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A Summary of Advancements in Lean Combustion through Mahle Jet Ignition (MJI)

***Nicholas Evans* [1], *Dr Don Law* [2]**
Coventry University, UK[1], *Unitec Institute of Technology, Auckland, New Zealand*[2]
Corresponding author's email id: *dlaw@unitec.ac.nz*[1]

Abstract

During the twentieth and twenty-first century many have taken the approach to develop lean combustion in gasoline engines using conventional fuel ling and ignition systems. While lean combustion is achievable, only small amounts of enleanment are achievable meaning that improvements are limited before the lean limits reached and combustion become suns table.

In the pursuit of efficiency both conventional and non-conventional operation methods have been explored. Whileλ1.3is achievable using conventional fuel and ignition systems, λ1.4 typically results in unstable combustion troughs lower flame fronts and higher hydrocarbon emissions than stochio metric combustion.

MAHLE have developed MJI (MAHLE Jet Ignition), a pre-combustion chamber with a small pre-chamber volume fit ting in the place of a conventional spark plug. Both pre-chamber and cylinder are supplied with fresh air fuel mix where fuel is delivered in an approximate3:97ratiorespectively. Like other pre-chamber combustion methods combustionis initiated in the pre-chamber as a rich Mixture where a thoroughly mixed lean mixture in the cylinder is ignited by the resulting flame front from the pre-chamber. Using these design stable lean limits have been dramatically improve do more conventional fuelling and ignition systemstoλ2.1. Faster CA10-90has also been achieved than conventional methods with significant high load knock limits improvements. The normal *efficiency in the engine tested increasedby25%resultingin a peak brake thermal efficiency (BTE) greater than 41%andfuelconsumptions of sub 200g/k Wh. additionally; nitrogen oxide (NOx) emissions have been significantly reduced.*

Keywords: *Mahle Jet Ignition (MJI), Lean Combustion, Advancements*

INTRODUCTION

Fuel economy and emissions have been an increa singly large focus when the CARBS legislation was introduced in California. Following this, Europe introduced emissions legislationin1995whichhas continued to develop into Euro 6 primarily governing mission of chemical species, particulate matter and fleet average fuel consumptions. These legislative changes shaveled to improvements in efficiency and emissions of the internal combustion engine through downsizing, catalytic converters and direct injection. However, with many countries now beginning to banor heavily tax the emissions of the combustion powered vehicles in favour of electrified vehicles further work is required to improve the efficiency and emissions (Delphi 2016)

It has been known for decades that lean combustion (λ>1) offers a significant advantage in reducing fuel consumption as well as emissions, however, operating an engine leaner than λ 1.4 is often not achievable through conventional means. MAHLE has addressed the issues in operating an extremely lean engine (λ>1.5) through their design of their MJI (MAHLE Jet Ignition). Both the issue with running ale an engine and how these have been addressed will be discussed in the following sections (Heywood 1988) (Attardetal 2011).

Legislation

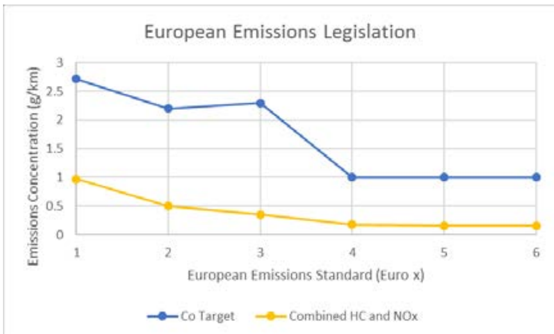

Figure1 - Emissions Legislation Summary for European Vehicles (Delphi 2016))

Emissions regulations have greatly developed since their introduction in Europe and Asia in 1995.

Figure1showshowEuropean emission legislation has developed where HC and

NO x has been combined for simplicity despite having individual limits. Europe a vehicles are currently tested against Euro6caccordingtoDirective70/156/ECwithvehiclesasofSeptember2017beingtested againEuro6d-TEMP. This legislative change is primarily a change in the test cycle changing from the NEDC to the WLTP and the emissions collection tomeasure Real Drive Emissions (RDE). Following this there will be full introduction of Euro 6 d introduction in 2021 where emissions are further tightened. However, the US and California are making similar emissions advancements changing to Tier3and LEV III legislation respectively in 2017 testing the light pedestrian vehicles againstFTP-75. (Delphi2016) (The European Parliament and of the Council 2007)

The test profiles for the NEDC, WLTC and FTP-75 have been shown in Figure2, Figure3 and Figure4.

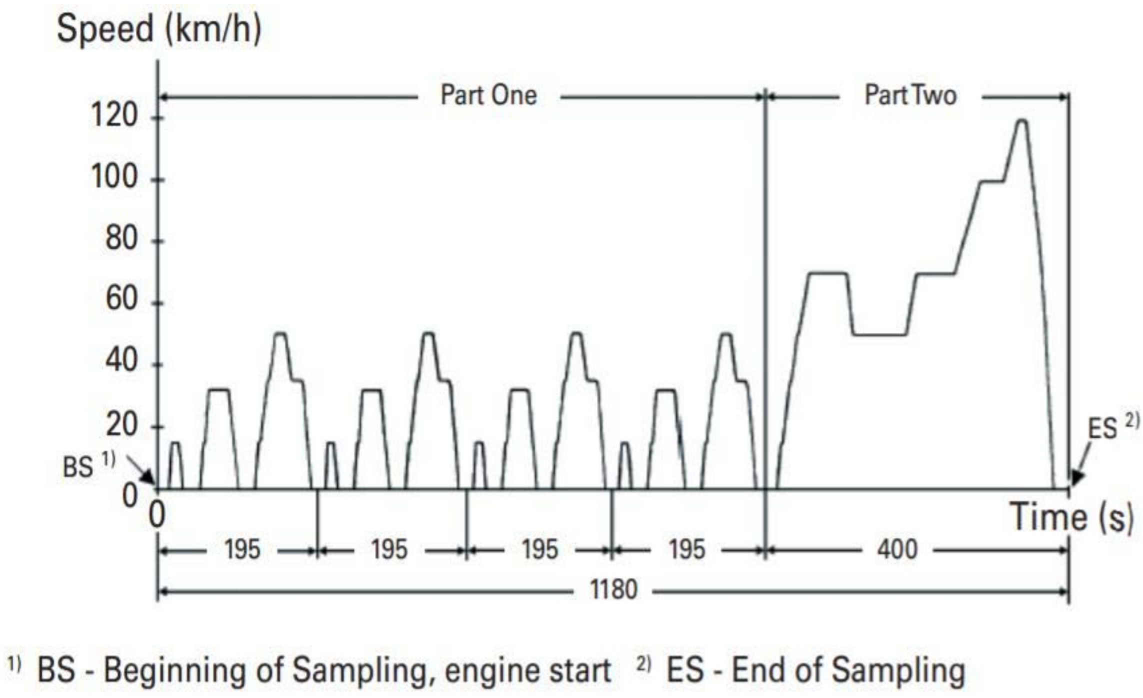

Figure2 – NEDC Test Profile as per Euro6 (The European Parliament and of the Council 2007)

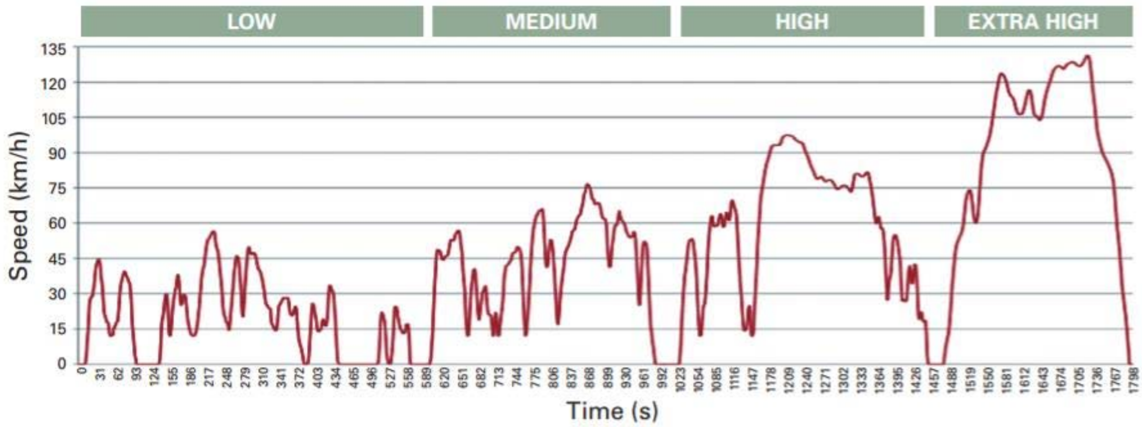

Figure3 - WLTC Test Profile as per Euro6c-TEMP (Delphi 2016)

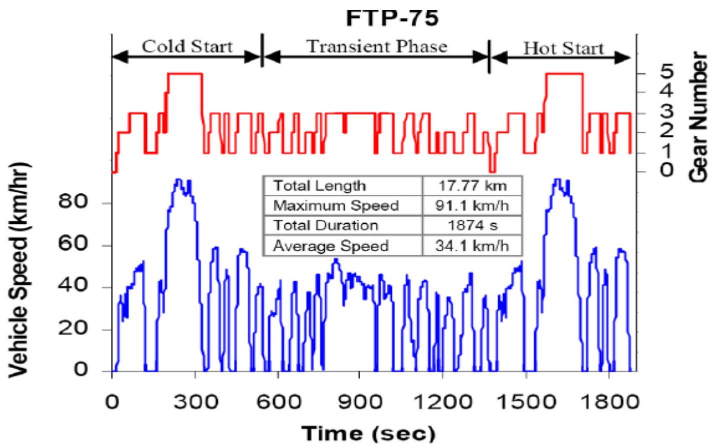

Figure4 - FTP-75Test Profile as per Tier 3 Legislation (Attardet al2011)

It should also be noted that the European Commission has set a future target for transport emissions to be reduced by 60% by 2050 compared to that measured in 1990.This is in pursuit to reduce total carbon emission of Europe across multiple sectors by 80% (European Commission 2017).

A BRIEF HISTORY OF LEAN COMBUSTION

Lean combustion engine have been around since the early 1900's with Ricardo' s Dolphin and Comet engines begin an early approaches, in Gas oline and Diesel engines respectively. While there have been large developments in pre-chamber combustion engines the application of the technology has largely featured in diesel engines, failing to come to fruition in gasoline engines in the automotive sector with the Honda CVCC being an exception to the rule (Attardetal2011)(Heywood1988).

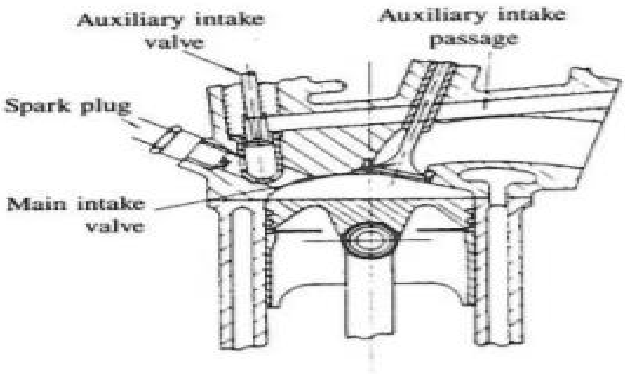

Figure5 – Honda CVCC Cylinder Head Cross Section Showing Pre-Combustion Chamber (Heywood etal 1988)

Table1: A Brief History of Small Pre-Chamber Combustion Initiation (Attardet al 2011)

Start Date	Jet Igniti on Systems	Researchers	Reference
1950s	Avalanche Activated Combustion	L.A. Gussak and colleagues	(Gussaketal 1984)(Gussaketal1974) (Gussaketal 1979)(Gusssaketal 1976) (Gussaketal 1983)(Gussaketal1973)
1984	Swirl Chamber Spark Plug	Reinhard Latsch at Bosch, Stuttgart	(Latschetal(1984)
1993	HFJI –Hydrogen Flame Jet Ignition	Toyota College of Technology and Gifu University, Japan	(Kitoetal2000)(Wakaietal1993)
2003	PJI –Pulse Jet Igniter	P.M. Najt etal. at General Motors	(Na j i etal2003)
2005	HCJI –Homogeneous Combustion Jet Ignition	Robert Bosch GmbH	(Kojicetal2005)(Kojicetal 2005)
2009	TJI –Turbulent Jet Ignition	MAHLE Power train	(Attardetal2010)(Attardetal2010) (Attardetal2010)(Attardetal2010)

Table: 1 show a list of contributors' that Blaxill discuss esmadea significant contribution to the field using small pre-chamber combustion. These lists only shows there search that manufacturer have to this approach where L.A. Gussak and colleagues have been included to show the approximate start of research.

COMBUSTION THEORY

Lean combustion can be favors able for combustion as very low fuel consumptions can be achieved while also lowering emissions such as Carbon Monoxide and Hydro Carbons at thes ame time. Additionally, increasing the enplanement of an engine has an effect on combustion

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temperatures as well as exhaust temperatures. These principles have been shown in Figure 6 and Figure 7.

It can be seen that increasing the enplanement of an engine for a given load site has a two sided effect. While NO x emissions can be seen to increase, HC,CO andCO2 are greatly reduced ata given combustion temperature, however, the combustion temperatures are also significantly reduced meaning that all emissions, including NO x, being greatly reduced again (Heywood etal1988).

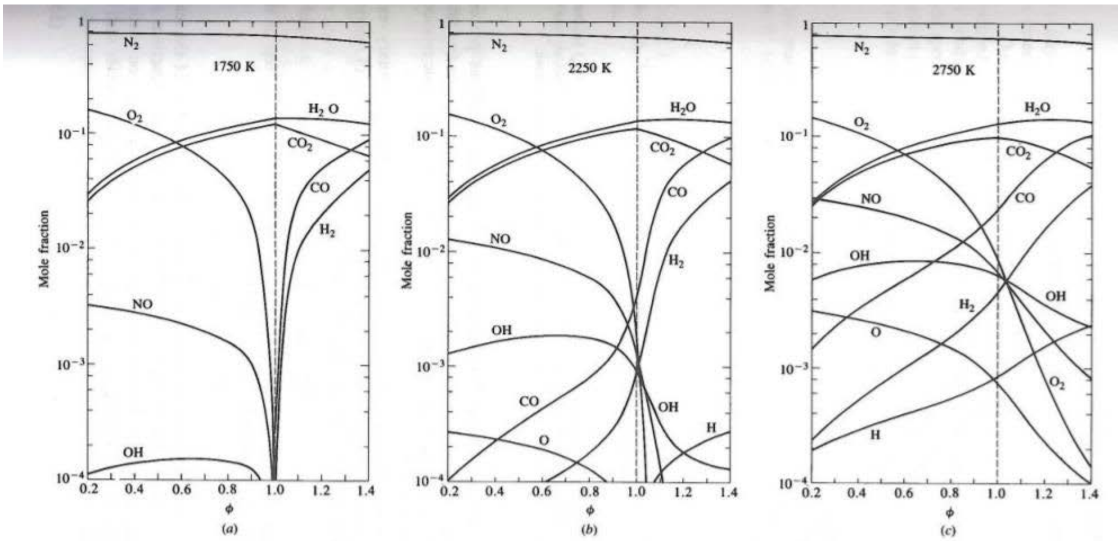

Figure6 –How Emissions Vary with Different Fuel-Air Ratios at Different combustion Temperature (Heywood etal 1988)

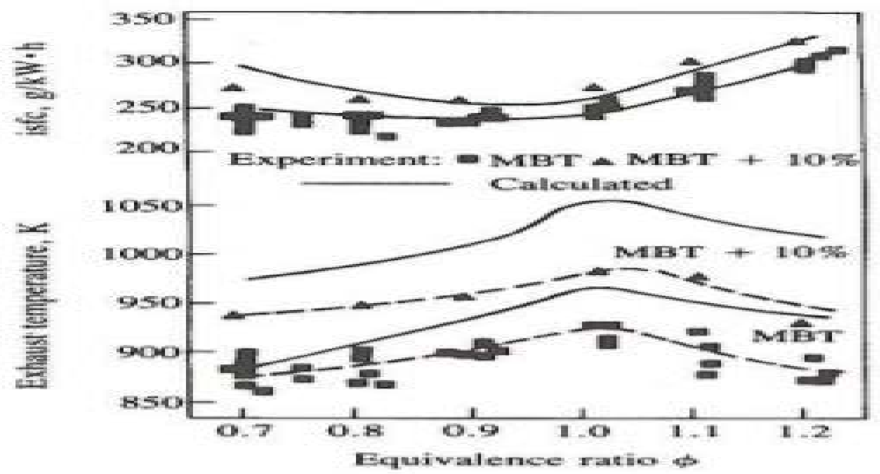

Figure7 - Combustion Temperature against Equivalence Ratio (Heywood et al 1988)

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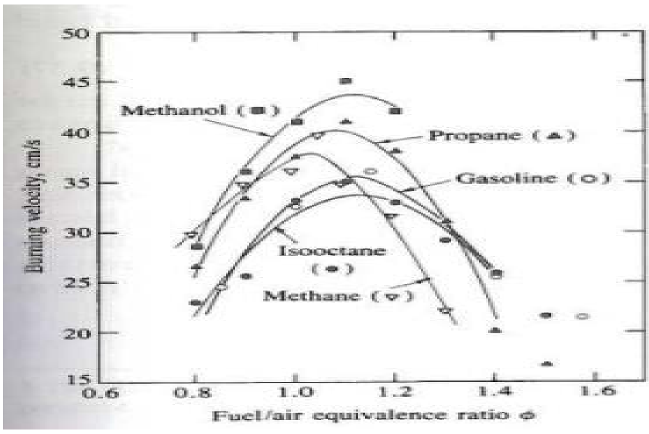

Figure 8: Combustion Velocities with Varying Fuel-Air Ratio (Heywood et al 1988)

However, running an engine significantly leaner than stochiometricon conventional fuelling and ignition systems, such as PFI and in cylinder spark plug, leads to slower travelling frame fronts leading to higher Co Vin IMEP result in ginuns table combustion. This has been shown in **Figure8.**

Heywood etal discusses that flame front velocities can be increased through increasing tumble and swirl at the expense of a slight increase of heat transfer at the cylinder wall. However, it should be noted that excessive mixing is not necessarily beneficial as this can result in turbulence and the Flame front being extinguished; furthermore, the benefits of swirl at lower engine speeds diminish at higher engine speeds. This means that consistent and stable engine operation through-out the engine speed range with lean combustion in not possible (Heywood1988).

Heywood etal discusses that the lean stability limit and emissions of an engine are also heavily affected by the design and operation of the spark plug. In Figure 9 it can be seen that spark current and spark duration have minimal effect at rich and slightly lean mixtures with regards to emissions and fuel consumption. However, at mixtures leaner than λ1.15 hydrocarbon emissions and fuel consumption begins to be effected with discharge current having much larger influence than the discharge duration (Heywoodetal1988)

Furthermore, spark plug gap and project ion in to the cylinder can have a dramatic influence on the lean limit in relation to spark times due to the speed of propagation with larger gaps sustaining more lean combustion (Heywoodetal1988).

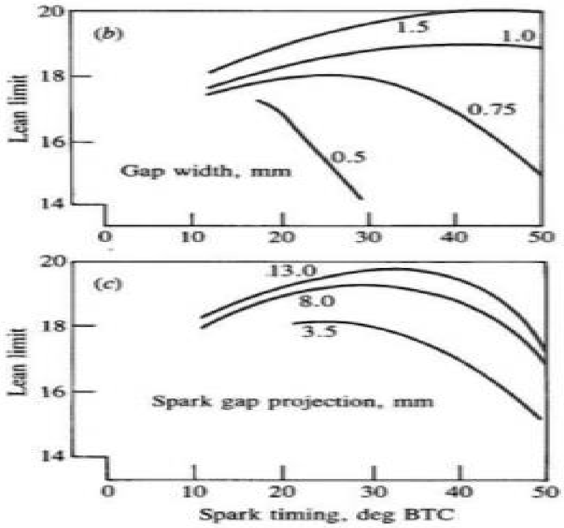

Figure9: Effect of Spark Plug Gap and Project ionin to the Cylinder on Lean Limit Achievable with varying Spark Timing (Heywood1988)

Furthermore, spark plug gap and project ion in to the cylinder can have a dramatic influence on the lean limit in relation to spark times due to the speed of propagation with larger gaps sustaining more lean combustion (Heywoodetal1988).

MJID IS CUSSION AND RESULTS

DESIGN AND OBJECTIVE

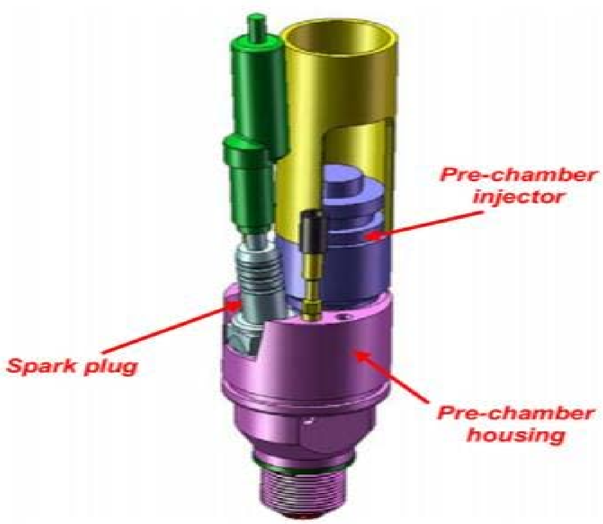

Figure10 –MJI Depiction (Attardet al 2012)

One of the main focuses during the development of MJI was focusing on making sure that the resulting product could be feasibly brought to market meaning that using ignition fuels such as hydrogen became unfeasible. This also mean that the use of readily available parts and not changing the existing architecture of the combustion chamber and cylinder head was also of great importance.Figure11showsthatMJI has been designed as a direct spark plug replace in order to comply with this ethos where the spark plug in the cylinder head in another spark plug (Attardetal 2011) (Attardetal 2012).

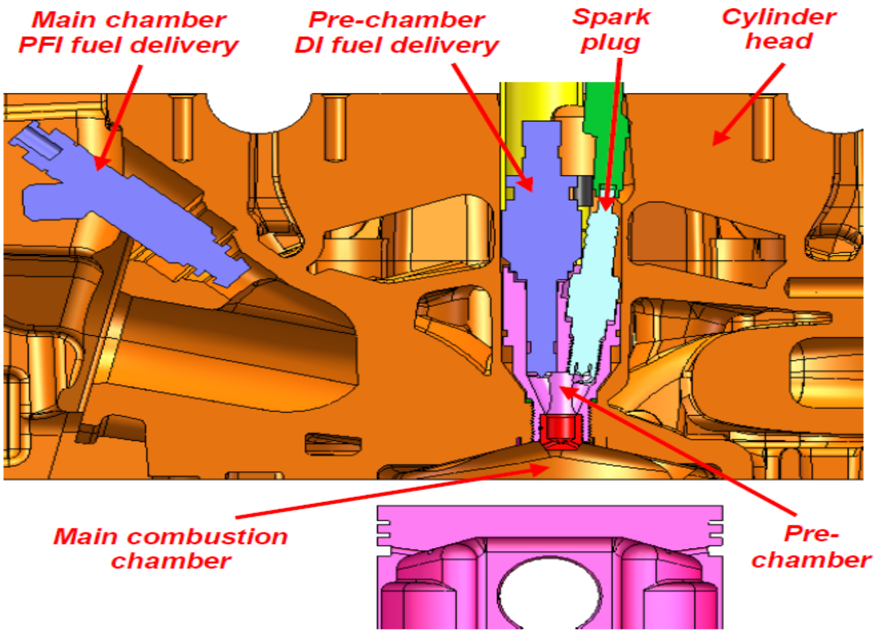

Figure11: Cylinder HeadCross-Section with MJI Installed (Attardet al 2012) Table2 - Design Requirements for MJI (Attardetal 2011)

Table2: Design Requirements for MJI (Attardetal 2011)

Feature	**Reasoning**
Small Pre-Chamber	• Reduce trapped HC in crevice volumes. • Reduce heat loss in pre-chamber
Connection to the Main Combustion by Multiple Small Orifices	• Promote flame quenching.

	• Promote turbule ntjetintrusion in to the main cylinder. • Create multiple ignition sites within the main chamber.
Separate Fuelling for Cylinder and Pre-Chamber	• Allow independently variable λ control in both main and pre-chamber. • Purge control for pre-chamber. • Allow for independent EGR dilution of main chamber and pre-chamber.
Spark Discharge in Pre-Chamber	• Allow for simple combustion control. • Allows for comparison to HCCI and comparison over conventional ignition methods.

OPERATION THEORY AND STRATEGY

The pre-chamber combustion technology has been developed to operate in two different modes, unfuelled and fuelled, each providing different benefits.

In unfuel ledmode the cylinder is fuell edonlybya PFI where the pre-chamber injector is turned off. The fuel-air mixture is the npushedupin to the pre-chamber during the compression nstroke. However, in fuel ledmodethe cylinder is fuelled by both PFI and the pre-chamber injector with the pre-chamber fuel being injected approximately 50degree before spark discharge to ensure sufficient mixing without escaping into the main chamber (Attard etal2012).

The combustion of both modes is very similar with the ignition of the air-fuel mixtures being started by the spark plug in the pre-chamber. heignited mixture travels at high speed through the small pre-chamber orifices where the flame front is quenched. The small volume of the pre-chamber enables the jets of the partially burnt mixture to penetrate deep into the main combustion chamber without colliding with the cylinder walls. The deep penetration of the partially burnt material creates multiple secondary ignition site senabling fast CA10-90 (Attardetal2012).

Experiments and Specifications

At tardetal mentions that the engine used in the experiments was a2.4LI4PFI engine from GM that had been adapted, using a modified crankshaft, into a single cylinder engine where the engine had on episton and no other alterations. The engine has been summaries in **Table 3** (Attard et al 2012).

Attar detal discusses that the engine was tested at1500rpmdue to the knock limitations typically seen at this speed where both the conventional sparking nition system and MJI were compared against one another at lambda 1.Both systems were tested using in dolene with varying knock

Resistances where camphasing were optimized form aximum IMEP at WOT which were then fixed for all test on both ignition systems. It should be noted that oil, water and air temperatures were kept consistent for all tests where inlet pressures conformed to SAEJ1349 and alltests for each In dolene blend were completed within a day of each other (Attard2012).

Table3 – Engine Specification (Attardetal 2012)

Category	**Specification**
Make	GM–I42.4LPFIEcotecLE5
Engine Classification	Single Cylinder, PFI, Naturally Aspirated, Central Spark Plug
Bore and Stroke(mm)	88x98
Displacement(L)	0.6
Compression Ratio	10.4:1
Valve train	DOHC, VVT,2-Inlet,2-Exhaust

Initial Assessment and Affect to the Knock Limitatλ=1

2012-01-1143

At tarde tal discusses that it is common to see engine reach 20 Bar BMEP (Attardetal2012) and this will only increase in future years as downsizing gets more extensive and more extremeas seen through project such as Ultra boost (Turneretal2014). It is also discussed that because of these higher pressures that pre-mixed end gases are often the source of knock in modern engines. Direct ioninjection has been used as are latively simple means of suppression by injecting fuel to cool cylinder temperatures through hvaporisation. However, while mixing the intake charge with cooled EGR has been successfully shown to improve the limit at which the auto-ignition of the end gasses occur At tardetal also mentions that these techniques in modern boosted engines places high demands on the air path ways of the engine (Attardetal 2012)(Blaxilletal2012).

EXPERIMENTAL RESULTS

As the MJI has two operational modes, namely UN fuel led and Fuelled Pre-Chamber, the benefits will bed is cussed separately.

Un fuelled Pre-Chamber

In unfuel led mode, it was found that the knock limited was dramatically extended with the knock limit of 83PRF in dolene initiated by the pre-chamber being estimated to match that of 93PRF indolene. Additionally, it was found that indolene of approximately 85PRF of greater were able to meet MBT targets for CA50. However, it should be noted that the stability limit of 3% Co VIMEP g used has not significantly changed for indolene of 87 and 93 PRF but for lower quality fuels this stability has been dramatically Improved with stable combustion having been achieved with indolence a slow as65PRM (Attardetal2012).

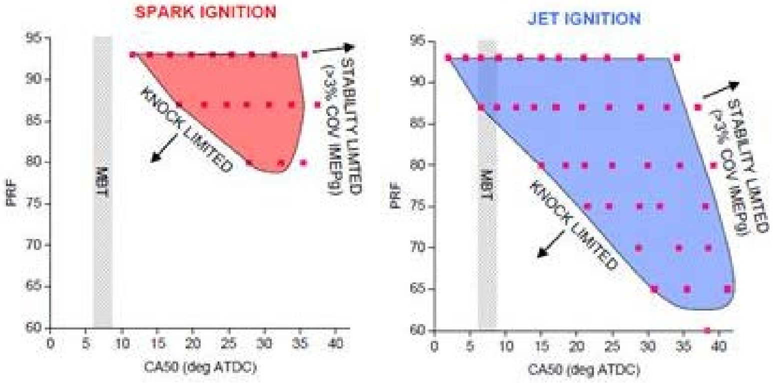

Figure12 –Knock Limit- Conventional Spark Ignitionvs MJI (Attardet al 2012)

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While more advanced CA50has been achieved, this has resulted in greater workout put from the engine with aCA50of13 degrees ATDC in thepre-chamber producing the same IMEP nasaCA50of 18 degrees ATDC (Attardetal 2012).

At tardetal also found that the best Co V in IMEPgof1.1% for the a conventional spark ignition engine could be matched by the unfuelled pre-chamber for indolene with a PRF lower than70and

When the PRM is 88 or above the MBT targets could be met with a lower Co V of 0.8% (Attardetal 2012).

At tar detal postulates that MJI engines requires a more retarded spark than a conventional engine because of the multiple ignition sites created by the pre-combustion chamber result in gin faster overall combustion despite no change in flame speed prorogation. This also has the added benefit of suppressing end-gas knock due to their duction in the distance for the flame front to propagate (Attard etal2011) (Attardetal2012).

Fuelled Pre-Chamber

In fuelled mode, the knock limit of the engine was further improved over the unfuelled mode with indolene with a PRF as low as 60achieving stable combustion. It can be postulated that this is due to the engine still operating at λ=1 meaning that the main combustion cylinder is running leaner than stochio metric. This means that the flame front propogation speed iss lower further reducing the like lihoodofend-gas knock ata given operation point. Additionally, due to the slight enrichment of the pre-chamber produces uniform jets reducing CoVinIMEP reducing end gas ignition. However, it should be noted that combustion stability has not been diminished when compared to the unfuelled operation mode (Attardetal 2012).

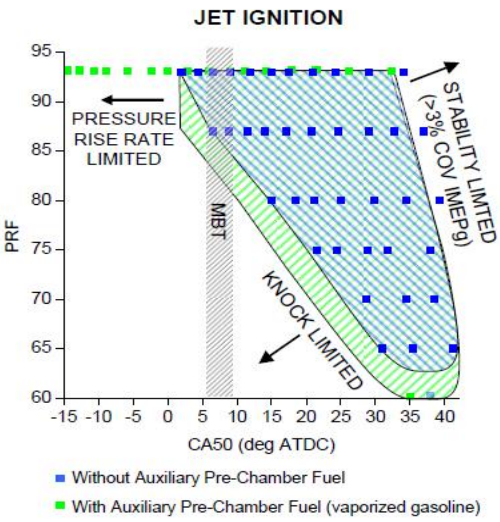

Figure 13 - Unfuelled MJI vs Fuelled MJI - Operational Limits at λ = 1 (Attard et al 2012)

Attard et al discusses that a slight enrichment of the fuelled pre-chamber results in early main chamber ignition meaning that a further retarded spark is needed to achieve MBT. However, it was found that this mode of operation was not as thermally efficient as the unfuelled mode despite having an improved knock boundary. Therefore, it can be deduced that in stochiometric operation the fuelled mode operation would be useful in boosted engines to increase engine output that the unfuelled mode would not be able to achieve (Attard et al 2012).

Stochiometric Evaluation

Attard et al discusses that for the majority of operation of the MJI in a naturally aspirated engine at 1500 rpm that the unfuelled mode is all that is required for a significant knock extension. It is also discussed that the real world benefits of the unfuelled mode run lean is limited without fuelling the pre-chamber with efficiency improvements running the engine in unfuelled mode would primarily come from a higher achievable compression ratio (Attard et al 2012).

It is discussed that one of the main drawbacks of unfuelled mode is proper ignition at part load due to lack of pre-chamber purging, this combined with the improved knock limit means that further downsizing or reductions in swept volume would lend themselves nicely to this technology (Attard et al 2012).

Lean Limit, Thermal Efficiency and Fuel Economy

As already discussed, operating an engine through lean combustion can give large BSFC benefits while reducing NOx emissions due to reduced combustion temperatures as well as reduced hydrocarbon emissions if the combustion is stable. As MJI was proven to be stable under stochiometric operating with greatly improved knock limits and faster combustion Attard et al discuss that investigating the combustion stability at a variety of enleanments as well as finding the lean limit in fuelled mode for all engine speeds was a natural progression. This was preformed using the same single cylinder engine as before using a range of readily available fuels (Attard et al 2012) (Attard et al 2011) ((Bunce et al 2016).

Figure 14 shows that MJI has extremely fast combustion mechanics with high enleanments of $\lambda = 2$ having CA10-90 to the conventional spark ignition engine. It can also be seen that the MJI in fuelled mode can maintain CA10 at almost all enleanments for CA10. This is due to the multiple ignition sites that the pre-chamber creates as well as the superior knock resistance that allow this to be maintain through spark advance. (Attard et al 2012)

In Figure 15 Attard et al show that the standard engine at 1500 rpm at enleanments beyond λ > 1.4 the CoV in IMEP become great than 5% therefore becoming unstable achieving a maximum thermal efficiency of approximately 38%, 10% greater than that of stochiometric (Attard et al 2012).

However, using vaporised gasoline as the pre-chamber and gasoline as the main fuel, stable combustion was pushed to the limit of stable combustion to λ = 2.12, where none vaporised gasoline achieved λ = 2.07 and propane as a pre-chamber fuel achieving λ = 1.94. The extra enleanment the using vaporizes gasoline enables resulted in a thermal efficiency of 40.6%, 18% higher than achieved by the stochiometric spark ignition engine. This resulted in a specific fuel consumption of 200 g/kWh ISFC (Attard et al 2012).

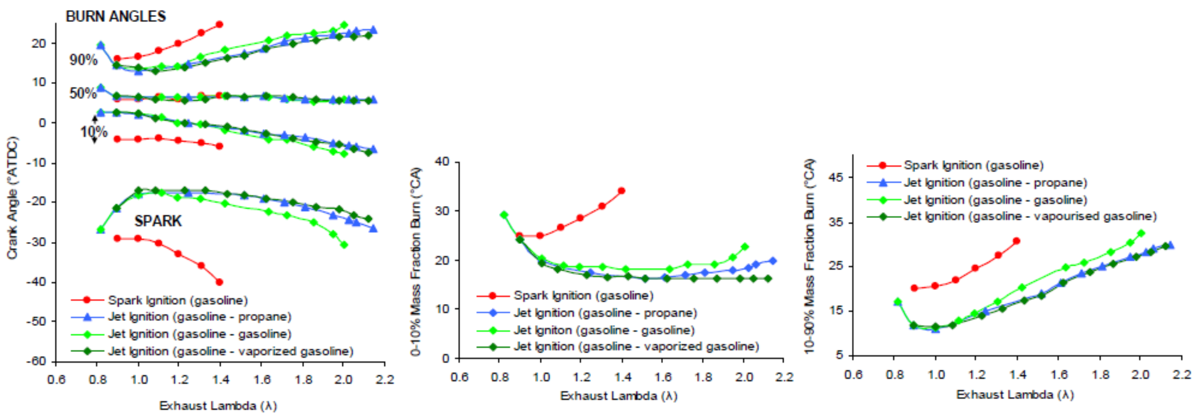

Figure 14 - Effects of varying Lam on Combustion Speed (Attard et al 2012)

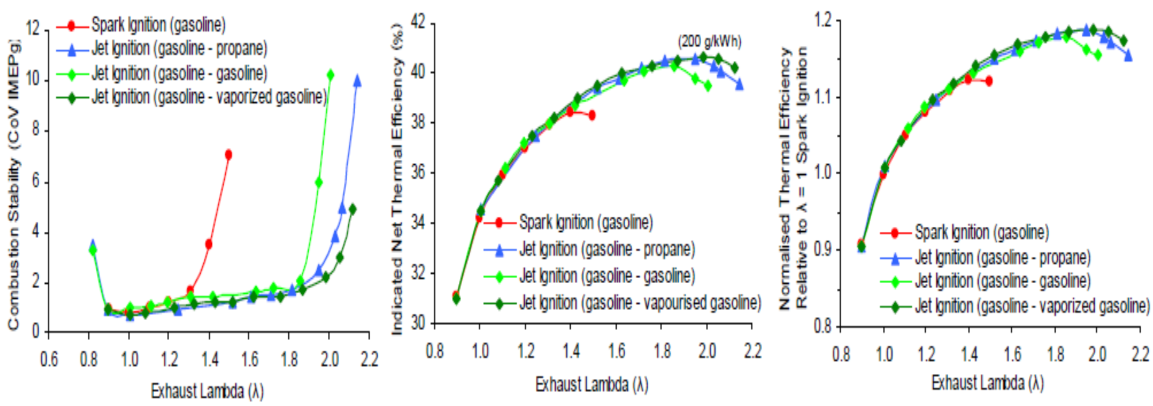

Figure 15 - Effect of varying λ on CoV, Indicated Thermal Efficiency (Attard et al 2012)

Attard et al discuss that when the emissions and thermal efficiencies are considered together, λ =2.12 for vaporised gasoline is no longer feasible as the HC emission dramatically increase to approximately 130% of the stochiometric spark ignition engine and thermal efficiencies have reduced from their peak seen at approximately λ = 1.9. Between Figure 15 and Figure 21 it can be seen that peak thermal efficiencies of vaporized gasoline operation extend to a little over λ = 2 with NOx emissions exhaust temperatures being lower than λ = 1.9 and HC emission only being slightly higher than that of the conventional spark ignition engine (Attard et al 2012).

Attard et al go on to show using a partial engine map that using MJI in the single-cylinder engine that a minimum ISFC figure of 196 g/kWh can be achieved with peak thermal efficient greater than 41% can be achieved. Additionally, it can be seen in Figure 17 that while fuel economy can be improved by as much as 20% at 1000 rpm, at higher engine speeds the improvements are reduced to around 10% at 3000 rpm. However, it should be noted that regardless of engine speed NOx emissions have been reduced by over 99%. This therefore means that MJI could mass the NOx emissions limits without the need for a catalytic converter (Attard et al 2012).

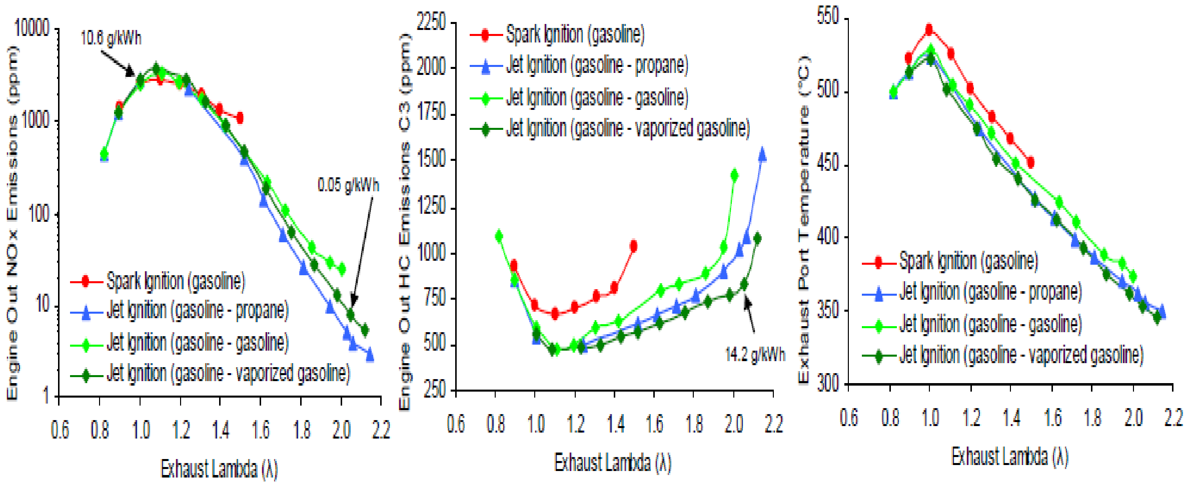

Figure 16 - Effect of Varying λ on NOx Emissions, HC Emissions and Exhaust Temperatures (Attard et al 2012)

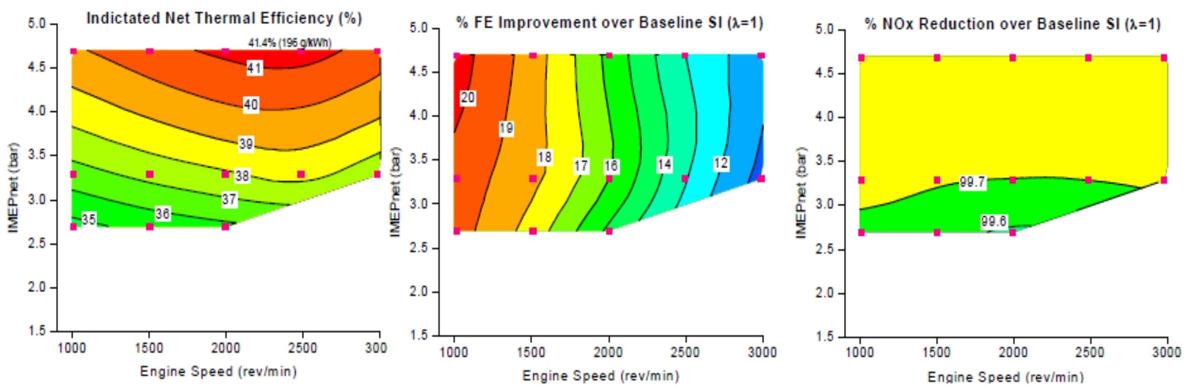

Figure 17 - Thermal Efficiency, Fuel Economy Improvmant and NOx Reduction of a PArtially Mapped Engine Running MJI (Attard et al 2012)

Multi-Cylinder Engine Operation

Attard's et al results show that MJI is able to sustain stable lean combustion much leaner than those achieved by Heywood at 2000 rpm at $\lambda > 2$ compared to $\lambda = 1.3$ respectively (Attard et al 2011). It is also mentioned that MJI is capable of lean combustion than published however, running the engine leaner offered no fuel consumption of emissions benefit despite being stable. Bunce et al discuss that when the full multi-cylinder engine map is calibrated for the GM engine using a CoV < 3% Figure 18 is the resulting engine λ map and Figure 19 is the resulting BSFC map (Bunce et al 2016).

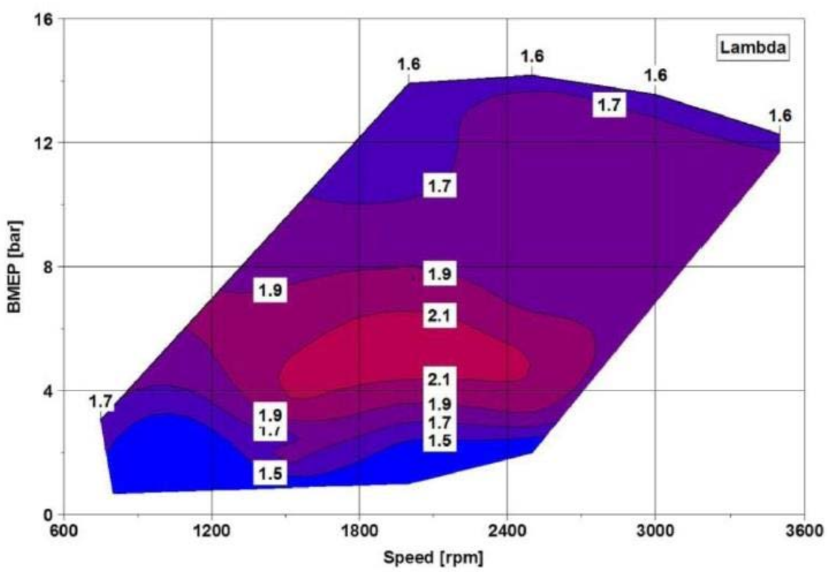

Figure 18 - Multi-Cylinder λ Map (Bunce et al 2016)

As can be seen in Figure 19, the specific fuel consumption has been improved upon from the single cylinder results at 1500 rpm from 200 g/kWh ISFC, to less than 200 g/kWh BSFC at 2000 rpm where BTE is approximately 42% (Bunce et al 2016).

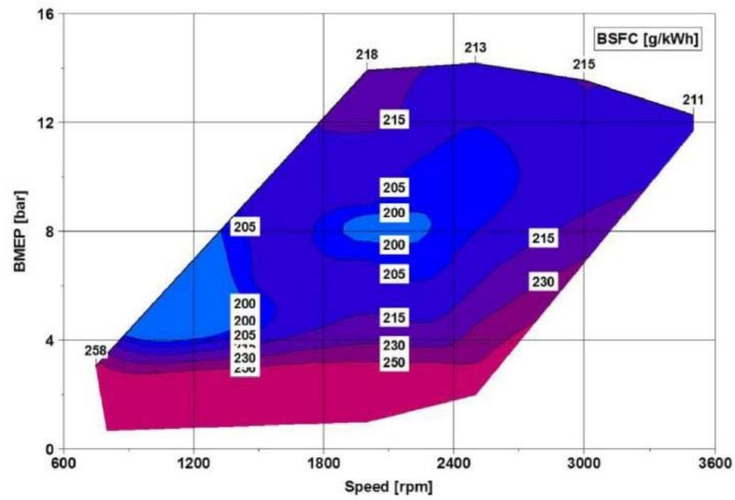

Figure 19 - Multi-Cylinder BSFC Map (Bunce et al 2016)

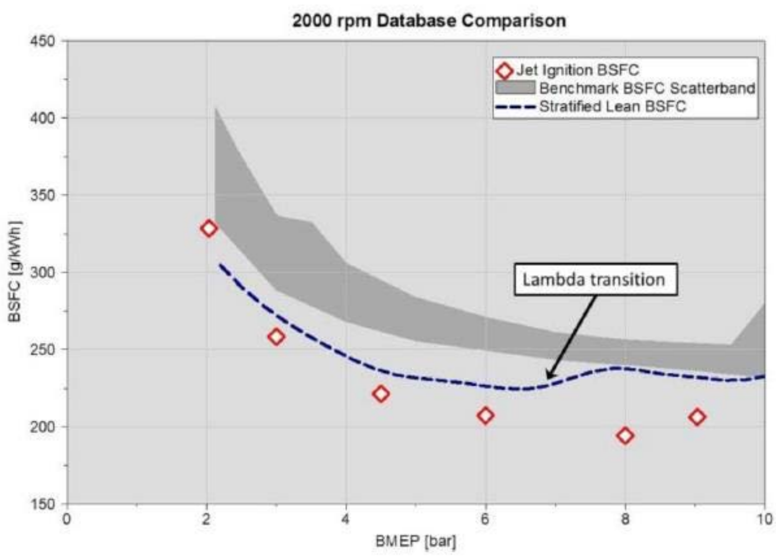

Figure 20 - Multi-Cylinder - Varying BSFC with Load Sweep at 2000 rpm (Bunce et al 2016)

Real World Analysis

Simulation and Considerations

In order to make a proper assessment as to the real-world potential William et al discuss that the technology should not only be assessed over multiple drive cycle profiles using a typical vehicle but also compared to future technologies as well as a baseline engine. Therefore, the potential of MJI's emissions have been simulated over the NEDC and FTP using a 2.4L Ecotec running at $\lambda = 1$ with spark initiation as a baseline, a homogeneous lean equivalent of the baseline engine, a downsized HCCI engine and a MJI equivalent of the baseline operating under lean burn conditions (Attard et al 2011).

GT-Drive has been used to simulate drive cycle profiles and engine parameters where a Chevrolet HHR and it's physical parameters such as gross vehicle mass, rolling radius and gearing have been used. Attard et al mentions that both drive cycle profiles are not aggressive drive cycles in terms of engine demand and engine speed spending the majority of their time at 3 bar BMEP or below with engine speeds mostly ranging from 1500 to 2500 rpm. Therefore, the results of the experiment will show the benefits gained when operating in low load conditions (Attard et al 2011).

Results

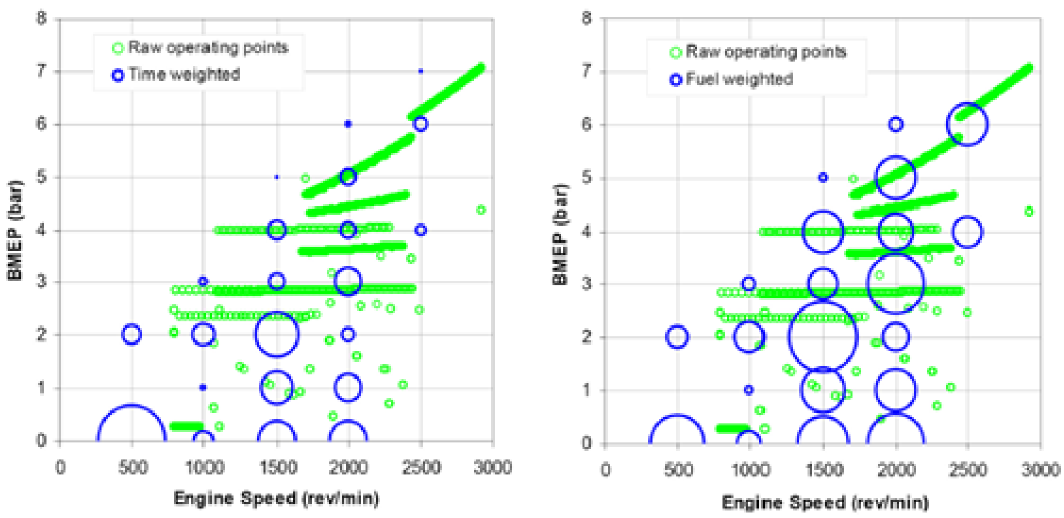

Figure 21 – Drive Cycle Operation Points with Weighted Fuel Consumption (Attard et al 2011)

Over the NEDC MJI saw a comparable improvement over the base engine as HCCI at 13%, double that of a conventionally fuelled engine running lean achieving 6%. However, it should be noted that the MJI results and HCCI results are not directly comparable. William et al discusses that the compression ratios of the HCCI engine modelled had a higher CR than that of the MJI engine at 11.8 and 10.4 respectively. Additionally, it should be noted that the HCCI engine featured turbocharging a more complex valvetrain as well as a complex EGR system. The increase in CR and boosting for the HCCI was to extract the greatest efficiency possible while maintaining an acceptable knock threshold giving MJI as greater challenge as possible. However, it is also discussed that the MJI engine has plenty of head room for a CR increase and hardware optimisation that the HCCI engine does not meaning that fuel economy improvements are likely to be in the region of 25% one optimised for both the NEDC and FTP-75. These results have been summarised in to Table 4 (Attard et al 2011).

Table 4 - Drive Cycle Comparison using With Different Combustion Technologies (Attard et al 2011)

Engine	Compression Ratio	Additional Components	Test Cycle	
			NEDC	FTP-75
SI, $\lambda = 1$,	10.4	-	-	-
SI, Lean Operation	10.4	Lean NOx Trap	6%	6%
MJI	10.4	MJI System	13%	13%
Optimised HCCI	11.8	Central DI, Cam-Profile Switching, Complex EGR Cooling Loop	13%	15%
Prediction for MJI once Optimised	13.5-14	Side DI, Optimised Jets	~25%	~25%

FUTURE VISION

Attard et al discuss that coupling MJI with a 50% downsized engine would yield further reductions in fuel consumption due to the reduction in throttling. Additionally, combining this technology with a more complex valve train and with HCCI for further improvements at part load, thereby removing throttling losses, would yield further fuel economy improvement over the previously mentioned 25% prediction. As previously mentioned this technology has the potential to pass emissions requirement without the need for a reduction catalyst for the NOx emissions (Attard et al 2011).

CONCLUSION

In this paper summary it has been shown that not only can MJI achieve stable combustion but at λ =1 combustion is more stable than a conventionally spark ignition engine with faster CA10-90 and a great end gas knock resistance in unfuelled mode. In fuelled mode the knock resistance further improved at the expense of reduced improvement in thermal efficiency.

From the naturally aspirated multi-cylinder results it was found that a BSFC of sub 200 g/kWh was achievable with a thermal efficiency increase at 2000 rpm of 18% with a peak thermal efficiency of 41% under legislative test cycles. By assessing the unoptimised engine over the NEDC and FTP-75 is was found there was an estimated improvement of 13% over both cycles comparable to that of an optimised HCCI engine. By optimising the engine through increased compression ratio for use with MJI as well as refinements to MJI it has been predicted that fuel consumption improvements could almost double to 25%.

As MJI is able to reduce Nox emissions by over 99% it is postulated that this technology could remove the need for a NOx specific catalyst due to its superiority. Additionally, when coupled with a downsized engine further reduction in exhaust gas temperatures could be seen with further increased thermal efficiencies and reductions in pumping losses.

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Abbreviations and Definitions

EGR– Exhaust Gas Recirculation

Indolene – Gasoline without additive

DI – Direct Injection

FE – Fuel Economy

SI – Spark Igniton

PFI – Port Fuel Injection

λ – Lambda – Fuel to air ratio where λ=1 is stochiometric

CA – Crank Angle

CA50 – Crank Angle for 50% MFB

CA10-90 – Crank Angle degree duration to burn between 10% and 90% of fuel to burn

MFB – Mass Fraction Burn

HC - Hydro Carbon

Ppm – Parts Per Million

CoV – Coefficient of Variance

NEDC – New European Drive Cycle

BMEP – Brake Mean Effective Pressure

IMEP – Indicated Mean Effective Pressure

IMEPg – Gross Indicated Mean Effective Pressure

IMEPn – Net Indicated Mean Effective Pressure

ABDC – After Bottom Dead Centre

ATDC – After Top Dead Centre

BBDC – Before Bottom Dead Centre

BTDC – Before top Dead Centre

FTP-75

HCCI – Homogenous

BSFC – Brake Specific Fuel Consumption

MJI – MAHLE Jet Ignition

WLTC – World Harmonized Light Vehicle Test Procedure

FE – Fuel Economy

CO – Carbon Monoxide

MBT – Maximum Brake Torque

CO2 – Carbon Dioxide

NOx – Nitrogen Oxides