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Fuel Efficiency Improvements from Lean, Stratified Combustion with a Solenoid Injector

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ABSTRACT

In light of the growing emphasis on CO_2 emissions reduction, Delphi has undertaken an internal development program to show the fuel economy benefits of lean, stratified combustion with its outwardly-opening solenoid injector in a vehicle environment. This paper presents the status of this ongoing development activity which is not yet completed. Progress to date includes a logical progression from single- and multi-cylinder dynamometer engines to the vehicle environment. The solenoid-actuated injector used in this development has an outwardly-opening valve group to generate a hollow-cone spray with a stable, well-defined recirculation zone to support spray-guided stratification in the combustion chamber. The engine management system of the development vehicle was modified from series-production configuration by changing the engine control unit to permit function development and calibration. The resulting full-size, V6-engine vehicle achieves significant fuel savings compared to homogeneous stoichiometric operation, while showing the potential to be the best-value Powertrain solution through the innovative use of solenoid injector technology.

INTRODUCTION

Lean, stratified combustion produces fuel savings in gasoline spark-ignited, direct injection (SIDI) engines for several reasons. First, unthrottled operation allows for a significant pumping loss reduction, especially at lower loads. Second, the lean mixture being compressed has a higher ratio of specific heats, commonly referred to as gamma. This allows for a more efficient compression and expansion process. Third, there are lower wall heat losses in the cylinder because of the centralization of the mixture away from the walls. In addition, the ability to operate with a higher compression ratio due to the use of direct injection brings efficiency advantages. A more detailed thermodynamic comparison of the advantages of this type of combustion can be found in [1].

In this paper, we discuss spray-guided stratified combustion, for which there are a number of component-level and system-level requirements. For a normally aspirated engine, a centrally-mounted direct injector with a hollow-cone spray is needed. The spark plug is mounted such that it can ignite a fuel-rich “recirculation zone” created by vortices just outside the spray cone. The fuel system has a high-pressure gasoline pump in addition to the tank-mounted lift pump. In order to produce the desired spray characteristics in the cylinder, a rail pressure typically in the range of 200 bar is used. For engine-out NOx emission reduction, exhaust gas recirculation is desirable. Due to the high intake air flow rates associated with lean operation, a high-flow EGR valve is needed in order to introduce meaningful amounts of exhaust gas. The use of camshaft phasers complements the external EGR by producing in-cylinder exhaust gas residuals. From an exhaust emissions perspective, a key sub-system which must be added is lean NOx aftertreatment, typically in the form of a NOx storage catalyst (NSC).

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OUTWARDLY-OPENING SOLENOID INJECTOR

Spray-guided combustion has higher requirements than homogeneous direct injection in terms of spray stability, fuel atomization, and the capacity for precisely controlled, closely-spaced multiple injections in order to produce the desired spray characteristics for flammability at the spark plug gap. To fulfill these requirements current production injectors use piezoelectric actuation in conjunction with an outwardly-opening valve. The objective of the Delphi fast single coil injector development was to maintain the performance benefit of the piezoelectric systems over conventional injection technology without the additional cost associated with the piezoelectric actuator and high-voltage electronic driver circuits. The resulting injector has been designated the Multec 20.

The Multec 20 injector shown in figure 1 is based on conventional single-solenoid direct actuation of the pintle. In order to drive the large valve diameters required for spray stability in stratified operation, the Multec 20 injector uses a pressure-balanced valve concept, which allows valve operation which is nearly independent of system fuel pressure. Similar to piezoelectric injectors, valve closing is powered by a spring. To ensure a fast closing without valve rebound and associated after-injection, the Multec 20 has implemented a novel decoupled valve-armature concept. This minimizes impact loads between seat and pintle and decouples the movement of the pintle and armature during the closing event. Because the injector does not require a physically long piezo element and associated thermal compensation hardware, there is packaging flexibility available in applications where a shorter injector is advantageous.

Figure 1: Multec 20 Injector Prototype

The requirements on the Multec 20 actuator are more demanding in terms of transient response and force than for solenoid multi-hole injectors. Yet, the target of packaging the actuator within the envelopes of both standard multi-hole and piezoelectric injectors was achieved while using conventional materials and driver currents. A particular focus was placed on material choices in the injector to be compatible with bio-fuels. The use of stainless steels and the avoidance of elastomers are two examples.

Multiple-injection capability was one of the injector's primary design goals. For spray-guided combustion, applying multiple short pulses to deliver the fuel reduces penetration and produces a superior fuel-air mixture in the area of the spark plug gap. Figure 2 shows a comparison of single, double, and triple pulse injections with the same total delivered fuel mass of 20 milligrams. It is clearly evident that the double and triple pulses reduce penetration and keep the fuel closer to the spark

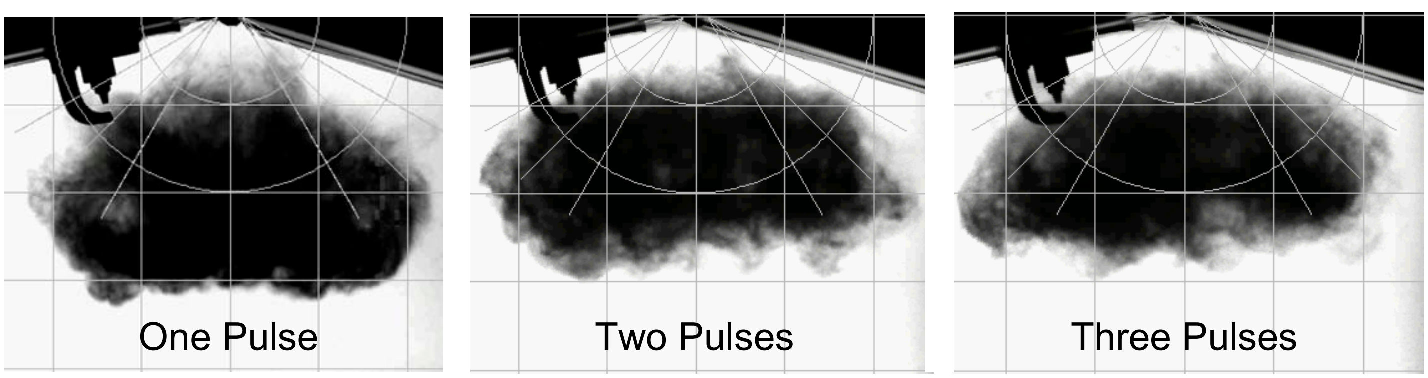

Figure 2: Pressure Chamber Spray Comparison Between Single, Double, and Triple Pulses with the Same Total Fuel Mass Delivered

plug. In the single pulse picture it can also be seen that the fuel tends to be pushed past the spark plug gap instead of dwelling closer to it and obscuring it as occurs in the second and third pictures.

Figure 3 shows the pintle stroke, the applied current, and the logic trigger signal for a triple injection sequence. This figure demonstrates the ability of the injector to operate close to present piezoelectric injector performance. In particular, hydraulic delays of less than 200 μs between subsequent pulses are achievable. The second and third pulses are shown in the "ballistic" region, with the injector starting to close before fully opening. Use of this injector in the ballistic regime is possible and tests have demonstrated repeatability of mass delivery with dispersion < 10%. Opening flight times and closing responses are also comparable to piezoelectric injectors presently in production.

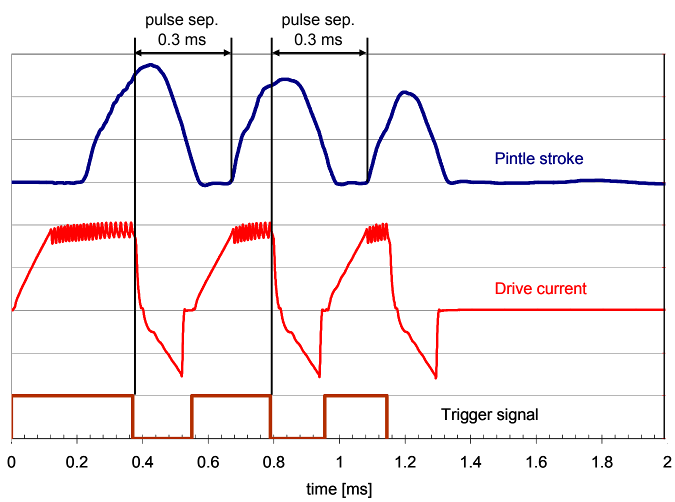

Figure 3: Multec 20 Multi-Pulse Performance

Another focus of the injector development was control of the spray shape and stability under the high pressure and temperature in-cylinder conditions of the compression stroke. The outwardly-opening valve creates a small conical gap in which a thin, hollow-cone spray sheet develops. This spray sheet then breaks up into finely atomized droplets. A key requirement is that the spray develops and maintains a recirculation zone outside the conical envelope so that fuel is transported to the spark plug location marked in Figure 4 with a circle. A computational fluid dynamics (CFD) simulation activity using the tool AVL Fire was used to augment understanding of the spray phenomena. Good agreement between pressure chamber shadowgraphy and the simulation results was achieved, as shown in Figure 5.

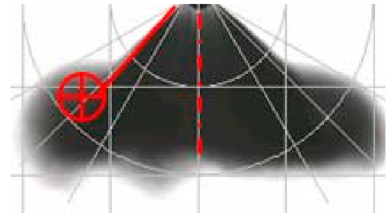

Figure 4: Spray Formation Recirculation Zone

MULTI-CYLINDER ENGINE APPLICATION

The injector development activity insured that the solenoid injector has the essential fundamental capabilities of spray and speed of response in both single-pulse and close-coupled, multi-pulse operation. It is relevant also to comment that the base injector development included extensive work in a single-cylinder engine.

Therefore, the next step in the system development was application of the injectors to a multi-cylinder engine. For this activity, Delphi selected the Mercedes 3.5 liter M272 DE V6 engine. This engine is in series production with spray-guided combustion and it features a central mounting of the injector as well as a spark plug location adapted for spray-guided combustion. The M272 is equipped with a 200-bar fuel injection pump, dual intake and exhaust camshaft phasers, and a variable intake manifold [2].

INJECTOR SPRAY POSITIONING

For application of the injector in the engine, the correct physical positioning of the spray recirculation zone for comparable overlap of the spark plug gap was accomplished with several considerations driven by the slightly-smaller exit diameter of the Multec 20 injector compared to the production injector.

- Positioning the injector in the vertical axis to match the position of the nozzle exit in the production application. This positioning is done with the dimensions of the spacer between the injector and the cylinder head.

- Increasing the hardware spray angle of the injector to compensate the slightly smaller valve exit diameter. The spray angle is modified by changing the geometrical dimensions of the injector components in the valve area.

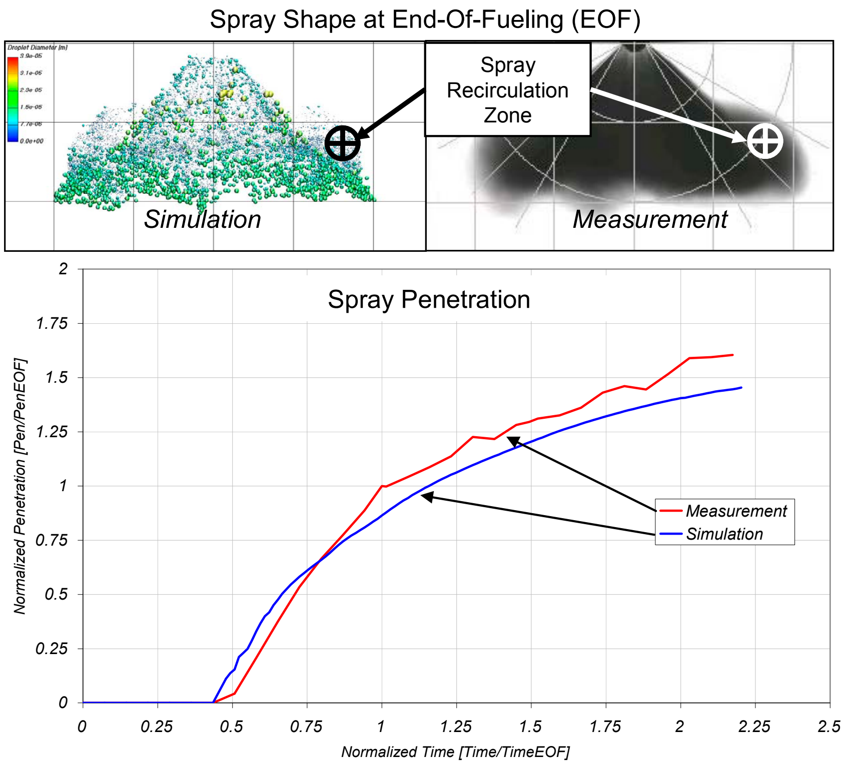

Figure 5: Comparison of Spray Simulation Results to Experimental Data for the Solenoid Injector

INJECTION PULSE SEQUENCE

The next consideration after physical positioning was to determine the best injector electrical command pulse sequence to produce the longest duration of optimum air-fuel ratio conditions at the spark gap. This was undertaken in a series of related activities. The first of these to be discussed is injector spray experiments with associated spray simulation.

Injection Sequence Spray Experiments

A number of the fuel injection variables were investigated by performing spray shadowgraphy in a pressure chamber. In these experiments, single-pulse, double-pulse, and triple-pulse injections were performed with multiple parameter variations with the Multec 20 solenoid injector and the production piezo injector. The goal of this activity was to learn what combination of injection parameters works best with the solenoid injector to produce spray mixture results in the spark gap that are comparable to the production piezo injector. Specifically, the two criteria were:

- to maximize the recirculated fuel spray in the zone near the spark gap, and
- to maximize the time duration of the crank angle "window" after end of injection command (EOIC) where the spray recirculation zone is physically co-located with the spark plug gap.

To evaluate the spray performance against these criteria, the shadowgraphy images were post-processed and the spray in the area of the spark plug gap was graded in terms of the amount it filled a circular area around the spark gap. The resulting spray grade is expressed as a number from 0 to 4 and is referred to as the recirculation zone criteria (RZC). An RZC value of 4 is highest and represents the best spray filling of the spark plug gap zone.

A designed experiment was conducted which varied the number of pulses, the fuel mass split between pulses, and the timing between pulses. The chamber test conditions were 15 bar N_2 counter-pressure at 150 degrees C to simulate in-cylinder conditions in the compression stroke where fuel injection occurs for stratified combustion. In addition to the Multec 20 solenoid injector, a production piezo injector was also tested to provide comparative data.

An example of the Multec 20 solenoid injector results from this testing is shown in Figure 6. The two injection patterns deliver the same quantity of fuel, 20 milligrams. The injector electrical input command to the driver circuit is shown as 0 to 1 square input pulses, with x-axis time scale set to 0 at the end of the last pulse in each case. The right injection sequence using a shorter second pulse and larger inter-pulse delay is better because it shows a wider time window duration when the RZC criteria is high (4) and more importantly, the RZC ≥ 3

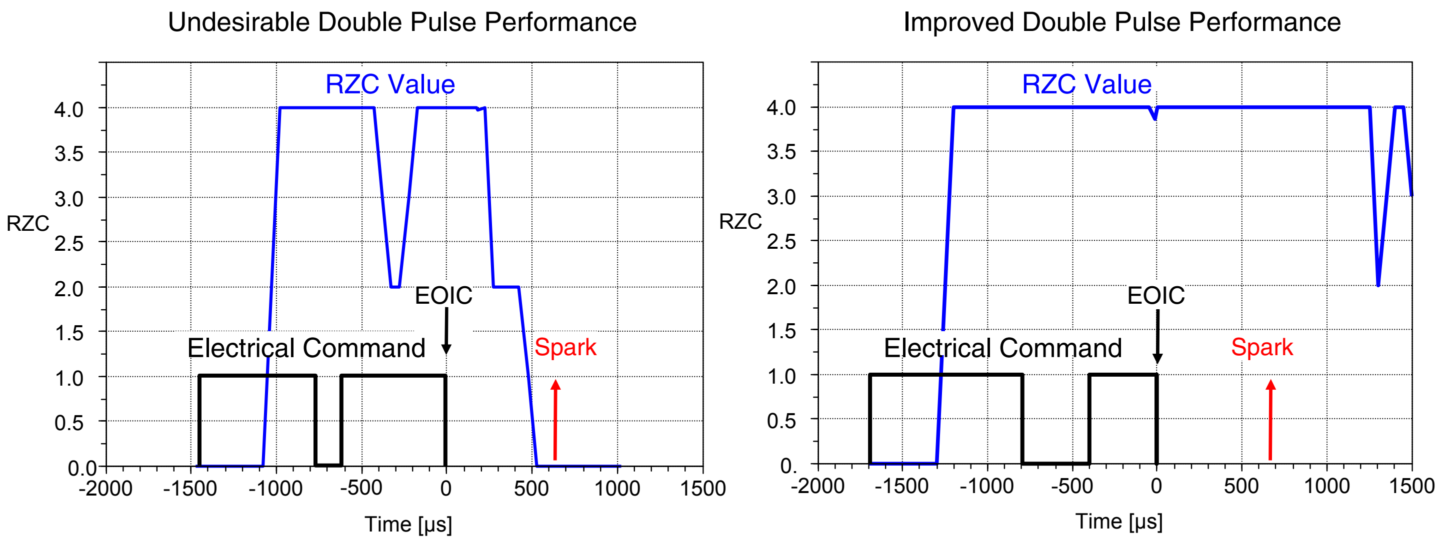

Figure 6: Multi-Pulse Comparison Showing Improved Fuel Parameters

during the spark event timing shown at time = 650 microseconds. The left injection sequence with even mass split between the two pulses and a short inter-pulse delay shows minimal fuel near the spark gap at the time of the spark event.

From these spray experiments it was learned that very short delays between pulses (< 50 us) do not improve RZC results with the Multec 20, and the pulse mass split should be planned to give a small mass in the final pulse before the spark event. These results were used to guide the calibration work on the multi-cylinder engine.

Single-Cylinder Engine Injection Experiments

In addition to spray measurement techniques, a single cylinder engine (SCE) was employed for evaluation of injection pulse sequences under firing conditions and in the presence of recirculated exhaust gas (EGR). Although the combustion system of the SCE is different compared to the multi-cylinder engine, the base stratified operation strategies are similar for both combustion systems as previous investigations indicated.

The goal of the SCE testing was twofold: (1) further augment the learning regarding injection pulse sequences in engine combustion conditions, while also adding the element of EGR into consideration, and (2) evaluate the most efficient engine mapping method to produce optimum injection pulse sequences.

In summary, the SCE testing confirmed the conclusion from spray experiments that the final injection pulse in a sequence should have a small mass. Additionally, a Design of Experiments mapping method was concluded to be superior because it produces similar results to in-house proprietary mapping sequence while offering a choice of multiple optima to chose from. The in-house mapping sequence produces only one final optimum combination with a considered prioritizing order of combustion stability (misfire-free), smoke numbers, fuel consumption and NOx emissions.

MULTI-CYLINDER ENGINE EXPERIMENTS

The requirements for a stratified engine management system, including the high-pressure fuel system, have been covered in detail in a previous paper [3]. For the multi-cylinder engine testing, the M272 V6 development engine previously mentioned was retrofitted with a Delphi engine management system including Multec 20 injectors, engine controller, linear oxygen sensors, and mass airflow sensor.

First, the engine was fully mapped in homogeneous stoichiometric mode in an engine dynamometer at Delphi's Bascharage, Luxembourg site. This mapping data was then transferred to a development vehicle to allow parallel progress to occur in the vehicle calibration development. The Delphi in-house-developed Residual Estimator Tool was used to map the engine for in-cylinder trapped exhaust gas residuals. The results were then implemented in a real-time residual gas estimator in the engine controller code [4].

After the homogeneous mapping was complete, the mapping activity was continued for the stratified combustion mode, an activity which is still ongoing. The focus of this mapping was to determine the correct combination of key control variables for optimum fuel efficiency, emissions, and combustion robustness. The variables calibrated included the injection pulse sequence, ignition angle, intake and exhaust cam phaser positions, variable intake manifold position (long or short runners), and EGR schedule. The combustion mode transition strategy between homogeneous and stratified combustion modes was also calibrated to ensure quick transitions with minimal torque perturbation.

MULTI-CYLINDER FUEL EFFICIENCY

Figure 7 shows a chart of brake specific fuel consumption (BSFC) results from the engine under controlled engine dynamometer conditions in lean, stratified combustion with exhaust gas recirculation. These fuel consumption values represent a significant benefit when compared to homogeneous stoichiometric operation, as will be highlighted in the vehicle results which follow. The dotted outline delineates the operating zone of the engine in the manual transmission development vehicle during the European NEDC emissions cycle, showing that the stratified operation range is broad enough to allow the flexibility of using stratified combustion when desired during the cycle.

VEHICLE FUEL EFFICIENCY IMPROVEMENT

For vehicle-level development of the stratified system using the solenoid-based injector, a 2006 Mercedes CLS 350 CGI was chosen. This vehicle is sold in Europe and features the same M272 3.5 liter V6 engine that was used in the dynamometer development, a 7-speed automatic transmission, and an aftertreatment system consisting of dual NOx storage catalysts, one for each bank of the V6 engine. Benchmark testing and data collection were performed on the vehicle in its production configuration, and then it was converted to a Delphi engine management system with Multec 20 injectors. To eliminate the software effort associated with replicating the high-speed CAN link between the engine controller and transmission controller, the vehicle was converted to a 6-speed manual transmission. The rear axle ratio was also modified so that the first gear and sixth gear final drive ratios match the original automatic transmission, as shown in table 1 below.

	Production 7-Speed Automatic		
	Transmission	Rear Axle	Overall
1st Gear	4.38	3.27	14.32
7th Gear	0.73	3.27	2.39
	Manual 6-Speed Transmission		
1st Gear	5.01	2.87	14.38
6th Gear	0.83	2.87	2.38

Table 1: Final Drive Ratio Comparison

VEHICLE FUEL ECONOMY BENEFITS

Figure 8 shows the fuel economy benefits achieved with the outwardly-opening solenoid injector in the manual transmission development vehicle. These results were obtained by operating the vehicle under steady-state conditions at the Delphi Vehicle Emissions Laboratory in Bascharage, Luxembourg, using the road-load model of the CLS development vehicle. The engine management system calibration derived from the engine dynamometer was used during these tests.

The points shown represent constant-speed portions of the European NEDC emissions drive cycle. At each point, the vehicle was operated in both homogeneous and stratified modes, and then the values were compared. The homogeneous operation employs an optimized cam phasing on intake and exhaust, so it represents a solid base for comparison. The resulting very good percentage improvement values show the fuel-saving capability of spray-guided combustion with the Multec 20 injector. However, the fuel efficiency penalty associated with NOx storage catalyst regenerations is not yet included in these values.

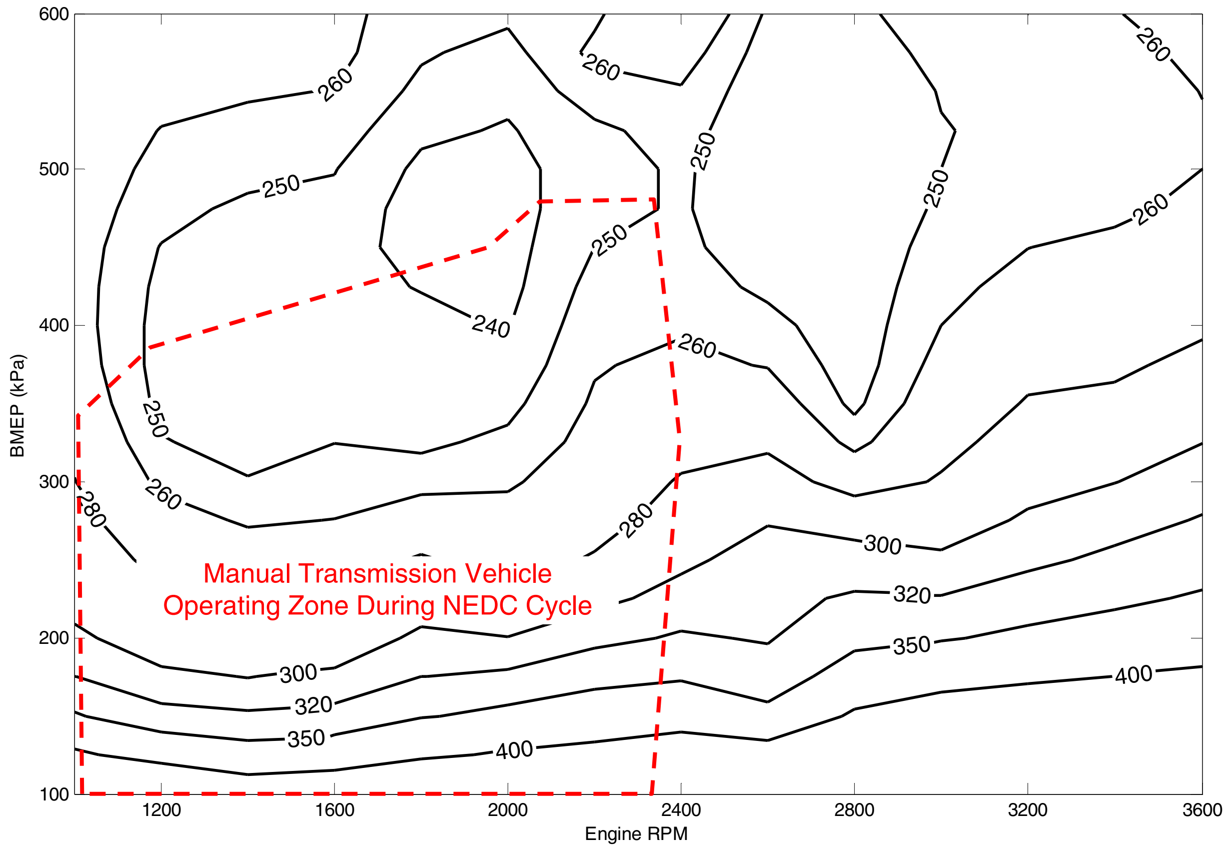

Figure 7: V6 Engine BSFC in Stratified Combustion, Steady-State Engine Dynamometer

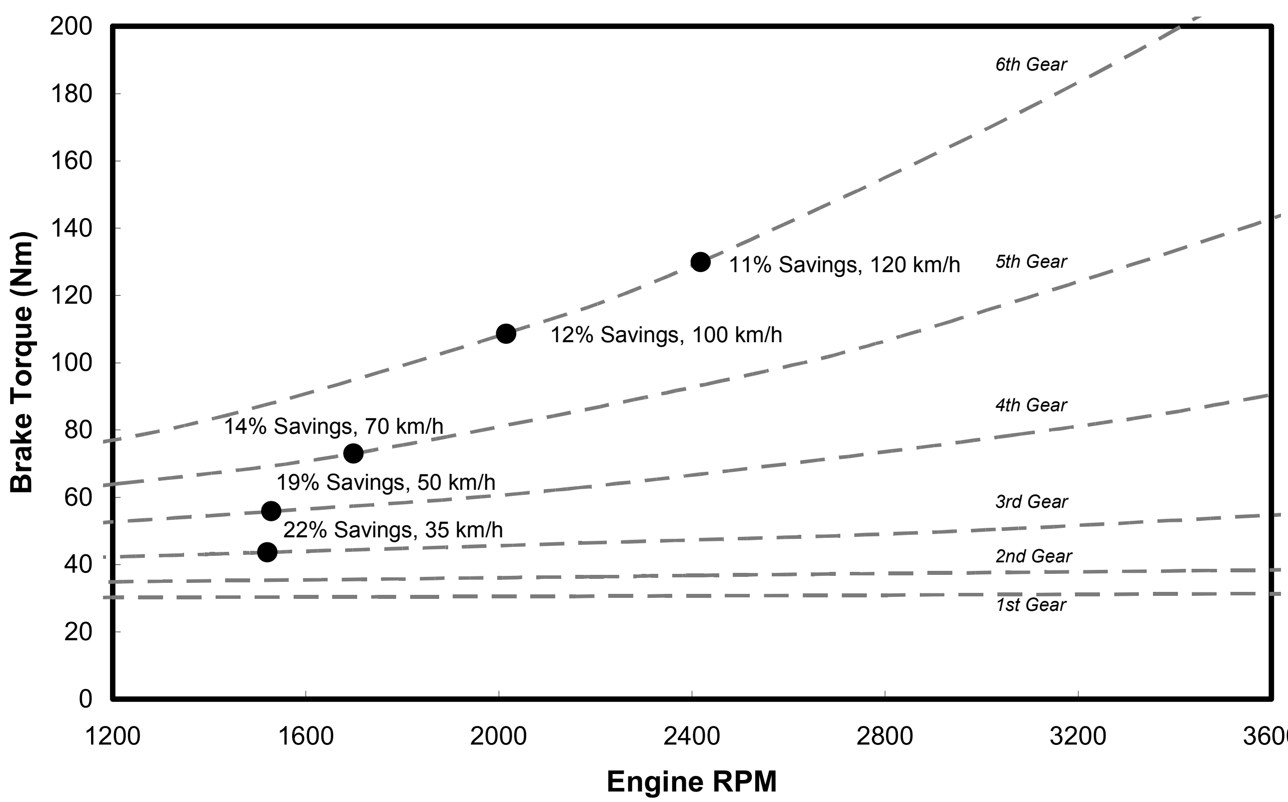

Figure 8: Vehicle Fuel Savings, Stratified Combustion vs. Homogeneous Combustion

CONCLUSION

The Multec 20 outwardly-opening solenoid injector offers excellent performance in homogeneous and spray-guided stratified combustion modes and is capable of delivering the fuel efficiency benefits expected of spray-stratified combustion under multi-cylinder engine and vehicle conditions. The solenoid actuator is compatible with the electronic peak-and-hold driver circuits for solenoid-based multi-hole injectors. This allows the flexibility to share a common electronic engine controller between multi-hole and outwardly opening injectors. When coupled with the lower cost of the solenoid actuator versus a piezo element, an engine management system using the Multec 20 offers the potential to be a best-value Powertrain solution.

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