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The Potential of Gasoline Direct Injection for Small Displacement 4-Stroke Motorcycle Applications

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ABSTRACT

With the introduction of increasingly more stringent emission standards, Engine Management Systems (EMS), including port fuel injection, are now being introduced in the 4-stroke motorcycle marketplace. These systems have been generally derived from the automotive industry, albeit with some significant changes to satisfy the strict cost and packaging constraints of the motorcycle applications.

Direct injection (DI) is positioned to become one of the next generation of technologies for the automotive engine, offering the potential for improved fuel economy, performance and emissions control. Direct injection can also provide similar benefits for motorcycle applications. However, direct transfer of the current production automotive systems is unlikely to suit the requirements of motorcycle applications, due to some of the specific challenges faced in the motorcycle market.

For small displacement motorcycle applications, a central injection, spray guided DI combustion may offer the characteristics required to meet many of the challenges of this difficult application. To demonstrate the potential of such an application, a 125cc engine has been developed using an air-assist DI spray guided combustion system. Results from the engine show significant fuel economy improvements when compared to the baseline carbureted engine, as well as potential to meet current and future emissions legislations with a variety of system configurations.

INTRODUCTION

The technology roadmap for motorcycles in response to the increasing requirement for emission control and enhanced products is closely following that of the automotive industry. This can be illustrated with the widespread introduction of exhaust aftertreatment systems and more recently the introduction of Engine Management Systems (EMS) to the lower displacement motorcycle engines. Although the motorcycle EMS and aftertreatment systems may be derived from the automotive development, they need to be tailored to the specific requirements of the motorcycle application.

The automotive technology roadmap now includes technologies such as direct in-cylinder injection, cylinder deactivation, downsizing and variable valve timing. Of these technologies, perhaps the most pertinent to small displacement motorcycle engines are direct injection and VVT technologies.

Direct injection is now becoming more commonplace in the automotive industry, is established in the recreational 2-stroke engine product industry and has been more recently introduced to 50 cc 2-stroke scooter engines. Direct injection can offer similar fuel economy, emission control and performance enhancement potential for a small 4-stroke engine as compared to the larger displacement automotive engines. There are, however, specific challenges in applying direct injection to this application in comparison to the automotive application, that will likely preclude direct transfer of the current production systems to the motorcycle, including:

- Packaging constraints of the Direct Injection systems
- Smaller bore size and often higher maximum operating engine speed
- System electrical current consumption consideration
- Significant cost constraints (market dependent)
- System ‘serviceability’ and consideration of ‘technology overload’ for dealers and service people whose training, and tools, relate to the simple carburetor.

This paper describes in more detail some of the major challenges in applying DI to small 4-stroke motorcycle engines, and provides an example of how an air-assist DI system can assist in meeting these challenges, including development level results from an application on a 125cc 4-stroke engine.

CHALLENGES FOR DIRECT INJECTION APPLICATION ON 4S MOTORCYCLES

Small bore sizes are inherent with the typical smaller displacement engines found in motorcycle applications compared to the typical automotive engine displacements, as shown in Figure 1. This small bore size can make implementation of current series production automotive direct injection systems difficult. These automotive systems typically use wall and/or air guided type combustion systems, also commonly known as side-injection systems, with the direct injector mounted on the side of the combustion chamber, between and below the inlet ports [1,2,3].

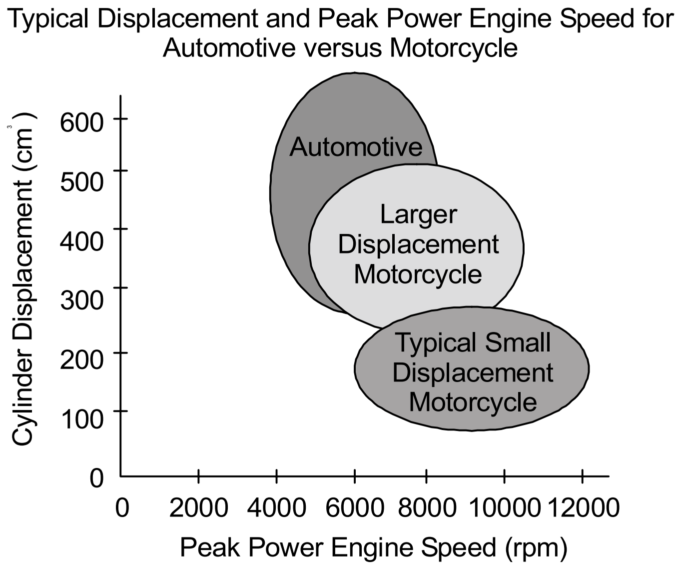

Figure 1 **Comparison of typical automotive and motorcycle engine size and rated speeds**

Due to the generally high penetration rates of high pressure injectors, the small bore size can lead to significant bore wall wetting from the injected fuel spray for the side injection systems. Not only does this cause poor charge preparation prior to combustion, but can also wash the lubricant from the bore walls, leading to potential engine durability issues.

Central injection, whereby the direct injector is located near to the center of the combustion chamber, with an injection axis near to parallel to the cylinder bore axis, helps to limit cylinder bore wetting caused by spray impingement. As the spray is aimed directly towards the piston crown, there is also no inherent limitation on injection timing in order to align piston and injected spray as is typical of side injection combustion systems. Piston crown wetting, however, may still be an issue, even for the central injection systems. The short distance between the injector and combustion chamber surfaces experienced on small displacement engines has been noted previously, and referred to by Inoue at al [4] as short “spray travel lengths”. In order to minimize issues associated with surface wettings due to the short spray travel lengths, rapid fuel evaporation and low fuel spray penetration rates are required.

The high-speed requirement of motorcycle engines, as shown in Figure 1, also imposes challenges for the application. Perhaps the most obvious is that of fuel preparation at high engine speed and high load conditions. The injection system, therefore, must have the ability for very high fuel flow rates, in order the deliver the fuel into the combustion chamber in a short time, and thereby maximize the mixture preparation time at high engine speed. The fuel system also needs to be able to deliver precise quantities of fuel at low engine speeds and loads (idle conditions), and therefore the dynamic range for the fuel metering requirement of the motorcycle engine can be extremely severe.

The high-speed element also tends to dictate “over-square” bore/stroke ratios in order to minimize piston speed. While the larger bore/stroke ratios offer increased space in the cylinder head to package the injection system, these engines become increasingly difficult to achieve high compression ratios, and all but precludes the use of deep, complex piston bowl shapes [5]. Indeed, even relatively small and shallow piston bowl cavities need to be carefully designed in conjunction with the cylinder head cavity to minimize compressed volume in order to achieve the desired compression ratio.

For high performance applications, there is also the need for good volumetric efficiency at high engine speeds. This encourages use of high flow efficiency ports, which in turn typically means low inlet port generated bulk air motion. Ideally, the combustion system should therefore not rely on large, complex piston cavity shapes, or high bulk air motion for the mixture preparation.

On the commercial side, perhaps the biggest challenge for introducing DI on small four stroke motorcycles is one of cost. To achieve an acceptable incremental cost, the EMS system, whilst it may be based on developments for the automotive market, must be configured to suit the local requirements. This typically precludes many of the additional components that have been implemented on automotive applications with direct injection, including electronically controlled inlet throttles (drive-by-wire), lean NOx catalysts, wide range oxygen sensors and NOx sensors. By this very nature, the control of the DI systems can not be as accurate on a motorcycle when compared to an automotive application, so the system needs to be robust and tolerant to variations in operating conditions.

AIR-ASSIST DIRECT INJECTION COMBUSTION SYSTEM APPLIED TO 4S MOTORCYCLE ENGINES

Air Assist Direct Injection has been commercially applied to a range of 2-stroke engines, from 50 to 500 cc/cylinder displacements, and developmentally on 4-

stroke engines, ranging from small motorcycle engines through to multi-cylinder automotive applications.

It is believed that many of the specific challenges related to the application of DI to small displacement motorcycle engines can be addressed with an air-assist DI combustion system.

AIR-ASSIST FUEL SYSTEM

The heart of the DI combustion system is the fuel injection system. The air-assist direct fuel injection system consists of the following major components as shown in Figure 2.

1. Metering (PFI) injector. A conventional port fuel injector is used to meter fuel into an interface region between the metering injector and the direct injector.
2. Air/Fuel Interface. An interface region exists to ensure correct fuel delivery from the metering injector into the direct injector. The interface also provides the link to the compressed air circuit that is used to force the metered fuel from the direct injector into the combustion chamber.
3. Direct (air) injector. This injector is best described as a charge injector, as it injects a mixture of fuel and air directly into the combustion chamber.

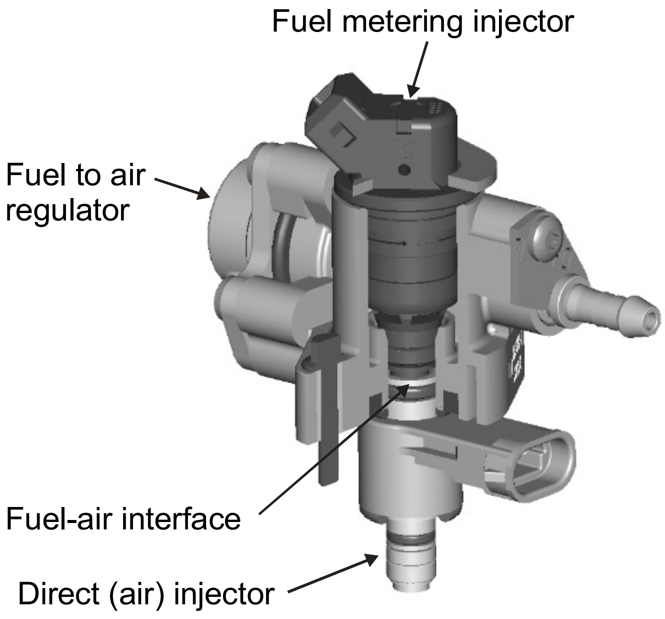

Figure 2 **Two-stroke 50cc motorcycle production fuel rail assembly**

The operation of the fuel system is shown schematically in Figure 3. The fuel metering injector is pulsed to accurately meter a defined quantity of fuel into the interface region. The direct injector is then operated, resulting in a mixture of fuel and air to be simultaneously injected into the combustion chamber. This sequence separates the fuel metering from the direct injection event, which enables similar fuel metering turn down ratios to port fuel injection systems to be achieved using a constant pressure differential.

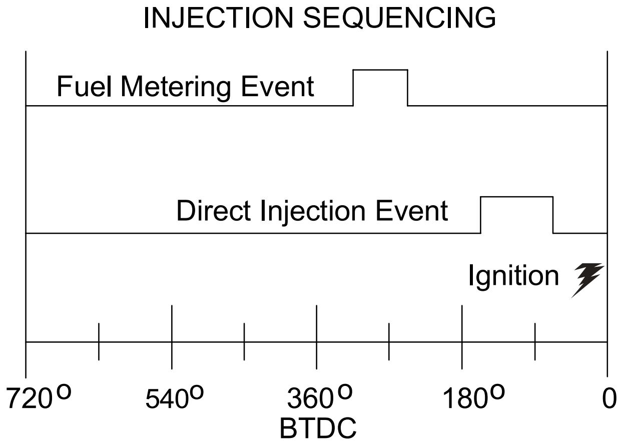

Figure 3 **Schematic of typical injection sequence for air-assist DI fuel system**

The air-assist injection system requires a supply of pressurized air and fuel. The typical air rail pressure of the system is between 500 to 650kPa (gauge). The fuel pressure is usually controlled via a pressure regulator with a reference relative to the air pressure (maintaining a constant metering pressure differential, typically between 100kPa to 250kPa). More details about the air-assist DI fuel system can be found in references [6] to [8].

The resulting spray characteristics of the system can be best described as a well atomized air/fuel mixture (droplet SMD generally less than 10μm), with a typically narrow cone shape. The small fuel droplet size becomes increasingly important to promote rapid evaporation of the fuel to minimize wall wetting and to promote good mixture formation during high engine speed operation.

The relatively low injection pressure also results in a low injection (penetration) velocity (see Figure 4). The injection velocity is especially low for injection timing during the compression stroke, which, combined with the narrow spray cone angle, results in a very compact spray plume. This is believed to be highly desirable for a small displacement engine application.

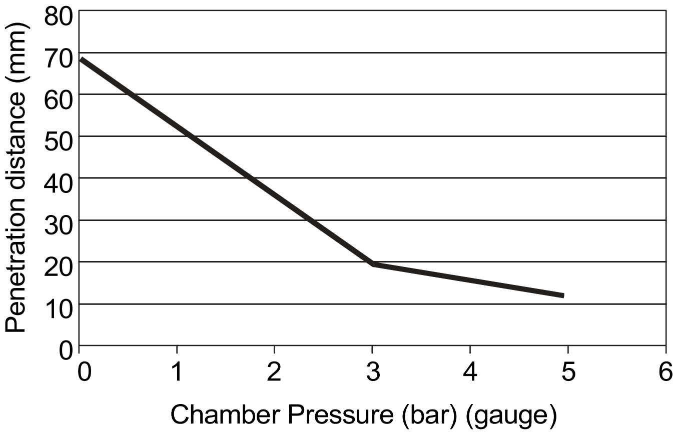

Figure 4 **Fuel spray penetration length vs chamber pressure measured at 2.0ms after start of injection**

The air-assist direct injector design can vary depending on the application. Synerject has been manufacturing the direct injector since 1997, and now supplies injectors (as well as complete systems) for many different applications. The new direct injector architecture (named Strata1^{TM}) is a flexible design where the power group (solenoid and armature) remains consistent across a variety of applications. This design philosophy allows the injector leg length, nozzle design and plastic overmolding to be varied according to what is required for the application. For example, the current production 2-stroke injector for small motorcycle/scooter applications features a short leg length, resulting in a very compact design as shown in Figure 5. The automotive 4-stroke injectors, however, have a much longer leg length due to the lack of space in the cylinder head near to the combustion chamber for the larger diameter solenoid. The nozzle design for the automotive injector is also different from the 2-stroke motorcycle injector, and includes the incorporation of a “projection” on the end of the poppet. This projection protrudes into the combustion chamber and helps to create a more repeatable spray pattern (both shot to shot and injector to injector), and is combined with a nozzle design which reduces the crevice volume around the poppet gauge line that is present on the 2-stroke motorcycle injector. The reduced crevice volume can result in reduced unburned hydrocarbon emissions.

For 4-stroke motorcycle applications, it is believed that the direct injector design will be a combination of the 2-stroke motorcycle design and the automotive 4-stroke designs. For instance, on some 2-valve, single cylinder applications, it is possible to use a short leg length injector similar to the 2-stroke motorcycle applications. For 4-valve, DOHC engines, the longer automotive style injector is required due to packaging constraints. While the spray stability and low crevice volume of the automotive injector is desirable, the projection becomes difficult to package due to clearances required between it and the spark plug earth electrode. To find a solution to this, a new type of injector nozzle is currently being developed by Orbital and Synerject. This nozzle design does not incorporate a projection, but has new features that minimize the crevice volume near the injector gauge line, while promoting a very stable spray formation.

Spray images produced with the different injector variants injecting into atmospheric conditions are shown in Figure 6. These images correspond to 1.0msec after the start of injection (SOI). As can be seen, all injectors produce a finely atomized spray with a relatively narrow, filled-in cone like spray structure. Comparing the spray images, it is noticeable that the automotive injector with the projection and the new development non-projection injector produce very similar spray structures.

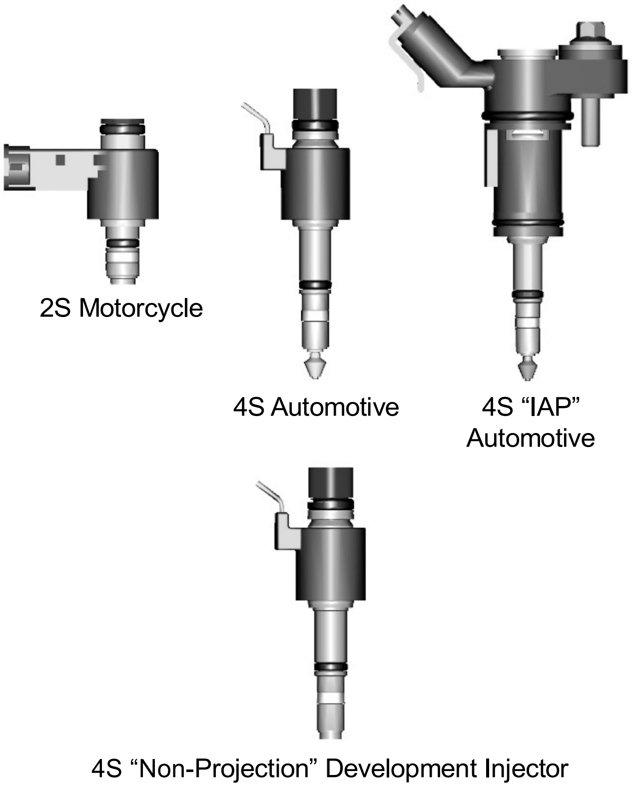

Figure 5 **Direct (air) injector design variants**

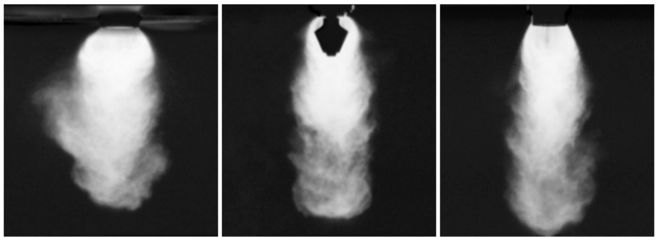
2S Motorcycle 4S Automotive 4S "Non-Projection" Development Injector

Figure 6 **Fuel spray visualisation of direct injector variants injecting into atmospheric conditions (5mg/shot recorded at 1.0msec after SOI).**

Table 1 summarizes the main characteristics of the fuel sprays produced by the different direct injector variants. All tests were conducted at atmospheric conditions, with a fuel injection quantity of approximately 5mg/shot. Spray width results were recorded at 1.8msec after SOI at a location 15mm downstream of the injector nozzle, with the standard deviation based on the shot-to-shot spray width measurements over 20 injection events. The penetration velocity is based on the spray penetration at 1.0msec after SOI. The results demonstrate the similarity in the spray geometry produced by the 4-stroke non-projection development injector with that produced by the automotive style injector which includes a projection. The spray stability (represented by the standard deviation of spray width) is also very good for the new injector.

	Direct Injector Type		
	2-stroke Motorcycle	4-stroke Automotive	4-stroke Non-projection
Spray width (at 15mm downstream)	19.4 mm	15.4 mm	16.9 mm
Std deviation of spray width	1.3 mm	0.6 mm	0.8 mm
Sauter Mean Diameter (SMD)	8 µm	6.8 µm	7 µm
Penetration rate into atmosphere	27.2 m/s	30.2 m/s	32.8 m/s

Table 1 Spray characteristics of direct injector variants into atmospheric conditions at 5mg/shot.

COMBUSTION SYSTEM

The combustion system can be described as an air-assist, direct injection, spray guided system, with the direct injector located as near to the center of the combustion chamber as possible, and the injection direction close to parallel with the cylinder bore axis. The system utilizes close spacing of the direct injector and spark location in order to promote true spray guided combustion, that is, an ignitable fuel mixture is created by injecting directly toward the spark location. Therefore, at highly stratified operation, there is no secondary mechanism required in order to promote an ignitable fuel-air mixture to the spark plug. This means that there is no requirement for specific in-cylinder bulk gas motion and the inlet ports can therefore be designed for high flow efficiency [9]. As such, there is no need for complex interaction of the spray with the piston crown surface to deflect or reflect the fuel towards the plug for ignition purposes. A small piston bowl in crown is recommended, however, but this is primarily used to prevent over mixing of the fuel during stratified operation, which helps to reduce unburned HC emissions and improve fuel economy at these conditions.

Figure 7 shows two typical combustion chamber designs for 2-valve and 4-valve per cylinder small displacement motorcycle engines. The close spacing between the injector and spark plug is evident in both of these designs. The relationship between the injector and spark plug is similar to that used in both the production 2-stroke motorcycle and marine applications, and in the prototype 4-stroke automotive applications. The packaging of the injector and spark plug in small bore engines requires careful design considerations in order to maintain (or minimize any reduction in) valve sizes. In most applications, this requires some level of freedom, including changes to the valve positions, valve angles, and in some cases, camshaft location compared to the carburetor or Port Fuel Injected (PFI) base engine design. Some assistance in achieving the tight packaging constraints is provided in the form of M10 spark plugs which are incorporated in these designs. The automotive applications, with more severe servicing schedules typically dictate the use of M12 or M14 spark plug designs.

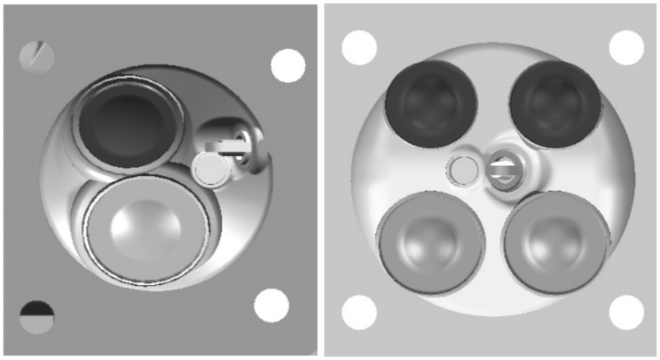
2V Layout 4V Layout

Figure 7 Typical combustion chamber configurations with air-assist, spray guided DI combustion system (2 valve and 4 valve examples)

AIR COMPRESSOR

The air-assist DI fuel system requires compressed air to be supplied to the injection system. This is typically supplied via a single cylinder reciprocating piston compressor, driven by the engine. For small 2-stroke motorcycle applications, the air compressor is installed in the crankcase of the engine, and driven by an eccentric that is incorporated on the engine crankshaft [8]. This design offers a very simple and low cost solution for these applications.

For 4-stroke applications, the same technique can not typically be used due to the engines having substantially different construction, including the use of “wet” sump lubrication. For 4-stroke motorcycle applications, there is a need for minimizing the cost of the compressor, as well as minimizing the parasitic losses. To minimize cost and complexity, a high level of integration with other engine components is desirable. To minimize parasitic losses, the compressor should be driven at reduced speeds in comparison to engine speeds [7]. Figure 8 shows an example of an integrated compressor design that is driven from a pin on the camshaft sprocket. This drive technique also enables the compressor to operate at half engine speed, which is especially relevant for high engine-speed motorcycle applications.

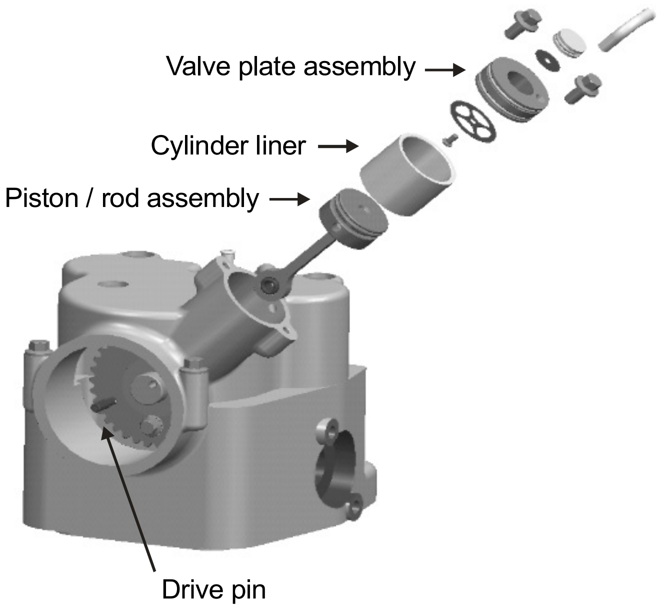

Figure 8 Cam sprocket driven air compressor installation

COMBUSTION SYSTEM CHARACTERISTICS OF DI 4S MOTORCYCLE

The Orbital Engine Company has been involved in programs applying the air-assist DI system to 4-stroke motorcycle applications. The results presented below are from a typical application on a single cylinder, 125cc geared motorcycle. The major engine specifications are summarized in Table 2.

Engine displacement	125cc
Compression Ratio	11.9:1
Cylinder head cavity	Pent-roof type with Orbital modifications
Piston crown	Centrally located, shallow bowl
Spark plug	M10 with approx 6.0mm reach
Fuel system	Air-assist DI, central injection
Direct Injector	Strata 1 with 97 deg seat angle
EGR system	External EGR system, electronically controlled EGR valve
Air pressure	650 kPa (gauge)
Fuel pressure	750 kPa (gauge)

Table 2 Development engine major specifications

The engine results are compared to a carburetor-equipped baseline engine where applicable. The baseline was performed with the flow adjustment capability of the carburetor in order to maintain a stoichiometric air/fuel ratio. In practice, for satisfactory driveability, the 4-stroke motorcycle engines are often calibrated at mixture strengths which are richer than stoichiometric. In this case, the fuel economy improvements of the DI engine are further increased with respect to the baseline carbureted motorcycle.

PART LOAD OPERATION

For a small displacement engine in a motorcycle application, the part load engine speeds are substantially higher than those encountered on automotive engines, with engine speeds less than 4000rpm (other than idle) having little relevance to normal operation. In order to provide any substantial fuel economy improvement, the combustion system must operate at high dilution ratios at high engine speeds. The part load combustion characteristics of the air-assist DI engine are well illustrated in Figure 9, which shows a load scan at 6000rpm engine speed. The indicated specific fuel consumption (ISFC) versus indicated mean effective pressure (IMEP) is compared to the carburetor baseline engine operating at stoichiometric air/fuel ratio. At each engine load, the DI engine was calibrated for the best compromise between low fuel consumption and low engine-out emissions levels, while maintaining a constant inlet manifold pressure (MAP) of approximately 96kPa. The air/fuel ratio and EGR rates were adjusted accordingly.

The air-assist DI engine demonstrated fuel consumption reductions of up to 23% over the baseline engine at the low load operating conditions, with air/fuel ratios of approximately 30:1. As the load increases, the fuel consumption reduction enabled by DI is smaller, however reductions of up to 10% were still shown at loads of up to 6bar IMEP.

The plot of air/fuel ratio at the different loads in Figure 9 shows a distinct change between 4 and 6 bar IMEP, going from approximately 30:1 at the lighter loads to 18:1 (or richer) at loads of 6bar IMEP and above. This is due to the transition between running in a highly stratified (late injection) operating condition, to a less stratified (more homogeneous, earlier injection) operating mode as the load increases. At the higher engine loads, the fuel economy is improved by running less stratified in order to increase the air utilization by promoting more mixing of the injected charge.

As previously stated, a major consideration for motorcycle applications is the aftertreatment system. The ability to reduce engine-out NOx emissions to the extent that emissions legislations can be achieved without further post treatment is advantageous from a cost and complexity perspective. Using external EGR has proven to be a very effective way to reduce engine out NOx emissions from DI engines [9]. In order to demonstrate the effect of reducing NOx emissions, different calibrations were developed to study the tradeoffs between fuel consumption and emissions. Figure 10 shows such a result from an air/fuel ratio scan performed at 6500rpm and 6.3bar IMEP. A constant inlet manifold pressure of approximately 96kPa was maintained while the air/fuel ratio was changed by varying the external EGR rate. At each air/fuel ratio, the ignition timing and injection timing was also optimized.

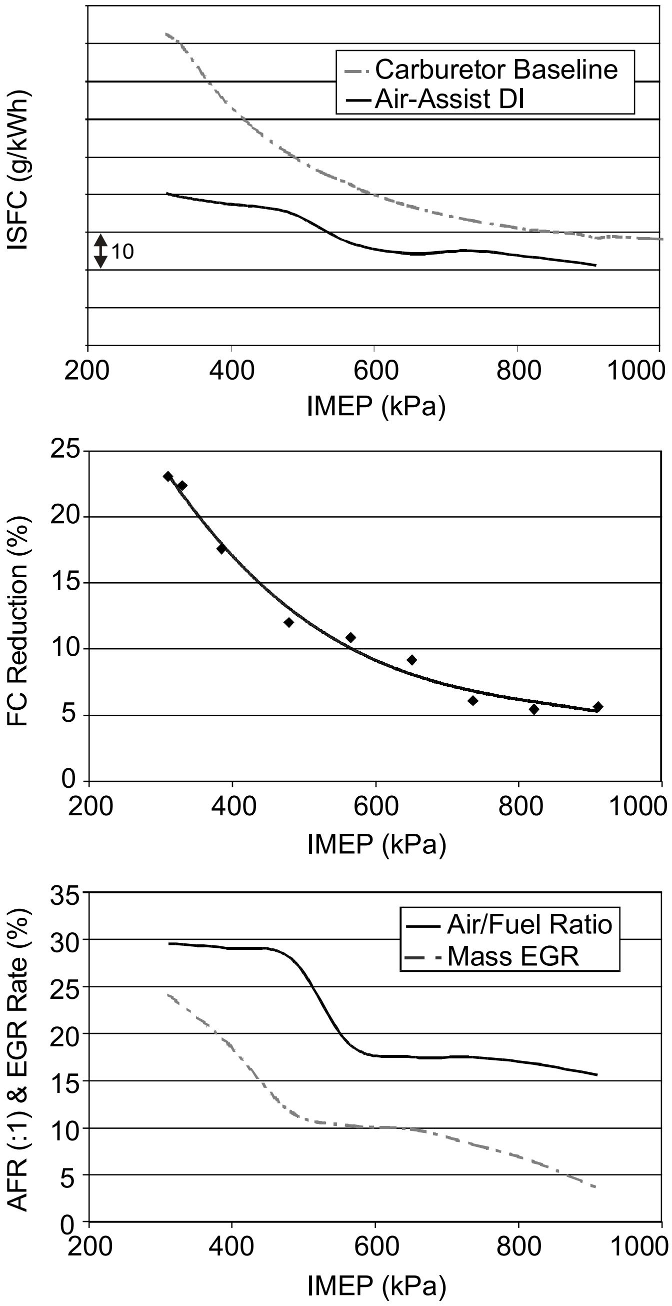

Figure 9 Load scan comparison at 6000rpm

Included in Figure 10 is the baseline engine fuel consumption measurement, at an indicated specific NOx emissions value of approximately 8.6 g/kWh. It can be seen that at ISNOx emissions larger than 3 g/kWh, the indicated specific fuel consumption was reduced for the DI engine. At ISNOx emissions levels lower than 3 g/kWh, the fuel consumption was increased above that of the carburetor baseline, even though the DI engine was operating at virtually unthrottled inlet conditions. The reason for the increased fuel consumption becomes evident when considering the air/fuel ratio. In order to reduce the engine-out NOx emissions to less than 3 g/kWh, the air/fuel ratio was reduced to below stoichiometric as the EGR was increased. By operating below stoichiometric air/fuel ratio, the combustion efficiency is degraded, which leads to the increase in specific fuel consumption shown. At lighter load conditions, it is possible to increase the level of EGR while maintaining a lean air/fuel ratio, and hence the trade-off in fuel consumption for low NOx emissions is reduced. Small displacement motorcycles tend to have higher relative loads over typical driving cycles compared to automotive engines, and therefore the tradeoff between NOx emissions and fuel consumption is higher. In order to evaluate the potential of motorcycle DI systems without closed-loop fuel control and three-way catalysts, it may be necessary to operate the engine at some speed/load conditions at air/fuel ratios which are richer than stoichiometric in order to satisfy some of the future emissions legislation targets.

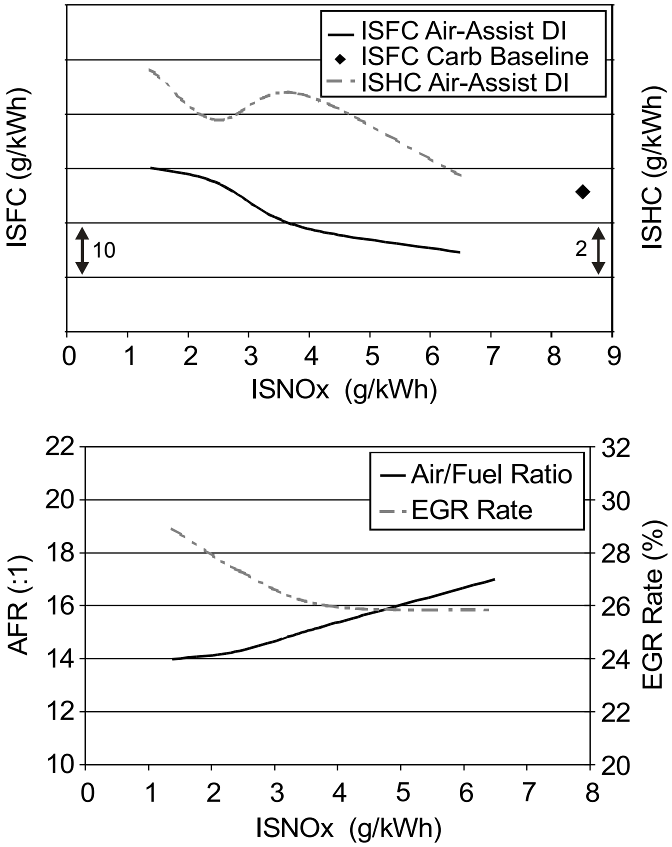

Figure 10 Fuel consumption and emissions trade-off at 6500rpm, 6.3bar IMEP

EUROPEAN DRIVE CYCLE SIMULATION RESULTS

Using the engine test results, a simulation of the vehicle was performed to predict the likely fuel consumption and emissions over the European (ECE40) drive cycle. The simulations included the parasitic losses associated with the air compressor for the system, as well as consideration of the fuel consumption and NOx emissions tradeoffs from a matrix of different part load calibrations.

Fuel economy improvement predictions relative to the carburetor baseline are shown in Figure 11 for two different engine calibrations. The “Low NOx Cal” refers to an engine calibration for minimizing the NOx emissions from the engine, while the “Low FC Cal” refers to a calibration which demonstrates low fuel consumption while still limiting the engine-out NOx emissions. The drive cycle simulations predict approximately a 10% fuel economy improvement for the low NOx calibration compared to the stoichiometric baseline performed with the carbureted engine. This fuel economy improvement is achieved with an engine–out NOx emissions level less than 0.1 g/km. This result shows the potential to meet the proposed Euro III motorcycle emissions legislation for engine displacements less than 150cc without any post-treatment of the NOx emissions in the exhaust gas. It is expected that an oxidizing catalyst is required in order to catalyze the engine-out HC emissions for Euro III compliance. By allowing the engine-out NOx emissions to increase, the fuel economy improvement can also be increased. The low fuel consumption calibration shows more than a 17% improvement in fuel economy compared with the baseline engine. The engine-out NOx emissions are increased to approximately 0.46 g/km for the ECE40 drive cycle simulation. Although this level of NOx emissions precludes the use of an oxidizing catalyst only for the Euro III legislation, there are many other motorcycle markets with either less stringent NOx emissions requirements or a combined HC+NOx emissions requirement. For these markets, it is possible to show increased fuel economy improvements without the need for post-treatment of engine-out NOx emissions.

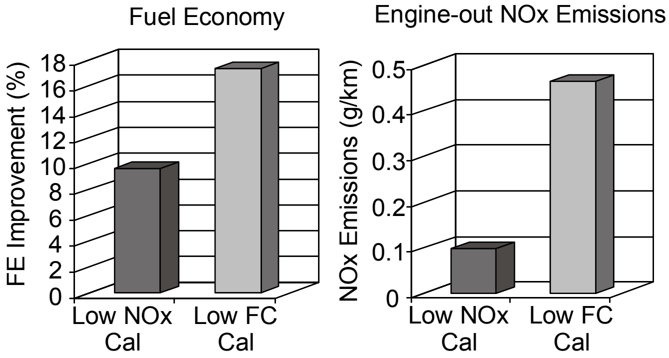

Figure 11 Fuel economy and engine-out NOx emissions predictions for an air-assist DI 125cc motorcycle over the ECE40 drive cycle

The fuel economy improvements shown in Figure 11 are compared to an optimized carbureted engine operating at stoichiometric conditions. In practice, both carbureted and PFI small displacement motorcycle engines are often calibrated to operate at mixture strengths richer than stoichiometric in order to achieve acceptable driveability. This results in a significant increase in fuel consumption, and as such, the predicted improvements for the DI engine would increase against this baseline. As well, the cycle simulation did not include any fuel savings associated with fuel cut-off under deceleration, which can be implemented for both a DI and (to a lesser extent) PFI system. Again, it is expected that the fuel economy improvements would be further increased compared to the baseline when this functionality is included.

CONSUMER BENEFITS WITH OPTIMISED DI4S MOTORCYCLE

Given the diversity of the emissions legislation requirements and customer needs for the different motorcycle markets, a single engine management system is unlikely to satisfy the range of different motorcycle applications. For the implementation of direct injection, while the core DI combustion system may remain common, the total system capability can be changed via the addition of various components and sub-systems. This includes, for example, the inclusion of external EGR systems, oxidation catalysts or three-way catalysts with closed loop fuelling control.

Table 3 summarizes the expected system definition variants able to satisfy some of the main motorcycle market emissions legislations in Europe, Taiwan and India. The estimated fuel economy improvement enabled by the various system definitions is also shown for comparison. This table shows that for a particular motorcycle market, there may be several different total system specifications, which offer various levels of fuel economy improvement. The selection of the most appropriate system is likely to be complex function of many influences including system cost, market trends, supplier base and customer needs.

A further benefit to the customer is the increased diagnostics, and engine condition warning systems available with the introduction of engine management systems. This can reduce the overall maintenance cost over the life of the engine. For this benefit to flow to the end user, it is necessary that the correct tools and training are made available, and supported at the dealer network.

	Emissions (gm/km)	Air Assisted DI system aftertreatment description			Fuel Economy compared to homogeneous PI system	Power potential compared to PI (equal valve area)
Emission Target		**EGR**	**Oxidizing catalyst**	**Closed loop TWC**		
Euro II (ECE 40) (2003)	HC/NOx/CO 1.2/0.3/5.5		✓		10%	100 to 105%, compared to equivalent emission homogeneous engine and based on equal valve area. Further gains possible due to removal of constraints of cam timing
		✓	✓		Up to 15%	
Euro III (ECE40 <150 cc) (2006)	HC/CO/NOx 0.8/2.0/0.15 Cold start + sample at T=0			✓	0 to 5%	
		✓	✓		10%	
		✓		✓	Up to 15%	
Euro III (ECE40 >150 cc) (2006)	HC/CO/NOx 0.3/2.0/0.15 Cold start + sample at T=0			✓	0 to 5%	
		✓	✓		10%	
		✓		✓	Up to 15%	
Taiwan 4th Regulation (CNS cycle) (2004)	HC+NOx/CO 2.0/7.0 Cold start				Up to 15%	
India Bharat II (IDC) (2005)	HC+NOx/CO 1.5/1.5 *		Small catalyst may be preferred to increase production margin		Up to 15%, compared to stoichiometric calibration	
India Bharat III (IDC) (2009)	HC+NOx/CO 1.0/1.0 *	✓			Up to 15%, compared to stoichiometric calibration	

* With DF allowance of 1.2

Table 3 Ait-assist DI total system definition options for different motorcycle markets.

CONCLUSION

The following conclusions can be drawn from the information presented in this paper:

1. The application of DI to small 4-stroke motorcycles presents many specific challenges. It is believed that a central injection, spray guided DI system is a good option to help satisfy the combustion system requirements of the small displacement engines.

2. Representative results from an air-assist, spray guided DI system applied to a 125cc displacement single cylinder 4-stroke engine show significantly improved fuel economy compared to the stoichiometric operation baseline engine. Test cycle simulation results based on steady state data show improvements of up to 17% can be achieved over the European ECE40 drive cycle.

3. By combining a direct injection 4-stroke combustion system with other engine management system components and sub-systems, the total EMS package can be tailored to suit different markets. For any particular market, there exists more than one combination to satisfy the emissions requirements, so some choice is available to select the best compromise between cost, risk, and performance to suit the specific application.

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