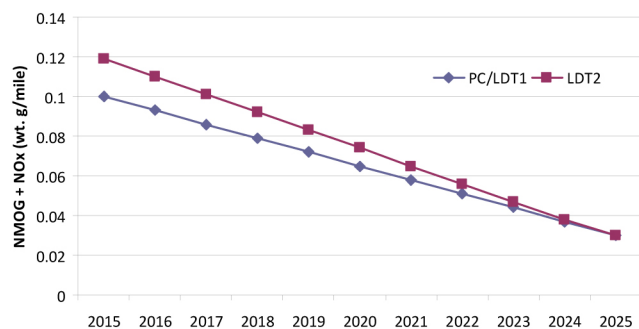


Figure 2. LEV-III Fleet Average Emissions of Passenger Cars and Light Duty Trucks to 2025.

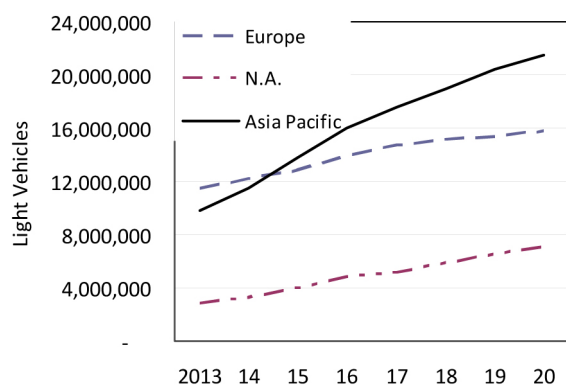


Figure 3. Light Vehicle Turbocharged Applications

Turbochargers can significantly reduce exhaust temperatures, which will impact the efficiency of the aftertreatment solutions. More and more calibrations are employing downspeeding (high gear transmissions), deceleration fuel-cuts (DFCOs), start-stop, and lean burn strategies, which will further lower exhaust temperatures. This will make the upcoming emission regulations even more challenging.

This work investigates the cold start calibration and hardware of four 4-cylinder vehicles marketed in the US. Two are PZEV certified vehicles and the others are Tier2 Bin5. This work presents three emission studies. One will show the importance of platinum group metal (PGM) placement in a CC location. Another study will clearly show how different catalyst technologies respond to DFCOs. The last study will show how a new HC trap with complementary vehicle calibration can significantly reduce HC emissions.

COLD START CALIBRATION AND HARDWARE

2013 Dodge Dart 1.4L

The 2013 Dodge Dart is equipped with a 1.4L turbocharged multi-port injected gasoline engine, with an output 160hp @ 5,500 RPM, and max torque of 184 lb-ft.

The Dart uses an advanced valve train system called “Multi-Air,” which uses a hydraulically actuated system that allows for the intake valves to be manipulated through 200 crank angle degrees of freedom. The Multi-Air valve train is used to maximize volumetric efficiency and induce intake charge motion in order to optimize power, fuel economy, and emissions. The turbocharger employed is single stage with an electromechanically actuated waste gate. The Dart is Tier2 Bin5 certified.

The Dart production exhaust system consists of a CC catalyst mounted to a 90° insulated downpipe originating from the turbocharger. The CC catalyst inlet face is approximately 40cm away from the turbocharger outlet. The CC volume is 1.4 L, making the ratio of catalyst to engine volume 1:1.

Figure 4 shows the temperature profile of the exhaust system during the first two cycles of the FTP. The CC bed lights off during the first cycle acceleration, operating in the range of 200-300°C. Once the initial cycle 1 acceleration is complete, the CC catalyst peak temperature is approximately 500°C. The underfloor (UF) catalyst is slow to light off and does not reach 300°C until the beginning of cycle 2.

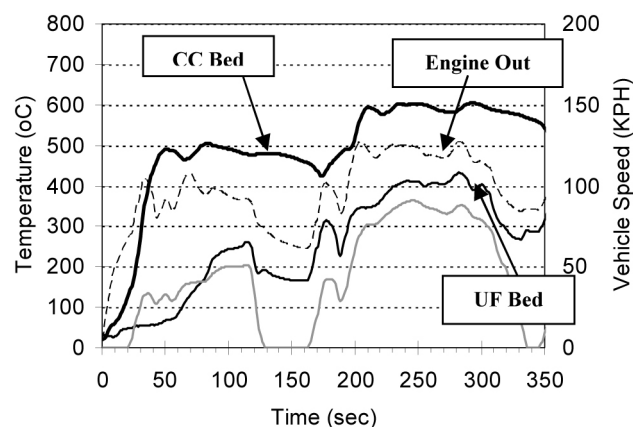


Figure 4. 2013 Dodge Dart Exhaust Temperatures

Figure 5 shows engine speed. After the initial RPM flair of 2,000 RPM after engine crank, the engine speed set point appears to be approximately 1,600 RPM during the first idle.

Figure 6 represents the amount of mass air flow traveling through the intake and inducted into the cylinders. During the first cold start idle, the mass air flow rate is approximately 9 g/s. This type of idle mass flow is fairly aggressive for a 1.4L engine.

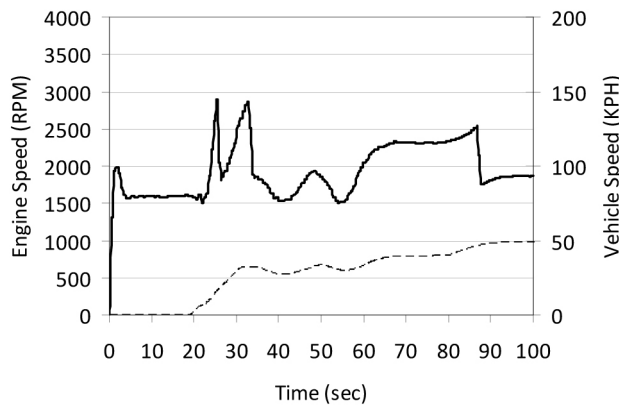


Figure 5. 2013 Dodge Dart FTP Cold Start Engine Speed

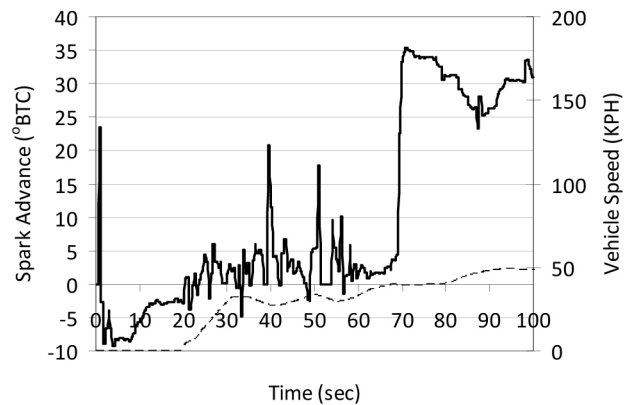


Figure 7. 2013 Dodge Dart FTP Cold Start Spark Timing

The turbocharger waste gate operating strategy is to remain fully open during the first idle, providing the maximum amount of energy to the catalyst rather than to the turbocharger. This high RPM/mass flow, combined with the full waste gate bypass strategy, is necessary to light-off the catalyst early in cycle 1.

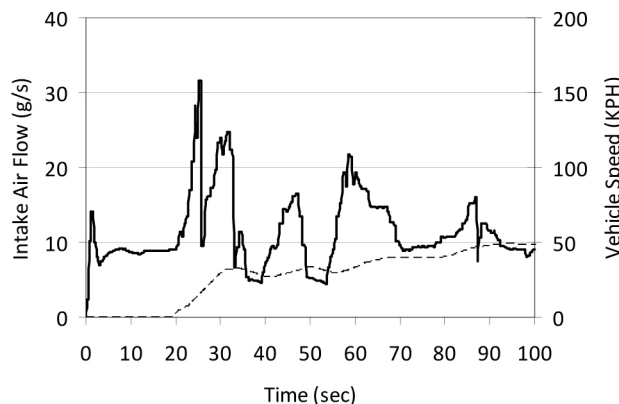


Figure 6. 2013 Dodge Dart FTP Cold Start Intake Air Flow

Figure 7 represents the engine control unit (ECU) “requested” spark timing. Typically, there are spark compensation tables that add or subtract to the base level of calculated ignition timing, based on several factors. It appears there is catalyst light-off compensation in the first idle and first half of cycle 1. Upon engine start, spark timing is retarded to a level near 10° after top dead center (ATC). It stays ATC all of the first idle, and levels off at 2.5° ATC leading into the first acceleration. Timing stays retarded, relative to a minimum timing for best torque (MBT) for the first half of cycle 1. At that point, timing step changes into a more common MBT range of 25-35° before top dead center (BTC). This step change likely represents a catalyst heating compensation table being shut off. The aggressive level of spark retard lasts for approximately the first 70 seconds of the FTP cycle.

Since the catalyst system is still in the process of lighting off during the first cycle acceleration, the AFR (air/fuel ratio) control during the same time is critical for minimizing emissions. Figure 8 shows engine out lambda, as well as ECU target lambda, for the first 100 seconds of the FTP. The target lambda begins rich upon engine start, at 0.8. It quickly ramps up and crosses stoichiometric to a lean value of 1.04 lambda at the point of the first acceleration. The actual lambda shown in the plot is a reading from the wide range O₂ sensor. Lambda data is not available until the sensor heats up enough to be functional, around 10 seconds into the FTP cycle. Actual lambda follows target lambda very well on this application. The system appears to go into closed-loop during the first acceleration where lambda begins to switch about stoichiometry. An important trait of the calibration for this application is the DFCOs that exist early in the FTP. Figure 8 shows that there are three DFCO events in cycle 1. A subsequent section will show that the DFCOs are important for optimizing HC trap performance in the UF position. Many times the criteria for enabling DFCO are not met this early in the FTP making this application unique.

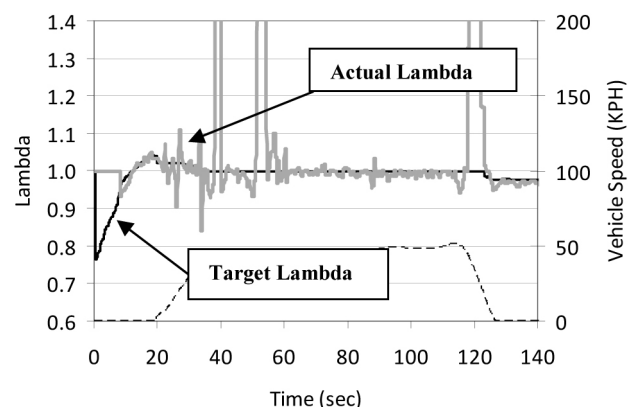


Figure 8. 2013 Dodge Dart FTP Cold Start Target & Measured Lambda

2013 Chevrolet Malibu LTZ 2.0L ECOTEC

The 2013 Malibu is equipped with a 2.0L DOHC turbocharged DI engine with variable valve timing. Output is 259hp @ 5,300 RPM and 260lb-ft of torque @ 5,200 RPM. The turbocharger employed is similar to the Dart in that it is a single stage system with an electromechanically actuated waste gate. The Malibu is calibrated to meet the federal Tier II certification level.

The Malibu exhaust consists of a CC catalyst with a short downpipe section originating from the turbocharger with a separate UF converter. The CC volume is 1.25 L, while the UF volume is 1.12 L, making the ratio of total catalyst to engine volume 1.19.

For development purposes, the UF assembly was eliminated and a portion of that volume was transferred to the CC assembly. This setup consisted of a CC inlet and outlet catalyst, both with volumes of 1.12 L.

Figure 9 shows the CC inlet and CC outlet catalyst temperatures for the first 350 seconds of the FTP. Out of the four applications represented in this study, the Malibu CC lights off the slowest relative to the other vehicles assessed or compared. The catalyst is crossing the typical light-off temperature regime of 300-400°C at the point of the first cycle acceleration. The outlet catalyst follows the temperature light-off profile of the inlet cat and both peak near 600°C in cycle 1. It is interesting to note that once the catalyst light-off calibration has completed and the control system enters closed-loop, there is around a 150°C loss in temperature for both catalysts, starting in the middle of cycle 1. This trend of cooling off is typical for turbocharged applications and needs to be evaluated closely in order to ensure adequate temperature for cycle 2 operation.

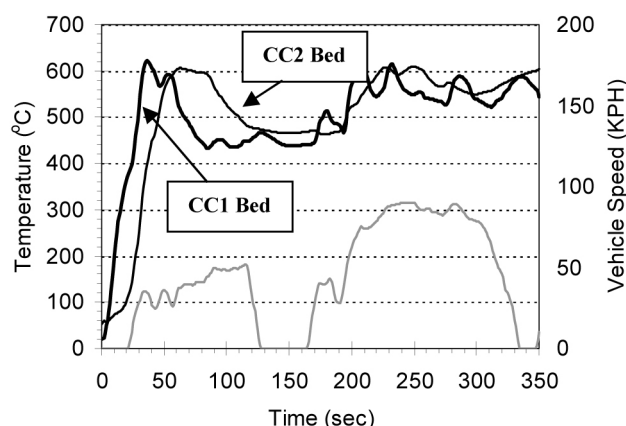


Figure 9. 2013 Chevrolet Malibu Exhaust Temperatures

The Malibu engine speed is approximately 1,400 RPM in the first idle of the FTP, as shown in figure 10. This is towards the upper end of the range of cold start idle engine speeds typical for PZEV vehicles (9). The Malibu does not employ an air pump; therefore, the higher engine speeds are used to ensure adequate mass flow through the catalyst to achieve sufficient warm up.

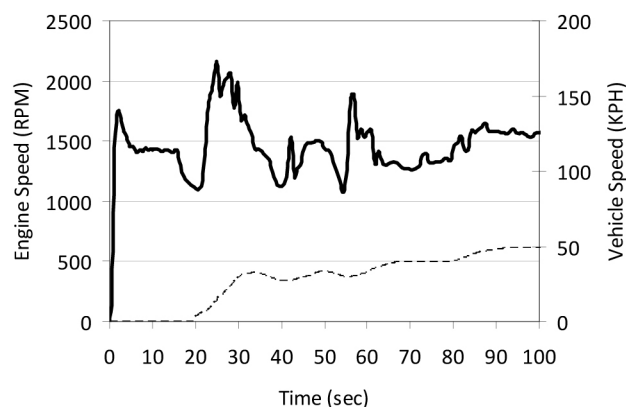


Figure 10. 2013 Chevy Malibu 2.0L Engine Speed

Spark timing is shown in Figure 11. Timing is retarded to a level of around 15° ATC in the first seconds after engine crank and ramps towards TDC during the first 20 second idle. Timing remains ATC for the initial portion of cycle 1, at which point the catalyst light-off spark compensation is shut off and timing returns near MBT level. The Engine torque requirements of this application during idle speeds are low, which allow for the retarded timing and subsequent application of heat energy to the exhaust, where it helps to warm up the catalyst.

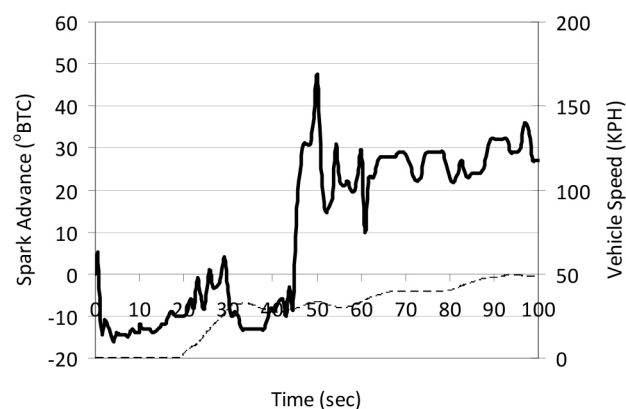


Figure 11. 2013 Chevy Malibu 2.0L Spark Advance

The Malibu has a lean cold start strategy in the first idle. It operates in a lambda range of 1.03-1.05, and goes into closed-loop on the first acceleration (figure 13). This type of lambda strategy is good for minimizing HC's and CO₂ in the first idle. As has been seen previously, this does not result in a catalyst heat ramp that is as aggressive as the other applications which do not stay at a constant lean AFR the entire 20 seconds. Good AFR control is crucial on the first acceleration to avoid an emissions breakthrough, since the catalyst is still crossing the light-off region of 300-400°C and entering closed-loop.