Available online at www.sciencedirect.com

ScienceDirect

Procedia IUTAM 20 (2017) 103 – 111

Procedia IUTAM

www.elsevier.com/locate/procedia

4th International Congress of Theoretical and Applied Mechanics

Emissions Control Challenges for Compression Ignition Engines

Daniel Carder[a,]*, Ross Ryskamp[a], Marc Besch[a], Arvind Thiruvengadam[a]

[a]*West Virginia University, 395 Evansdale Drive, Morgantown, WV 26505, USA*

Abstract

As emission standards continue to evolve, it is clear that future engine control strategies will involve the integration of combustion optimization, fuel refinement and advanced exhaust after-treatment technologies. The West Virginia University (WVU) Center for Alternative Fuels Engines and Emissions (CAFEE) continues to engage the challenge of future regulation in a multi-pronged approach, investigating advanced combustion regimes, alternative fuels, and next-generation emissions control technology. Results presented herein summarize recent regulatory challenges for compression ignition engines and discuss future pathways.

Peer-review under responsibility of organizing committee of the 24th International Congress of Theoretical and Applied Mechanics

Keywords: Engines; Diesel; Emissions;Greenhouse Gas; Alternative Fuels, Biofuels

1. Introduction

Modern Compression Ignition (CI) engines, commonly referred to as diesel engines, face continually evolving challenges with respect to meeting United States federal- and state-mandated exhaust emissions and fuel consumption standards. Throughout the last two decades, diesel engine and exhaust aftertreatment technology has advanced significantly to meet increasingly strict regulations, particularly with regards to oxides of nitrogen (NO_X) and particulate matter (PM). The difficulty in reducing these particular emissions constituents lies in the proverbial NO_X versus PM tradeoff; in essence engine control strategies that reduce NO_X emissions in turn increase PM emissions and vice versa. Although this tradeoff still exists from an engine perspective, exhaust aftertreatment systems such as selective catalytic reduction (SCR) and diesel particulate filters (DPF) provide a means to simultaneous reduce tailpipe emissions of NO_X and PM, albeit at an increased cost of technology, fuel for DPF regeneration, diesel exhaust fluid (DEF) for SCR operation, and system maintenance. In recent years, fuel consumption standards and greenhouse gas emission (GHG) standards limiting carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have created a new challenge for engine and vehicle manufacturers; maintain low NO_X, PM and other regulated emissions while reducing fuel consumption which have historically

* Corresponding author. Tel.: +1-304-293-0650; fax: +1-304-293-6689.
E-mail address: Daniel.Carder@mail.wvu.edu

Peer-review under responsibility of organizing committee of the 24th International Congress of Theoretical and Applied Mechanics
doi:10.1016/j.piutam.2017.03.015

speaking opposed each other. These laws have forced manufacturers to continually innovate and look to new strategies and technologies to meet current and future regulations.

Nomenclature

CAC	Charge Air Cooling
CAFEE	Center for Alternative Fuels Engines and Emissions
CH_4	Methane
CI	Compression Ignition
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
GHG	Greenhouse Gas
HC	Hydrocarbon
HD	Heavy-Duty
L	Liter
LD	Light-Duty
LNT	Lean NO_X Traps
MD	Medium-Duty
N_2O	Nitrous Oxide
NO_X	Oxides of Nitrogen
ON	Octane Number
PM	Particulate Matter
RCCI	Reactivity Controlled Compression Ignition
SCR	Selective Catalytic Reduction
WHR	Waste Heat Recovery
WVU	West Virginia University

2. Compression Ignition Emission Standards and Current Compliance Solutions

NO_X and PM were arguably the most challenging regulated emissions to control for CI engines prior to GHG emissions standards. Since 1990, emissions standards for NO_X and PM from medium-duty (MD) and heavy-duty (HD) diesel engines have decreased by approximately 97 and 98 percent, respectively [1]. Until the implementation of the current PM and NO_X standards for MD and HD engines, which were phased in from 2007 to 2010, these emissions were primarily controlled in-cylinder and in some instances with diesel oxidation catalysts (DOC). To meet the current standards, engine manufacturers have developed complex engine and after-treatment technologies. Diesel engines typically operate at a lean air-to-fuel ratio, one of the reasons for their superior fuel economy when compared to spark ignited engines that generally operate at a stoichiometric air-to-fuel ratio. Lamentably, this lean operation is not conducive to the use of well-established three-way catalysts (used to control NO_X, carbon monoxide and hydrocarbons from SI engines) for NOx abatement and requires the use of more complex technologies such as SCR. SCR, while very effective at reducing NO_X from CI engines, requires a large catalyst and a reductant fluid, DEF, which must be refilled periodically. Less intrusive technologies such as NO_X storage catalysts or lean NO_X traps (LNT) have been explored and commercially implemented, however their success has been marginal at best, linked to an emissions cheating scandal, and ultimately most manufacturers have come to rely on SCR. Additionally, diesel engines predominantly feature direct injection and stratified combustion which can result in the formation of soot or PM, which on the exhaust side must be controlled with technologies such as a DPF. Furthermore, these engines and their emissions control subsystems must comply with emissions standards for “useful life” periods of up to 435,000 miles, all while retaining the fuel efficiency and durability for which diesel engines are renowned.

3. GHG and Fuel Economy Standards

In August 2011 the first federally mandated GHG and fuel consumption standards for medium and heavy-duty vehicles were adopted [2]. The GHG portion of the standard pertains to CO_2, N_2O, and CH_4 exhaust emissions. Phase 1 of these standards became applicable in 2014, with stringency increasing through Phase 2 which will cover model years 2021 through 2027. Based on the fact that complete combustion of a hydrocarbon fuel entails chemically converting that fuel to CO_2, a reduction in CO_2 emissions is essentially accomplished by a reduction in fuel consumption. The intersection of these standards with existing pollutant standards, especially for NO_X emissions, presents a challenge to manufacturers. Engine based technologies that reduce engine-out NO_X emissions, such as exhaust gas recirculation (EGR) and certain injection strategies, are typically associated with CO_2 emissions and fuel economy penalties. Placing further reliance on after-treatment systems to reduce NO_X emissions can increase the consumption of reductants such as DEF for SCR systems, and present duty-cycle challenges with respect to fatigue and warranty concerns. In summary the implementation of these aftertreatment technologies and GHG regulations has shifted the conventional NO_X versus PM tradeoff for diesel engines to a NO_X versus fuel consumption, DEF consumption, and durability tradeoff.

Perhaps adding to the challenges that lie ahead, regulations for light-duty (LD) diesel engines differ from heavy-duty in that they are certified in a vehicle on a chassis dynamometer. Consequently, LD diesel vehicles must meet the same standards as their gasoline counterparts with the same regulatory classification (tier and bin). LD vehicles must also comply with GHG and fuel economy standards for which a 2^{nd} phase of increased stringency is to be phased in from 2017 to 2025 [3]. As emissions regulations progressed into the 21st century, the emissions reduction technologies for LD diesel vehicles had not commercially progressed as quickly as those for gasoline vehicles. This resulted in very few diesel vehicle models being offered in the United States and ultimately less domestic research and development compared to LD gasoline engines. Introduction and improvement of LNT and SCR technologies has helped to increase light-duty diesel vehicle market-shares today. However, the recent Volkswagen emissions scandal has insinuated that LNTs are not as efficient as claimed, which leaves few options other than SCR systems. Compared to LNT, SCR systems occupy more space, require more equipment and DEF to be carried on LD vehicles where space is already at a premium. These developments have also spawned regulatory agencies to announce future changes regarding certification and compliance programs targeting “off cycle” (e.g. real world driving conditions) emissions and fuel consumption.

4. Strategies and Technologies to Maintain Low Regulated Emissions while Adhering to GHG and Fuel Economy Standards

A multitude of strategies and technologies are being investigated as potential pathways to ensure compliance with regulated emissions while reducing fuel consumption. The Department of Energy's SuperTruck program has demonstrated that accomplishing this task must include a multipronged, holistic vehicle approach that includes reducing aerodynamic drag, overall vehicle weight, drivetrain and road friction losses, and increasing powertrain efficiency. However, not all of these approaches are applicable to all vehicles, for example vocational applications such as refuse trucks or city buses likely will not achieve the same fuel consumption benefit from aerodynamic improvements as a long haul tractor-trailer would. Thus, improvement of powertrain efficiency remains a vital tool in reducing fuel consumption.

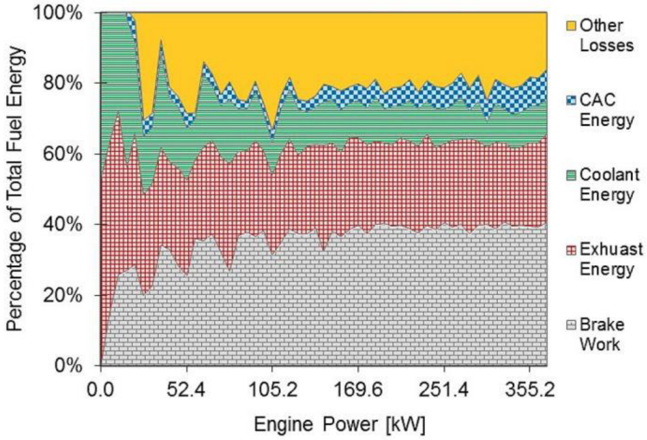

Figure 1: Energy Audit from 13 L HD Diesel Engine [4]

With regards to fuel efficiency CI engines generally have an inherent advantage over SI engines due to their lean operation, higher compression ratios, and lack of throttles in the intake stream. However, further improving that efficiency is a continual research focus. Figure 1 displays the results of an energy audit performed on a 13 liter (L) HD diesel engine. The results demonstrate that as a percentage of the total fuel energy input to the engine, approximately 40 percent is converted to brake work. A significant amount of energy is dissipated through the exhaust, cooling system, charge air cooling system (CAC), and other losses, which includes friction, pumping losses, accessory loads, etc.

4.1. Waste Heat Recovery

As demonstrated in Figure 1, there exists several waste heat sources in which fuel energy input to the engine could be theoretically recovered. Energy dissipated through the exhaust system is one of the largest waste heat sources and as such has been targeted by researchers as an optimal source of energy recovery. Two predominant approaches are thermoelectric generators and Rankine cycle systems. Thermoelectric generators offer a relatively simple approach to recovery energy, however their thermal efficiency is still low, typically in single digits of percent. Rankine cycle based waste heat recovery (WHR) systems are more complex, but offer more potential for energy recovery. Several variations of these systems have been developed, but the concept is the same; extract thermal energy from a waste heat source to a working fluid and expand that working fluid across a turbine. The mechanical output of the turbine can be connected directly to a generator or to the engines flywheel or drivetrain. While both thermoelectric generators and Rankine cycle WHR systems offer the potential to improve engine efficiency the technologies have not become cost prohibitive for commercial implementation. An additional obstacle to their implementation is exhaust aftertreatment systems and the engine itself must remain warm enough to operate effectively. For example, if too much thermal energy is extracted from the exhaust prior to the SCR catalyst, NO_X reduction efficiency may decrease such that the powertrain is no longer in compliance with emissions regulations.

4.2. Electrical Hybridization

Electrical hybridization is a commercially available technology that can be found on many LD to HD on-road vehicles. Fuel economy benefits, while depending on the architecture of the hybrid system, are typically realized at lower speed, and stop and go operation where the electric motor and energy storage system can capture regenerative braking energy. Other benefits of these systems include electrification of engine accessories such as air conditioning, power steering, coolant pump, etc. which provides the ability to shut down the engine when the vehicle is stopped (start/stop technology) or at low speeds and use stored energy for the accessories and vehicle propulsion. The added cost and complexity of these systems have driven the development of partial hybridization systems, which lack the ability to propel the vehicle, but still allow for electrification of accessories and start/stop technology. These systems in essence use an oversized alternator/generator which in certain instances also acts as starter motor for the engine. They also incorporate an energy storage system, most commonly in the form of a larger battery or battery pack. One attractive aspect of such systems is the enlarged energy storage system or battery can be used to supply energy to pre-heat and maintain the temperature of after-treatment components. When catalyst temperatures are not high enough to effectively convert regulated emissions species electrical heaters could be used to pre-heat or maintain satisfactory operating temperatures. This technology could become critical as emissions regulations continue to tighten and the mitigation of cold start or low load emissions (i.e. insufficient catalyst temperature) becomes essential to regulatory compliance.

4.3. Advanced Combustion Regimes

Advanced combustion research has been on-going for several decades. Notable advanced combustion strategies include homogenous charge compression ignition, premixed charge compression ignition, low temperature combustion, and reactivity controlled compression ignition (RCCI), among others. Although differences in the approach and control of these strategies exist, the general purpose behind them is the same; achieve a lean homogeneous or near homogenous air and fuel mixture and achieve combustion at low temperatures with multiple ignition points and limited flame propagation. The homogenized air and fuel mixture limits soot formation while combustion at lower temperatures reduces thermal NO_X formation. Lean air-to-fuel ratios, multiple ignition points and limited flame propagation reduces heat transfer to the combustion chamber boundaries which maintains high thermal efficiency. In the late 1990s and early to mid-2000s there were significant research efforts focused on using advanced combustion strategies to meet the impending low NO_X and PM emissions regulations for CI engines without extensive aftertreatment systems. Ultimately the challenges of advanced combustion strategies, primarily limitations of minimum and maximum engine load, cycle-to-cycle variability, and elevated hydrocarbon (HC) and carbon monoxide (CO) emissions, proved insurmountable for widespread commercial adoption.

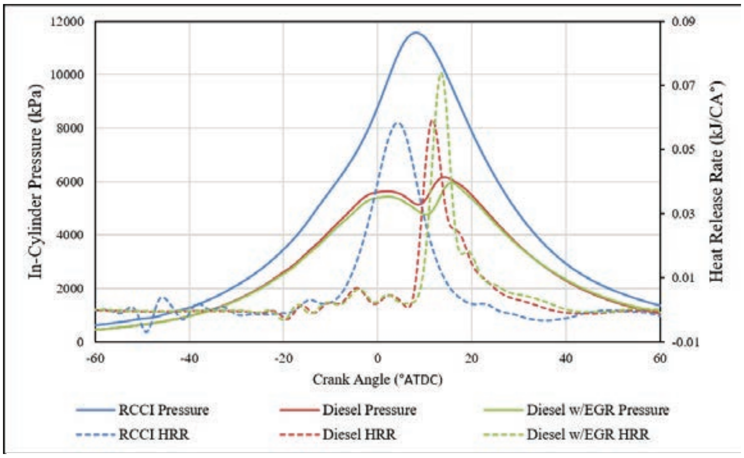

Figure 2: In-Cylinder Pressure and Heat Release Rate from RCCI and Conventional Diesel Combustion

The limiting factor for increasing the operable load range of advanced combustion regimes is in-cylinder pressure and pressure rise rates. Figure 2, which presents in-cylinder pressure and heat release rate traces for RCCI and conventional diesel combustion, with and without exhaust EGR, demonstrate the elevated pressure and pressure rise rates that constrain engine load. Additionally, lean operation and enhanced mixing often leads to unacceptable cycle-to-cycle variability that can create drivability issues. Despite these challenges advanced engine hardware and control technologies are providing the means to overcome and push the limitations of advanced combustion. A prime example is RCCI (Figure 2), a form of dual fuel combustion utilizing a high reactivity, i.e. high cetane number (CN) fuel and a low reactivity, i.e. high octane number (ON) fuel mixed at such a ratio used to provide optimal combustion phasing. This approach allows the final reactivity of the fuel mixture to be tailored specifically to the speed and load point at which the engine is operating and effectively provides another means of combustion phasing control which extends the range of low NO_X, soot, and high efficiency RCCI operation. Furthermore, advanced engine hardware such as variable compression ratio, variable valve timing, and advanced air handling and fuel injection technologies also provide opportunities to extend the load range of advanced combustion strategies and meet current challenges to commercial adoption.

One encouraging and potentially influential technology for not only advanced combustion, but also conventional combustion is closed loop combustion control. In-cylinder pressure measurement hardware and controller processing power has advanced to the level where this technology has become commercially viable. Using feedback from in-cylinder pressure measurements, engine subsystems (fuel injection, intake manifold pressure and temperatures, valve timing, compression ratio, etc.) can be controlled to prevent dangerous in-cylinder pressures, ensure stable combustion from cycle to cycle, and provide the best combustion characteristics for high fuel efficiency and minimal regulated emissions.

4.4. Advanced Engine Technologies and Architectures

Advanced engine technologies such as those mentioned previously, can not only provide a means to enable and extend advanced combustion regimes, but also benefit conventional combustion. The ability to alter an engines compression ratio during operation, be it static or dynamic, allows the manufacturer to tune for optimum efficiency and performance. Variable valve technology is a commercially available technology found on many existing LD engines that typically provides earlier or later intake valve opening and closing. Concepts to alter the static compression ratio, i.e. adjusting the clearance volume, have been developed and allow for more significant compression ratio changes. In addition to efficiency and performance benefits, such systems also provide a pathway to operate efficiently on a wide range of fuels with significantly different fuel property values, such as CN or ON.

Previously researched technologies are also being reinvestigated for new efficiency gains. One example is variations of two stroke engines. The prevalence of two stroke engines has slowly diminished primarily due to emissions control concerns, however their power density and high efficiency in conjunction with exhaust aftertreatment advances has provided renewed interest. One variation of 2 stroke technology is linear engines, which contain a combustion chamber at opposing ends with no reciprocating crankshaft. A linear engine with an incorporated alternator for power generation is currently being developed at WVU. Another technology that eliminates extra strokes or processes for charge intake and exhaust are rotary engines. Again, touted for their efficiency and power density, rotary engines are once again being investigated as other technological advances have improved their reliability and performance potential.

4.5. Fundamental Combustion Research and Modeling

Advanced combustion concepts have demonstrated promise, however fundamental understanding of fuel-air mixing, ignition delays and control of in-cylinder pressure rise rates are key in the translation of such strategies to production platforms. Furthermore, understanding of fundamental combustion characteristics is essential to produce and maintain accurate combustion models. Combustion modeling has proven to be a less time consuming and cost effective method of developing new technologies and combustion control strategies. WVU's Advanced Combustion Laboratory contains two optical engines, other single cylinder research engines, and a constant volume combustion bomb. These tools can be used to verify the results of modeling efforts, as well as investigate new fuels and technologies.

4.6. Bio-derived and Alternative Fuels

Bio-derived and alternative fuels present an opportunity to reduce CO_2 emissions and in certain instances NO_X, and PM emissions, when compared to petroleum derived diesel fuel. Although benefits in these exhaust constituents have been realized, increased CO and HC emissions have been observed during recent studies performed at WVU from i) biodiesel fuels investigated for the U.S. Navy and ii) dual-fuel diesel-natural gas retrofit kits for heavy-duty diesel engines. There can also be challenges related to the implementation of biodiesel in fueling systems designed for petroleum based diesel fuel as well as bio fuels for SI engines such as ethanol. Adding to the challenges of widespread implementation, bio-derived diesel fuel is often costlier to produce than petroleum derived diesel and with the currently low petroleum prices, investment in natural gas as a transportation fuel has also declined. None the less, bio-derived fuels and other alternative fuels have reemerged as a means to meet GHG emissions standards, comply with renewable fuel standards, achieve optional low NO_X standards, and facilitate advance combustion regimes. In fact, the first midrange engine to comply with California's optional low NO_X emissions standard (0.02 g/bhp-hr) while meeting current GHG regulations was the Cummins ISL-G Near Zero natural gas SI engine [5].

Hydrogenated vegetable oil (HVO) based renewable diesel is another form of bio-derived diesel fuel that has been commercially introduced. It is produced by hydrogenation, a process that is already used at petroleum refineries to remove sulfur and other containments from crude oil. Its properties more closely resemble petroleum based diesel than those of conventional bio-diesel produced from transesterification. Furthermore, HVO renewable diesel has a very high CN, in the range of 70 to 95, whereas petroleum derived diesel fuel exhibits a CN around 45 to 50. This high CN can be advantageous for NO_X emissions and the lower carbon content of this fuel, as well as other bio-derived and alternative fuels make their combustion less susceptible to soot production. The high CN of HVO renewable diesel coupled with the high ON of natural gas is especially well suited for RCCI, where it has been demonstrated by WVU researchers that a larger reactivity difference between the two fuels can extend the operable load range while sustaining low NO_X and soot emissions and high thermal efficiencies.

RCCI and conventional dual fuel technology (e.g. diesel and natural gas) offer a pathway to utilize domestically abundant natural gas reserves in CI engines. In addition to the availability from large scale natural gas reserves in the shale gas region, the production of bio-methane from biomass has significantly increased as well. As of 2015 there were 645 operational landfill gas plants in the U.S. Waste Management estimates renewable natural gas could provide 25% lower diesel fuel consumption in the state of California [6]. However, alternative fuel approaches, such as dual-fuel diesel-natural gas CI, and dedicated natural gas engines are often associated with high levels of CH_4 exhaust emissions that are not easily reduced by after-treatment based on current CH_4 catalyst technologies. Ultimately, reducing the global warming potential of natural gas vehicle exhaust is the key to promoting natural gas technology over traditional diesel technology.

5. Conclusion

The CI engine will remain the primary workhorse of the economy for the foreseeable future. However, currently available powertrain technology heavily depends on after-treatment systems to reduce regulated pollutants to the required low levels. This poses a challenge, especially for applications subjected to lower engine operating loads such as drayage operation around ports, refuse hauling and urban driving, where after-treatment components experience lower than optimal thermodynamic exhaust gas conditions. In order to achieve high pollutant reduction efficiencies exhaust gas temperatures are being raised via thermal management strategies that in most cases adversely affect fuel consumption which stands in direct contrast to increasingly stringent fuel economy requirements by the U.S. Environmental Protection Agency. Additionally, projected improvements in thermal engine efficiencies will further escalate this problem by reducing exhaust gas temperatures. This discrepancy between improved energy efficiency and low emissions shows the need for a multifaceted approach between improvements in combustion strategies leading to reduced engine-out emissions rates, development of advanced fuels that enable and support advanced combustion regimes, advanced engine technologies, and finally after-treatment systems that are capable of efficiently mitigating regulated emissions at a broad range of exhaust temperatures.

References

[1] W. J. Charmley, "The Federal Government's Role in Reducing Heavy Duty Diesel Emissions," in SAE Commercial Vehicle Engineering Conference & Exhibition, Rosemont, 2004.
[2] ECOpoint Inc., "Heavy-Duty Vehicles: GHG Emissions & Fuel Economy," September 2011. [Online]. Available: https://www.dieselnet.com/standards/us/fe_hd.php. [Accessed 10 January 2016].
[3] Environmental Protection Agency, “Regulations and Standards: Light-Duty” February 2016. [Online]. Available: https://www3.epa.gov/otaq/climate/regs-light-duty.htm. [Accessed 21 July 2016].
[4] S. Pradhan, A. Thiruvengadam, P. Thiruvengadam, M. Besch, D. Carder, “Investigating the Potential of Waste Heat Recovery as a Pathway for Heavy-Duty Exhaust Aftertreatment Thermal Management,” SAE Technical Paper, 2015-01-1606.
[5] Cummins Westport Inc., “ISL G Near Zero.” [Online]. Available: http://www.cumminswestport.com/models/isl-g-near-zero. [Accessed 21 July 2016].

[6] California Natural Gas Vehicle Coalition, "NGVs Run on Low-Carbon Renewable Fuel," 2016. [Online]. Available: http://www.cngvc.org/why-ngvs/renewable-fuel.php. [Accessed 23 July 2016].