

3-Cylinder Turbocharged Gasoline Direct Injection: A High Value Solution for Low CO₂ and NO_x Emissions

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04/12/2010John E. Kirwan, Mark Shost, Gregory Roth and James Zizelman
Delphi Powertrain Systems

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ABSTRACT

Today turbo-Diesel powertrains offering low fuel consumption and good low-end torque comprise a significant fraction of the light-duty vehicle market in Europe. Global CO₂ regulation and customer fuel prices are expected to continue providing pressure for powertrain fuel efficiency. However, regulated emissions for NO_x and particulate matter have the potential to further expand the incremental cost of diesel powertrain applications. Vehicle segments with the most cost sensitivity like compacts under 1400 kg weight look for alternatives to meet the CO₂ challenge but maintain an attractive customer offering. In this paper the concepts of downsizing and downspeeding gasoline engines are explored while meeting performance needs through increased BMEP to maintain good driveability and vehicle launch dynamics. A critical enabler for the solution is adoption of gasoline direct injection (GDi) fuel systems. GDi provides the ability to utilize increased scavenging without sacrificing hydrocarbon emissions because fueling and air controls can be separated. In-cylinder injection with GDi also provides charge cooling benefit yielding the knock reduction necessary for turbocharged applications. Several options within GDi are explored including multi-hole and single pintle spray generators, as well as side-mount versus central-mount applications. Both 3-cylinder and 4-cylinder base engine configurations are explored for turbocharged engines downsized to 1.2 L. Improvements in hydrocarbon emissions, heat losses and scavenging favor fewer cylinders. This is reinforced by packaging and cost considerations. The next system aspect considered is emissions aftertreatment. Stoichiometric turbocharged GDi provides the lowest cost using the established 3-way catalyst. Stratified GDi is expected to require a lean NO_x trap (LNT) and Diesel Euro 6 systems require addition of a diesel particulate filter (DPF)

and possibly NO_x aftertreatment. Although the aftertreatment system to meet Euro 6 NO_x requirement is not known today, addition of a DPF, DPF with LNT, or DPF with urea selective catalytic reduction (SCR) represent significant cost and packaging challenges. The analysis concludes by comparing the 3-cylinder turbocharged GDi to other offerings in the context of value tradeoff of CO₂ reduction to system on-cost. Stratified 3-cylinder turbocharged GDi systems offer up to 22% CO₂ reduction compared to a baseline port fuel injected 4-cylinder engine. CO₂ reduction of 18% is possible for a stoichiometric GDi mechanization that employs variable valve actuation (VVA) and a conventional 3-way catalytic converter. At Euro 6 emission levels, stoichiometric 3-cylinder turbocharged GDi powertrains offer excellent value. The 3-cylinder turbo-Diesel offers similar value if it is capable of meeting the NO_x emissions standard without lean aftertreatment. Powertrains with higher engine-out NO_x levels that require lean aftertreatment are significantly disadvantaged. Based on the price sensitivity of the compact car segment, the value analysis predicts the 3-cylinder turbocharged GDi engine as the powertrain of choice.

INTRODUCTION

Dramatic fuel consumption / CO₂ reductions are necessary, both near-term and long-term, while tailpipe emission standards are becoming increasingly stringent. [Figure 1](#) indicates the rollout of US and European light-duty emission standards and fuel consumption targets over the next several years. Particularly interesting is the sharp reduction in NO_x emissions and the trend toward elimination of relief in the Euro NO_x emissions standard for vehicles with Diesel engines. The European overall light duty vehicle mix is roughly 50% powered by turbo-Diesels for vehicles meeting the Euro 4 emissions standards. This is one reason that fleet-

averaged CO₂ emissions are lower in Europe compared to the US, because turbo-Diesels at the same rated power emit less CO₂ compared to baseline naturally aspirated (NA) gasoline vehicles with multi-port fuel injection (MPFI).

However, the cost of Euro 4 turbo-Diesels is significantly greater than a baseline Euro 4 gasoline engine due largely to the common rail high pressure (1500 - 2000 bar) fuel system, the turbocharger, and differences in the powertrain structure to accommodate Diesel combustion that produces higher maximum cylinder pressures. As a result, the European Diesel market share is markedly lower than 50% for smaller vehicles driven by vehicle purchase price sensitivity. A recent DRI survey [1] indicates that the Diesel market share is approximately 30% for subcompact and compact vehicles lighter than approximately 1400 kg. Euro 5 and Euro 6 emission standards will increase the incremental Diesel costs even more due to more stringent NO_x and particulate standards. Lower cost alternatives for reduced CO₂ emissions are thus especially attractive for smaller vehicles.

Recent development efforts have been published documenting the benefits and challenges of 3-cylinder turbocharged gasoline direct injection (GDi) engines (see, for example [2,3,4,5,6]). The present paper represents an evaluation of this technology as a high value solution providing low CO₂ and NO_x emissions for smaller vehicles. The discussion is divided into two sections. First is a technology analysis of downsizing and turbocharging, GDi fueling and its synergies with turbocharging, and an analysis of downsized 3-cylinder versus 4-cylinder engines. The second major section is a value analysis comparing CO₂ benefits for 3-cylinder and 4-cylinder gasoline and Diesel powertrains. Vehicle electrification is outside the scope of the analysis. It is expected that hybrid vehicle growth continues as well as widespread implementation of stop-start technology in Europe. These technologies complement Diesel and gasoline powertrains, and their implementation does not change the stand-alone analysis or conclusions provided.

<figure 1 here>

TECHNOLOGY ANALYSIS

TURBOCHARGED GASOLINE DIRECT INJECTION OVERVIEW

Figure 2 is a schematic diagram illustrating the concepts of downsizing, shown in the top half of the figure, and downspeeding, depicted in the bottom half of the figure. Both are effective methods to meet vehicle power needs with reduced fuel consumption. Downsizing refers to reducing total engine displacement. Downsizing the engine shifts operation from the solid line to the dashed line as shown in the top-right graph of Figure 2. For a given vehicle power

requirement at constant speed, a downsized engine operates at increased BMEP (specific load), which results in greater overall efficiency and thus reduced fuel consumption. Downsizing refers to reducing engine speed through changes to the transmission and/or final drive ratio. Maintaining a given vehicle power requirement at reduced engine speed also requires that the engine operate at higher specific loads which again results in greater overall efficiency and reduced fuel consumption. Viewed schematically on an engine speed-load map (see Figure 3), downsizing results in purely vertical displacement to higher brake mean effective pressures (BMEPs) at constant speed and downsizing results in a simultaneous upward and leftward movement to higher load and lower engine speed.

Combining downsizing with downspeeding is particularly effective for reducing fuel consumption and CO₂ emissions. However, sufficient torque is required across the engine speed range, and particularly at lower speeds, to maintain vehicle gradeability and launch performance. Turbocharging is a well-known technology that uses exhaust energy to drive a compressor to increase charge air pressure. With intercooling, turbocharging significantly increases the maximum mass of air delivered to each engine cylinder to increase the maximum specific torque and specific power. Engine knock is a limiting factor for high load operation with turbocharging. Higher charge temperatures at increased loads increase the chemical reaction rates for auto-ignition. At lower engine speeds, with increased cycle times, increased reaction rates can lead to substantial knock and potential engine damage.

GDi is an excellent complementary technology for turbocharged engines. Figure 4 shows a schematic for a turbocharged stoichiometric GDi engine. Major differences compared to a baseline NA engine with multi-port fuel injection (MPFI) are a higher pressure fuel system with 120 - 200 bar typical maximum fuel pressure, and turbocharger with intercooler. (We note here that the GDi fuel pump is drawn to the side of the engine in Figure 4 for visual clarity. The pump is actually located near the top of the engine and is driven by lobes on the camshaft.) Exhaust aftertreatment is accomplished with a conventional 3-way catalytic converter for stoichiometric engines. Due to the higher power densities provided, turbocharged gasoline engines are being developed and implemented in production vehicles with increased frequency [7,8,9,10,11,12,13,14].

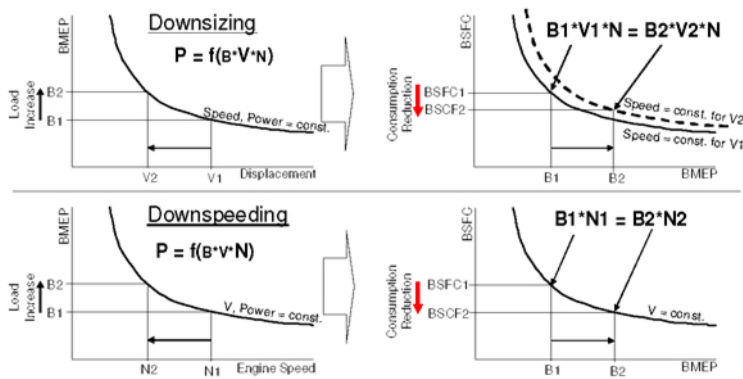


Figure 2. Effect of engine downsizing and downspeeding.

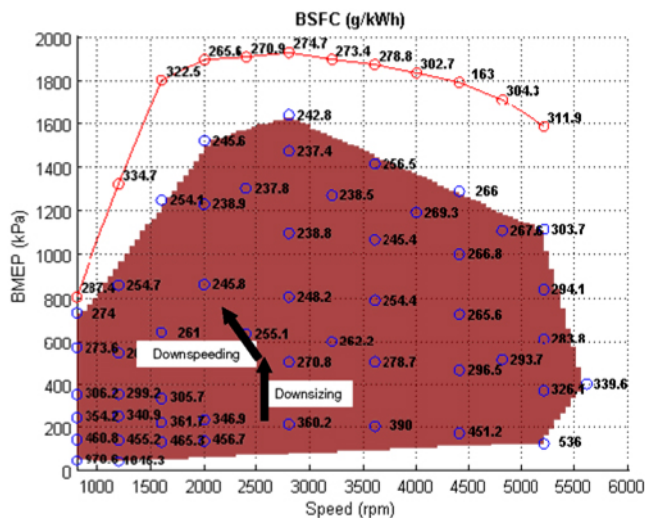


Figure 3. Schematic representation of engine downsizing and downspeeding on an engine map.

<figure 4 here>

GDi offers a number of fundamental advantages that enable improved engine performance compared to traditional port fuel injection. In-cylinder injection offers advantages during engine warm-up. GDi improves fuel control compared to PFI in a cold engine when fuel vaporization characteristics are compromised in the intake port. GDi also enables a split injection strategy during engine warm-up. Split injection can provide a locally rich mixture near the spark plug. This improves combustion robustness to enable greater spark retard for catalyst heating while the globally leaner mixture provides reduced HC emissions compared to PFI [4, 5, 7, 9].

Additionally, GDi has key features that improve maximum torque. First, injecting directly into the cylinder improves fuel control and mixture motion to improve combustion efficiency. Direct injection also allows substantially better scavenging in turbocharged engines at lower speeds and high load. Under these conditions, intake pressure is higher than

exhaust pressure, so appropriate valve overlap via cam phasing allows intake air to blow through the cylinder with an open exhaust valve to force additional residual gas into the exhaust. This process results in some of the intake charge to also be exhausted. With MPFI, the intake charge comprises a fuel-air mixture so that scavenging would lead to substantial amount of unburned fuel blown through to the exhaust. However with GDi, the fuel can be injected into the cylinder after the exhaust valve has closed. The intake charge flowing into the exhaust does not contain fresh fuel, and thus scavenging can be much more aggressive. In-cylinder injection also results in charge cooling because the heat of fuel vaporization is absorbed from the in-cylinder air mass. Scavenging and charge cooling provide increased volumetric efficiency and lower charge temperatures to reduce knock for improved combustion phasing, efficiency and maximum torque. This propensity to reduce knock can be augmented by use of fuels containing increased alcohol content (such as E85) because these fuels have higher heat of vaporization and increased octane number compared to gasoline [15,16,17].

GASOLINE DIRECT INJECTION FUEL SYSTEMS

GDi imposes substantially greater requirements on fuel delivery compared to MPFI. In an MPFI engine the fuel is traditionally injected onto the back of a closed intake valve. During standard, warmed-up MPFI engine operation, heat from the intake valve rapidly vaporizes the fuel in the port before the fuel and air are simultaneously inducted into the cylinder during the intake stroke. By contrast, fuel vaporization and mixing for GDi engines must occur rapidly in the cylinder. This process is largely influenced by fuel spray characteristics such as droplet size and spray penetration. These characteristics are achieved through careful injection system design with injectors operating at moderate fuel pressures currently up to 200 bar.

Homogeneous GDi Fuel Systems

GDi operates in both homogeneous and lean stratified engine configurations. Figure 5 shows the major components for Delphi homogeneous GDi fuel systems comprising Multec 12 inwardly-opening, multi-hole GDi injectors, a fuel rail and an engine-driven high pressure fuel pump. Key injector requirements for homogeneous GDi injection are the capability to operate at fuel pressures up to 200 bar, good linearity over a wide flow range to ensure precise delivery over the full engine map, and spray generation that provides good vaporization and mixing without wetting in-cylinder surfaces. Injection is typically during the intake stroke to improve vaporization and mixing. Stoichiometric operation with homogeneous GDi allows the use of conventional 3-way exhaust catalysts and thus worldwide application without concerns for lean NOx production and aftertreatment.

Two different injector lengths are shown in the figure. Depending on the engine application, the injectors may be in either side-mount (as shown in [Figure 6](#)) or central-mount configurations. The longer injector shown in the figure is required for some engines with central-mount injection. Side-mount injectors are frequently easier to package in an engine, but the off-axis mounting location makes uniform mixture preparation more challenging and increases concerns for impingement of the spray on the cylinder wall or piston top that causes increased smoke emissions. Central-mount injectors provide a more symmetric location that improves mixing and generally reduces the potential for fuel droplet impingement. However in-cylinder access through the head often is prohibited due to packaging conflicts with the valvetrain components and spark plug. Regardless of the mounting location, multi-hole injectors produce distinct spray streams from each hole as shown in [Figure 7](#). Characteristics of these streams are specific to a given engine to conform to spray targeting needs, and can differ substantially between applications (see [Figure 8](#)). Designing the injector utilizes both experimental and modeling tools to simultaneously optimize the parameters required for spray formation appropriate to the specific engine [18].



Figure 5. Delphi homogeneous GDi fuel system components.



Figure 6. Side-mounted homogenous GDi.

<figures 7, 8 here>

Stratified GDi Fuel Systems

For stratified GDi fuel systems, the characteristic fuel pressure is 200 bar, and the rail and pump characteristics are substantially similar between homogeneous and stratified configurations. However the injector required for stratified operation is significantly different than the homogeneous multi-hole injectors described above. Modern stratified systems rely principally on spray characteristics for stratification. Because the fuel mixture burns with only a portion of the air mass in the cylinder, the fuel spray must be carefully controlled in both space and time so that a well prepared, combustible charge is provided at the spark plug when it fires.

[Figure 9](#) shows the Delphi Multec 20 stratified fuel injector. Side- and end-views of the spray are included in [Figure 9](#) to help illustrate injector spray characteristics. Further details are available in [19]. As shown in [Figure 10](#), the fuel injector is centrally-mounted in close proximity to the spark plug, and fuel is injected during the compression stroke in a brief window around the timing of spark ignition. The injector opens outwardly to produce a hollow cone, thin fuel sheet. When injected into elevated pressures characteristic of in-cylinder conditions during compression, the fuel sheet forms a recirculation zone to help place a combustible mixture at the spark plug location. The circular white marker in [Figure 9](#) depicts the location of this spray recirculation zone. Modeling and simulation are used extensively in developing the injector to ensure the spray characteristics are appropriately tailored to the engine geometry [19, 20]. Multiple injection pulses are typically used to reduce fuel penetration. [Figure 9](#) shows that the fuel spray is better stratified in the area of the spark plug

by increasing the number of spray pulses from a single pulse to multiple, closely spaced fuel pulses. Thus, the injector delivers multiple, closely spaced injection pulses with high precision over a very short time window.

Stratified spray development can also have a significant impact on ignition requirements. The fuel spray from the closely-spaced injector imparts significant momentum and turbulence in the area of the spark gap around the time of ignition. This, combined with the substantial variations in fuel air mixture associated with a stratified fuel charge, can create significant variability at the spark plug gap. A high energy multi-charge ignition system can improve ignition consistency to reduce cycle-by-cycle combustion variability (see, for example [21, 22], for further discussion).

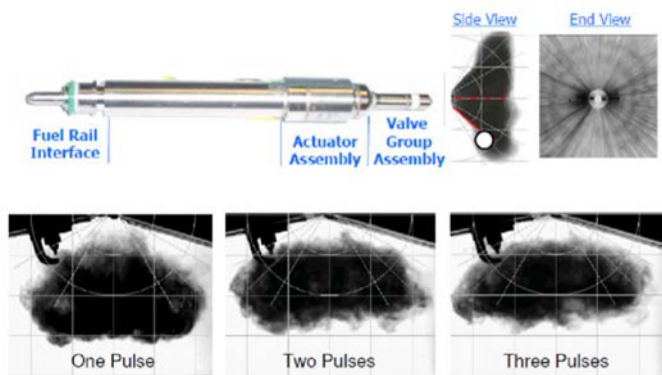


Figure 9. Delphi Multec 20 injector and spray characteristics.



Figure 10. Centrally-mounted stratified GDi.

3-CYLINDER VS 4-CYLINDER DOWNSIZED ENGINE EVALUATION

Engine downsizing can be accomplished via reduction in the number of cylinders, and/or a reduction in the displaced volume of each cylinder. The value analysis in the next section begins with a 1.6L naturally-aspirated baseline vehicle and evaluates the benefit of 25% (modest) downsizing to 1.2L turbocharged engines with downsizing. Compared here are 4-cylinder naturally-aspirated configurations versus downsized turbocharged 3-cylinder applications.

Fuel consumption / CO₂ and regulated emissions favor reduction in cylinder number. Weinowski et al [6] evaluated the brake specific HC emissions of 134 engines. While there was a fairly wide scatter band, HC emissions plotted against cylinder displacement showed a significant decrease in HC emissions with increasing cylinder volume (and thus fewer cylinders at constant engine displacement). Removing a cylinder results in smaller quench layers and crevice volume. This improves combustion efficiency for lower hydrocarbon emissions and reduced fuel consumption. Removing a cylinder also reduces heat transfer surface area for a given displacement volume. Lower heat loss to the head and cylinder walls improves thermal efficiency for reduced fuel consumption. Finally, fewer cylinders reduce friction for an additional fuel consumption reduction. The overall effect of reducing the number of cylinders on fuel consumption can be substantial. Heil et al [23] evaluated downsized 2.2 L turbocharged GDi engines configured either with 6-cylinders or 4-cylinders. Compared to a 6-cylinder 3.0 L naturally-aspirated baseline engine at a steady 10 KW operating point, downsizing to 2.2 L with 6-cylinders produced a 4% reduction in fuel consumption while downsizing to 2.2 L with 4-cylinders reduced fuel consumption by 9% compared to the baseline.

High load performance also favors a 3-cylinder engine because it offers better high load scavenging [2]. Scavenging efficiency in turbocharged engines is affected by the differential pressure between the intake and exhaust during the gas exchange process. With 4-cylinder engines, the firing frequency is 180 deg. Consequently, while one exhaust valve is open near TDC during the gas exchange process, the exhaust valve for the next cylinder has already opened near bottom-dead-center to begin the exhaust stroke. Initiation of the exhaust stroke creates a pressure wave that raises exhaust pressure and reduces scavenging for the cylinder undergoing gas exchange. The firing frequency for 3-cylinder engines is 240 deg so that an additional exhaust valve is not open near top-dead-center during gas exchange. Thus the three cylinder engine experiences a more favorable pressure differential and improved scavenging to increase full load torque.

Finally, cost and packaging favor a 3-cylinder engine. Reducing cylinder count reduces the number of required components leading to a direct reduction in cost. Additionally, the need for fewer components and the greater cylinder size offers packaging relief that can further reduce cost and allow better optimization of the fuel injector location.

One clear disadvantage to a 3-cylinder engine is degraded NVH. A 3-cylinder engine is inherently balanced for rotation. However, there are unbalanced 1st and 2nd order moments along the length of the engine. These unbalanced moments induce a front-back rocking motion, such that compensation should be provided for a turbocharged 3-cylinder engine. The required measures include a counterbalancing shaft, and perhaps a modified engine mounting configuration. Counterbalancing results in sufficient compensation for cylinder displacements up to approximately 0.5 L, but results in increased cost, size and friction. Coltman et al [2] implemented roller bearings to the balance shaft in order to minimize friction effects.

Overall, for a downsized and turbocharged GDi engine a 3-cylinder configuration is favored for reduced fuel consumption and regulated emissions. A 3-cylinder engine also offers cost and packaging advantages and provides acceptable NVH with counterbalancing. We will therefore carry forward a 3-cylinder mechanization as the 1.2 L turbocharged engine considered in the value analysis below.

VALUE ANALYSIS

In this section we evaluate CO₂ emissions reduction potential and OEM on-cost for 3-cylinder and 4-cylinder gasoline and Diesel powertrains in smaller vehicles (under 1400 kg). We limit our scope only to powertrains and resulting aftertreatment needs. Additional cost measures related to noise reduction, etc. are not included. For this analysis, we define the baseline to be an 1160 kg European gasoline vehicle with a 1.6L NA MPFI engine meeting Euro 4 emissions standards. (Diesel powertrains are heavier, so CO₂ comparisons are made with 40 kg higher mass for Diesel vehicles.) Let us first consider attributes of this baseline engine compared to turbocharged Diesel engines in 2008 Model Year. Figure 11 shows that the baseline gasoline engine and the turbocharged Diesel have comparable specific power. The turbo-Diesels generate substantially greater specific torque. This enables a 25% longer gear ratio for the Diesel powertrains so that they generally operate at higher loads. Diesel vehicles from 2008 show approximately 24% lower CO₂ emissions compared to baseline gasoline vehicle

To evaluate CO₂ emissions reduction potential against this baseline, we look to the expected performance of future turbocharged engines meeting substantially tighter emissions

standards (i.e. Euro 6). Figure 12 offers a look at the performance attributes assumed in our analysis for these future engines compared to series production vehicles of today. A survey of current production powertrains shows that current turbocharged vehicles deliver typical specific torque values of 150 N-m/L for both common rail Diesel and GDi vehicles. The EU agreement defines first implementation of Euro 6 standards in 2014. We expect moderate increases in specific torque and power for turbocharged engines by that time. Thus for our analysis we have assumed a 20% increase in specific torque for turbocharged vehicles to provide a maximum value of 180 N-m/L. Specific power for GDi vehicles is assumed to be 80 kW/L and common rail Diesels are assumed to deliver 65 kW/L. Clearly these values do not represent the “best in class” for future powertrains. In fact, engines exist today that exceed our assumed engine performance for 2014, and we expect performance and fuel efficiency advancements to continue for GDi turbocharged engines by using cooled EGR [24 - 25] and other innovations. However, we have chosen performance estimates that we expect to represent average vehicles 5 years from now using single-stage turbocharging, no cooled EGR, and transmissions designed to accommodate average torque levels. These numbers are more appropriate for our analysis to better assess the value of the technologies for widespread reduction of vehicle CO₂ / fuel consumption and are appropriate for the smaller, lighter-weight, value-segment of the market.

Table 1 indicates the technologies considered in the analysis. The left-hand side of the table describes the engine technology. The columns in the center of the table offer a relative assessment of the major contributors to system cost. The right-hand section of the table estimates CO₂ emissions (also depicted graphically in Figure 14). The first two rows in the table comprise the 2008 gasoline and Diesel engines we have discussed above meeting Euro 4 emissions. The remaining rows consider turbocharged GDi and Diesel common rail technologies we project for smaller vehicles meeting Euro 6 emissions standards in 2014.

<figure 11 here>

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The major factors leading to cost differences between the powertrain technologies fall into four categories: base engine, fuel system, air delivery system, and aftertreatment system. GDi fuel systems operate at maximum fuel pressures of roughly 200 bar, resulting in a moderate cost increase compared to MPFI. Fuel systems for the Diesel technologies operate at significantly elevated pressures (1500 - 2000 bar). This leads to a substantial increase in system cost for all