CRC Report No. AVFL-35

ADVANCED COMBUSTION LITERATURE SURVEY

Final Report

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COORDINATING RESEARCH COUNCIL, INC.
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ADVANCED COMBUSTION LITERATURE SURVEY

FINAL REPORT

CRC Project No. AVFL-35

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POWERTRAIN ENGINEERING DIVISION

LIST OF ACRONYMS

AKI	-	Anti-Knock Index
AMFI	-	Additive Mixing Fuel Injection
BMEP	-	Brake Mean Effective Pressure
BSFC	-	Brake Specific Fuel Consumption
BTE	-	Brake Thermal Efficiency
CA{x}	-	Crank Angle Location Where {x}% of Combustion is Complete
CFR	-	Code of Federal Regulations
CFR	-	Coordinated Fuel Research
CI	-	Compression Ignition
CN	-	Cetane Number
CO_2	-	Carbon Dioxide
CoV	-	Coefficient of Variability
DI	-	Direct Injection
DOE	-	Department of Energy
DPF	-	Diesel Particulate Filter
ECU	-	Engine Control Unit
EIVC	-	Early Intake Valve Closing
EGR	-	Exhaust Gas Recirculation
EOI	-	End of Injection
EPA	-	Environmental Protection Agency
EVC	-	Exhaust Valve Closing
EVO	-	Exhaust Valve Opening
FSN	-	Filter Smoke Number
FTP	-	Federal Test Procedure
GCI	-	Gasoline Compression Ignition
GDI	-	Gasoline Direct Injection
GHG	-	Greenhouse Gas
GM	-	General Motors
GPF	-	Gasoline Particulate Filter
HC	-	Hydrocarbon
HCCI	-	Homogeneous Charge Compression Ignition
HD FTP	-	United States Heavy-Duty Engine Federal Test Procedure
HLSI	-	Homogeneous Lean Spark Ignition
HWFET	-	EPA Highway Fuel Economy Test Cycle
IC	-	Internal Combustion
IMEP	-	Indicated Mean Effective Pressure
$ISNO_X$	-	Indicated Specific NO_X Emissions
ISG	-	Integrated Starter Generator
IVC	-	Intake Valve Closing
IVO	-	Intake Valve Opening
LIVC	-	Late Intake Valve Closing
LNT	-	Lean NO_X Trap
LTC	-	Low Temperature Combustion
LTGC	-	Low Temperature Gasoline Combustion
MAP	-	Manifold Air Pressure

MPR	-	Mean Pressure Rise Rate
Nm	-	Newton Meter
NMHC	-	Non-Methane Hydrocarbon
NMOG	-	Non-Methane Organic Gas
OBD	-	On-Board Diagnostics
OEM	-	Original Equipment Manufacturer
ON	-	Octane Number
NVO	-	Negative Valve Overlap
PCCI	-	Premixed Charge Compression Ignition
PFI	-	Port Fuel Injection
PPC	-	Partially Premixed Combustion
PRF	-	Primary Reference Fuel
PRR	-	Pressure Rise Rate
RCCI	-	Reactivity Controlled Compression Ignition
RON	-	Research Octane Number
SACI	-	Spark Assisted Compression Ignition
SCOTE	-	Single Cylinder Oil Test Engine
SCR	-	Selective Catalytic Reduction
SI	-	Spark Ignited
SOC	-	Start of Combustion
SOI	-	Start of Injection
SPCCI	-	Spark Plug Controlled Compression Ignition
SULEV	-	Super Ultra Low Emission Vehicle
TDC	-	Top Dead Center
TRL	-	Technology Readiness Level
TWC	-	Three Way Catalyst
UDDS	-	Urban Dynamometer Driving Schedule
VGT	-	Variable Geometry Turbocharger
VNT	-	Variable Nozzle Turbocharger
WHR	-	Waste Heat Recovery

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1.0 INTRODUCTION

1.1 The Advanced Combustion Continuum

The regulatory environment for IC engine-powered transportation has grown increasingly challenging over the decades since emissions limits were first implemented in the 1970's. Criteria pollutant limits are approaching the detection limit of standard analysis methods, and CO_2 emission limits are bringing increasing powertrain electrification to vehicles. Given these considerations, it is worth considering the potential of advanced combustion systems to see what role they might play in the transportation powertrain of the future.

This report considers several variants of advanced combustion, some of which have commonly been referred to as "low temperature combustion". Low temperature combustion (LTC) refers to the reduced local temperatures generated in some advanced combustion approaches when compared to conventional SI and CI combustion systems. These reduced local temperatures bring advantages both to efficiency and criteria emissions. A lower peak temperature in the combustion chamber will reduce heat losses, so there is potential for more of the fuel energy to be given to the pressure work done on the piston. The lower temperatures also reduce NO_X formation, while the leaner local equivalence ratios of advanced combustion reduce particulate formation. The pathway by which these emissions can be avoided is shown in Figure 1, taken from Neely at al. [1.1]. Within the context of the systems considered in this report, the evolution of combustion system design has led to hybrid combustion approaches that feature both low-temperature phases and more conventional phases that correspond to higher flame temperatures. It is these systems that are perhaps of highest interest within the engine community, for reasons that will be discussed in the relevant sections of the report. Because of this hybrid nature, the combustion approaches will be broadly referred to as "advanced combustion" but detailed terms such as "low temperature combustion" or "kinetically controlled combustion" will be used as appropriate for the discussion.

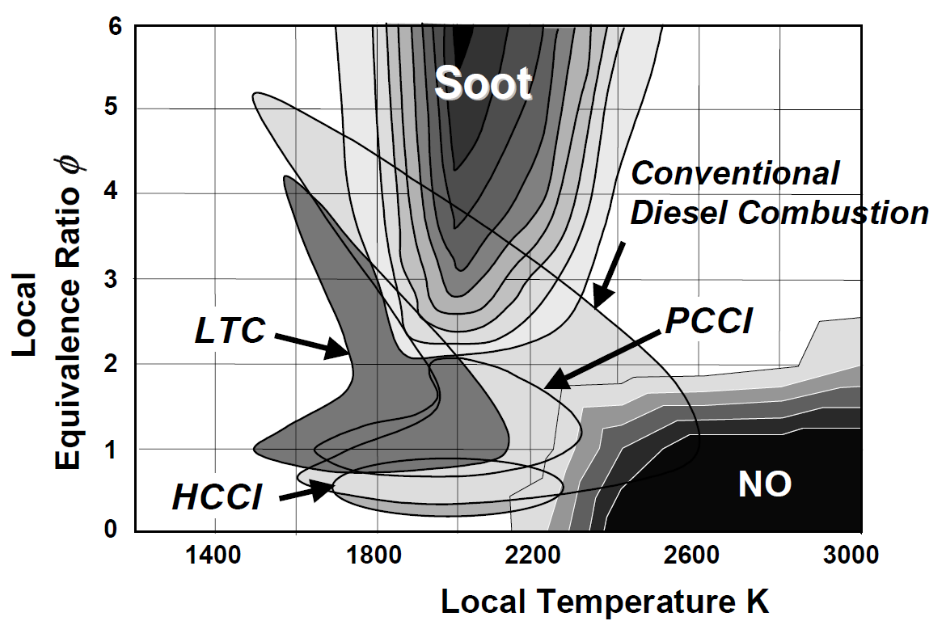

FIGURE 1: COMBUSTION REGIONS WITHIN THE PHI-T SPACE (FROM [1.1])

The canonical advanced combustion approach (which also is a low-temperature combustion approach) is homogeneous charge compression ignition (HCCI). In this system the fuel and air are completely premixed as they enter the combustion chamber and are compression-ignited without any positive ignition source. In a pure HCCI engine there is no flame propagation, but all the fuel is consumed near-instantaneously in a rapid kinetic autoignition event. Anyone experienced in engine combustion will see the challenges inherent in this approach: without a positive ignition event the control of combustion timing is dependent on a wide array of variables, many of which are uncontrollable in a practical engine. Furthermore, the autoignition event will yield a very rapid heat release and corresponding rapid rise in the cylinder pressure. This is both loud and physically difficult to accommodate with reasonable engine mechanical designs. Many research programs have sought to address these challenges through a variety of methods. A previous study performed for the Coordinating Research Council investigated the state of the art for HCCI combustion in the 2006 timeframe [1.2]. That report is suggested as background to the present study, particularly Appendix A, a literature survey of the state of the art at that time.

A wide range of other advanced combustion approaches have been developed and studied to try to address the significant practical challenges of a pure HCCI combustion system. In list form they are: Spark Assisted Compression Ignition (SACI), Partially Premixed Combustion (PPC), Gasoline Compression Ignition (GCI), and Reactivity Controlled Compression Ignition (RCCI). These various systems all attempt to combine the homogeneous and non-propagating combustion of HCCI with a positive ignition control method and various approaches to diluting the charge to limit the pressure rise rate. Shown in a continuum that also considers the nature of the combustion event, these systems can be considered as shown in Figure 2.

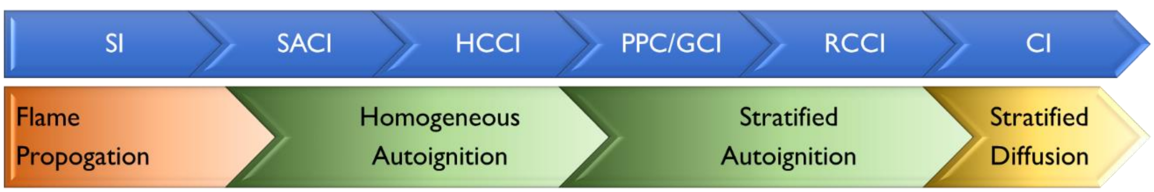

FIGURE 2: COMBUSTION CONTINUUM

Considering advanced combustion approaches within the continuum of Figure 2 indicates how they relate to the well understood foundations of spark ignition (SI) or flame propagation combustion and compression ignition (CI) or diffusion combustion. As one progresses from left to right in the figure there is an increasing transition away from flame propagation to homogeneous kinetic autoignition and then onward to increasing reliance on diffusion combustion. Reasonable arguments could be made for reordering some of the systems on this continuum, so the order shown here should be considered as an illustration of the continuum concept more than a hard-and-fast ordering. It should also be noted that this continuum is not a novel ordering concept but has been used by the report author and others in service to classifying combustion systems [1.3, 1.4].

1.2 Fuel Aspects of Advanced Combustion

Beyond the question of combustion systems, there is the related question of fuel selection, or fuel design. Historically the goal of combustion researchers has been to develop advanced combustion approaches that can work with existing fuel supplies, either gasoline or diesel. The results of these development studies have generally shown the difficulty of using these fuels. A key characteristic of gasoline is its octane number (ON) which is a measure of how hard it is to autoignite the fuel. For Diesel fuel the analogous metric is cetane number (CN) which is a measure of how easy it is to autoignite the fuel. Both fuels are designed to yield values of their respective metrics which perform well for spark-ignited flame propagation combustion and compression-ignited diffusion combustion, respectively. But advanced combustion approaches generally need fuel behavior that is in between gasoline and diesel fuel. Diesel ignites so easily that significant amounts of dilution are required to reduce mixture reactivity, while gasoline is not reactive enough and requires high temperature at IVC to enable autoignition-driven combustion. Studies as discussed in this report have shown that fuels with intermediate ignitability can simplify operation of an engine for these advanced combustion approaches, and RCCI uses the different ignition characteristics of gasoline and diesel fuels in combination to achieve a similar end.

Recent R&D has attempted to ask and answer the question: What if a fuel was developed to ideally match the demands of a combustion system? This approach is most fully represented in the Co-Optima program, funded by the US Department of Energy [1.5]. If a fuel can be created which provides the desired physical properties and combustion characteristics, Advanced combustion approaches using low-temperature combustion can be much more easily realized. And if this fuel can be less carbon intensive then it provides additional benefits in terms of well-to-wheels CO_2 emissions. This could be achieved via renewable fuels, lower carbon-intensity refinery stream fuels, or potentially from synthesized e-fuels in the future.

For the present study, papers which addressed fuel sensitivity of the combustion systems and papers which considered non-market fuels which can enable advanced combustion were both considered. Understanding fuel sensitivity is crucial for any production-intent combustion approach, given the wide range of fuel properties that can be seen in the market (including seasonal variation, regional variations, market regulation differences, and out-of-spec fuels). Knowledge of when a non-market fuel can improve or enable advanced combustion is also of value, particularly in light of the developments in renewable fuel production and e-fuel production where fuels in the future may be more easily customized than in today’s production processes.

1.3 Combustion System Categorization

As seen in Figure 2, there are many different “versions” of advanced combustion, with five called out in the figure. In the present study the categories were reduced to four: SACI, HCCI, GCI, and RCCI. These encompass essentially all the pathways to advanced or low-temperature combustion:

- SACI has been demonstrated with fully premixed and homogeneous mixtures, with lean and stratified mixtures, and with varying ratios of flame propagation to homogeneous autoignition combustion. The essential feature of SACI is that a spark plug ignites the fuel-air mixture and generates a propagating flame. The mixture conditions are set so that this propagating flame increases the temperature and pressure of the unburned mixture to initiate a homogeneous combustion event that consumes the majority of the fuel under HCCI-like conditions, but with positive timing control from the spark event.
- HCCI is the most general and broadest of the combustion systems, with the pure form being fully premixed air and fuel with homogeneous autoignition of the entire mixture and no flame propagation. This pure form is of limited practicality due to pressure rise rate limits and minimal controllability. Most research efforts have provided improved control of

combustion phasing and rates through moderate levels of charge stratification which maintain kinetically driven compression ignition while addressing the practical challenges of HCCI.

- PPC (or PPCI / PCCI) and GCI are the same basic combustion approach. PPC is generally used to describe this system when diesel fuel is used, and GCI when gasoline is used. This approach uses the flexibility of modern fuel systems to premix part of the fuel/air charge prior to the main injection event. Depending on the fuel and other factors this premixed charge will undergo some degree of low-temperature combustion. Later injections can still burn in a traditional diffusion flame. Moving from diesel to gasoline allows for more of the fuel to burn as a homogeneous charge rather than as a diffusion flame. This reduces heat losses and criteria pollutant formation. It could be argued that conventional diesel engines sometimes move towards PPC operation with the sophisticated pilot injection strategies in use, but the key differentiating factor is the dependence of ignition on physical mixing and chemical kinetic timescales in PPC/GCI vs. the traditional diffusion flame ignition process in diesel combustion. As compared to HCCI, a PPC/GCI approach has significantly greater charge stratification that contributes to the improved controllability of combustion.
- RCCI can be viewed as an extension from PPC and GCI, where the additional stratification of fuel reactivity is introduced to further enhance the ignition control via the injection system. In most other respects, RCCI is essentially the same as PPC.

With these categories, the broad spectrum of combustion approaches can be categorized and analyzed, and in general these categories are consistent with the papers identified using keyword searches for the various combustion methods.

1.4 Literature Review Approach

The study presented here considered work published since 2005 to capture studies which post-dated the previous CRC literature review on advanced combustion [1.2]. Papers were selected from combustion and fuel journals, conference proceedings, the SAE paper database, and Department of Energy presentation databases. The research team then evaluated the papers for their significance to the development of the specific combustion system, and the best papers were retained for detailed review. Roughly twenty papers for each of the four combustion systems were identified for detailed review from this filtering. These papers were then reviewed, and the key findings summarized. These studies informed the preparation of this report, using the following breakdown of major focus areas:

- Overall combustion concept
- Hardware requirements
- System performance
- Technical challenges to be addressed
- Fuel property impacts
- Production feasibility

For each of the combustion systems, there were key papers which directly addressed these areas, and which are specifically cited in the report text. The remaining papers were still of high value but did not require citation for additional depth. Papers directly cited in the report are listed separately from other papers which provided background information, but which were not cited.

No judgement is intended in terms of paper quality or significance between the two groupings, but only that the cited papers most directly addressed the considered focus areas for the purpose of this review.

1.5 Report Outline

The report is divided into five major sections:

- Meta-analysis: the combustion system categories will be considered as a group both to identify similarities which can be discussed in unison and differences which will be further explored in the report sections.
- SACI
- HCCI
- GCI
- RCCI

The report will conclude with a section that revisits some of the meta-analysis discussion and which summarizes the broad findings of the literature review.

Each report section will include a table summarizing key facts for each combustion system. One of these will be the author's estimate of the technology readiness level of the combustion system. Definitions as given by the US Department of Energy's Energy Efficiency and Renewable Energy Office will be used[1]:

TRL-1. Basic principles observed and reported: Scientific problem or phenomenon identified. Essential characteristics and behaviors of systems and architectures are identified using mathematical formulations or algorithms. The observation of basic scientific principles or phenomena has been validated through peer-reviewed research. Technology is ready to transition from scientific research to applied research.

TRL-2. Technology concept and/or application formulated: Applied research activity. Theory and scientific principles are focused on specific application areas to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

TRL-3. Analytical and experimental critical function and/or characteristic proof of concept: Proof of concept validation has been achieved at this level. Experimental research and development is initiated with analytical and laboratory studies. System/integrated process requirements for the overall system application are well known. Demonstration of technical feasibility using immature prototype implementations are exercised with representative interface inputs to include electrical, mechanical, or controlling elements to validate predictions.

TRL-4. Component and/or process validation in laboratory environment- Alpha prototype (component): Standalone prototyping implementation and testing in laboratory environment

[1] https://www1.eere.energy.gov/financing/docs/technology_readiness_levels.docx

demonstrates the concept. Integration and testing of component technology elements are sufficient to validate feasibility.

TRL-5. Component and/or process validation in relevant environment- Beta prototype (component): Thorough prototype testing of the component/process in relevant environment to the end user is performed. Basic technology elements are integrated with reasonably realistic supporting elements based on available technologies. Prototyping implementations conform to the target environment and interfaces.

TRL-6. System/process model or prototype demonstration in a relevant environment- Beta prototype (system): Prototyping implementations are partially integrated with existing systems. Engineering feasibility fully demonstrated in actual or high-fidelity system applications in an environment relevant to the end user.

TRL-7. System/process prototype demonstration in an operational environment- Integrated pilot (system): System prototyping demonstration in operational environment. System is at or near full scale (pilot or engineering scale) of the operational system, with most functions available for demonstration and test. The system, component, or process is integrated with collateral and ancillary systems in a near production quality prototype.

TRL-8. Actual system/process completed and qualified through test and demonstration- Pre-commercial demonstration: End of system development. Full-scale system is fully integrated into operational environment with fully operational hardware and software systems. All functionality is tested in simulated and operational scenarios with demonstrated achievement of end-user specifications. Technology is ready to move from development to commercialization.

1.6 References

[1.1] Neely, G., Sasaki, S., Huang, Y., Leet, J., and Stewart, D.; "New Diesel Emission Control Strategy to Meet US Tier 2 Emissions Regulations"; SAE Technical Paper 2005-01-1091; 2005

[1.2] Shen, Y., "Fuel Chemistry Impacts in Gasoline HCCI, CRC Project AVFL-13", Coordinating Research Council, 2006

[1.3] Briggs et al., "High Efficiency Clean Combustion in Multi-Cylinder Light-Duty Engines", Presented at the 2011 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review, 2011 (https://www.energy.gov/sites/prod/files/2014/03/f11/ace016_curran_2011_o.pdf)

[1.4] Curran et al., "High Efficiency Clean Combustion in Multi-Cylinder Light-Duty Engines", Presented at the 2013 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review, 2013, (https://www.energy.gov/sites/prod/files/2014/03/f13/ace016_curran_2013_o.pdf)

[1.5] https://www.energy.gov/eere/bioenergy/co-optimization-fuels-engines

2.0 META-ANALYSIS OF ADVANCED COMBUSTION

2.1 Introduction

As presented in the report introduction, low temperature combustion systems exist on a continuum (see Figure 3); each can be seen to merge gradually into the next when the details of how combustion occurs are considered, and in many cases there are multiple combustion modes being applied for a practical application of any of the systems.

FIGURE 3: COMBUSTION CONTINUUM

This section of the review will consider how these combustion systems exist on the continuum and how they relate to other approaches which have not been explicitly called out in this proposal.

2.2 Combustion System Cross-Analysis

There are other ways to consider the combustion continuum. Dempsey et al. considered many of the combustion systems in terms of the degree of fuel stratification [2.1]. Figure 4 shows the ordering with this approach. SI combustion would be fully premixed or partially stratified, and CI combustion is fully stratified. All the advanced combustion systems then use some level of fuel stratification to provide a measure of control over combustion. A pure HCCI approach, having no stratification, is the ideal low temperature combustion system, but as has been discussed comes with the challenge of minimal combustion control potential. SACI resolves this problem with HCCI by including a positive ignition device, and that the stratification level is designed to limit the degree of flame propagation and resulting high temperature combustion. A production example of SACI is the Mazda Skyactiv X engine which will be discussed in the SACI section of this report.

If GCI and RCCI are considered within this definition of the combustion continuum, it becomes evident that both of those approaches as well as PCCI are essentially the same. Many papers conflate those approaches, in fact. The goals for each combustion system are the same – stratify the fuel/air charge to create a zone where kinetic autoignition occurs at the desired start of combustion timing, which then causes the kinetic autoignition of the next zone, and so on. PCCI accomplishes this with premixing of diesel fuel, and generally is a combination of low temperature combustion of part of the fuel with diffusion combustion for the remaining fuel. GCI extends the PCCI approach to a higher volatility, lower reactivity fuel where the diffusion combustion can largely be eliminated. RCCI then adds a second fuel to include not only equivalence ratio stratification but also chemical reactivity stratification. This commonality makes the defining points between the combustion approaches fluid and primarily a function of fuel choice rather than any fundamental difference in the combustion chemistry or physics. There are no engines of this kind in production as of this report, but both Delphi and Hyundai have demonstrated production-like GCI engines as will be discussed in this report.

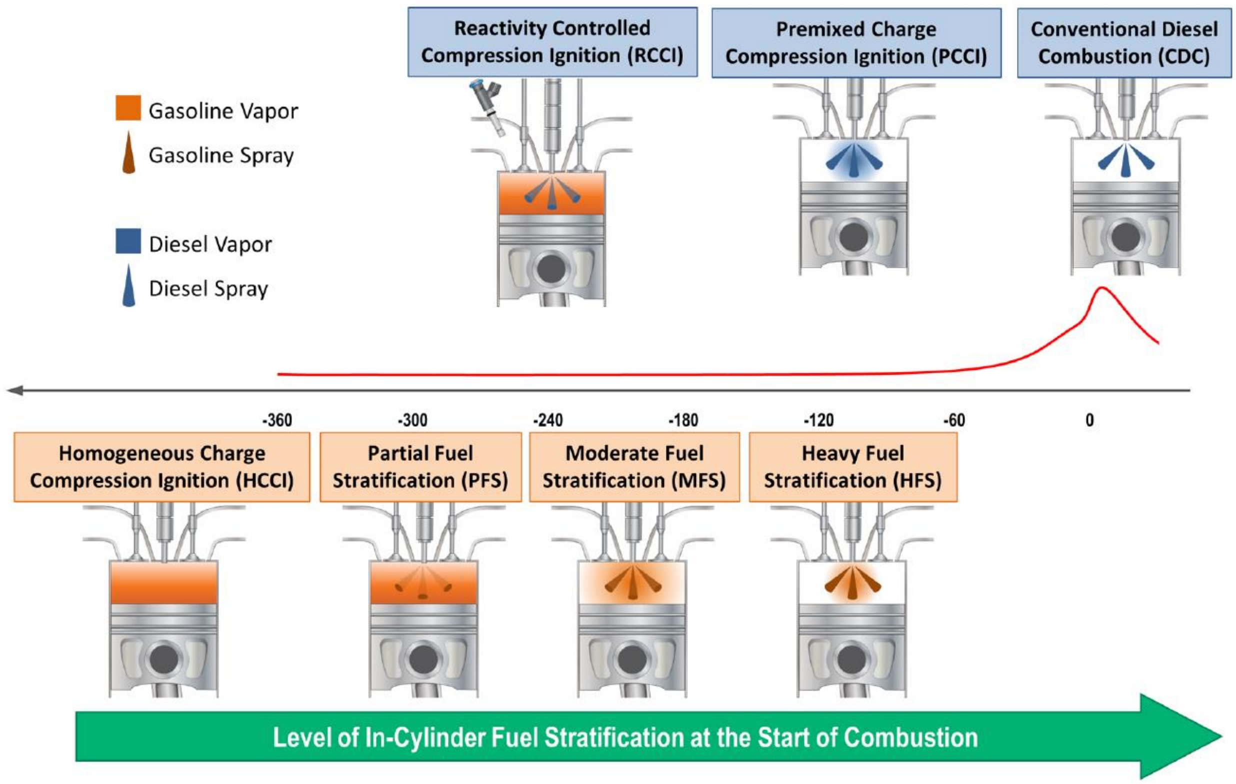

FIGURE 4: COMPARISON OF FUEL STRATIFICATION FOR VARIOUS ADVANCED COMBUSTION SYSTEMS (FROM [2.1])

The stratification axis can also be followed from GCI/PCCI/RCCI towards HCCI. There is significant blurring in between these modes as well. As will be seen in the HCCI section, most researchers have implemented some degree of fuel stratification to bring controllability to HCCI combustion; at the extreme it can be difficult to define the break between GCI and HCCI systems; both can have a high degree of premixing, similar dilution levels, and similar NO_X emissions.

Another way to view the combustion systems in terms of charge stratification is to also include the degree of separation between the end of injection (or spark) and the start of combustion. This second dimension considers how tightly coupled the combustion event is to the positive timing control method for the combustion approach. Figure 5 shows the combustion systems mapped into this space. Arguments can be made for the exact location of each combustion system in the stratification / EOI-SOC separation space, so transparent regions indicate ranges for the advanced combustion systems. The mapping indicates the major differences, with SACI generally being unreliant on charge stratification but highly coupled to the spark event (as indicated by the very name of the combustion approach) and HCCI being canonically fully decoupled from the positive ignition control (but with practical implementations having a wide range of stratification levels to bring some coupling back to EOI).

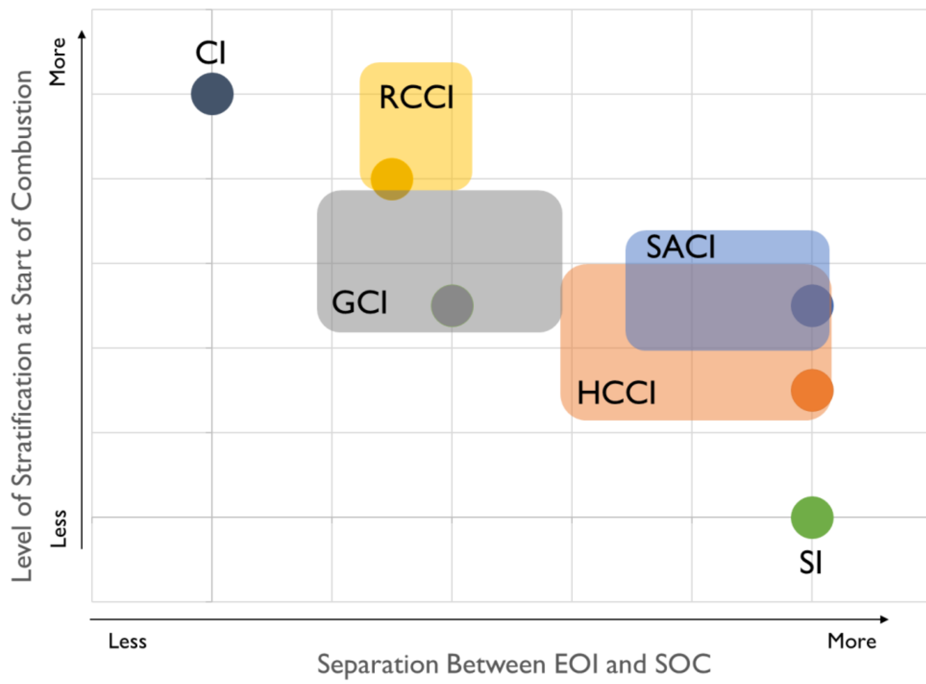

FIGURE 5: MAPPING OF COMBUSTION SYSTEMS AGAINST CHARGE STRATIFICATION AND SEPARATION FROM POSITIVE TIMING CONTROL

An additional factor that distinguishes the combustion modes is their reliance on the fuel reactivity, or autoignition propensity. Figure 6 shows the reliance of the advanced combustion modes (and conventional SI and CI combustion) on relative fuel reactivity. A high fuel reactivity indicates an easier to ignite fuel, while a low fuel reactivity indicates a more difficult to ignite fuel. The visualization shows how some combustion modes have logically developed from conventional combustion, and how some evolved from a more fundamental approach to advanced combustion. SACI is confined to the use of conventional fuels for SI engines since it must operate in a multi-mode approach. RCCI could offer a broader acceptance of fuel reactivity but was generally developed with a practical approach of using existing market fuels for SI and CI engines. GCI initially was developed with the idea of using gasoline, but many studies have shown the benefit of a fuel that is more reactive than gasoline (but less than diesel) in taking full advantage of a GCI combustion approach. HCCI has been shown to be possible with a wide range of fuel reactivities, and like GCI has shown perhaps the most promise with a fuel lying somewhere between gasoline and diesel fuel.

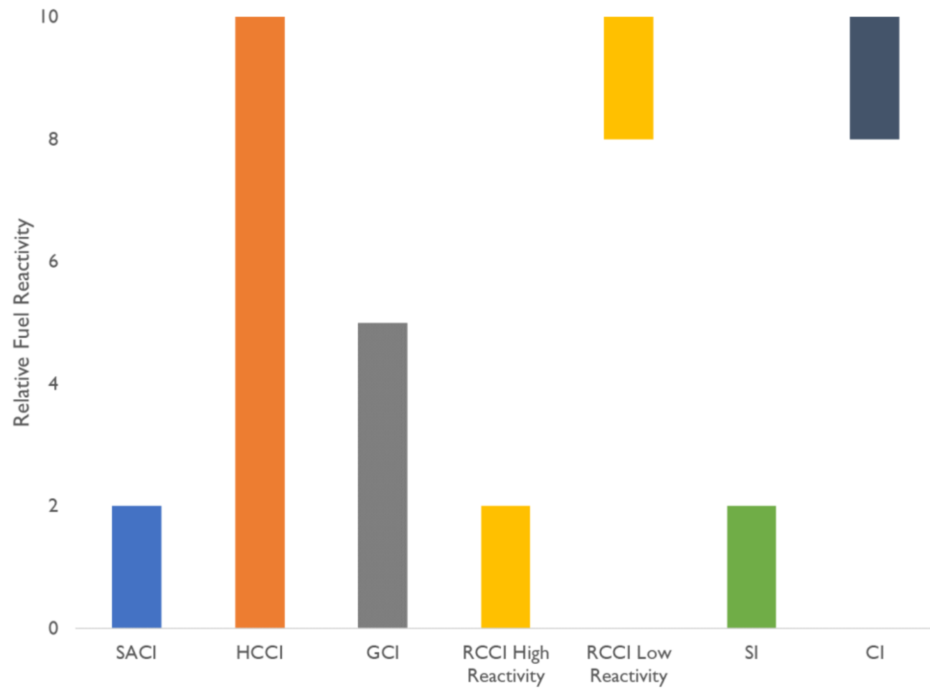

FIGURE 6: COMBUSTION SYSTEM RELIANCE ON FUEL REACTIVITY

Ultimately, the goal of all these systems is to achieve high efficiency with fully controlled combustion. Depending on the degree of stratification and the fuel reactivity, the combustion approaches under consideration rely to varying degrees upon mixing and kinetic timescales to achieve this control. This leads to real differences between the various combustion systems, but also with significant commonality in the challenges each face and the resulting engineering solutions which have been investigated.

2.3 Common Development Challenges

Many of the development challenges that will be discussed are common among the combustion systems. A listing of development challenges can go on at length when all of the varying requirements of different OEMs, customers, regulating bodies, and use scenarios are considered. The most pressing development challenges can easily be summarized and are generally applicable to all of the advanced combustion systems:

- Combustion control and robustness to uncontrolled independent variables
- Air handling system design to accommodate high dilution and reduced exhaust temperatures
- Fuel availability and system robustness to real-world fuel variations
- Emissions control

Each low temperature combustion system has some degree of challenge in each of these areas. SACI addresses combustion control using a spark ignition event, though it still requires more sophisticated sensors and control methods than standard SI combustion. Mazda and Hyundai have shown that air handling can be accommodated with a single-stage boost system, at least at the power densities they are targeting. But the remaining challenges continue to be open issues for all these advanced combustion systems.

Emissions control will appear repeatedly within this report as a challenge for advanced combustion systems. Many advanced combustion approaches can yield lower engine-out emissions than conventional SI or CI combustion. However, the progression of stricter tailpipe emissions limits and the associated requirements to ensure that in-use emissions are compliant is likely to ensure that aftertreatment remains necessary regardless of the engine-out emissions. For the US, this means that a light duty vehicle must satisfy EPA Tier 3 emissions (or the similar California LEV III standard) [2.2] and a heavy-duty vehicle must soon satisfy CARB lower NO_X regulations (which is expected to be largely adopted by the EPA) [2.3]. These rules require most light duty automobiles sold in 2025 to certify at the 30 mg/mile NO_X+NMOG emission level, and heavy-duty trucks sold in 2024 to certify at 0.05 g/hp-hr NO_X, decreasing to 0.02 g/hp-hr NO_X in 2027 (and this new regulation also includes low load cycle testing to ensure compliance under extended idle and low-load operation). In practice this will require the vehicles, when new, to emit no more than 50% of the certification level to account for in-use degradation; the EPA and CARB can obtain used vehicles from the market and perform audit testing to confirm that the in-use emissions remain under the certification value.

In addition to satisfying the tailpipe emission limits, the advanced combustion systems must also address on-board diagnostics requirements[2]. Any powertrain system which is associated with achieving emissions compliance must be able to be monitored by the control system, and the system must be able to detect when any part of the emissions control system deviates from normal operation sufficiently to cause excess emissions to be released. If a system with no aftertreatment was to be sold, the combustion system itself would require detailed monitoring to ensure that the engine-out emissions were always within specification. This report will not speculate on the feasibility of that approach but will note that including aftertreatment provides a significant measure of insurance that the vehicle emissions can be maintained and monitored using existing technical approaches.

Some global markets offer easier emission regulation scenarios at the time of this report. Mazda was able to achieve satisfactory control for the European and Asian markets with a three-way catalyst on their SACI engine (the Skyactiv X). Updated regulations are expected for Europe (and other markets using the European regulations) and China; there is not enough information on these regulations yet to know if they will approach the strictness of the US regulations, or if they will remain less stringent.

2.4 Fuel Effects on Combustion Development

The primary research into fuel effects on advanced combustion has been in two directions:

- Opportunities to use existing fuel variation in the market to enhance combustion (ethanol-containing gasoline, biodiesel, etc.)
- Potential for improved combustion control with sub-91 RON gasoline

[2] See https://dieselnet.com/standards/us/obd_ca.php for a discussion of OBD requirements for California as an example

These studies have shown potential for all the combustion systems, as discussed in their respective review sections. More broadly there is still a need for an understanding on how real-world fuel properties can affect advanced combustion systems.

Research for both GCI and HCCI has shown an opportunity for improved engine performance with a low-octane gasoline (perhaps around 65 RON as shown in [3.10]). If such a fuel could be brought to market in concert with the introduction of these engines, the engine development could be simpler thanks to the improved combustion control offered with a low-octane gasoline. This would require significant coordination between the automotive and petroleum industries, so is not a simple thing to achieve. As a consequence, for an advanced combustion system to be realized in production it mostly likely must be both competitive with existing engine designs while using existing market fuels. If it could perform better with alternative fuels it could potentially drive distribution and adoption of new fuels.

Within the US market, gasoline fuel can range from 89 to 97 RON; globally the range in RON values is even wider. Diesel also has significant global variation in cetane number. It is unlikely that an advanced combustion engine developed for, say, 91 RON gasoline would perform acceptably if fueled with high RON fuel in Europe. Beyond the octane and cetane ratings, there are other concerns with fuel properties – volatility, chemical speciation, and viscosity can all impact combustion in systems where spray stratification and chemical kinetics are crucial. Biodiesel in the global market comes from a wide range of feedstocks, and bring corresponding variations in hydrocarbon chain lengths, acids, and other fuel characteristics which can already cause challenges with conventional CI engines, let alone engines that rely so heavily on the fuel properties to function. There is a need for more research into these issues of fuel impacts on advanced combustion before commercialization of these engines is feasible.

2.5 Production Feasibility

The combustion systems with the strongest market potential are SACI and GCI. Mazda has already released the Skyactiv X SACI engine into the European and Japanese markets; this demonstrates that a robust and reliable combustion system solution has been developed. Delphi and Hyundai have, with significant DOE support, shown that a GCI system can be built, can handle real-world driving, and has a pathway to meet emissions. As a light-duty engine the system cost is likely to be high relative to conventional SI engines, which must be considered against the cost of hybridization that can yield similar vehicle efficiency. If GCI is considered for heavy duty applications where the engine system complexity is similar to modern CI engines the market potential appears to be more promising.

HCCI and RCCI are likely to have a more difficult path to market. HCCI has the most control challenges since it has the least reliance on stratification or other methods of generating positive combustion timing control. This is a large hurdle to overcome for a typical transport application with highly transient operation through rapidly changing environmental conditions. For a single-speed engine (power generation, or even a series hybrid vehicle) it is easier to envision a satisfactory technical solution to HCCI production barriers, but there will still be a need to develop more robust control solutions than currently exist simply to accommodate fuel property variability and environmental factors.

In many ways a RCCI engine has similar production challenges as a GCI engine, so there is a technical path to production (and like GCI a more natural fit in the heavy-duty market). However, the requirement for two fuels as well as urea for NO_X reduction brings a significant market acceptance challenge for RCCI; the practical challenges of refueling such a vehicle may be difficult to overcome, if only in terms of human factors. The relative lack of RCCI R&D activity compared to the other advanced combustion approaches also pushes production feasibility out, as there are still unique engineering requirements for RCCI that would have to be addressed (fuel system design and integration, controls, OBD, and so on).

Ultimately the real competition for advanced combustion engines is the rapid pace of powertrain electrification. Satisfying greenhouse gas regulations in major markets will force increasing electrification of powertrains (primarily as hybrid systems). Given the cost of electrification there will be an economic push to reduce the cost of the internal combustion engine to minimize the total powertrain cost. With the extra complexity of advanced combustion engines, there will need to be other factors which can help to drive the adoption of these engines within an electrified powertrain.

However, powertrain electrification also will yield significant opportunities to integrate advanced combustion engines more easily into vehicles. Two clear synergistic areas are to enable combustion mode switching in transient operation and transient response buffering. As will be discussed in the specific sections, advanced combustion engines generally need to transition between different combustion modes (Mazda's Skyactiv X engine moves from lean SACI to stoichiometric EGR SACI to conventional SI, as an example). Transitioning between these modes can sometimes be difficult to do while maintaining a smooth torque and speed progression; with even modest hybridization it becomes easy to smooth these transitions by using the electric motor to compensate for step changes in the engine torque delivery. Transient operation of advanced combustion engines can also be slower than what is demanded by the driver in real driving scenarios; the high dilution levels required can slow the response of the engine while the air handling system responds to the change in in-cylinder conditions. Again, a hybrid powertrain can be used to provide the rapid torque change required while the engine systems "catch up" to the vehicle demand. In both of these scenarios, hybridization becomes an enabler for advanced combustion and reduces or eliminates a significant challenge that has been identified for these engines.

It is outside the realm of this report to consider the likely growth of fully electrified powertrain systems. But within the context of advanced combustion engines, the synergistic combination of powertrain electrification and advanced combustion does provide a path to satisfy future greenhouse regulations across the full range of transportation systems, where the advanced combustion engines allow maximization of the use of fuel resources to satisfy energy density and vehicle range requirements while the hybrid systems allow overall system optimization of greenhouse emissions.

2.6 Overall System Comparison

These advanced combustion concepts can be mapped onto a spider plot which considers various factors that impact their producibility and practicality in relation to each other and to conventional SI and CI combustion systems. Figure 7 shows a mapping of the combustion modes considering some key details: the aftertreatment challenge, control challenge, hardware complexity, transient challenge, mode switching challenge, and sensitivity to environmental factors. The numeric rankings are subjective, so they should not be considered as a quantitative measure. A greater "score" for a given category implies that a given combustion system has a lesser challenge in that category. Viewing the plot does give a quick visual indication of the production challenge for a combustion system; both SI and CI systems cover a large area, while the advanced combustion systems cover much smaller areas. But within the space, a more challenging combustion approach like HCCI covers a much smaller area than a simpler system like SACI.

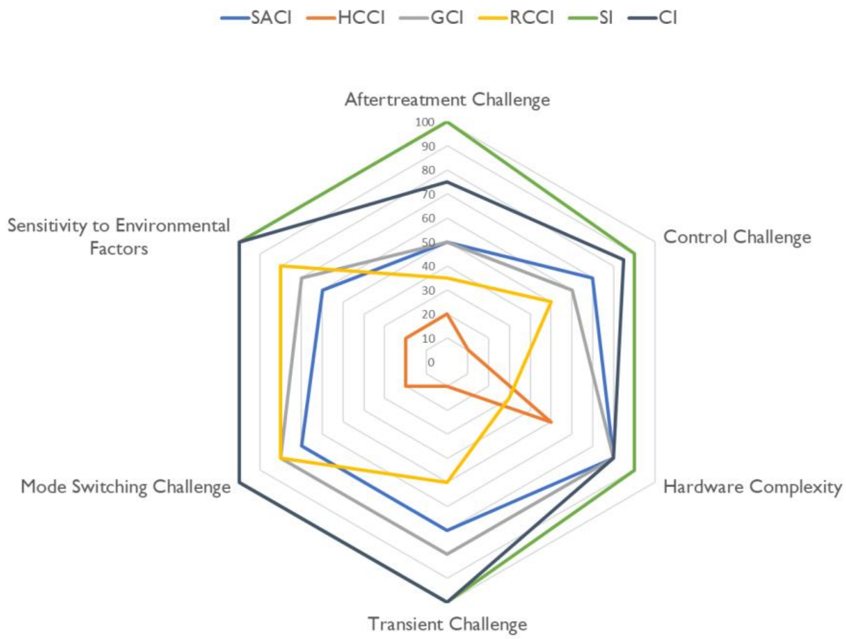

FIGURE 7: MAPPING OF ADVANCED COMBUSTION CHARACTERISTICS

2.7 Cited References

[2.1] Dempsey, A., Curran, S., and Wagner, R.; "A Perspective on the Range of Gasoline Compression Ignition Combustion Strategies for High Engine Efficiency and Low NOX and Soot Emissions: Effects of In-Cylinder Fuel Stratification"; *International Journal of Engine Research*; 17(8) 897-917; 2016

[2.2] EPA, 2014. "Control of Air Pollution from Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards", US Environmental Protection Agency, Final Rule, EPA-HQ-OAR-2011-0135, http://www.gpo.gov/fdsys/pkg/FR-2014-04-28/pdf/2014-06954.pdf

[2.3] https://ww2.arb.ca.gov/rulemaking/2020/hdomnibuslownox

3.0 SPARK ASSISTED COMPRESSION IGNITION

3.1 Summary of Concept

Spark assisted compression ignition, commonly termed SACI, is an approach to solving multiple challenges with HCCI combustion. In this approach, the combustion event is started with a spark as in conventional SI combustion. The combustion process then begins as a flame propagation event, but the rising temperature and pressure from the flame leads to a homogeneous ignition of the remaining unburnt mixture relatively early in the combustion process. While this is similar to end-gas knock in a spark-ignited engine, here the homogenous ignition is desired. The spark ignition provides positive control of ignition timing, and the flame propagation combustion consumes some of the fuel to reduce the pressure rise seen from the homogeneous combustion phase (as does the dilution from air or EGR in the bulk mixture). These features serve to improve the controllability of the combustion event and to extend the load and speed range where homogeneous combustion can be used.

Implementing SACI requires higher compression ratio combustion systems (to improve auto-ignition and to increase thermodynamic efficiency). Because the engines still need to run in conventional SI mode at high loads, SACI engines require EGR or lean operation to control end-gas knock at high loads. These requirements bring challenges to boost system design to provide the EGR and/or airflow required, especially with the lower exhaust enthalpies that high-dilution combustion yield. Aftertreatment is then also more challenging; EGR dilution allows maintaining stoichiometric operation so that conventional 3-way catalysts can be used, but the post-turbo exhaust temperature must be maintained at a sufficiently high temperature to maintain catalyst activity. If lean operation is used then NO_X storage generally must be provided, with the NO_X reduction occurring during higher-load operation when the engine runs at stoichiometric conditions.

These features, while challenging, are generally compatible with technologies which have been developed for IC engines. To date, only Mazda has successfully brought SACI to production, with generally positive performance reports in markets where the engine is presently available. The Skyactiv-X powertrain does include mild hybridization with a belt starter-generator which can provide torque assist.

It should be noted that SACI is most suited for light-duty applications. The largest benefit of SACI is improved efficiency at low loads where a light duty vehicle spends significant time. For heavier-duty applications, even if SI engines are sometimes used, the load factor on the engine is higher such that the engine will spend more time in the SI mode of a SACI engine, limiting the potential benefit from the advanced combustion system.

3.2 Mazda Skyactiv X Engine

As the only production SACI engine in existence, some discussion of the Mazda Skyactiv X is useful to understand what was required to enable production application of SACI. Figure 8 shows the layout of the engine. Several key features stand out: a belt-driven supercharger is used to provide the required air flow for both lean and EGR dilution, an in-cylinder pressure sensor is used for combustion feedback control, and aftertreatment is handled by a three-way catalyst and GPF. The supercharger is not used for high power density; the engine power density is 65 kW/L which is achievable by a naturally aspirated engine. The engine is sold in regions using Euro 6 and

Japanese emission standards; the required NO_X emissions are roughly double those generally targeted for certification in the US and so the three-way catalyst provides sufficient NO_X control in those regions. The lean operating region of the engine is noted to be at an air-to-fuel ratio of 30:1; at this lean mixture the NO_X emissions from the engine would be quite low, allowing for the simple aftertreatment system in combination with moderately permissive regulations.

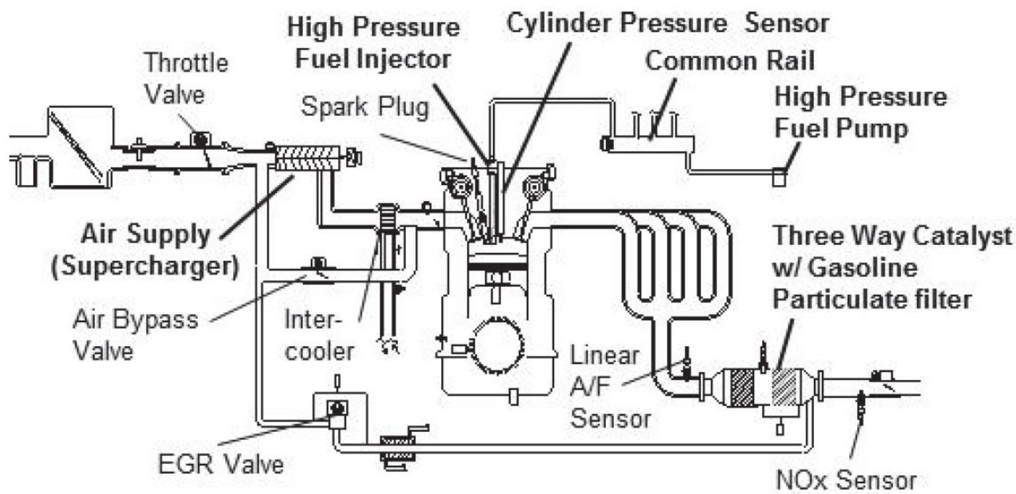

FIGURE 8: MAZDA SKYACTIV X ENGINE LAYOUT (FROM [3.1])

As will be discussed, advanced combustion modes are sensitive to thermal conditions; combustion is generally at least partially dependent on chemical kinetics which are primarily driven by temperature. To address the need for the engine to be robust against thermal variation, Mazda applied a thermal encapsulation system to the engine as shown in Figure 9. In addition to the sound control that engine covers are used for in modern vehicles, the more comprehensive encapsulation also allows for a more consistent thermal envelope around the engine.

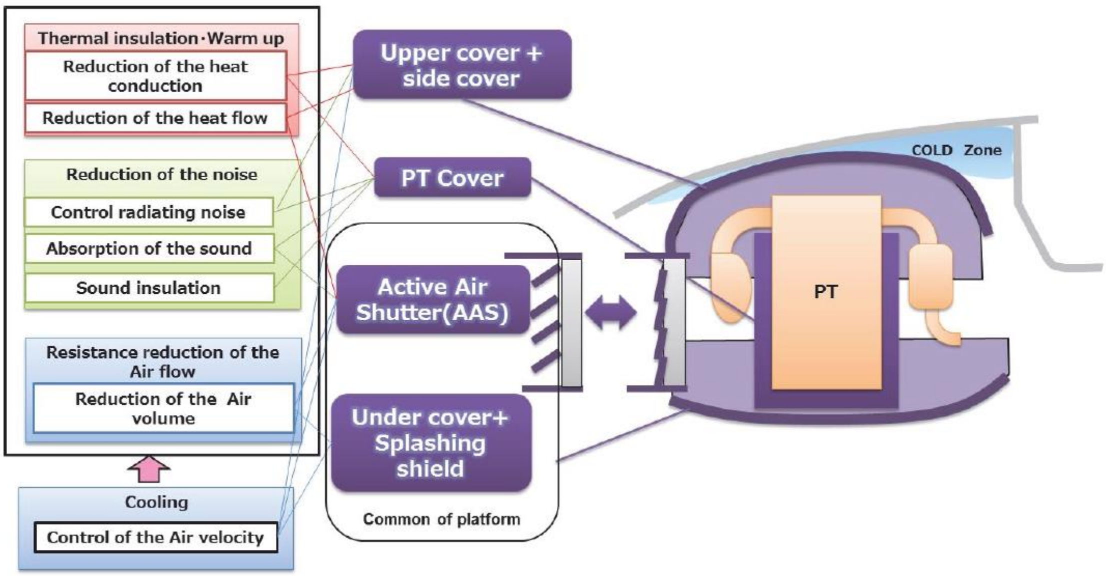

FIGURE 9: THERMAL ENCAPSULATION OF THE MAZDA SKYACTIV X ENGINE (FROM [3.1])

This short discussion of the Skyactiv X engine addresses the primary features which were incorporated for enabling SACI operation in the engine; following sections will revisit some of these in the more general discussion of SACI.

3.3 Engine Hardware Characteristics

SACI engines are broadly like SI engines; the combustion chamber geometry will be the same with a spark plug for ignition control. The compression ratio is generally higher, both for increased thermal efficiency and to allow for HCCI-like operation at the lowest loads. The engine control system will generally be more complicated; Mazda has noted the use of combustion pressure sensors in their production engine [3.1].

The engine will operate at both lean and stoichiometric conditions; the use of EGR under stoichiometric operation will expand the region of SACI operation. At the lowest loads the engine could run in a pure lean HCCI mode, and then as load increases the engine would transition to lean SACI, then stoichiometric dilute SACI, with conventional SI required at the highest loads. The dilution requirements will put additional demand on the boosting systems as compared to a conventional SI engine. Engine supercharging could be via a turbocharger or a supercharger. For a turbocharged engine, the compressor power demand will be relatively high compared to the turbine power since the intake flow will include air or EGR dilution while the exhaust temperature will be lower than for conventional SI engines. High power densities will then require multi-stage boosting solutions to accommodate this imbalance in compressor and turbine flows. Transient operation is also challenging with the required dilution levels; the selection of a supercharger in the Skyactiv X engine would enable much faster transient response than a turbocharger solution would.

Aftertreatment for SACI engines will be highly dependent on the details of the combustion mode selections and the regulatory scheme that the engine must satisfy. When the engine is operating in stoichiometric mode (EGR-diluted SACI or SI) a three-way catalyst will provide effective control of gaseous emissions. When the engine is operating in air diluted SACI mode, the three-way catalyst will not be effective for NO_X reduction. The amount of lean operation and the regulatory scheme will determine if additional aftertreatment is required. For the US, light duty automakers need most of their vehicle fleet to have tailpipe NO_X+NMOG emissions of 30 mg/mile or lower. At this level, it is likely that lean NO_X aftertreatment would be required for emissions compliance. The aftertreatment could be a lean NO_X trap ahead of the three-way catalyst or a SCR catalyst. For Euro 6 or similar schemes, the engine-out NO_X under lean operation may be acceptable; the Skyactiv X engine was certified for Euro 6 without lean NO_X aftertreatment [3.1].

3.4 Performance Characteristics

Generally, an HCCI engine is limited to a maximum of 3-4 bar BMEP [3.2] due to the high pressure rise rates when the homogeneous charge ignites. The goal of SACI is to consume part of the fuel in a flame propagation event, raising the temperature and pressure of the unburned mixture until it experiences homogeneous autoignition. Since only part of the charge burns homogeneously the load limit can be increased. Researchers have shown up to 7-8 bar net IMEP load limit with SACI [3.3].

HCCI requires high dilution levels to moderate the pressure rise from combustion; this dilution can be from EGR but is generally from lean operation. SACI can also be a lean combustion strategy; in this case there must be some mechanism for generating an ignitable mixture near the spark plug; this is generally produced by an injection event timed to enrich the mixture near the spark plug. A combined PFI/GDI injection system can be used to accomplish this, as shown in Figure 10 (taken from a study by Urushihara et al. [3.4]). The lean premixed charge is generated using the PFI injector, and the GDI injector is used to create a richer mixture around the spark plug to improve ignition and flame propagation.

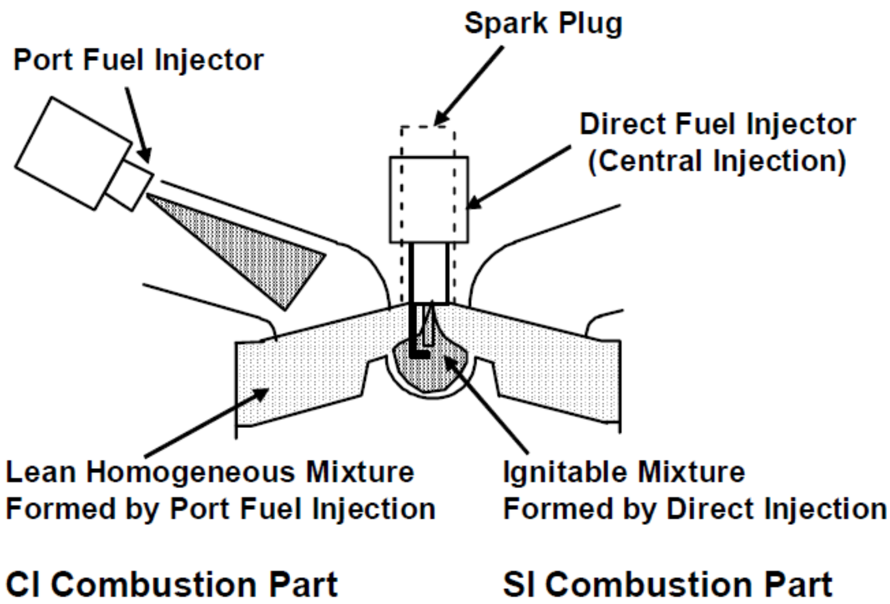

FIGURE 10: PFI + GDI SYSTEM TO ACHIEVE FUEL STRATIFICATION FOR SACI IGNITION ENHANCEMENT (FROM [3.4])

It is also possible to operate SACI combustion systems with stoichiometric mixtures, as was done by Szybist et al. in [3.3]. An engine map showing the full SI load range as well as the range over which SACI combustion was employed is shown in Figure 11. Note that the restriction to homogeneous operation restricted the low-load potential for SACI; typically, the lowest loads would be operated in a lean HCCI mode, with mid-load being SACI and high load being conventional SI. In this study the engine was operated in SI mode from up to the minimum load where SACI combustion could be used. Low load operation of SACI was noted to be limited by either misfire or unstable combustion (defined as a CoV of nIMEP>3%). The high load limit was based on an allowable pressure rise rate of 700 kPa/°CA. The authors noted that engine efficiency was improved most strongly at low loads (9% reduction in indicated specific fuel consumption at 1500 rpm, 4 bar nIMEP) while at higher loads the efficiency was similar or sometimes lower than for conventional SI operation. The efficiency gain was primarily linked to reduced pumping losses and faster combustion, provided better cycle efficiency.

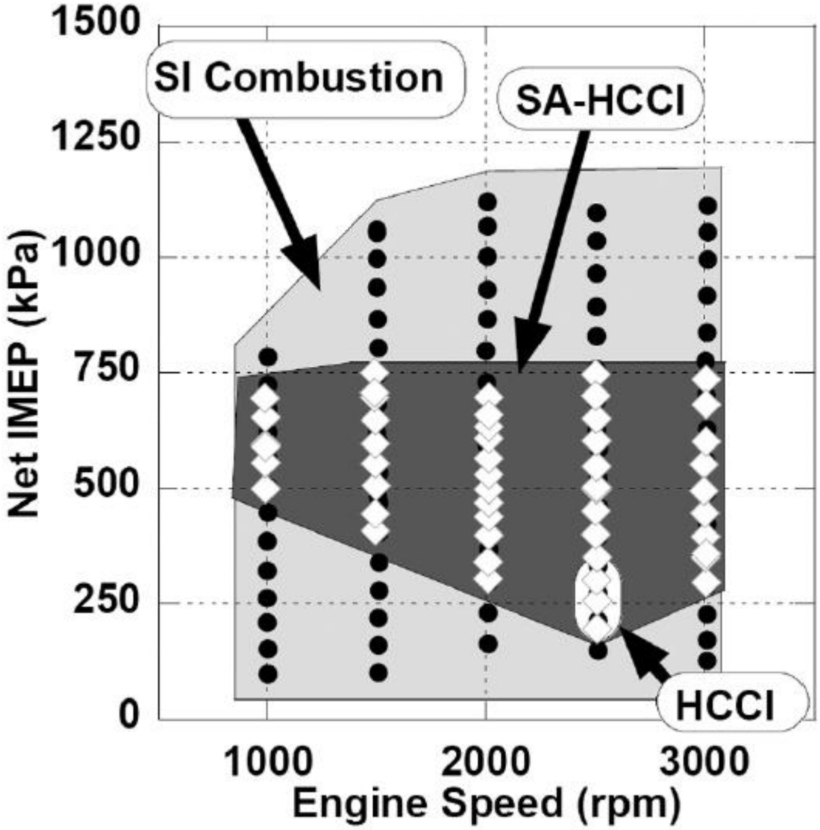

FIGURE 11: LOAD-SPEED MAP OF SI AND SACI COMBUSTION REGIMES FOR A STIOCHIOMETRIC ENGINE (FROM [3.3])

Many researchers have used the flexibility of modern valvetrains or of hydraulic valvetrains to benefit SACI operation through the application of negative valve overlap (NVO). NVO is a strategy where the exhaust valve is closed before the intake valve opens. This retains some burned gas mixture in the cylinder that would ordinarily be scavenged by the incoming fresh charge. For SACI engines this retained residual gas is beneficial since it is hot and can provide sufficient thermal energy for autoignition in HCCI and SACI combustion modes. Typical production SI engines cannot achieve significant NVO operation with a normal production cam profile, but modified cams can allow for both positive and negative valve overlap operation.

The operating map for the Skyactiv X engine shows how the full range of engine speeds and loads was accommodated (see Figure 12, from [3.1]). The spark is always used to give positive control over ignition timing. At the lowest loads, the engine is run lean and with both swirl and late injection to get a stratified mixture near the spark plug. As the engine load increases the engine moves to stoichiometric SACI operation with high EGR levels. At the highest speeds and loads the engine runs at stoichiometric SI conditions. Without independent benchmarking data it is not possible to quantify exactly what load and speed conditions correspond to these three operating modes, but the general approach is consistent with research studies on SACI operation. This map is qualitatively similar to that shown in Figure 11, indicating some broad commonality in how SACI must be implemented for effective engine operation.

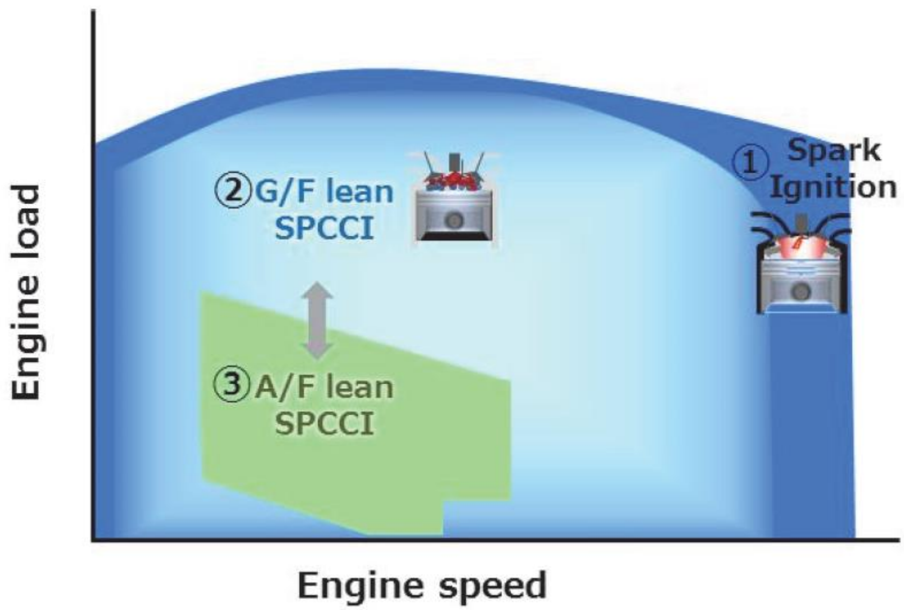

FIGURE 12: MAZDA SKYACTIV-X OPERATING MAP (FROM [3.1])

The promise of SACI operation is that it has generally been found to offer a 10% improvement in fuel conversion efficiency (for example, increasing efficiency from 37% to 40-41%) over SI operation [3.5]. This gain in efficiency is significant, particularly as the SACI operating range covers a large fraction of the engine map which is used in typical driving. Mazda, in [3.1], claimed a 10% improvement over their Skyactiv-G engine over the SACI range and up to a 20% improvement in the low load range where they can run at very lean conditions. This implies a peak brake thermal efficiency of around 40% for the Skyactiv-X engine, given the peak efficiency of 37% for the Skyactiv-G reported by the EPA [3.6]. For comparison, Toyota claims around 40% peak brake thermal efficiency for a conventional SI engine of similar power density to the Skyactiv X engine [3.7]; if a similar improvement from SACI could be achieved from an engine with this base efficiency the resulting engine would be competitive with diesel engines in terms of efficiency.

3.5 Key Technical Challenges

There are a range of technical challenges inherent in SACI operation; most of the literature describes the work done to address these challenges to create production potential for the technology. Many of the challenges that have been studied for SACI can be broadly classified under the areas of combustion control and emissions control.

A broad review of control issues was presented by Robertson and Prucka [3.5]. They noted that SACI has significant sensitivities to thermal boundary conditions due to the autoignition portion of the combustion process. Table 1 shows the sensitivities identified from the literature. This shows that even with the stabilizing influence of the spark there is still a significant combustion variation from temperature, humidity, and fuel quality. A production-level control system must detect and respond to these factors rapidly if the engine is to perform well enough to satisfy both regulations and customer expectations.

TABLE 1: SACI SENSITIVITY TO BOUNDARY CONDITIONS (ADAPTED FROM [3.5])

Parameter	Value
Intake Temperature Sensitivity	0.2° CA50 advance per +1 °C
Humidity Sensitivity	2° CA50 retard per +0.5%
Wall Temperature Sensitivity	0.1 – 0.4° CA50 retard per +1 °C
Ethanol Sensitivity	0.2° CA50 retard per +1% ethanol
AI/Spk Sensitivity	0.2-0.5, varies with dilution

The need for charge stratification to achieve good ignition quality has already been mentioned. The control to achieve this has generally been via a charge motion valve (to induce swirl as in Mazda's engine [3.1]) or via multiple injections (from a dedicated injector or a multi-event GDI injection). Persson et al. investigated the impact of swirl on SACI combustion [3.8]. They noted a significant increase in the SI portion of the combustion event with valve deactivation (to increase the turbulence in-cylinder) as seen in Figure 13.

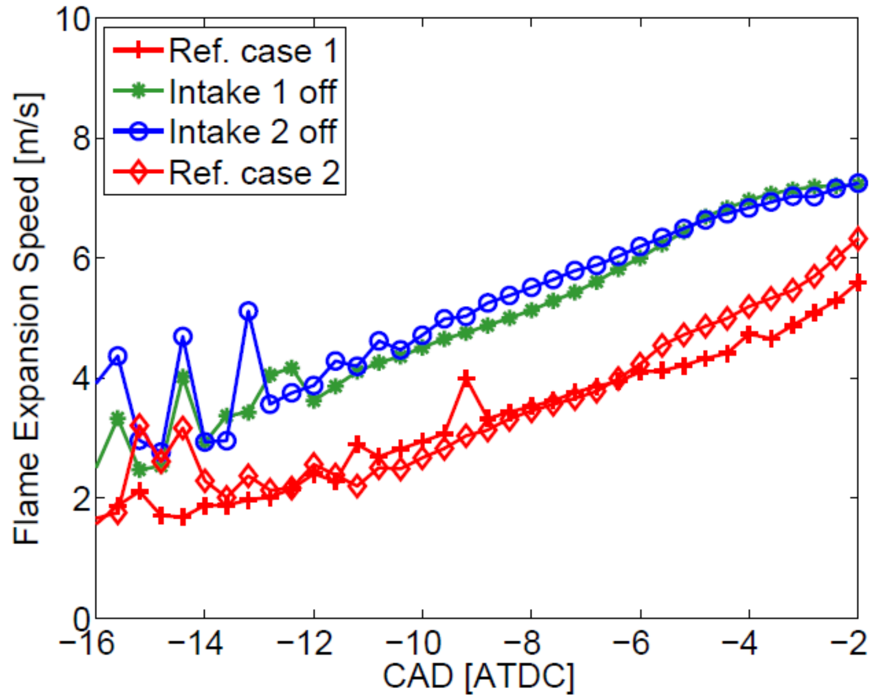

FIGURE 13: IMPACT OF VALVE DEACTIVATION ON FLAME SPEED [FROM [3.8])

The increase in flame speed with increasing turbulence is not a surprising finding. But the authors noted that the improved SI burn allowed for more control over the autoignition event as well. Figure 14 shows that the CA50 location when both intake valves were operating was relatively insensitive to the amount of negative valve overlap used. Once the turbulence level was increased with the deactivated intake valve, the NVO duration offered a strong control influence on the CA50 location.

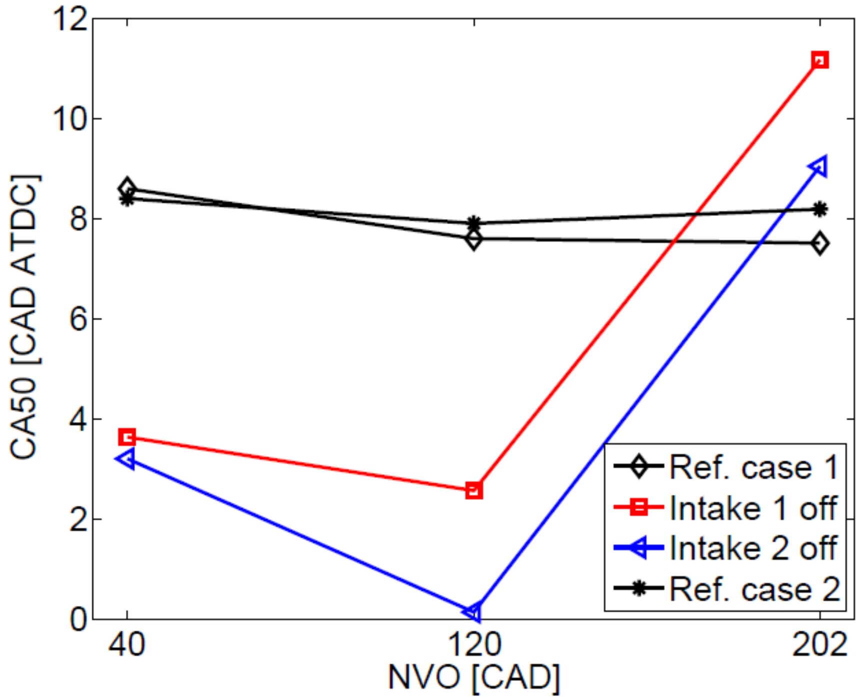

FIGURE 14: CA50 LOCATION AS A FUNCTION OF NEGATIVE VALVE OVERLAP DURATION WITH AND WITHOUT INTAKE VALVE DEACTIVATION (FROM [3.8])

Robertson and Prucka [3.5] summarize the work performed to address fuel stratification in the combustion chamber. There have been studies which show good performance with single injection strategies, while others use multiple injections to achieve greater homogeneity [3.1] and yet others use multiple injections to achieve a richer zone near the spark plug to take advantage of the flame speed peak at an equivalence ratio near 1.2. There does not appear to be a single best approach to the question of fuel homogeneity, but a holistic design approach will tend to favor one or the other approach when considered in conjunction with aftertreatment and other control actuators.

As SACI relies on high dilution, there is also a need to control dilution levels. If EGR is used, then the EGR rate must be controlled accurately. For steady-state operation this is relatively simple, but under transient conditions the in-cylinder EGR level can vary widely from the target setting. Robertson and Prucka [3.5] note that this has not been a strong area of SACI research, though there have been published studies on controlling EGR rates for SI engines that are likely to be relevant to SACI operation as well.

Combustion feedback control is a beneficial approach for SACI combustion; Mazda is using an in-cylinder combustion sensor on the Skyactiv X engine [3.1], and most laboratory research has relied on combustion sensing to both measure the engine performance and to guide the researchers in controlling the engine properly. Controlling the split between SI and homogeneous combustion, combustion phasing, and monitoring pressure rise rates would be challenging without a feedback sensor. Particularly when the sensitivity of SACI to small changes in temperature, fuel quality, and even humidity is considered, the application of combustion feedback control appears near essential.

The other major area of challenge for SACI is emissions control. Mazda's Skyactiv-X engine uses a three-way catalyst and GPF [3.1]. This is sufficient to satisfy Euro 6 emission standards for Europe and Japan but is expected to be insufficient to satisfy EPA Tier 3 emissions, particularly the SULEV20 or SULEV30 emissions bin limits (20 or 30 mg/mile NMOG+NO_X emissions, respectively).

If lean operation is to be used at low loads, then a lean NO_X aftertreatment system is likely to be required to satisfy current Tier 3 US emission standards and probably future European standards as well. Options include adding a lean NO_X trap (LNT) upstream of the three-way catalyst (TWC), zone-coating a single catalyst to include LNT and TWC functionality, or to use a SCR catalyst for NO_X reduction downstream of the TWC.

Easter and Bohac [3.9] investigated the potential of passive ammonia generation in a TWC by modulating the combustion stoichiometry of a SACI engine. The ammonia was then used in a downstream SCR to reduce the NO_X emissions from the engine. The general approach is shown in Figure 15.

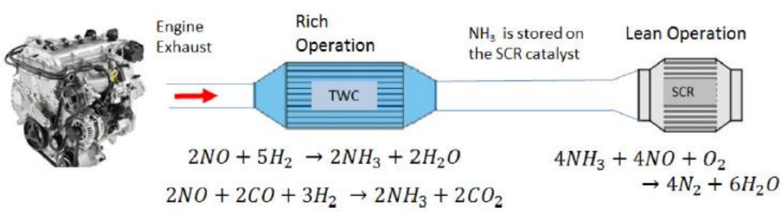

FIGURE 15: ENGINE / AFTERTREATMENT LAYOUT FOR A TWC-SCR SYSTEM ON A SACI ENGINE (FROM [3.9])

The authors found that while it was possible to generate NH_3 under SACI operation, the rate of generation was much lower than that seen for SI operation and the time to see NH_3 upstream of the SCR was much longer for SACI operation than SI. Figure 16 shows the comparison of SI and SACI operation. Note that the SI condition could run at a higher equivalence ratio and that NH_3 was found upstream of the SCR in roughly one third the time required for the SACI condition.

Ultimately the authors did not discount the potential for TWC-SCR aftertreatment with passive ammonia generation, but they did note that significant research and development would be required to yield a robust system.

The use of an LNT for SACI NO_X control has been broadly discussed in the context of emissions control, but there have not been any significant studies to apply the technology to an engine. LNT catalysts have challenges with deactivation at high temperatures, and since a SACI engine will revert to SI combustion at high loads the catalyst can be expected to see very high temperatures under wide open throttle conditions.

It is to be expected that solutions for emissions compliance of a SACI engine can be found; significant R&D effort will be required to adapt existing technologies to the engine, but there are technical solutions. Minimizing cost will likely be the larger challenge, as lean NO_X aftertreatment for diesel engines is complex and expensive.

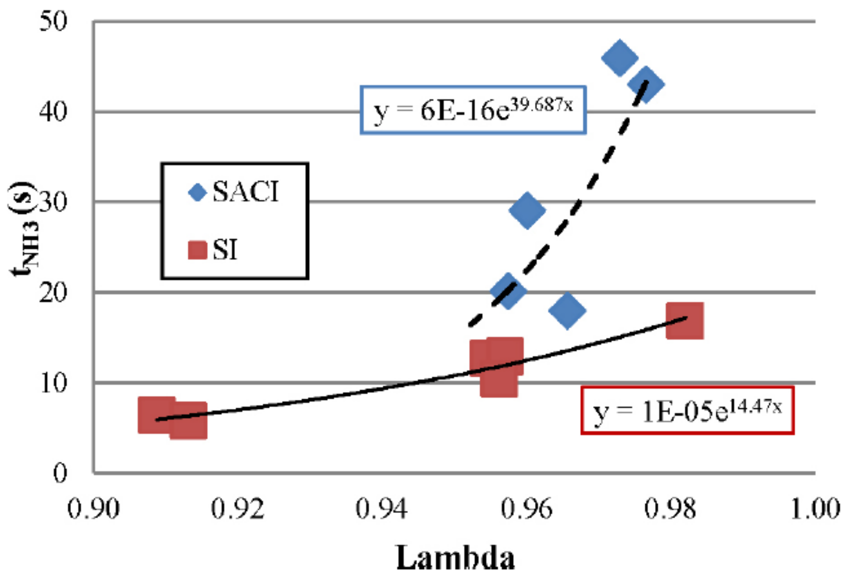

FIGURE 16: TIME TO SEE NH_3 UPSTREAM OF THE SCR AFTER STARTING A RICH TRANSIENT (FROM [3.9])

The challenges for SACI are graphically depicted relative to the other combustion systems of interest in this report as shown in Figure 17. Relative to conventional SI and CI there are significant gaps for SACI, but relative to other advanced combustion systems SACI is much less challenged (as would be expected for a system which has been brought to production).

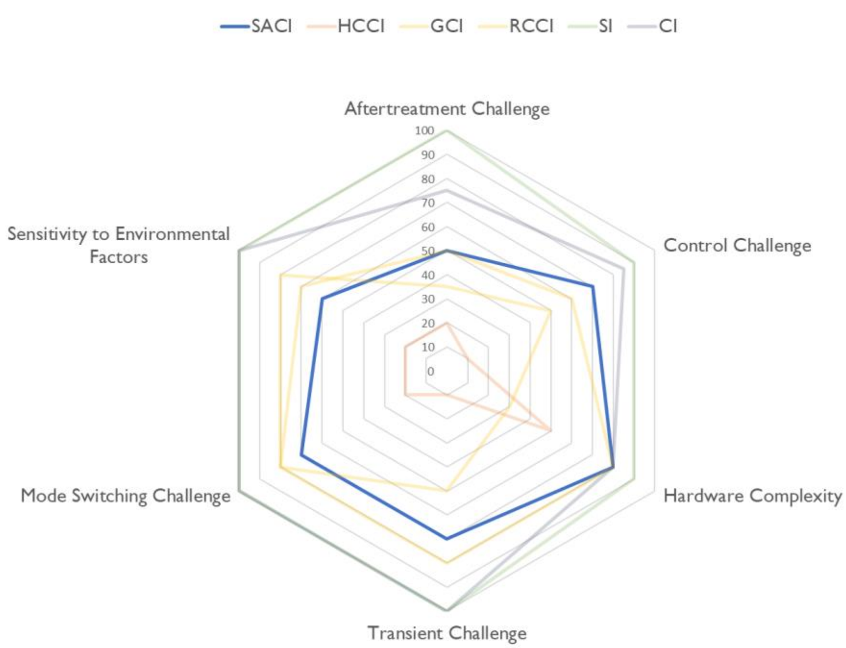

FIGURE 17: MAPPING OF ADVANCED COMBUSTION CHALLENGES

3.6 Fuel Property Impacts

SACI has generally been evaluated with gasoline-type fuels since it is targeted as an improvement on the SI engine as such the fuel property studies have generally considered fuel variations that are consistent with market fuels for SI engines.

Weall and Szybist [3.10] investigated SACI combustion with gasoline, a 50/50 blend of iso-butanol and gasoline, and E85. The study showed significant fuel sensitivity; Figure 18 shows the CA50 location as a function of spark timing for the three fuels. To achieve the same CA50, E85 required a significantly earlier spark timing than the gasoline and iso-butanol/gasoline blend (which would be expected from the difference in flame speed for the two fuels). This earlier spark timing also increased the fraction of the fuel burned in flame propagation. The authors did note that they were able to achieve SACI operation with all three fuels despite the wide difference in RON between them. The maximum loads achieved with the three fuels were similar, but the test methodology did not focus on increasing the load range by fuel property variation. Robertson and Prucka [3.5] used the results from this study to estimate that spark timing must be advanced by 0.2 °CA for each percentage point increase in ethanol content for a fuel.

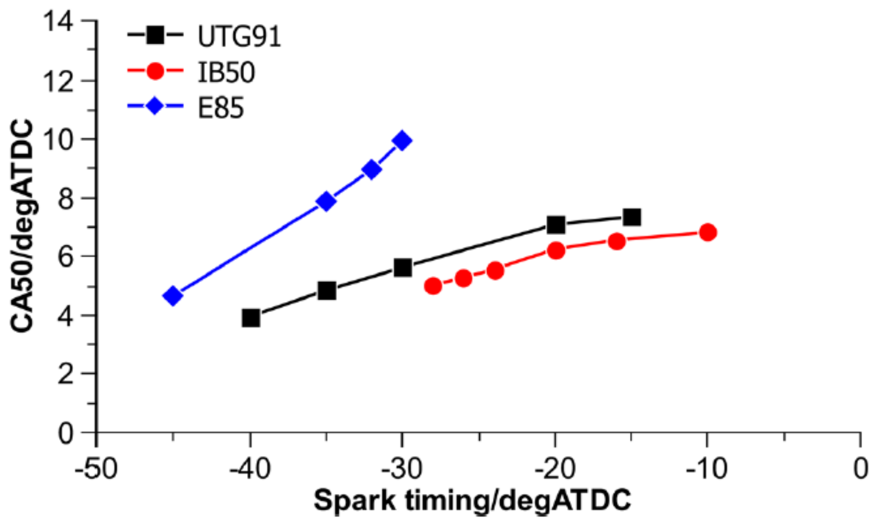

FIGURE 18: CA50 LOCATION VS. SPARK TIMING FOR VARIOUS FUELS UNDER SACI OPERATION (FROM [3.10])

3.7 Production Challenges

The primary production challenge for SACI is emissions compliance. While there are many open questions about SACI in the broad research sense, Mazda's commercialization of SACI show that they are addressable for compliance under some emissions regimes, though with some significant hardware additions (in-cylinder pressure transducers and a 700 bar injection system are two notable items) to the engine as described by Mazda in [3.1].

While Euro 6 emissions have been addressed, satisfying the expected lower NO_X limits for post-Euro 6 regulations and for US Tier 3 regulations present a significant challenge. Achieving these low tailpipe NO_X emissions will require lean NO_X aftertreatment to address, but also stoichiometric aftertreatment for higher-load stoichiometric SACI and conventional SI. This demands an expensive and complicated aftertreatment system. Ongoing developments have the potential to simplify this challenge, but it remains the primary barrier to the introduction of SACI into the US market and to the ongoing sales of SACI vehicles in future global markets.

3.8 SACI Summary

The overall state of development of SACI is detailed in Table 2. This summarizes the key development details which have been presented in the preceding sections.

TABLE 2: CURRENT DEVELOPMENT STATUS OF SACI

Demonstrated Fuels	Gasoline, iso-butanol, E85
Key Fuel Properties	Gasoline octane rating and properties for high load SI operation
Operating Window (Demonstrated)	Per Mazda, up to 10-12 bar with mode switching for full map performance. Other studies 8 bar
Key Challenges	Combustion timing control, boost system for high dilution, aftertreatment for US Tier 3
Required Enablers	Lean aftertreatment, combustion feedback control
Development Stage	Production
TRL	9 (In Production)

3.9 Cited References

[3.1] Nakai, E., Goto, T., Ezumi, K., Tsumura, Y., Endou, K., Kanda, Y., Urushihara, T., Sueoka, M., and Hitomi, M.; "Mazda Skyactiv-X 2.0 L Gasoline Engine"; Presented at the 28th Aachen Colloquium on Automobile and Engine Technology; 2019

[3.2] Cairns, A. and Blaxill, H.; "The Effects of Combined Internal and External Exhaust Gas Recirculation on Gasoline Controlled Auto-Ignition"; SAE Technical Paper 2005-01-0133; 2005

[3.3] Szybist, J., Nafziger, E., and Weall, A.; "Load Expansion of Stoichiometric HCCI Using Spark Assist and Hydraulic Valve Actuation"; *SAE Int. J. Engines* **3**(2):244-255; 2010

[3.4] Urushihara, T., Yamaguchi, K., Yoshizawa, K., and Itoh, T.; "A Study of a Gasoline-fueled Compression Ignition Engine – Expansion of HCCI Operation Range Using SI Combustion at a Trigger of Compression Ignition"; SAE Technical Paper 2005-01-0180; 2005

[3.5] Robertson, D. and Prucka, R.; "A Review of Spark-Assisted Compression Ignition (SACI) Research in the Context of Realizing Production Control Strategies"; SAE Paper 2019-24-0027; 2019

[3.6] Ellies, B., Schenk, C., and Dekraker, P.; "Benchmarking and Hardware-in-the-Loop Operation of a 2014 Mazda Skyactiv 2.0 L 13:1 Compression Ratio Engine"; SAE Paper 2014-01-1007; 2014

[3.7] Hakariya, M., Toda, T., and Sakai, M.; "The New Toyota Inline 4-Cylinder 2.5L Gasoline Engine"; SAE Technical Paper 2017-01-1021; 2017

[3.8] Persson, H., Johannson, B., and Remon, A.; "The Effect of Swirl on Spark Assisted Compression Ignition (SACI)"; SAE Technical Paper 2007-01-1856; 2007

[3.9] Easter, J. and Bohac, S.; "NH3 Generation and Subsequent Storage across a TWC-SCR System"; SAE Technical Paper 2016-01-0951; 2016

[3.10] Weall, A. and Szybist, J.; "The Effects of Fuel Characteristics on Stoichiometric Spark-Assisted HCCI"; *Journal of Engineering for Gas Turbines and Power;* 134(7):72805; 2012

3.10 Other Relevant References

[3.11] Benajes, J., Garcia, A., Domenech, V., Durrett, R.; "An Investigation of Partially Premixed Compression Ignition Combustion Using Gasoline and Spark Assistance"; *Applied Thermal Engineering*; 52(2) 468-477; 2013

[3.12] Temel, V. and Sterniak; J.; "Characterization of SACI Combustion for Use in Model Based Controls"; SAE Technical Paper 2014-01-1289; 2014

[3.13] Larimore, J., Hellstrom, E., Sterniak, J., Jiang, L. and Stefanopolou, A.; "Experiments and Analysis of High Cyclic Variability at the Operational Limits of Spark-Assisted HCCI Combustion"; Presented at the 2012 American Control Conference, Montreal, Canada; 2012

[3.14] Laovie, G., Martz, J., Wooldridge, M., and Assanis, D.; "A Multi-Mode Combustion Diagram for Spark Assisted Compression Ignition"; *Combustion and Flame*; 157(6) 1106-1110; 2010

[3.15] Li, L., Xie, H., Chen, T., Yu, W., and Zhao, H.; "Experimental Study on Spark Assisted Compression Ignition (SACI) Combustion with Positive Valve Overlap in an HCCI Engine"; SAE Technical Paper 2012-01-1126; 2012

[3.16] Manofsky, L., Vavra, J., Assanis, D., and Babajimopolous, A.; "Bridging the Gap Between HCCI and SI: Spark-Assisted Compression Ignition"; SAE Technical Paper 2011-01-1179; 2011

[3.17] Natarajan, V., Sick, V., Reuss, D., and Silvas, G.; "Effect of Spark-Ignition on Combustion Periods During Spark-Assisted Compression Ignition"; *Combustion Science and Technology*; 181(9) 1187-1206; 2009

[3.18] Mendrea, B., Chang, Y., Abidin Akkus, Y., Sterniak, J., and Bohac, S.; "Investigations of the Effect of Ambient Conditions on SACI Combustion Range"; SAE Technical Paper 2015-01-0828; 2015

[3.19] Olesky, L., Martz, J., Lavoie, G., Vavra, J., Assanis, D., Babajimopoulos, A.; "The Effects of Spark Timing, Unburned Gas Temperature, and Negative Valve Overlap on the Rates of Stoichiometric Spark Assisted Compression Ignition Combustion"; *Applied Energy*; Vol. 105, Pages 407-417; 2013

[3.20] Persson, H., Hultqvist, A., Johansson, B., and Remon, A.; "Investigation of the Early Flame Development in Spark Assisted HCCI Combustion Using High-Speed Chemiluminescence Imaging"; SAE Technical Paper 2007-01-0212; 2007

[3.21] Persson, H., Sjoholm, J., Kristensson, E., Johansson, B., Richter, M., and Alden, M.; "Study of Fuel Stratification on Spark Assisted Compression Ignition (SACI) Combustion with Ethanol using High Speed Fuel PLIF"; SAE Technical Paper 2008-01-2401; 2008

[3.22] Polovina, D., McKenna, D., Wheeler, J., Sterniak, J., Miersch-Wiemers, O., Mond, A., and Yilmaz, H.; "Steady-State Combustion Development of a Downsized Multi-Cylinder Engine with Range Extended HCCI/SACI Capability"; SAE Technical Paper 2013-01-1655; 2013

[3.23] Takazawa, M., Komura, K., and Kitamura, T.; "Transient Control Technology of Spark Assisted HCCI"; SAE Technical Paper 2015-01-0880; 2015

[3.24] Wang, Z., Wang, J., Shuai, S., He, X., Xu, F., Yang, D. and Ma, X.; "Research on Spark Induced Compression Ignition (SICI)"; SAE Technical Paper 2009-01-0132; 2009

4.0 GASOLINE COMPRESSION IGNITION

4.1 Summary of Concept

Gasoline Compression Ignition (GCI) is a combustion system that leverages the volatility and lower reactivity of gasoline to create an in-cylinder mixture that can autoignite in a controllable manner and then burn the fuel within a lower temperature and at a lower equivalence ratio than diesel combustion can achieve. Referring to Figure 1, the zone denoted PCCI is also representative of the combustion zone for GCI.

The desired mixture and combustion is generated by fuel injection during the compression stroke with the aim to achieve a mixture with an equivalence ratio below 2.0 and with stratification of the fuel-air distribution. Given proper control of injection and charge temperature, ignition will be seen near top dead center (TDC) and combustion will occur primarily as an autoignition event. This leads to very short combustion durations (under 20 °CA). The early injections and mixing lead to local equivalence ratios lean enough to prevent soot formation and the use of dilution (both air and EGR) keeps the local temperatures low enough to greatly minimize NO_X formation. This provides for high indicated thermal efficiencies with low engine-out NO_X and soot emissions.

GDI engines have been investigated for both light- and heavy-duty applications and have shown promising results in both situations. For a light-duty application the GCI engine will bring similar hardware requirements and system complexity as a CI engine. While some markets continue to have significant light duty CI engine sales, the challenges of emissions compliance and the increasing need to hybridize the powertrain to satisfy GHG emissions rules has reduced the market penetration of CI engines. This may limit the opportunity for light duty GCI engines despite the significant efficiency improvement relative to SI engines in that application. For heavy-duty applications, a GCI engine will have similar hardware requirements and system complexity to a CI engine, which is already accepted and dominant in the market. As such, the author would argue that there is more opportunity for GCI to penetrate the medium- and heavy-duty markets.

4.2 Engine Hardware Characteristics

A GCI engine is an interesting hybrid of SI and CI engine design details. Figure 19 shows a cutaway of a GCI engine developed by Delphi under a Department of Energy Program [4.1]. The common features with a diesel engine can be seen; a central DI injector sprays the fuel in spread plumes, and the piston crown shape conforms to the plumes to minimize piston-spray contact near TDC. The blue device seen is not for ignition but is a pressure sensor for feedback. The compression ratio is significantly higher than that used for SI engines, generally around 15:1. The injector in the Delphi work is a GDI injector with maximum injection pressures of around 350 bar. The high volatility of gasoline combined with the strategy to inject on the compression stroke reduces the injection pressures required compared to a diesel-fueled CI engine. Not all GCI engines use these lower injection pressures though; more recent development of a multi-mode SACI/GCI engine by Hyundai uses an injector capable of 1000 bar injection pressure [4.2].

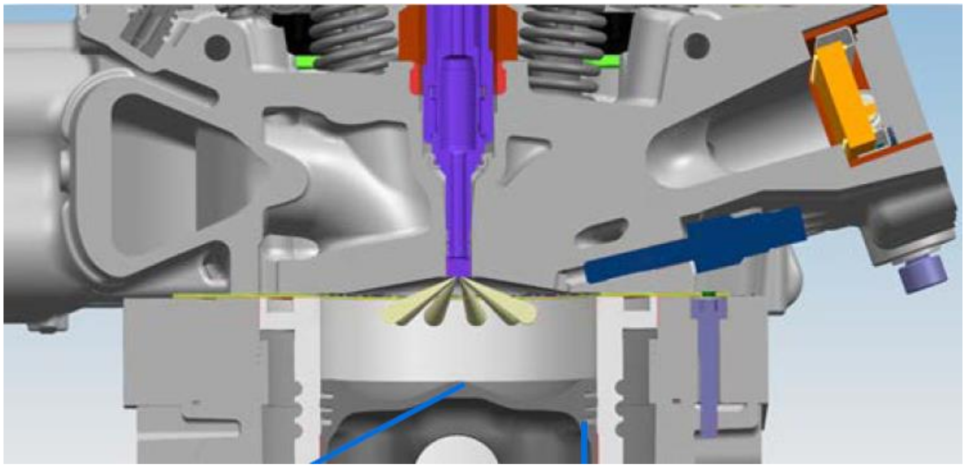

FIGURE 19: CUTAWAY OF THE DELPHI GCI ENGINE (FROM [4.1])

The rest of the engine systems are relatively conventional. Boost can be supplied by one or more turbochargers and superchargers. Because GCI combustion yields relatively cool exhaust, the enthalpy flow is much lower than that for SI or CI engines. This can make boosting a challenge since the available energy to drive the exhaust turbine is low, while the need for both excess air and EGR increases the power demand by the compressor wheel. Confer and Kirwan [4.1] were able to identify a variable nozzle turbocharger (VNT) that satisfied the boost requirements for a multi-cylinder engine, while earlier work at Delphi by Sellnau used both a fixed geometry turbocharger and an engine-driven supercharger to meet boost requirements [4.3]. Ideally a single-device boost system can be identified to minimize the cost and complexity of the air handling system.

A GDI engine generally does require valve event flexibility; negative valve overlap (NVO) or exhaust rebreathing (see [4.2]) can be used to increase the temperature of the charge at low loads to improve autoignition. A relatively common variable lift and timing cam system can accommodate the flexibility, allowing use of common engine components. Another option that has been used for low load combustion enhancement is an intake heater (see [4.1]); particularly for production-intent designs that need to deal with cold starting and the full range of environmental conditions, an intake heater may be required. These heaters are not generally used often, but primarily for cold starting. The power demand is not expected to be very high either, so while they do bring additional hardware complexity the impact on other powertrain systems will be minor.

Engine structure for a GDI engine will be more aligned with diesel engine design practice; cylinder pressures will be higher for GDI than for SI, so requirements for 150 to 200 bar peak cylinder pressure can be expected. The piston will also need to be more durable than common SI engine practice; this will cause a conflict between the friction characteristics of the piston and the strength of the piston, as continues to exist in diesel engine design. Since GCI combustion is more sensitive to thermal boundary conditions than conventional CI combustion, the piston cooling design will require evaluation and development, and possibly the ability to disable piston cooling for increased cylinder temperatures under some conditions.

EGR is required both for dilution of the fuel/air mixture and to give more control over the intake charge temperature. EGR also helps to provide combustion phasing control via the impact on in-cylinder temperature and chemical reactivity. Various EGR layouts have been shown in the literature, with high pressure [4.12], low pressure [4.3, 4.5], and both high- and low-pressure EGR systems shown [4.11].

Aftertreatment will be similar to a diesel engine, with an oxidation catalyst, particulate filter, and SCR for NO_X reduction. While the engine-out emissions can be low when compared to SI or CI combustion, they are still far higher than allowable for modern emissions requirements. Combustion calibration for thermal management will also be key; some studies have shown catalyst inlet temperatures below 200 °C which is too low for effective aftertreatment. The low exhaust temperatures sometimes seen with GCI may require additional aftertreatment complexity to ensure compliance with regulatory standards.

Finally, combustion pressure sensing has been a common feature of GCI engines to date, both for laboratory data collection and analysis and for the control scheme. Since ignition is largely dependent on kinetic autoignition, a fast feedback loop is needed so that the controller can adjust injection timing, EGR rates, and other control inputs to maintain combustion phasing at the desired location.

4.3 Performance Characteristics

The primary promise of GCI combustion is combined high efficiency and low engine-out emissions. More recent work by Delphi on a light-duty GCI engine has shown peak brake thermal efficiencies of 43% in the laboratory and simulations indicating a path to 48% peak brake thermal efficiency [4.4]. The GCI combustion approach is also adaptable to heavy duty engines, with studies showing brake thermal efficiencies similar to current CI engines [4.5]. Simultaneously with these positive efficiency results, engine-out emissions of particulates and NO_X can be reduced significantly. Satisfying current and proposed future emission regulations will still require aftertreatment, but the lower engine-out numbers may allow for a simplification of the aftertreatment system relative to that required for CI combustion.

One benefit of GCI is that it has proven to be capable of full engine map operation. Delphi's third-generation GCI engine has been demonstrated to full load (21 bar IMEP) [4.4]. The brake specific fuel consumption map for the engine is shown in Figure 20. Achieving stable operation at low loads does require intake air heating, NVO operation, or other methods for increasing the charge temperature to stabilize combustion. Delphi has also shown the ability to operate the GCI engine over transient drive cycles in [4.1].

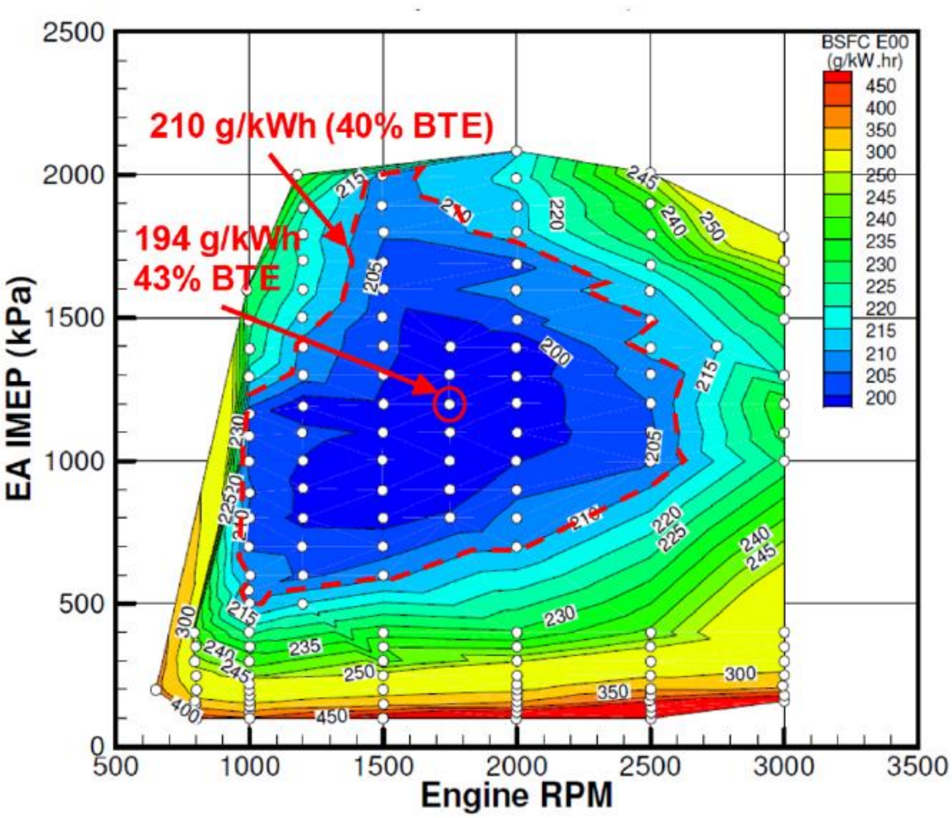

FIGURE 20: BSFC MAP FOR THE DELPHI THIRD-GENERATION GCI ENGINE (FROM [4.4])

For heavy-duty engines, the high BMEP capability of GCI makes it an attractive alternative to diesel fuel CI operation. Kavuri et al. compared RCCI and GCI operation at 1300 rpm, 20 bar BMEP in a 2.44 L single cylinder heavy duty engine [4.6]. Both advanced combustion modes yielded similar gross indicated thermal efficiencies of around 46%. While not best-in-class for a heavy-duty diesel engine, these efficiencies are competitive and with development would be expected to offer similar engine efficiency at high load, with generally better than diesel efficiency at lower loads. Combining this efficiency potential with the reduced engine-out emissions that GCI yields may allow for overall powertrain improvements beyond the engine alone.

Engine-out emissions from GCI engines have been measured at widely varying levels. Wang et al. [4.5] investigated the operation of a heavy-duty engine with “high temperature GCI” to maintain higher exhaust temperatures to enable conventional aftertreatment. They achieved the higher temperatures by reducing the EGR levels in the engine. Figure 21 shows the engine-out emissions measured; note the high NO_X emissions recorded. A typical modern diesel engine calibrated for the US market has engine-out NO_X emissions of 3-4 g/kWh [4.13]; these GCI results are significantly higher and would be challenging to robustly comply with stringent tailpipe emission standards.

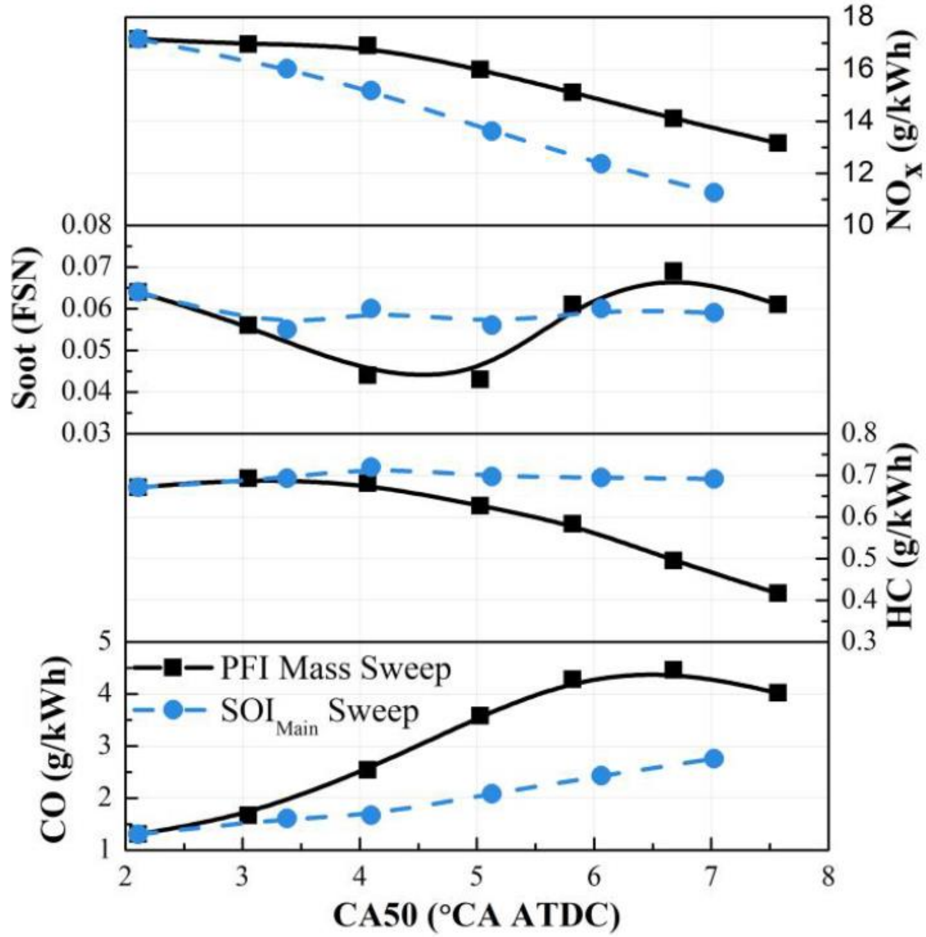

FIGURE 21: ENGINE-OUT EMISSIONS FOR A HEAVY-DUTY ENGINE WITH HIGH TEMPERATURE GCI COMBUSTION (FROM [4.5])

Another study of GCI using moderate EGR levels showed lower NO_X emissions, but still on par with typical diesel emissions [4.7]. In this work the EGR levels varied from 0 to 25% and three gasoline-like fuels were considered. The engine-out NO_X emissions ranged from 4 to 1.5 g/kWh with increasing EGR fraction, as shown in Figure 22.

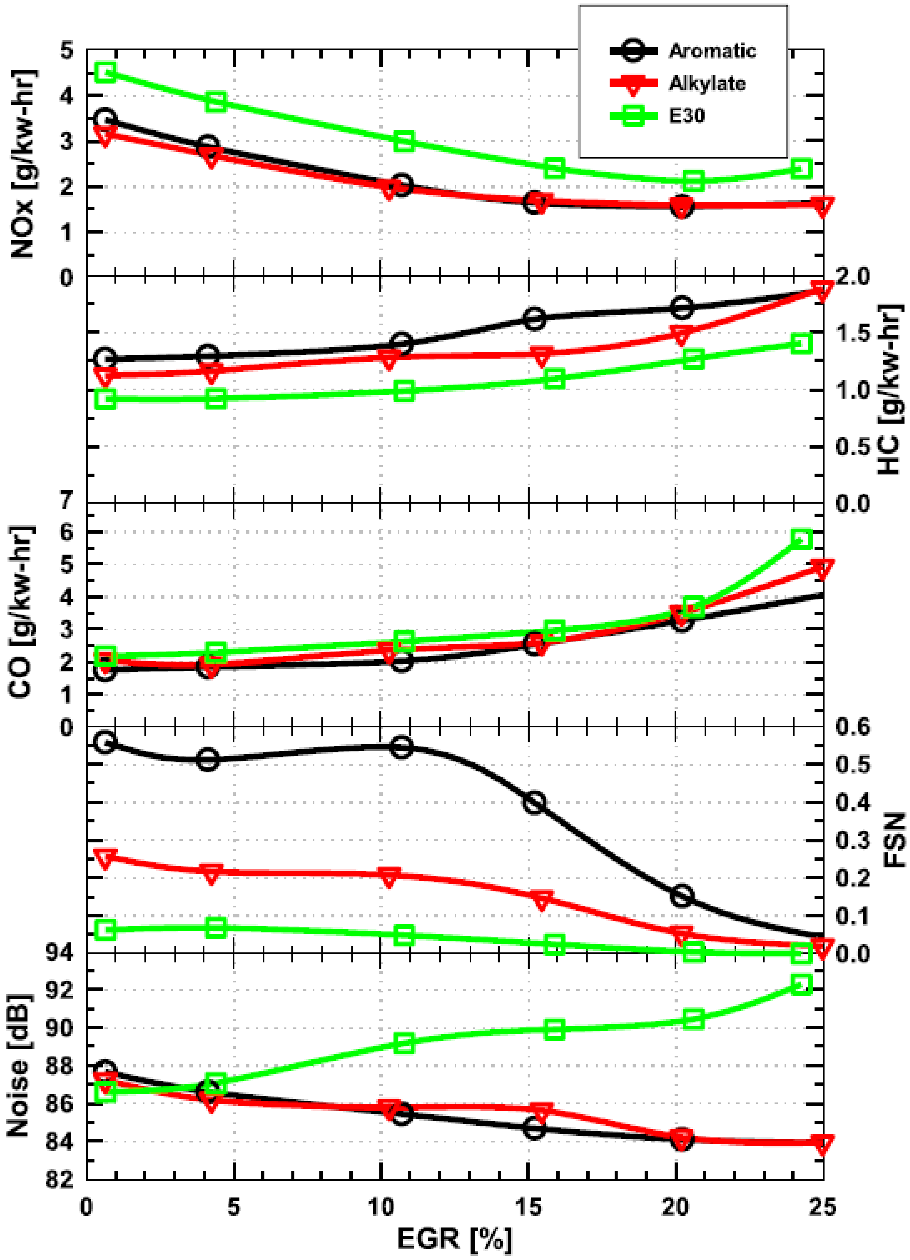

FIGURE 22: ENGINE-OUT EMISSIONS FOR A 1.9 L ENGINE OPERATING WITH GCI (FROM [4.7])

Sellnau et al. [4.4] show more promising NO_X emission results as seen in Figure 23. The emissions level for normal oxygen concentrations is a similar magnitude to that seen in the above studies, but as the oxygen concentration is reduced via EGR, the NO_X emissions show the strong reduction that is a feature of low temperature combustion.

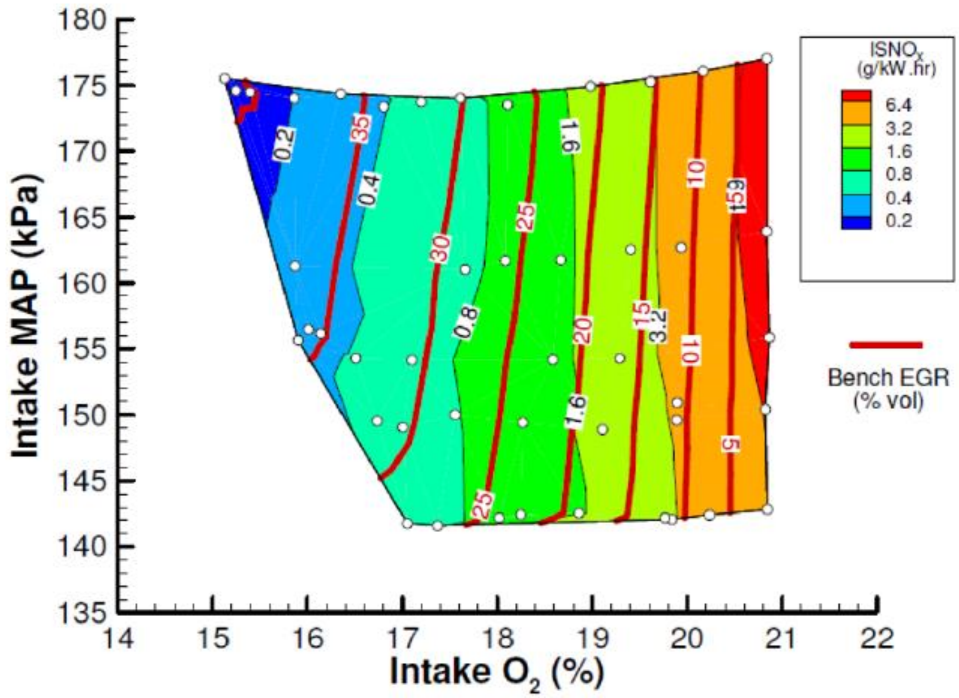

FIGURE 23: INDICATED SPECIFIC NOX EMISSIONS AS A FUNCTION OF INTAKE PRESSURE AND INTAKE OXYGEN CONCENTRATION (FROM [4.4])

Further development of the Delphi combustion system was reported by Kolodziej et al. [4.15]. Indicated specific emissions for criteria pollutants were evaluated at multiple engine speeds and with four fuels having RON values ranging from 60 to 91. The authors specified an engine-out NO_X target of 0.2 g/kWh (selected to meet Tier 2 Bin 5 emissions without aftertreatment). Examining Figure 24, note that for most of the speed-load range evaluated the engine was able to generate NO_X emissions below that target, particularly with the 60 RON fuel. Figure 25 also shows that except for the 800 rpm speed, the exhaust temperature was high enough for good catalyst function. These results are promising in showing the ability of GCI combustion to simultaneously offer an improvement in engine efficiency relative to conventional CI combustion while also reducing engine-out emissions.

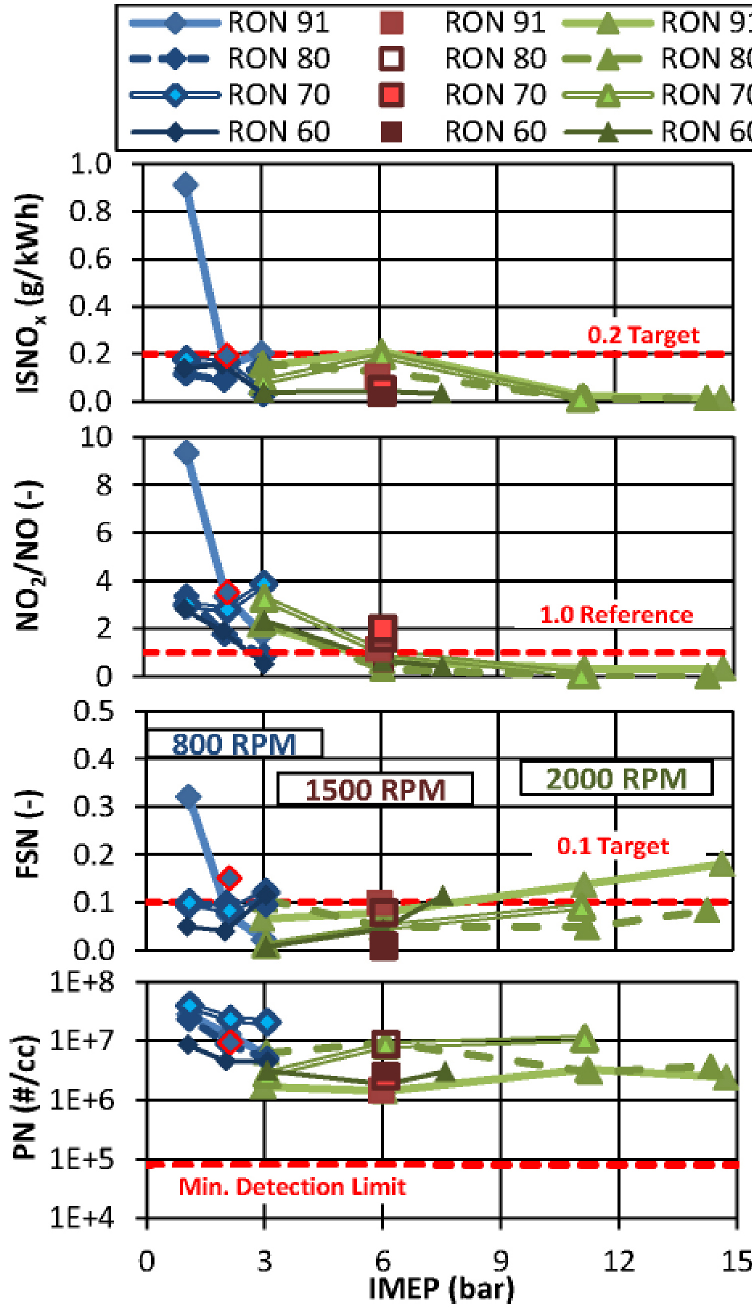

FIGURE 24: NOX AND PARTICULATE EMISSIONS FOR A LIGHT DUTY GCI ENGINE (FROM [4.15])

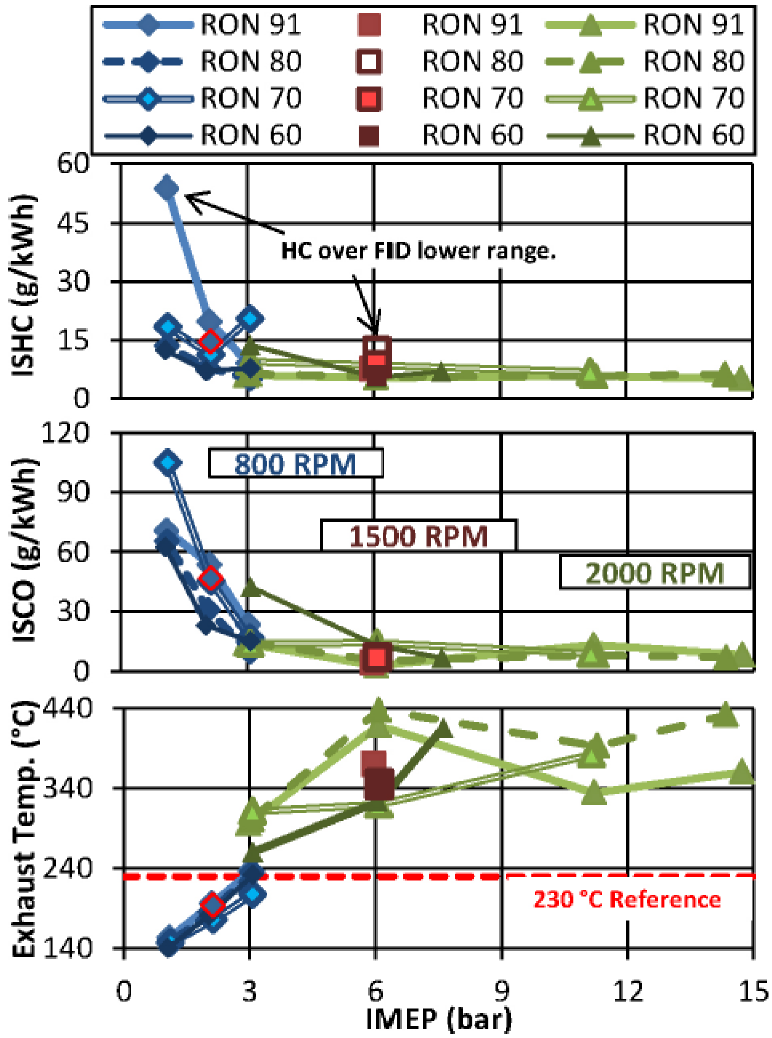

FIGURE 25: HC AND CO EMISSSIONS, AND EXHAUST TEMPERATURE FOR A LIGHT DUTY GCI ENGINE (FROM [4.15])

4.4 Key Technical Challenges

Solanki et al. have delineated the major challenges of GCI combustion in as shown in Figure 26 [4.8]. Some of the challenges are general engine development challenges (hardware optimization) while others are more unique to GCI combustion (cold starting, high CO and HC emissions, …). One challenge which is not addressed in this figure is the general challenge of GCI aftertreatment with the relatively low exhaust temperatures seen with GCI combustion. Particularly at cold start where it is critical to bring the catalysts to their light-off temperature quickly, GCI presents a major challenge.

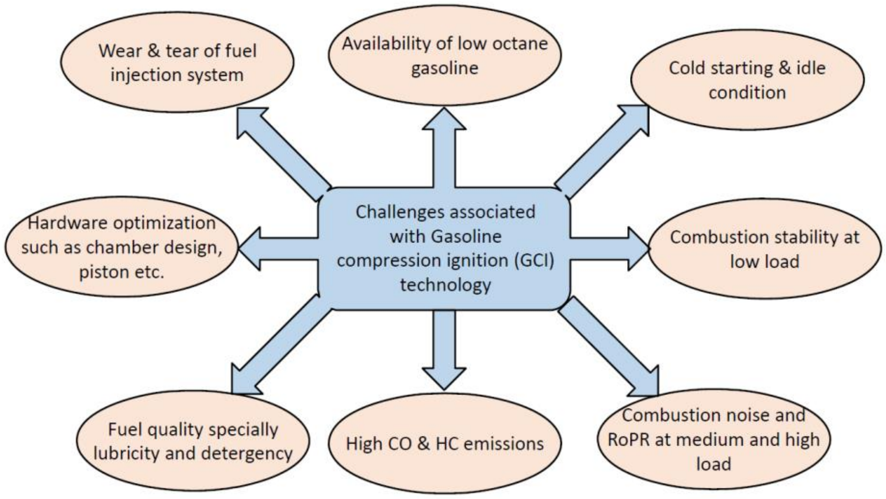

FIGURE 26: CHALLENGES FOR GCI ENGINE TECHNOLOGY (FROM [4.8])

The aftertreatment challenge has been addressed in multiple ways. Delphi used a conventional aftertreatment system layout in [4.4], but with the addition of an oxidation catalyst in the exhaust ports pre-turbo. Development in that program has shown that trading off oxygen dilution and EGR dilution allows for balancing engine-out NO_X emissions and increasing aftertreatment bed temperature to ensure high conversion efficiency. In parallel, there are efforts within the research community to develop catalysts with improved low temperature activity. Work at Oak Ridge National Laboratory is showing the potential for moving light off temperatures down to 150 °C [4.9].

It must also be noted that many GCI studies, such as [4.15] show low engine-out emissions with respect to older emission standards. In the case of the subject study, the emissions target for NO_X was set at 0.2 g/kWh, which was estimated to allow the engine to satisfy EPA Tier 2 Bin 5 emissions (0.5 g/mile NO_X emissions) without aftertreatment. However, at the time of report preparation the EPA emissions standards require light-duty automakers to meet SULEV30 emissions by 2025 (30 mg/mile NO_X+NMOG emissions). And in the heavy-duty space, CARB has proposed regulations requiring 0.05 g/hp-hr NO_X emissions in the near future with a path towards 0.02 g/hp-hr. Both light- and heavy-duty regulations now include strong audit requirements, and there is minimal leeway for out-of-compliance emissions during engine operation, even under extended idle periods and other operation where the engine exhaust temperature will be low. These stronger regulations eliminate the potential for any combustion system to certify without aftertreatment. GCI could still potentially reduce the cost of aftertreatment with the lower NO_X emissions, but there has not been any research to date to confirm this potential.

Control of GCI engines has been proven to be feasible based on the work at Delphi [4.4] and Hyundai [4.2]. In both cases there is feedback control on combustion so that combustion phasing control can be maintained. Zoldak [4.2] discusses the planned development of a controller with prediction of in-cylinder conditions to ensure combustion robustness and to enable mode switching on an engine that transitions between GCI and SACI combustion modes. Despite these promising programs, there will need to be additional control system development both for real-world robustness of control and to support on-board diagnostic systems.

The air handling system of GCI engines also presents challenges. The NO_X emission results shown in the previous section indicate the strong impact of EGR on emissions levels. The high levels of EGR required make significant demands on the boosting system; as EGR increases, exhaust temperatures decrease. Providing sufficient boost energy to drive the combined air and EGR flow required can be challenging. Multi-cylinder engine demonstrations have used two-stage boosting with a supercharger and turbocharger [4.3] or a variable-geometry turbocharger [4.2, 4.4]. These solutions have proven to work relatively well, but the wide range of automotive applications may lead to scenarios where the higher-cost two-stage boost system satisfies the performance demand at too high a cost, or the single-stage boost system cannot meet performance targets. Each individual application will be different, so this is a manageable challenge but a challenge, nonetheless.

The challenges for GCI are considered graphically in Figure 27. Development and demonstrations by Delphi and Hyundai have yielded solutions to many challenges, so the area enclosed in the spider plot is relatively large for GCI. The remaining challenges require continued investment to address for production readiness and system robustness if GCI is to be a commercial solution for future IC engines.

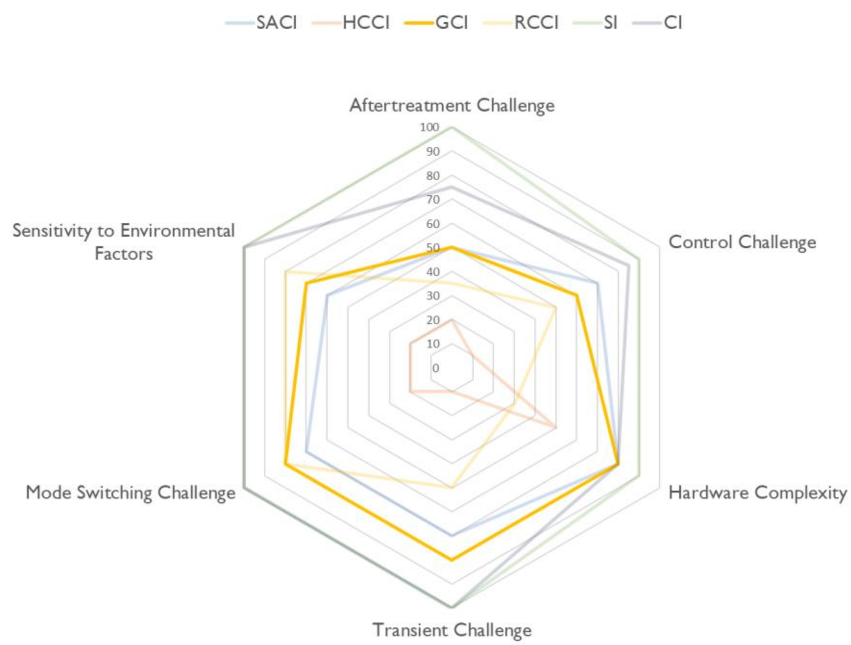

FIGURE 27: MAPPING OF ADVANCED COMBUSTION CHALLENGES

4.5 Fuel Property Impacts

GCI research has been a fertile ground for fuel property studies. Much of the research has been directed at using market-like gasoline fuels, as is a practical approach for developing a new engine. However, the studies generally have shown that market fuels are not ideal for GCI; a more reactive fuel (so lower RON) that retains the physical properties of gasoline would be better for improving combustion phasing control and for easing the challenges of low-load operation.

Badra et al. investigated the combustion of three lower-octane fuels in a GCI engine: two naphtha refinery streams (RON values of 62 for SALN and 60 for HSRN) and a PRF blend to match the octane number of the naphtha fuels (65 RON) [4.10]. The study showed promising results for combustion control with low-octane fuels. Figure 28 shows the combustion phasing response of the fuels to injection location. There was a strong correlation between SOI and combustion phasing, implying strong control authority with these low octane fuels (which is not necessarily unique to these lower-RON fuels; the other studies reviewed here also demonstrated strong control authority with higher-RON fuels).

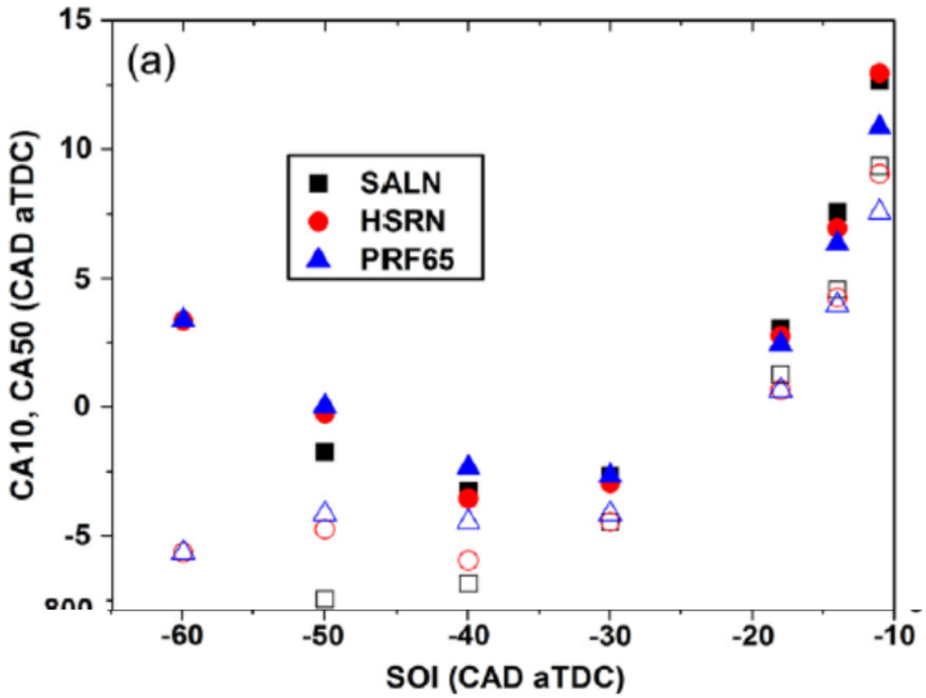

FIGURE 28: CA10 AND CA50 LOCATIONS VS. SOI FOR THREE LOW-RON GASOLINE FUELS (SALN = 62 RON, HSRN = 60 RON) (FROM [4.10])

Solanki et al. [4.8] considered the availability of low RON fuel as a production challenge; while these fuels show significant promise for improved combustion performance but bringing a new fuel to market in concert with the introduction of new engine designs would require significant cross-industry coordination to achieve. That said, since GCI engines have shown compatibility and good performance with current pump-grade gasoline there is the potential for introduction of engines that run well with current fuels, but which can also take advantage of lower-RON fuels in the future. This would allow for development of an installed base of vehicles that could eventually create a market to justify introduction of lower-RON fuel.

Other researchers have considered E85 [4.5] and other gasoline-like fuels. The general findings are like those with conventional gasoline. Ultimately, the primary fuel impact addressed in the literature is the octane rating; lower octane fuels reduce the challenges associated with low-load operation and offer improved control authority from the injection event. But as long as the fuel has volatility characteristics similar to that of conventional pump gasoline, the essence of GCI combustion can be achieved – premix the fuel sufficiently to allow for combustion to occur in the desired lower-equivalence ratio / lower-temperature regime noted in Figure 1.

4.6 Production Challenges

Significant challenges remain for bringing a GCI engine to production. Delphi [4.4] and Hyundai [4.2] have both executed DOE-supported programs to develop GCI engines that can satisfy, in prototype form, the performance, emissions, and drivability requirements for a production engine. However, these engines still require significant development to be production ready.

Engine controls are reasonably well developed but will continue to evolve to address operation challenges under extreme environmental conditions, robustness to driver input, and accommodation of fuel variability across markets. The control system remains dependent on combustion feedback in current engines, which brings significant system complexity to both the sensors and the processing power in the engine control unit. These are all solvable issues but will require time and effort to address.

Cold start, environmental robustness, and drivability will require significant development. The vehicle-intent engines demonstrated to date have included intake heaters to ensure acceptable cold start performance (with Hyundai targeting -20 °C cold start capability). Indications are that the power demand from the heaters is reasonable, but they still represent increased system complexity that must be considered in light of production requirements (durability, OBD, etc.).

Emissions control is probably the biggest production challenge for GCI. As noted in Chapter 2 of this report, even the low engine-out emissions reported in some of the studies considered are insufficient for compliance with light- or heavy-duty regulations without aftertreatment. It is highly likely that a diesel-style aftertreatment system will be required for full compliance. For a heavy-duty application this is already the expectation in the industry, and so will not present any significant market problem. In the light-duty space the incumbent powertrain is generally a spark-ignited engine with a three-way catalyst for aftertreatment. The engine + aftertreatment system complexity will be significantly greater for a light-duty GCI engine; this is not a technical barrier but a potential market barrier.

There is a great need for further R&D to fully evaluate the challenge of satisfying the stringent emission regulations that the industry faces; CARB-funded efforts to demonstrate technical pathways for meeting the heavy-duty regulations with SI and CI engines have been successful, but also identified that thermal management, high-efficiency catalysis, and engine-out emission calibration are all critical components of a compliant engine. Research to date on GCI has not addressed these issues in light of the new regulations, leaving a significant knowledge gap between the current state of GCI emissions and the required state for production.

There does appear to be a feasible path to production for GCI engines; they reuse common engine design practice and hardware in many cases. It will just take time and development effort to address the areas mentioned above to develop robust and producible solutions. When considering specific target markets, the report author sees a simpler path to commercialization in the medium- and heavy-duty spaces. These markets already use CI engines; GCI engines require a comparable hardware configuration. These markets also already have accepted the costs and complexity of lean aftertreatment systems, so the emissions compliance path for GCI is consistent with the market. For light-duty markets, there is still an attractive efficiency benefit from GCI that would be useful in many vehicle segments. The significantly more complicated engine and aftertreatment hardware required for GCI when compared with SI engines complicates market acceptance of the combustion approach.

4.7 GCI Summary

The overall state of development of GCI is detailed in Table 3. This summarizes the key development details which have been presented in the preceding sections.

TABLE 3: CURRENT DEVELOPMENT STATUS OF GCI

Demonstrated Fuels	Gasoline, E85, naphtha
Key Fuel Properties	Gasoline-like volatility, RON (studies show 60-70 RON may be "ideal" but up to 91 RON has been used successfully)
Operating Window (Demonstrated)	Full engine load (18-20 bar)
Key Challenges	Boost system for high dilution (demonstrated, but remains more complicated than SI/CI systems), aftertreatment for current/future emissions standards, thermal management, transient response with high dilution
Required Enablers	Multi-cylinder engine in vehicle
Development Stage	Primarily single-cylinder engine, with some multi-cylinder engine demonstration (in-vehicle by GM)
TRL	7

4.8 Cited References

[4.1] Confer, K. and Kirwan, J.; "Ultra Efficient Light-Duty Powertrain with Gasoline Low-Temperature Combustion"; Presented at the 2017 DOE Vehicle Technologies Office Annual Merit Review; 2017

[4.2] Zoldak, P., "Co-Optimized Multi-Mode Light-Duty Vehicle Engine"; Presented at the 2020 DOE Vehicle Technologies Office Annual Merit Review; 2020

[4.3] Sellnau, M., Foster, M., Hoyer, K., Moore, W., Sinnamon, J., and Husted, H.; "Development of a Gasoline Direct Injection Compression Ignition (GDCI) Engine"; SAE Technical Paper 2014-01-1300; 2014

[4.4] Sellnau, M., Foster, M., Moore, W., Sinnamon, J., Hoyer, K., and Klemm, W.; "Pathway to 50% Brake Thermal Efficiency Using Gasoline Direct Injection Compression Ignition"; SAE Technical Paper 2019-01-1154; 2019

[4.5] Wang, B., Pamminger, M., and Wallner, T.; "Optimizing Thermal Efficiency of a Multi-Cylinder Heavy Duty Engine with E85 Gasoline Compression Ignition"; SAE Technical Paper 2019-01-0557; 2019

[4.6] Kavuri, C., Paz, J., and Kokjohn, S.; "A Comparison of Reactivity Controlled Compression Ignition (RCCI) and Gasoline Compression Ignition (GCI) Strategies at High Load, Low Speed Conditions"; *Energy Conversion and Management;* 127 (2016) 324-341; 2016

[4.7] Cung, K., Ciatti, S., Tanov, S., and Andersson, O.; "Low-Temperature Combustion of High-Octane Fuels in a Gasoline Compression Ignition Engine"; *Frontiers in Mechanical Engineering;* 3:22; 2017

[4.8] Solanki, V., Mustafi, N., and Agarwal, A.; "Chapter 5: Prospects of Gasoline Compression Ignition (GCI) Engine Technology in Transport Sector"; *Advanced Combustion Techniques and Engine Technologies for the Automotive Sector;* 2020

[4.9] Toops, T.; "Low-Temperature Emission Control to Enable Fuel-Efficient Engine Commercialization"; Presented at the 2020 DOE Vehicle Technologies Office Annual Merit Review; 2020

[4.10] Badra, J., Viollet, Y., Elwardany, A., Im, H., and Chang, J.; "Physical and Chemical Effects of Low Octane Gasoline Fuels on Compression Ignition Combustion"; *Applied Energy;* Vol. 183; 2016

[4.11] Cung, K. and Ciatti, S.; "A Study of Injection Strategy to Achieve High Load Points for Gasoline Compression Ignition (GCI) Operation"; *Proceedings of the ASME 2017 Internal Combustion Engine Division Fall Technical Conference*; 2017

[4.12] Dempsey, A., Curran, S., and Wagner, R.; "A Perspective on the Range of Gasoline Compression Ignition Combustion Strategies for High Efficiency and Low NOX and Soot Emissions: Effects of In-Cylinder Fuel Stratification"; *International Journal of Engine Research*; 17(6) 897-917; 2016

[4.13] Neely, G., Sharp, C., and Rao, S.; "CARB Low NO_X Stage 3 Program – Modified Engine Calibration and Hardware Evaluations"; SAE Technical Paper 2020-01-0318

[4.14] Wang, B., Pamminger, M., and Wallner, T.; "Effects of Port Fuel and Direct Injection Strategies and Intake Conditions on Gasoline Compression Ignition Operation"; *Proceedings of the ASME 2018 Internal Combustion Engine Division Fall Technical Conference*; 2018

[4.15] Kolodziej, C. P., Sellnau, M., Cho, K., and Cleary, D.; "Operation of a Gasoline Direct Injection Compression Ignition Engine on Naphtha and E10 Gasoline Fuels"; SAE Technical Paper 2016-01-0759

4.9 Other Relevant References

[4.16] Kalghatgi, G.; "The Outlook for Fuels for Internal Combustion Engines"; *International Journal of Engine Research*; 15(4) 383-398; 2014

[4.17] Kalghatgi, G. and Johansson, B.; "Gasoline Compression Ignition Approach to Efficient, Clean, and Affordable Future Engines"; *Proceedings of the Institute of Mechanical Engineers, Part D: Journal of Automobile Engineering*; 232(1) 118-138; 2018

[4.18] Kolodziej, C., Kodavasal, J., Ciatti, S., Som, S., Shidore, N., and Delhom, J.; "Achieving Stable Engine Operation of Gasoline Compression Ignition Using 87 AKI Gasoline Down to Idle"; SAE Technical Paper 2015-01-0832; 2015

[4.19] Loeper, P., Ra, Y., Adams, C., Foster, D., Ghandhi, J., Andrie, M., and Krieger, R.; "Experimental Investigation of Light-Medium Load Operating Sensitivity in a Gasoline Compression Ignition (GCI) Light-Duty Diesel Engine"; SAE Technical Paper 2013-01-0896; 2013

[4.20] Noh, H., and No, S-Y.; "Effect of Bioethanol on Combustion and Emissions in Advanced CI Engines: HCCI, PPC, and GCI Mode – A Review"; *Applied Energy*; Vol. 208; Pages 782-802; 2017

[4.21] Putrasari, Y. and Lim, O.; "A Review of Gasoline Compression Ignition: A Promising Technology Potentially Fueled with Mixtures of Gasoline and Biodiesel to Meet Future Engine Efficiency and Emissions Targets"; *Energies*; 12(2); 2019

[4.22] Rose, K., Ariztegui, J., Cracknell, R., Dubois, T., Hamje, H., Pellegrini, L, Rickeard, D., Heuser, B., Schnorbus, T., and Kolbeck, A.; "Exploring a Gasoline Compression Ignition (GCI) Ignition Concept"; SAE Technical Paper 2013-01-0911; 2013

[4.23] Sellnau, M., Sinnamon, J., Hoyer, K., and Husted, H.; "Gasoline Direct Injection Compression Ignition (GDCI) – Diesel-like Efficiency with Low CO_2 Emissions"; SAE Technical Paper 2011-01-1386; 2011

[4.24] Yoshizawa, K., Teraji, A., Miyakubo, H., Yamaguchi, K., and Urushihara, T.; "Study of High Load Operation Limit Expansion for Gasoline Compression Ignition Engines"; *Journal of Engineering for Gas Turbines and Power*; Vol. 128; 2006

5.0 HOMOGENEOUS CHARGE COMPRESSION IGNITION

5.1 Summary of Concept

Homogeneous charge compression ignition (HCCI) is the canonical advanced combustion approach; it has been studied since the late 1970's [5.1, 5.2] and in principle allows an engine to most closely approach the Otto cycle ideal. An HCCI engine is ideally fueled with a fully premixed air/fuel charge (potentially with EGR). The mixture is ignited near TDC via compression heating and is consumed homogeneously with no propagating flame front. If realized, this dilute combustion event yields low gas temperatures that avoid both soot and NO_X formation. Since combustion is extremely fast the indicated efficiency of the combustion event is high.

In HCCI, combustion occurs spontaneously according to the chemical kinetics of the fuel/air mixture. The primary challenge for implementing HCCI is to control the in-cylinder conditions so that combustion occurs at the desired timing on every cycle. Even small changes in any of these will yield large shifts in the ignition timing, making combustion control challenging even in the laboratory, let alone in a vehicle which is immersed in variable weather conditions, altitudes, and driver behavior. The instantaneous heat release event also brings challenge, as the pressure rise rate will quickly exceed limits for combustion noise and eventually mechanical strength if high load HCCI operation is attempted. Emissions control also presents a challenge; engine-out NO_X and particulate emissions are generally lower than for SI or CI combustion, but a combination of low exhaust temperature and high HC emissions requires novel aftertreatment solutions.

HCCI has been a fertile ground for research; it is a fascinating fundamental combustion phenomenon and has problems to solve in every aspect of automotive engineering from basic combustion, to fuels chemistry, to controls development, to aftertreatment. In the years since the previous CRC literature review on HCCI, work has continued globally to address these research questions and in the process the definition of HCCI has been altered. Other sections of this report discuss SACI, GCI, and RCCI combustion systems; it is not unfair to say that these are all evolutions of the pure HCCI concept to deal with one or more of the challenges listed.

That said, there is still significant work underway that is most properly termed HCCI research, and that will be discussed in the following sections.

5.2 Engine Hardware Characteristics

Nearly every engine variety known has been adapted for HCCI research. The earliest work [5.1] was performed on a two-stroke gasoline engine where the unburned combustion products enhanced the autoigition process. Much work has been performed on CFR gasoline engines to take advantage of variable compression ratio control. Development has also been performed on diesel engines converted to HCCI operation [5.3]. There is a wide variation in the injection systems used; for a canonical HCCI engine the fuel delivery would be via port injection or even from further upstream to ensure full premixing. However, it has been shown by researchers that direct injection of some, or all, of the fuel can offer a valuable control mechanism for combustion phasing. Direct injection can yield mixture stratification, which provides a measure of control on ignition timing and also slows the rate of combustion to reduce the pressure rise rates.

This multitude of approaches indicates that a strict definition of engine characteristics is challenging to quantify. A potential engine that used HCCI combustion would have both port- and direct fuel injection, a moderate compression ratio (around 14:1 as in the work by Pintor [5.4]), a boosting system to enable lean dilution, a cooled EGR system, and lean aftertreatment. HCCI can be applied to engines of almost any size; research has been performed on virtually every displacement range of engine seen in transportation. The most defining characteristic of HCCI is that there must be no positive ignition source. Because of the rapid pressure rise rates, an engine implementing HCCI generally would use diesel-style components for high peak cylinder pressure capability. Use of stratification in an HCCI combustion approach may allow for weight and friction reductions through the use of SI engine hardware, particularly as SI engines continue to move to higher cylinder pressure limits.

5.3 Performance Characteristics

Unlike SACI and GCI combustion, there have been few published accounts of production-style development of HCCI engines. That is not to say that there has not been development; General Motors had a significant development program for HCCI engines which included vehicle demonstration of the combustion system [5.5]. So, the discussion of performance characteristics will generally address steady-state laboratory demonstration and development results.

An example of the potential efficiency benefit of an HCCI engine was shown by Dec [5.6]. Figure 29 shows an engine map for a 0.98 L single cylinder diesel engine modified to run as a stratified HCCI engine using a 92 RON E10 fuel. The red markers indicate speeds and loads that have been evaluated on the engine, overlaid on the brake specific fuel consumption (BSFC) map used in the GREET software[3] for a generic 7 L diesel engine [5.7]. Over most of the map the HCCI engine shows a significant increase in brake thermal efficiency (predicted from the single cylinder indicated thermal efficiency) relative to the diesel comparison. The improvement from HCCI may not be as large as indicated here; the assumptions made to determine the brake efficiency of the HCCI engine could be unrealistic, and a best-in-class diesel engine can be expected to have a higher peak efficiency than 40%. But there is still a clear efficiency benefit from HCCI thanks to the lower heat loss from decreased combustion gas temperatures and the ideal combustion energy release phasing.

[3] GREET is a software package developed at Argonne National Laboratory to analyze greenhouse gas emissions for different fuel production and transportation fuel use pathways. More information is at http://greet.es.anl.gov

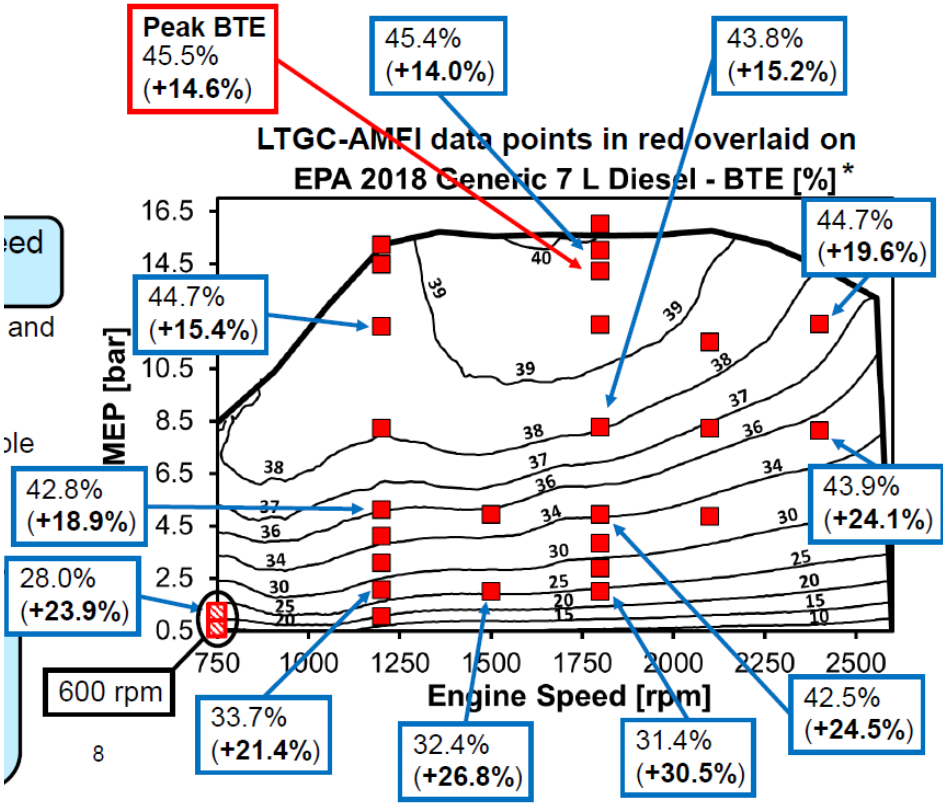

FIGURE 29: EFFICIENCY MAP FOR A 0.98 L SINGLE CYLINDER HCCI ENGINE (FROM [5.6])

Beyond efficiency, the other attraction of HCCI is the low engine-out soot and NO_X emissions. A study of HCCI combustion on a 2.2 L gasoline engine converted to HCCI operation [5.8] shows a typical trend for NO_X emissions in Figure 30. As the boost level to the engine is increased, thereby increasing dilution, the in-cylinder lambda increases and engine-out NO_X decreases. It is difficult to fairly ascertain the meaning of emissions values stated in ppm, since they do not account for the flow rate of exhaust gas, which impacts the mass emissions from the engine. But the trend still shows the benefit of HCCI; at the highest boost level evaluated the NO_X emissions were reduced to 20 ppm. When HCCI was first studied, these low engine-out NO_X levels were very exciting since aftertreatment technology was immature and HCCI seemed to offer a pathway to eliminating aftertreatment. In the intervening years, regulations have become more and more strict, to the point where it is near-certain that even an HCCI engine would require aftertreatment for emissions compliance. But the promise of reduced demand on the catalyst systems still has attraction, for reducing catalyst loading and size, reducing urea consumption in SCR systems, and ultimately for reducing the costs associated with aftertreatment.

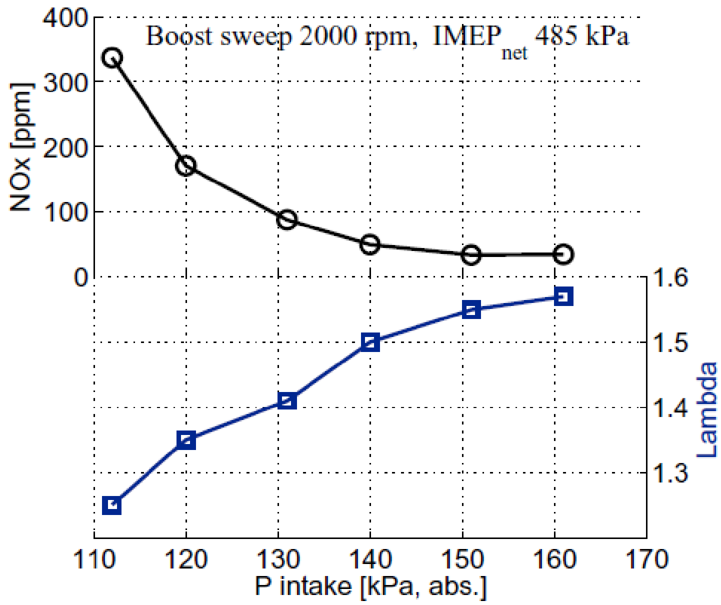

FIGURE 30: ENGINE-OUT NOX AND LAMBDA AS A FUNCTION OF INTAKE PRESSURE FOR AN HCCI ENGINE (FROM [5.8])

One area where the performance of HCCI engines is less clear is transient operation. While the previously mentioned work by GM indicates that solutions to achieve good transient performance exist, most published work has avoided the question of transient performance, particularly in terms of real-world driving where the driver input can rapidly change. More discussion of the difficulty of this issue will be discussed in terms of the technical challenges of HCCI.

5.4 Key Technical Challenges

For researchers, HCCI is ripe for study as there are technical challenges with virtually every aspect of implementation. This section will review highlights that have seen recent research efforts to address.

High pressure rise rates are a significant challenge for HCCI combustion. Fast pressure rise leads to excessive combustion noise, to mechanical stresses, and to pressure waves that strip boundary layers from the piston and liner thereby increasing the metal temperature. The pressure rise rate can be controlled by changing the residual fraction in-cylinder (to delay ignition), reducing boost, or using multiple injections to stratify the charge so that the entire mixture does not ignite at the same time, but in a staged autoignition process. A study examined the impact of these three factors on pressure rise rate [5.9]. Figure 31 shows the impact of exhaust valve closing (EVC) and intake valve opening (IVO) timing at fixed manifold pressure on the pressure rise rate in the engine. Note that the valve timings indicate NVO operation with the exhaust valve closing before the intake valve opens. For this work, shortening the NVO period offered some reduction in pressure rise rate; for the shortest NVO periods the rise rate should be within acceptable production limits.

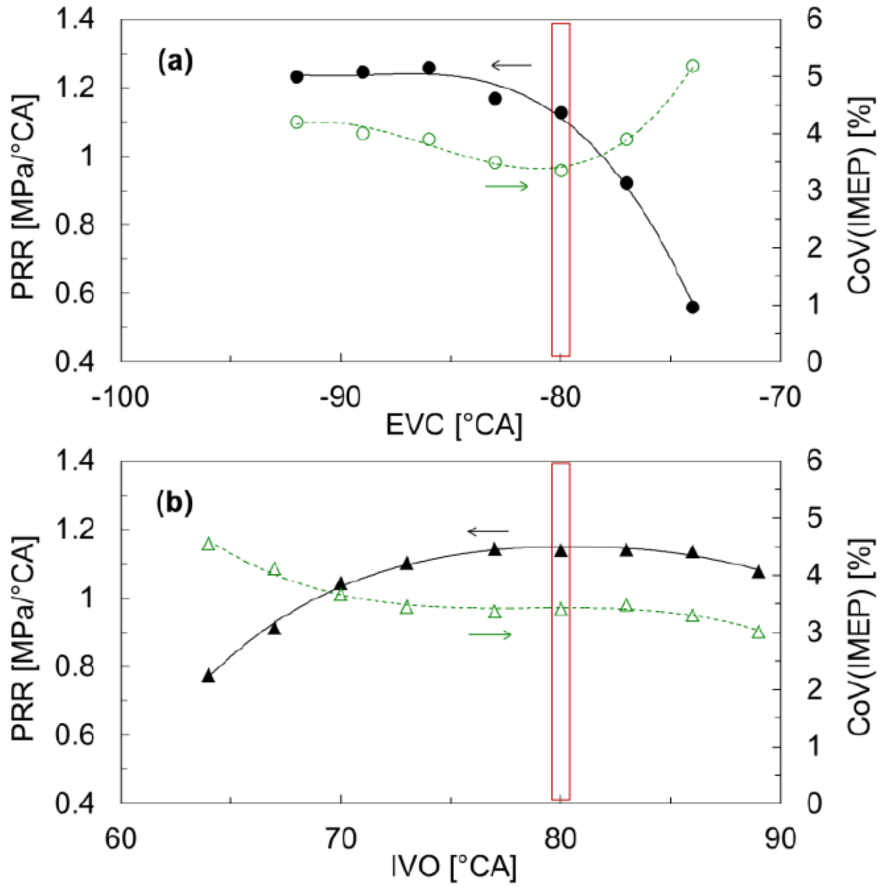

FIGURE 31: IMPACT OF EVC AND IVO ON PRESSURE RISE RATE IN AN HCCI ENGINE (FROM [5.9])

The same study considered the impact of injection quantity early in the NVO process on pressure rise rate. Injection of fuel during NVO allows for some chemical reactions to occur, yielding more reactive partial oxidation products that can enhance ignition during the later combustion event. These results show that reducing the fuel quantity during this period reduces the pressure rise rate; this is consistent with the general behavior of fuel injected during this period. Less fuel injected would imply fewer radical species to enhance ignition during the main combustion event.

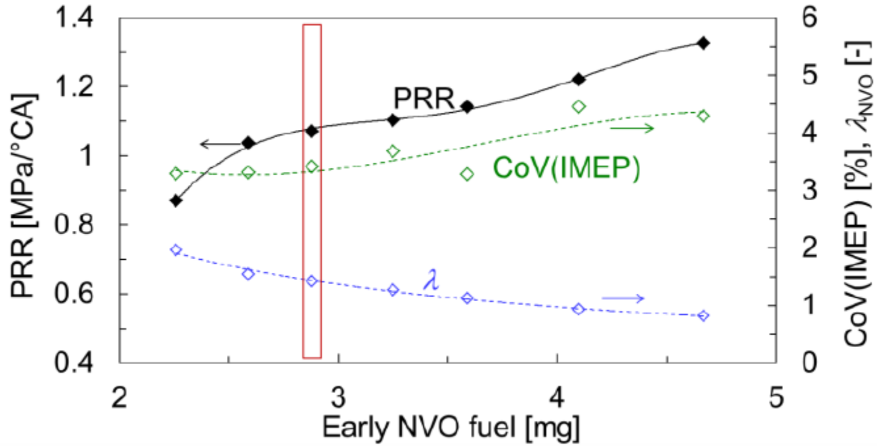

FIGURE 32: IMPACT OF EARLY NVO FUEL INJECTION QUANTITY ON PRESSURE RISE RATE (FROM [5.9])

Mode switching is another challenge for controls of HCCI; for most approaches to HCCI there is an upper bound on the engine load achievable, above which the engine must run in SI or CI mode, depending on the general recipe for the engine. Fang et al. developed methods for switching between CI and HCCI modes by taking advantage of engine controls and an integrated starter generator (ISG) motor for torque smoothing [5.10]. An example of the switching sequence is shown in Figure 33; from a stable CI operating point the various actuator settings are adjusted to bring each to their HCCI setpoints while maintaining acceptable engine operation (within the limits of what the ISG can compensate for). For a given engine, transitions into and out of HCCI mode will be required with consideration to hysteresis, emissions compliance, and drivability. This has been shown to be a solvable problem, but one that requires ongoing development to ensure production readiness.

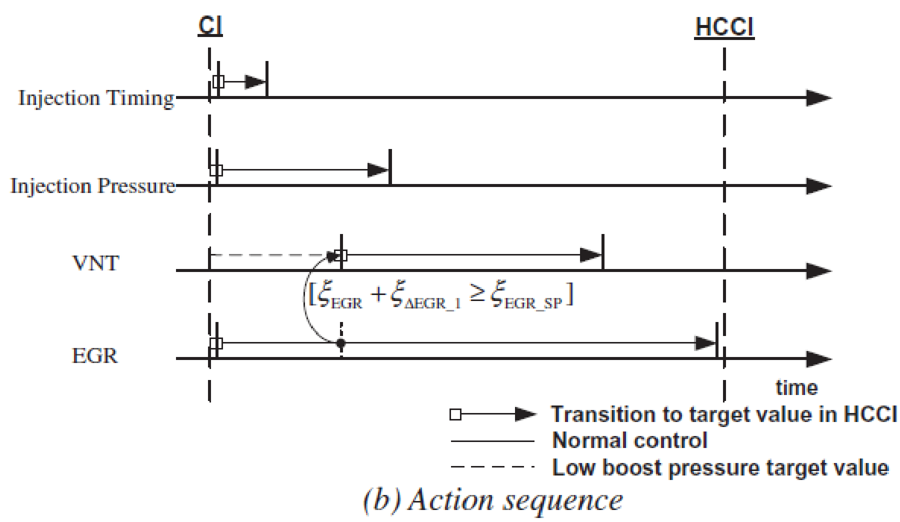

FIGURE 33: CI TO HCCI MODE SWITCHING SEQUENCE (FROM [5.10])

Emissions, as for all advanced combustion systems, are a major challenge for HCCI. A modeling study of HCCI combustion showed that very low engine-out NO_X emissions are achievable [5.11]. Figure 34 shows the NO_X emissions for two cylinder wall temperatures over a range of lean equivalence ratios. The solid lines show total NO_X emissions – the rates are quite low, especially at the leanest conditions. The emissions are stated in g/kg fuel, so these are not directly comparable with regulated emission limits. But it is certain that aftertreatment would still be required to meet the tightest current regulations, and any future regulations that can be expected to be even stricter. The exhaust temperature for these simulations was not given in the paper, but for such lean combustion it can be expected to be quite cool when compared to diesel exhaust. Given the existing challenge to maintain exhaust temperature for catalyst activity with a diesel engine, it should be expected that aftertreatment conversion efficiencies would be very low for conditions such as were simulated in this work. This indicates the challenge for aftertreatment of HCCI – the low engine out NO_X emissions still are not low enough for regulatory compliance, but the efficiency of HCCI leads to low exhaust temperatures which limit aftertreatment performance, making emissions compliance difficult to achieve with current aftertreatment technology.

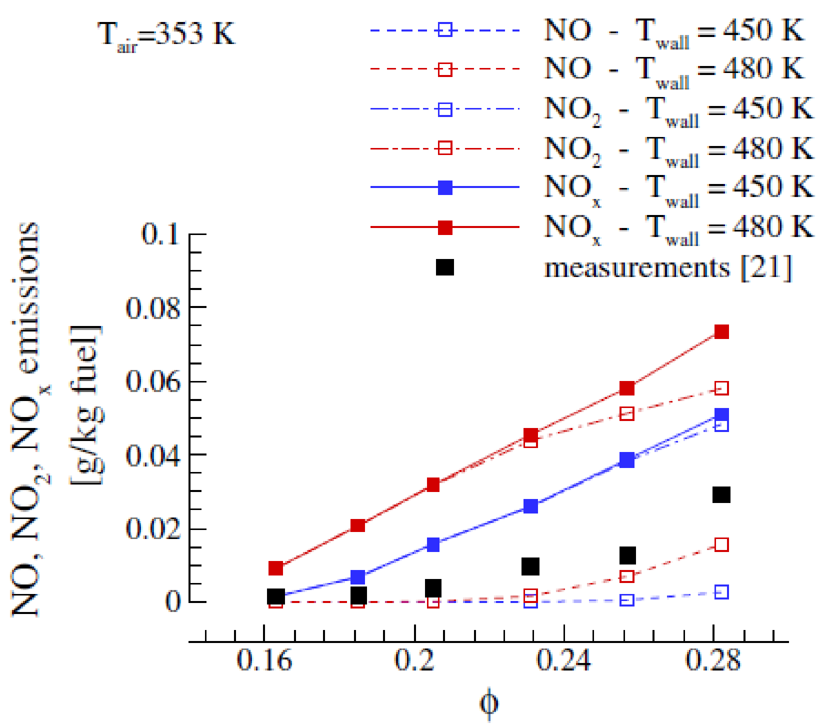

FIGURE 34: NO_X EMISSIONS AS A FUNCTION OF QUIVALENCE RATIO FOR VARYING CYLINDER WALL TEMPERATURE (FROM [5.11])

The key technical challenges for HCCI are shown in the spider plot of Figure 35. Of note is the relatively small area enclosed; the reliance on kinetic autoignition leads to the most severe challenges of any of the considered combustion approaches. Much of the work considered in this report has been intended to address these challenges, but in the view of the author the remaining difficulty remains significant for HCCI.

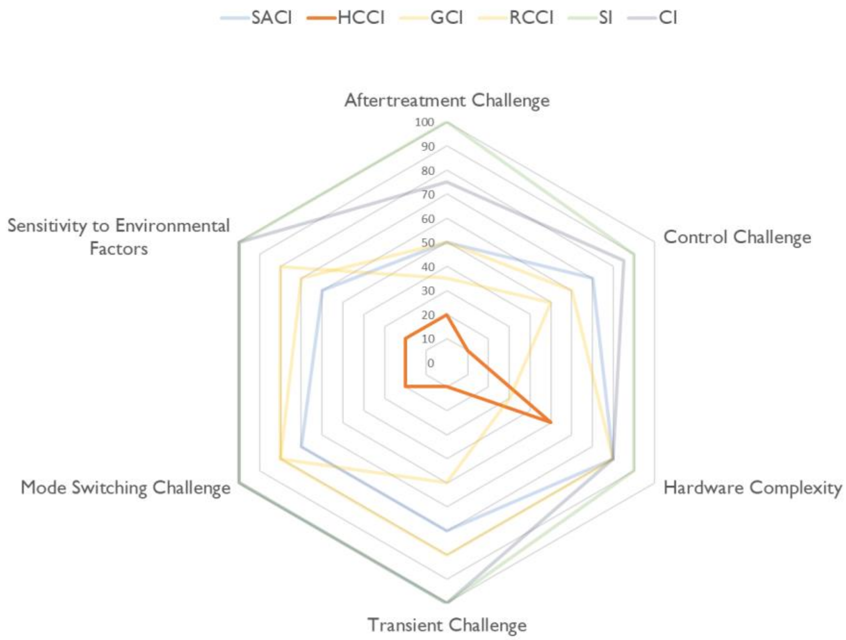

FIGURE 35: MAPPING OF ADVANCED COMBUSTION CHALLENGES

5.5 Fuel Property Impacts

HCCI research has been the most fertile ground for fuel property studies, since so much of the combustion event is determined by the fuel. Papers considered for this review have evaluated a multitude of fuels, from diesel [5.12] to gasoline [5.13] to low-octane fuels [5.14]. In general, the approach to HCCI is the same; successful development includes charge stratification and balancing of excess air, EGR and residuals, and thermal conditions to obtain control over the combustion event. A diesel-fueled HCCI engine seeks to delay ignition long enough to obtain homogeneity, while a gasoline-fueled HCCI engine seeks to enhance ignition to get a suitable combustion phasing. As with GCI, a low octane gasoline is the more "ideal" fuel since it combines the high volatility of gasoline with a moderate ignition characteristic, which maximizes the opportunity to gain a measure of positive ignition timing control from the injection event.

An interesting approach to fuel property enhancement that has been reported on recently is work by Dec to blend an ignition improver into gasoline at the injector inlet, allowing for dynamic control of the ignitability of the fuel [5.15]. The authors developed a system to add an ignition enhancer, 2-ethylhexyl nitrate, to the gasoline as it enters the GDI injector. A diagram of the system configuration is shown in Figure 36. While there is some delay between the command to add the ignition improver and its injection into the combustion chamber, this system has been shown to offer reasonably effective control over combustion.

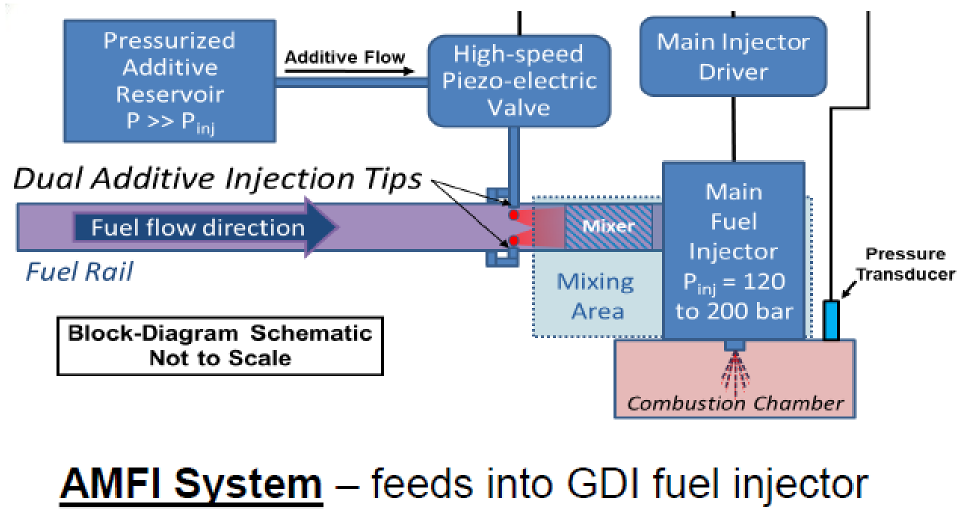

FIGURE 36: SYSTEM TO ADD AN IGNITION IMPROVER TO GASOLINE FOR HCCI CONTROL (FROM [5.6])

A simple transient demonstration is shown in Figure 37 [5.16]. This shows a timing shift and the resulting change in fire deck temperature. Changing the quantity of ignition enhancer allows for a relatively direct change in combustion phasing. This system is not developed past the laboratory stage but does show potential directions for HCCI research to develop.

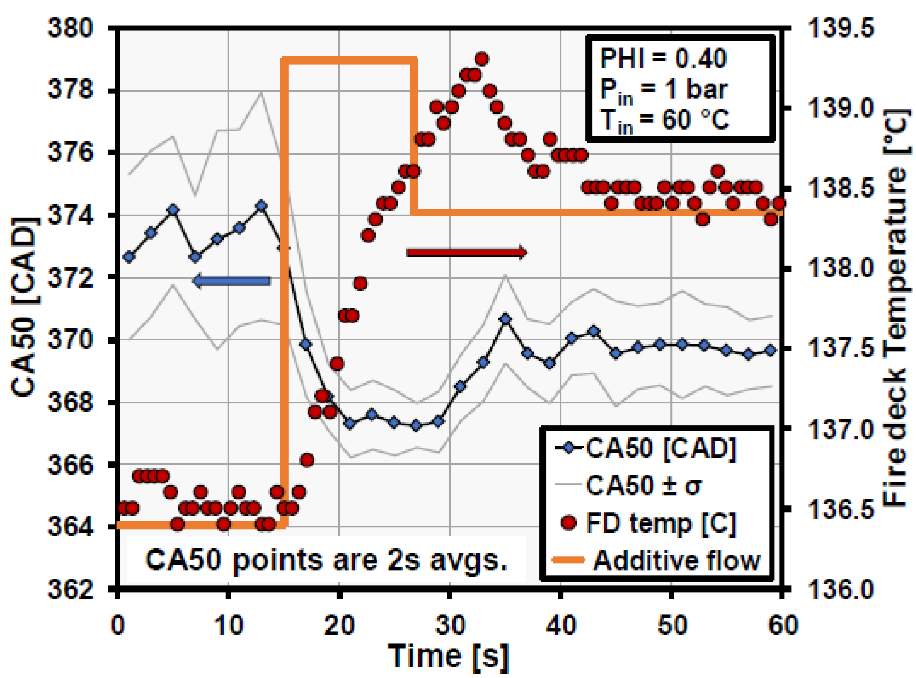

FIGURE 37: TRANSIENT RESPONSE WITH IGNITION ENHANCER ADDITION (FROM [5.16])

5.6 Production Challenges

At this point it is not clear that there is a viable path to production for pure HCCI operation. The extreme sensitivity to thermal boundary conditions, fuel properties, and other factors makes difficult the idea of developing a robust combustion system that can accommodate real world conditions. The ongoing R&D interest in basic combustion physics, controls, fuels, and emissions control shows that there are still opportunities for this situation to change as new discoveries and inventions are made.

More practically, the path to production for HCCI as part of a mixed-mode combustion system has already been seen with Mazda's Skyactiv-X engine. In that engine there is no pure HCCI mode where the spark ignition system is not used, but research presented in the SACI section of this report showed that it is feasible to have a combustion recipe that uses HCCI at the lowest loads, then transition to SACI to extend the low temperature combustion regime, and finally use conventional SI operation for peak loads. It could also be argued that some GCI combustion solutions are essentially stratified HCCI; again, a mixed-mode system allows for HCCI operation to be used where it is more easily implemented, and then a more controllable combustion approach is applied for other portions of the engine map.

5.7 HCCI Summary

The overall state of development of HCCI is detailed in Table 4. This summarizes the key development details which have been presented in the preceding sections.

TABLE 4: CURRENT DEVELOPMENT STATUS OF HCCI

Demonstrated Fuels	Gasoline, diesel, E85, naphtha, others… (RON range from 0 to near 100)
Key Fuel Properties	High volatility for mixing, moderate auto-ignition characteristic (RON near 60 gives best controllability)
Operating Window (Demonstrated)	Up to 15 bar BMEP
Key Challenges	Combustion timing control, boost system for high dilution, aftertreatment for current/upcoming emissions standards
Required Enablers	Lean aftertreatment, combustion feedback control
Development Stage	Primarily single-cylinder engine, with some multi-cylinder engine demonstration (in-vehicle by GM)
TRL	6

5.8 Cited References

[5.1] Noguchi, M., Tanaka, Y, Tanaka, T., and Takeuchi, Y.; "A Study on Gasoline Engine Combustion by Observation of Intermediate Reaction Products During Combustion"; SAE Technical Paper 790840; 1979

[5.2] Najt, P. and Foster, D.; "Compression-Ignited Homogeneous Charge Combustion"; SAE Technical Paper 830264; 1983

[5.3] Sjoberg, M. and Dec, J.; "Influence of Fuel Autoignition Reactivity on the High-Load Limits of HCCI Engines"; SAE Technical Paper 2008-01-0054; 2008

[5.4] Pintor, L., Dec., J., and Gentz, G.; "Experimental Evaluation of a Custom Gasoline-Like Blend Designed to Simultaneously Improve ϕ-Sensitivity, RON and Octane Sensitivity"; SAE Technical Paper 2020-01-1136; 2020

[5.5] Williams, M.; "HCCI: GM Making Advances with its "Newest" Fuel-Economy Improving Engine Tech"; Motortrend Online; https://www.motortrend.com/news/gm-hcci-fuel-efficient-system/; Accessed 2020-06-07

[5.6] Dec, J. and Pintor, D.; "Low-Temperature Gasoline Combustion for High Efficiency Medium- and Heavy-Duty Engines"; Presented at the 2020 DOE Vehicle Technologies Office Annual Merit Review; 2020

[5.7] https://www.epa.gov/regulations-emissions-vehicles-and-engines/greenhouse-gas-emissions-model-gem-medium-and-heavy-duty; Accessed 2020-06-07

[5.8] Johansson, T., Johansson, B., Tunestal, P., and Aulin, H.; "HCCI Operating Range in a Turbo-charged Multi-Cylinder Engine with VVT and Spray-Guided GDI"; SAE Technical Paper 2009-01-0494; 2009

[5.9] Hunicz, J. and Mikulski, M.; "Application of Variable Valve Actuation Strategies and Direct Gasoline Injection Schemes to Reduce Combustion Harshness and Emissions of Boosted HCCI Engine"; *Proceedings of the ASME 2018 Internal Combustion Engine Division Fall Technical Conference*; 2018

[5.10] Fang, C., Yang, F., Ouyang, M., Gao, G., and Chen, L.; "Combustion Mode Switching Control in a HCCI Diesel Engine"; *Applied Energy*; Vol. 110; Pages 190-200; 2013

[5.11] Viggiano, A. and Magi, V.; "A Comprehensive Investigation on the Emissions of Ethanol HCCI Engines"; *Applied Energy*; Vol. 93, Pages 277-287; 2012

[5.12] Muether, M., Lamping, M., Kolbeck, A., Cracknell, R., Rickeard, D., Ariztegui, J., and Rose, K.; "Advanced Combustion for Low Emissions and High Efficiency Part 1: Impact of Engine Hardware on HCCI Combustion"; SAE Technical Paper 2008-01-2405

[5.13] Dec, J. and Yang, Y.; "Boosted HCCI for High Power without Engine Knock and with Ultra-Low NOX Emissions – using Conventional Gasoline"; SAE Technical Paper 2010-01-1086; 2010

[5.14] Yang, Y., Dec, J., Dronnious, N., and Cannella, W.; "Boosted HCCI Combustion Using Low-Octane Gasoline with Fully Premixed and Partially Stratified Charges"; SAE Technical Paper 2012-01-1120; 2012

[5.15] Dec, J., Gentz, G., and Lopez-Pintor, D.; "Low-Temperature Gasoline Combustion (LTGC) Engine Research"; Presented at the 2018 DOE Vehicle Technologies Office Annual Merit Review; 2018

[5.16] Dec, J., Gentz, G., and Lopez-Pintor, D.; "Low-Temperature Gasoline Combustion (LTGC) Engine Research"; Presented at the 2019 DOE Vehicle Technologies office Annual Merit Review; 2019

5.9 Other Relevant References

[5.17] Andreae, M., Cheng, W., Kenney, T., Yang, J.; "On HCCI Engine Knock"; SAE Technical Paper 2007-01-1858; 2007

[5.18] Bidarvatan, M., Kothari, D, and Shahbakhti, M.; "Integrated Cycle-to-Cycle Control of Exhaust Gas Temperature, Load, and Combustion Phasing in an HCCI Engine"; Presented at the 2015 American Control Conference, Chicago, Illinois; 2015

[5.19] Cracknell, R., Rickeard, D., Ariztegui, J., Rose, K., Muether, M, Lamping, M., Kolbeck, A.; "Advanced Combustion for Low Emissions and High Efficiency Part 2: Impact of Fuel Properties on HCCI Combustion"; SAE Technical Paper 2008-01-2404; 2008

[5.20] Kalghatgi, G.; "Auto-Ignition Quality of Practical Fuels and Implications for Fuel Requirements of Future SI and HCCI Engines"; SAE Technical Paper 2005-01-0239; 2005

[5.21] Lawler, B., Ortiz-Soto, E., Gupta, R, Peng, H., and Filipi, Z.; "Hybrid Electric Vehicle Powertrain and Control Strategy Optimizations to Maximize the Synergy with a Gasoline HCCI Engine"; SAE Technical Paper 2011-01-0888; 2011

[5.22] Lee, K., Cho, S., Kim, N., Min, K.; "A Study on Combustion Control and Operating Range Expansion of Gasoline HCCI"; *Energy*; Vol. 91; Pages 1038-1048; 2015

[5.23] Nishi, M., Kanehara, M., and Iida, N.; "Assessment for Innovative Combustion on HCCI Engine by Controlling EGR Ratio and Engine Speed"; *Applied Thermal Engineering*; Vol. 99; Pages 42-60; 2016

[5.24] Saxena, S. and Bedoya, I.; "Fundamental Phenomena Affecting Low Temperature Combustion and HCCI Engines, High Load Limits and Strategies for Extending These Limits"; *Progress in Energy and Combustion Science*; 39(5) 457-488; 2013

[5.25] Sjoberg, M. and Dec, J.; "Ethanol Autoignition Characteristics and HCCI Performance for Wide Ranges of Engine Speed, Load and Boost"; SAE Technical Paper 2010-01-0338; 2010

[5.26] Starck, L, Lecointe, B., Forti, L., and Jeuland, N.; "Impact of Fuel Characteristics on HCCI Combustion: Performances and Emissions"; *Fuel*; 89(10) 3069-3077; 2010

[5.27] Truedsson, I., Cannella, W., Johansson, B., and Tuner, M.; "Development of New Test Method for Evaluating HCCI Fuel Performance"; SAE Technical Paper 2014-01-2667; 2014

[5.28] Wagner, R., Edwards, K., Daw, C., Green, J., Bunting, B.; "On the Nature of Cyclic Dispersion in Spark Assisted HCCI Combustion"; SAE Technical Paper 2006-01-0418; 2006

[5.29] Wu, H., Collings, N., Regitz, S., Etheridge, J., and Kraft, M.; "Experimental Investigation of a Control Method for SI-HCCI-SI Transition in a Multi-Cylinder Gasoline Engine"; SAE Technical Paper 2010-01-1245; 2010

[5.30] Yang, X. and Zhu, G.; "SI and HCCI Combustion Mode Transition Control of an HCCI Capable SI Engine"; *IEEE Transactions on Control Systems Technology*; 21(5) 1558-1569; 2013

[5.31] Yao, M., Zheng, Z., and Liu, H.; "Progress and Recent Trends in Homogeneous Charge Compression Ignition (HCCI) Engines"; *Progress in Energy and Combustion Science*; 35(3) 398-437; 2009

6.0 REACTIVITY CONTROLLED COMPRESSION IGNITION

6.1 Summary of Concept

Reactivity controlled compression ignition (RCCI) is the last major category of low temperature combustion systems, again intended to offer more control of combustion phasing than can be achieved with HCCI. An RCCI engine is a dual fuel engine that uses both lower reactivity (natural gas, ethanol, or gasoline for example) and higher reactivity (diesel) fuels. The lower reactivity fuel can be port or direct injected and is intended to be reasonably well premixed by the time of intended ignition. The higher reactivity fuel is then directly injected into the combustion chamber so that it also mixes and initiates a homogeneous autoignition event that then leads to the homogeneous autoignition of the lower reactivity mixture.

The promise of RCCI is that the injection timing of the higher reactivity fuel can be used to affect a positive control over combustion timing based on ignition timing as long as the mixture equivalence ratio, intake temperature, and EGR rate are properly controlled.

RCCI is distinguished from conventional dual-fuel combustion in that the higher reactivity injection event is completely ended before ignition, while in conventional dual-fuel combustion the diesel spray ignites as a diffusion combustion event that then initiates a flame propagation event in the premixed lower-reactivity fuel mixture. Both combustion systems use similar fuel system configurations and even can use the same fuels, but with very different resulting combustion events.

RCCI has been studied in both light- and heavy-duty applications and has similar challenges for market introduction as GCI in terms of engine hardware requirements and system complexity. Following the same logic as was used in consideration of GCI, RCCI is likely to have a more natural fit in heavy-duty applications. Additional comments on this potential will be made in the remainder of this chapter.

6.2 Engine Hardware Characteristics

An RCCI engine is generally based on a diesel engine architecture; the piston bowl geometry can be that of a conventional diesel engine, but the bowl shape is less critical than for diesel combustion since the injection event is significantly earlier and has less interaction with the piston. There will be an EGR system, a boosting system, and two fuel systems for the higher- and lower-reactivity fuels. The lower reactivity fuel can be directly injected if two DI injectors can be accommodated in the cylinder head or can be port injected (or fumigated upstream of the intake manifold if natural gas is used as the lower reactivity fuel). An early example of an RCCI laboratory engine is shown in Figure 38 [6.1]. RCCI has been evaluated for both light- and heavy-duty engines with similar configurations.

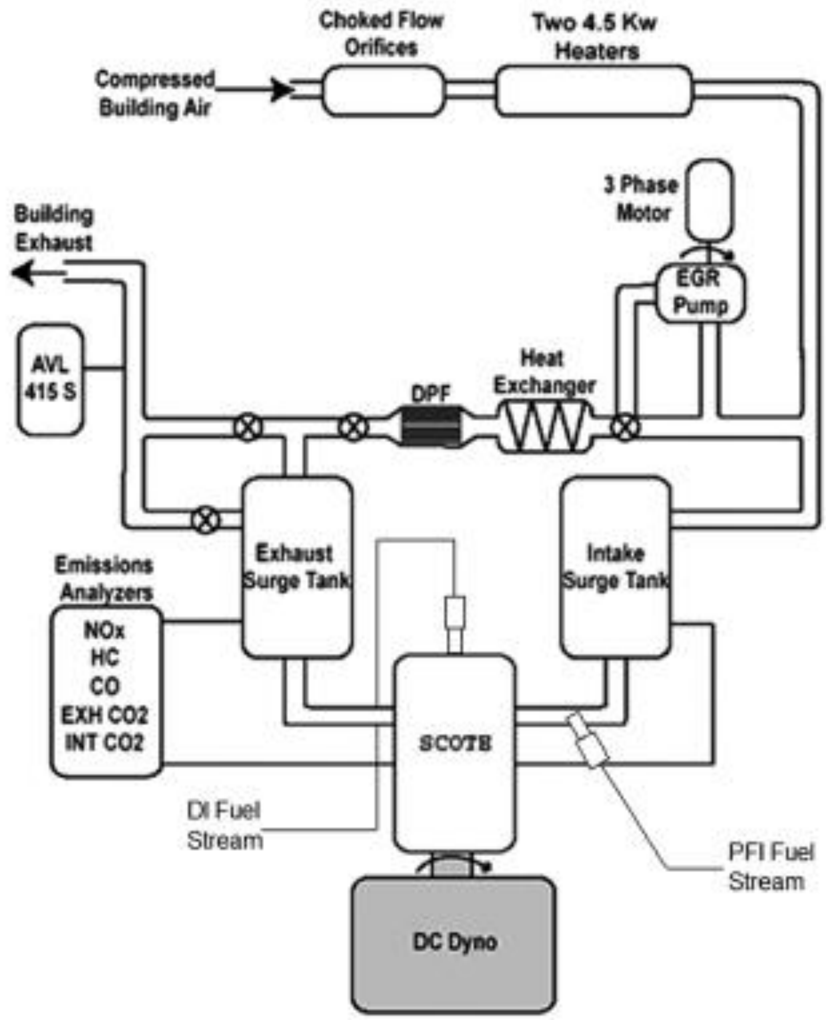

FIGURE 38: LABORATORY ENGINE CONFIGURATION FOR A RCCI ENGINE (FROM [6.1])

6.3 Performance Characteristics

RCCI has generally been shown to have a narrow region of acceptable operation, limited at high load by pressure rise rate constraints and at low loads by CO emissions (and ultimately CoV of IMEP). A light-duty implementation shows a typical load-speed range as seen in Figure 39 [6.2]. The authors used a 10 bar/°CA pressure rise rate limit; this is a frequent laboratory limit used, though production limits can be lower based on OEM considerations. This operating range is not sufficient to satisfy all driving situations, but can accommodate some scenarios, as the authors show by an overlay of operating points on the UDDS cycle (see Figure 40). Much of the drive cycle is contained within the RCCI operating window, so if there are benefits to RCCI operation then there is good opportunity to take advantage of it in a light-duty low-load drive cycle.

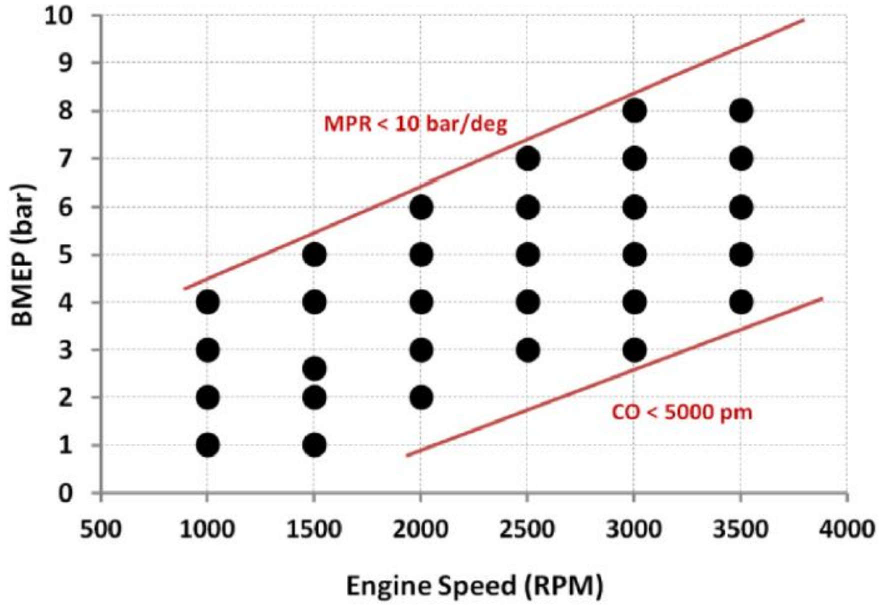

FIGURE 39: RCCI LOAD-SPEED RANGE FOR A LIGHT-DUTY ENGINE (FROM [6.2])

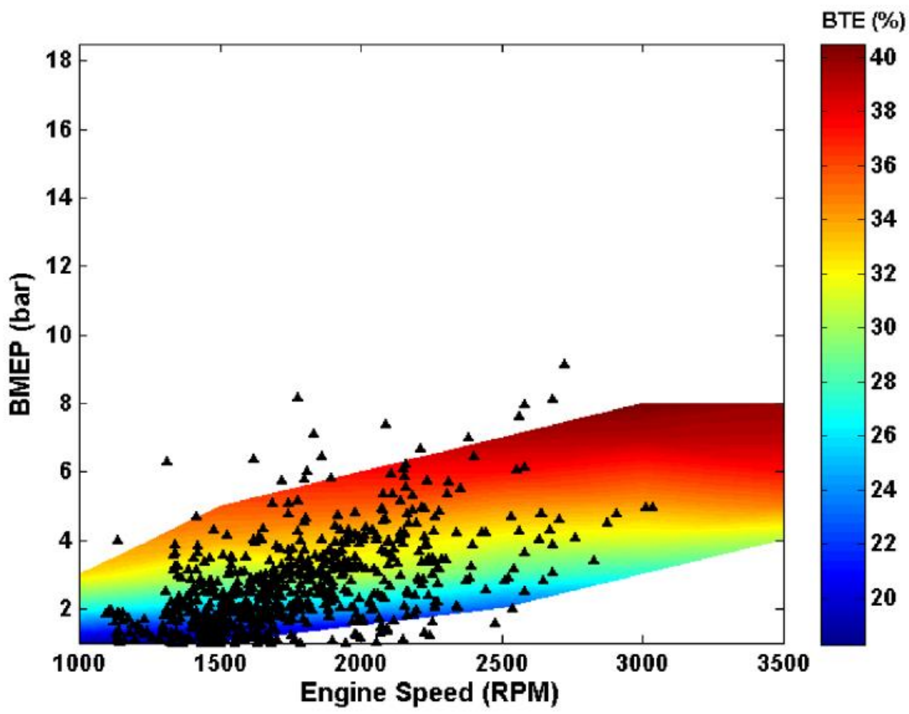

FIGURE 40: UDDS DRIVE CYCLE POINTS RELATIVE TO THE RCCI OPERATING RANGE (FROM [6.2])

However, the published multicylinder results on RCCI operation have shown that there is minimal efficiency benefit to be gained relative to CI operation. Figure 41 shows the brake thermal efficiency maps of the same engine operated both in RCCI mode and in standard diesel mode. While there are some minor differences, the efficiencies are quite similar between the two modes, indicating that the fuel economy potential of RCCI is not massively increased over conventional diesel combustion.

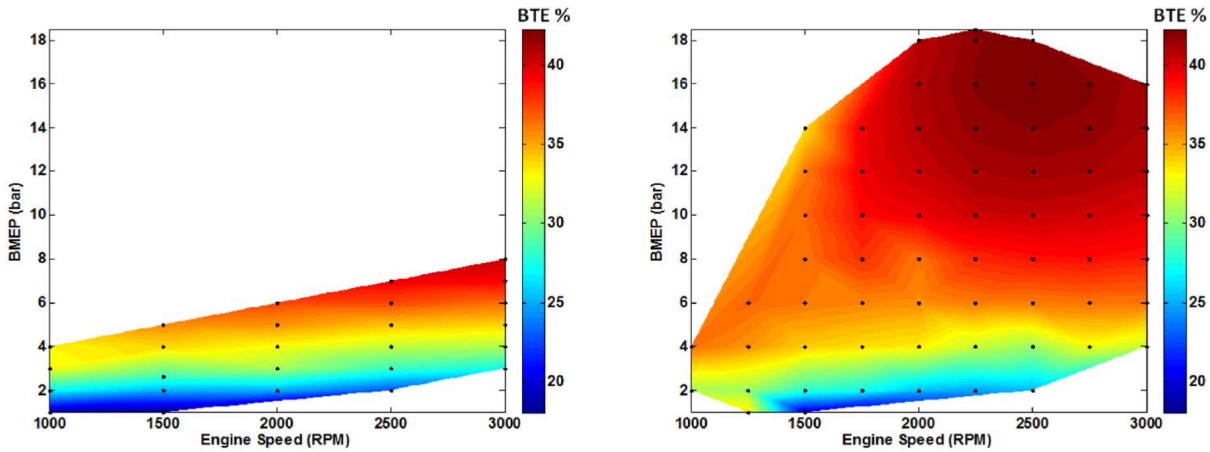

FIGURE 41:COMPARISON OF RCCI (LEFT) AND STANDARD DIESEL (RIGHT) ENGINE EFFICIENCY (FROM [6.2])

This comparison of efficiencies does not tell the entire story; later work performed at Oak Ridge National Laboratory [6.3] with a multi-mode RCCI/diesel engine on a transient dynamometer indicated the potential for a 25% improvement on a simulated HWFET drive cycle.

NO_X emissions are significantly reduced with RCCI operation as shown in Figure 42. The authors of [6.2] noted that the diesel calibration was a Euro 4 calibration and targeted engine-out NO_X to satisfy the emissions regulations without aftertreatment. The RCCI NO_X emissions were roughly an order of magnitude lower than the diesel NO_X emissions over most of the operating range.

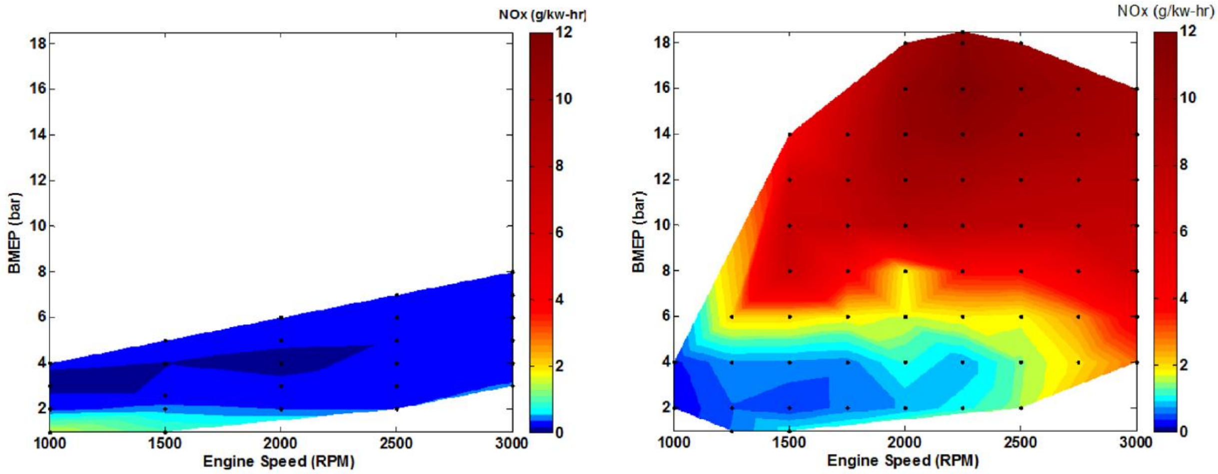

FIGURE 42: COMPARISON OF RCCI (LEFT) AND STANDARD DIESEL (RIGHT) NO_X EMISSIONS (FROM [6.2])

The low engine-out NO_X levels are exciting, but it must be noted that they are still not sufficient to satisfy the stringent SULEV20/30 emissions requirements in the US or expected future European emissions regulations. Therefore, aftertreatment is still necessary, which means that exhaust temperature is a factor in maintaining catalyst function and in achieving light-off during cold start. Figure 43 shows the exhaust temperature map for the light-duty engine under discussion. The relatively low temperatures of the exhaust can be seen, with temperatures below 200 °C below around 3 bar BMEP and below 250 °C below 5 bar. Obtaining high NO_X conversion efficiency on current SCR systems is challenging at these temperatures; this implies either a need for improved catalyst function or a change to the operating conditions to increase the exhaust temperature (and generally giving up efficiency). As with most advanced combustion modes this remains a key challenge for real-world viability.

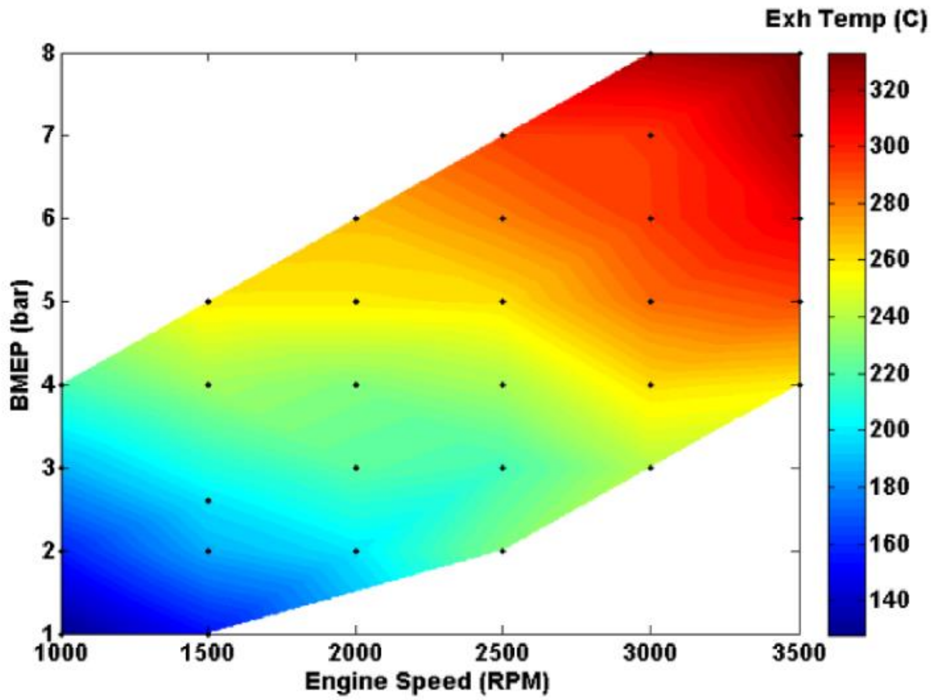

FIGURE 43: EXHAUST TEMPERATURE MAP FOR RCCI OPERATION (FROM [6.2])

6.4 Key Technical Challenges

RCCI does successfully address a challenge for low temperature combustion. The use of two fuels allows stratification of not only equivalence ratio but effective octane or cetane number of the mixture – this provides a stronger link between injection timing and combustion phasing, allowing for a reliable control method for combustion. However, most of the other challenges remain; combustion will still be sensitive to thermal boundary conditions, fuel quality, and other factors which are difficult or impossible to control outside the laboratory. And as discussed above, the low exhaust temperature of RCCI leads to significant emissions challenges.

The spider plot comparing the challenges faced by the various advanced combustion approaches with RCCI highlighted is in Figure 44. The dual-fuel solution does effectively address some challenges associated with advanced combustion, but other aspects are either unexplored in the literature or remain unaddressed. The close similarity of RCCI and GCI suggests that similar solutions are likely to be successful in addressing these challenges, but further work to demonstrate this possibility would be required to further expand the area or the RCCI boundary in this visualization of the situation.

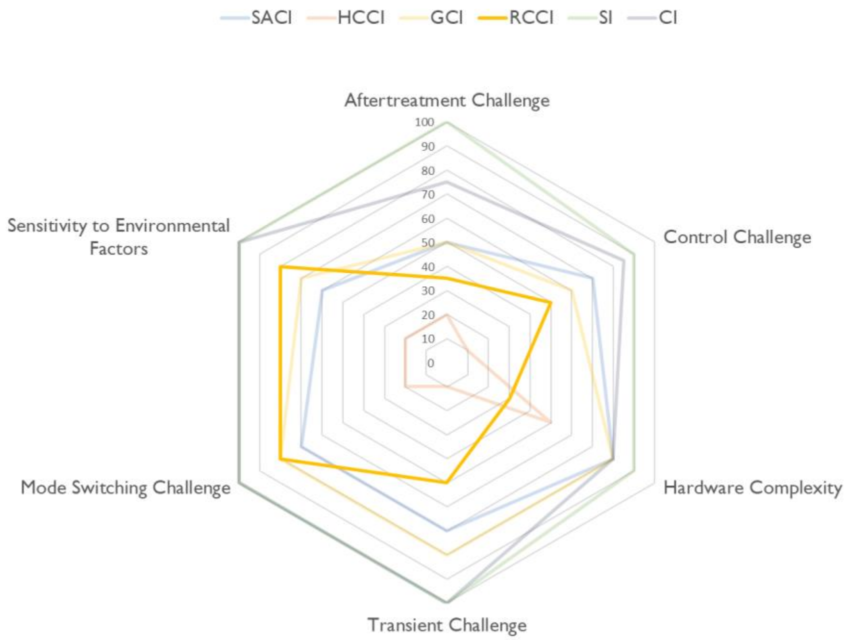

FIGURE 44: MAPPING OF ADVANCED COMBUSTION CHALLENGES

6.5 Fuel Property Impacts

RCCI is essentially a combustion approach that exploits fuel properties to function. It uses two different fuels to control mixture reactivity spatially and temporally to achieve controlled low temperature combustion. The initial work considered gasoline and diesel fuel, respectively, as the two fuels. But RCCI research has considered a broader range of fuels than these two.

Natural gas is another interesting fuel for RCCI; pilot-ignited natural gas engines have been in use for many years in heavy-duty and large engine applications, so it is a natural fit to consider natural gas RCCI as a potential path to higher efficiency and lower engine-out emissions. A study by Nieman et al. showed good performance with natural gas as the lower-reactivity fuel [6.4]. A slight reduction in gross indicated efficiency was seen for natural gas RCCI when compared to gasoline RCCI (50% vs. 52%) which the authors attributed to the higher adiabatic flame temperature of natural gas.

A "single-fuel" RCCI approach has also been evaluated using an ignition improver that was blended into gasoline for the higher reactivity fuel injection [6.5]. In this study di-tert butyl peroxide was used to increase the ignitability of the gasoline injected for timing control while the premixed charge used un-blended gasoline. Combustion control was successful, with the authors noting a 1 percentage point increase in indicated gross engine efficiency via a decrease in low temperature heat release. This approach did offer some potential to address the two-fuel requirement of RCCI which, as will be discussed below, has been a major challenge for the production potential of RCCI.

These studies broadly address the desired fuel properties for RCCI. The lower reactivity fuel should have high volatility for fast evaporation so that it can achieve a homogeneous mixture. The higher reactivity fuel should have lower volatility so that it can generate a stratified mixture to enable the required control of ignition timing and resulting combustion rate.

6.6 Production Challenges

RCCI shares many of the challenges discussed for GCI combustion, but brings some additional practical challenges. The requirement for two fuels has been noted as a significant problem for this combustion approach; drivers would have to monitor two fuel tank levels and fill both up. While this is in principle not a massive challenge, it has been shown time and time again that changing driver behavior is very difficult and there is an expectation that consumers would not accept the two-fuel requirement in the marketplace, and many fueling stations would also require modification to allow for easy refueling of RCCI vehicles.

An additional limit that has not been addressed is the limited operating range of RCCI combustion. GCI has been demonstrated over the entire load-speed range of an engine, but to date RCCI cannot reach high enough loads to cover the entire operating envelope of an engine. This either needs to be expanded to allow full-range RCCI operation, or the engine must transition to CI combustion for higher loads.

6.7 RCCI Summary

The overall state of development of RCCI is detailed in Table 5. This summarizes the key development details which have been presented in the preceding sections.

TABLE 5: CURRENT DEVELOPMENT STATUS OF RCCI

Demonstrated Fuels	Gasoline, diesel, E85, natural gas
Key Fuel Properties	Relatively fuel-flexible, require a diesel-like and gasoline-like fuel but properties are not strictly limited
Operating Window (Demonstrated)	8-10 bar
Key Challenges	Load limit expansion, combustion phasing control, boost system design to drive high dilution, two-fuel acceptance
Required Enablers	Lean aftertreatment, combustion feedback control
Development Stage	Multi-cylinder laboratory R&D
TRL	5

6.8 Cited References

[6.1] Kokjohn, S., Hanson, R., Splitter, D., and Reitz, R.; "Fuel Reactivity Controlled Compression Ignition (RCCI): A Pathway to Controlled High-Efficiency Clean Combustion"; *International Journal of Engine Research*; 12(3):209-226; 2011

[6.2] Curran, S., Hanson, R., and Wagner, R.; "Efficiency and Emissions Mapping of RCCI in a Light-Duty Diesel Engine"; SAE Technical Paper 2013-01-0289; 2013

[6.3] Curran, S.; “High Efficiency Clean Combustion in Multi-Cylinder Light-Duty Engines”; Presented at the 2017 DOE Vehicle Technologies Office Annual Merit Review; 2017

[6.4] Nieman, D., Dempsey, A., and Reitz, R.; “Heavy-Duty RCCI Operation Using Natural Gas and Diesel”; SAE Technical Paper 2012-01-0379; 2012

[6.5] Splitter, D., Reitz, R., and Hanson, R.; “High Efficiency, Low Emissions RCCI Combustion by Use of a Fuel Additive”; SAE Technical Paper 2010-01-2167; 2010

6.9 Other Relevant References

[6.6] Chuahy, F. and Kokjohn, S.; “Effects of the Direct-Injected Fuel’s Physical and Chemical Properties on Dual-Fuel Combustion”; *Fuel*; Vol. 207, Pages 729-740; 2017

[6.7] Dempsey, A., Walker, N., and Reitz, R.; “Effect of Piston Bowl Geometry on Dual Fuel Reactivity Controlled Compression Ignition (RCCI) in a Light-Duty Engine Operated with Gasoline/Diesel and Methanol/Diesel”; SAE Technical Paper 2013-01-0264; 2013

[6.8] Kokjohn, S., Hanson, R., Splitter, D., and Reitz, R.; “Experiments and Modeling of Dual-Fuel RCCI and PCCI Combustion Using In-Cylinder Fuel Blending”; SAE Technical Paper 2009-01-2647; 2009

[6.9] Lim, J., Walker, N., Kokjohn, S., and Reitz, R.; “High Speed Dual-Fuel RCCI Combustion for High Power Output”; 2014-01-1320; 2014

[6.10] Reitz, R. and Duraisamy, G.; “Review of High Efficiency and Clean Reactivity Controlled Compression Ignition (RCCI) Combustion in Internal Combustion Engines”; *Progress in Energy and Combustion Science*; Vol. 46, Pages 12-71; 2015

[6.11] Splitter, D., Wissink, M., Kokjohn, S., and Reitz, R.; “Effect of Compression Ratio and Piston Geometry on RCCI Load Limits and Efficiency”; SAE Technical Paper 2012-01-0383

7.0 CONCLUSIONS

Advanced combustion systems, low temperature combustion systems, kinetically controlled combustion systems – all these terms can be used to describe the subjects of this report. In many ways they are all the same basic combustion system with modifications that have been developed to improve the ability to practically implement some level of low temperature combustion. These have been a strong area of research for decades and continue to hold promise for cleaner and more efficient engines in the future.

The future of advanced combustion is not clear; major gains in emissions and efficiency have been achieved for conventional SI and CI systems, partly by taking advantage of learnings from low temperature combustion research and partly through development of improved after-treatment systems. And at the same time hybridization and electrification of the powertrain has grown exponentially and impacted the regulatory systems of most major global markets. Advanced combustion systems have potential to continue to improve engine efficiency but will need to be developed within the framework of an electrified powertrain development. It is foreseeable that electrified powertrains could help solve many of the challenges identified with advanced combustion systems (transient response, mode switching, limited operating envelope) to help their move to production.

Practical consideration of the scale of transportation energy use makes clear that we will continue to rely on combustion energy for transportation for many decades. The goal will then be to reduce the criteria emissions and greenhouse gas emissions as much as is possible. This is a goal that advanced combustion development is well aligned with. It is impossible to predict what the engine of a decade from now will look like, but the combustion system will continue to develop and improve, and that advanced combustion system research will be part of the development of that future engine.

Table 6 compiles the information from the end-of-section tables detailing the development and challenges for the various advanced combustion approaches. The differing development stages are apparent, along with the largely common challenges and required enablers for the different systems. The key factor with the development of advanced combustion relying on kinetic autoignition has been to add positive combustion phasing control to HCCI, through various means, to enable to practical use of these systems. The research that has been reviewed here primarily seeks to address remaining fundamental challenges in control, basic combustion, and load limit extension. There are still critical areas of development remaining though. In particular, the practical aspects of advanced combustion engine development need focused programs of development; real-world fuel property impacts on combustion performance, aftertreatment development and integration, and controls development to provide vehicle drivability are key areas that must be addressed for market introduction, but which have been only lightly addressed in the research literature. Solving these challenges will bring one or more of these systems into a position for market success.

It is also useful to revisit the spider plot from the meta-analysis, shown again as Figure 45. There is a clear differentiation between the advanced combustion systems considered when the fundamental challenges for each system are considered. These rankings are subjective and represent the current status of development for each system. Further research and development may lead to a reassessment of the challenges and a resulting change in the overall potential for a given system.

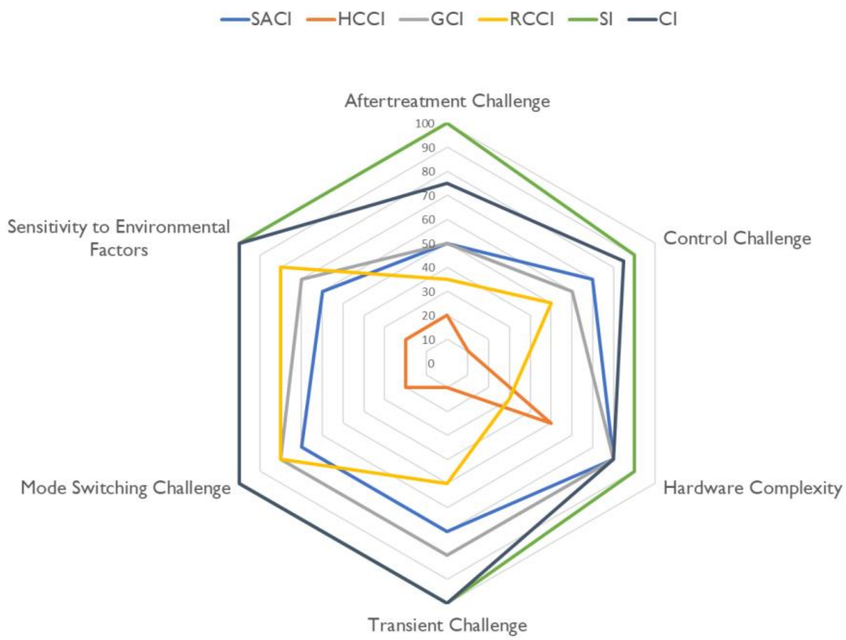

FIGURE 45: MAPPING OF ADVANCED COMBUSTION CHARACTERISTICS

The view of the author is that the most feasible advanced combustion systems are SACI and GCI. SACI is clearly feasible, as it has already reached production with one OEM. GCI has not yet reached production, but demonstrations are showing significant progress towards production readiness. Both combustion systems need significant development to ensure emissions compliance with upcoming regulations but adapting advanced diesel engine aftertreatment should prove successful. Improving combustion control and transient response is also essential. Ideally the control approach could avoid the use of in-cylinder combustion sensing, but to date that has not been demonstrated as a feasible production option. Transient response can be addressed directly on the engine or can take advantage of hybrid powertrain systems to address the transient challenges. Significant research effort is being expended on both SACI and GCI, which may lead to solutions to the production challenges discussed in this report.

TABLE 6: COMPARISON OF ADVANCED COMBUSTION APPROACHES

Combustion system	RCCI	HCCI	GCI	SACI
Demonstrated Fuels	Gasoline, diesel, E85, naphtha, others…	Gasoline, diesel, E85, naphtha, others…	Gasoline, E85, naphtha/low octane gasoline	Gasoline, iso-butanol, E85
Key Fuel Properties	High volatility for mixing, moderate auto-ignition characteristics	High volatility for mixing, moderate auto-ignition characteristics	Gasoline properties. Reduced octane is desirable for improved combustion phasing	Gasoline octane rating and properties for high load SI operation
Operating Window (Demonstrated)	15 bar	15 bar	Full engine load (18-20 bar)	Per Mazda, up to 10-12 bar. Other researchers 8 bar
Key Challenges	Combustion timing control, boost system for high dilution, aftertreatment for US Tier 3	Combustion timing control, boost system for high dilution, aftertreatment for US Tier 3	Boost system for high dilution, aftertreatment for US Tier 3, thermal management	Combustion timing control, boost system for high dilution, aftertreatment for US Tier 3
Required Enablers	Lean aftertreatment, combustion control	Lean aftertreatment, combustion control	Lean aftertreatment, combustion control	Lean aftertreatment, combustion control
Development Stage	Primarily single-cylinder engine, with some multi-cylinder engine demonstration (in-vehicle by GM)	Primarily single-cylinder engine, with some multi-cylinder engine demonstration (in-vehicle by GM)	Multi-cylinder engine in vehicle	Production
TRL	6	6	7	9