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# Dual-Fuel Combustion

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## Abstract

The implementation of a dual-fuel combustion strategy has recently been explored as a means to improve the thermal efficiencies of internal combustion engines while simultaneously reducing their emissions. Dual-fuel combustion is utilized in compression ignition (CI) engines to promote the use of more readily available gaseous fuels or more efficient, advanced combustion modes. Implementing dual-fuel injection technologies on these engines also allows (1) for improved control of the combustion timing by varying the proportion of two simultaneously injected fuels, and (2) for the use of more advanced combustion modes at high load since the two injected fuels ignite in succession reducing the high peak pressures that generally act as a limiting factor. In spark-ignited (SI) engines, the implementation of a dual-fuel combustion strategy serves as an alternative approach to avoid engine knock. The dual-fuel SI engine relies on the simultaneous injection of a low knock resistance and high knock resistance fuel to dynamically adjust the fuel mixture's resistance to knock as required. The dual-fuel SI engine thereby successfully suppresses knock without compromising the engine efficiency. This chapter discusses the technological advancements associated to dual-fuel combustion and the respective gains in fuel efficiency and emissions reductions that have been achieved.

**Keywords:** dual-fuel, RCCI, alternative fuels, natural gas, ethanol, knock suppression

## 1. Introduction

Energy demands in the transportation sector are increasing due to a growing population and simultaneously economic policies are aiming to improve efficiency and reduce hazardous pollutant emissions including nitrogen oxides (NO<sub>x</sub>), unburned hydrocarbons (UHC) and particulate matter (PM). This has led to a great deal of interest in vehicle electrification as well as cleaner and more efficient engines. While vehicle electrification and hybridization has been growing, the cost and energy density limitations of batteries still pose challenges. As such, it is predicted that internal combustion engines will still power 60% of light-duty vehicles in 2050 [1] and the heavy-duty market will likely be mainly powered by engines for the foreseeable future.

In order to abide by the stringent emissions regulations and deliver power efficiently, there is a need for clean, high efficiency engines. A variety of strategies have been investigated in order to improve the efficiency of today's engines. These include technologies such as variable valve timing that aim to reduce pumping losses associated with the gas exchanges process and variable geometry turbochargers that seek to harness exhaust energy to improve the power density of engines. In addition, more advanced fuel injection systems have also been

implemented in order to inject fuel at higher pressures and thereby promote fuel and air mixing. Improved mixing will increase the combustion efficiency and also reduce emissions of particulate matter. More complex fuel injection systems can also be used in order to develop dual-fuel combustion strategies.

Dual-fuel combustion strategies have been demonstrated to be advantageous on both spark-ignited (SI) and compression-ignited (CI) engines. On SI engines, dual-fuel technologies can be leveraged to combat knock. Knock typically occurs in high temperature and high pressure in-cylinder conditions at which the fuel-air mixture will auto-ignite creating pressure shock waves in the cylinder. Knock can significantly damage the engine and is most prevalent at high loads where the efficiency reaches its peak. As such, high efficiency engine performance with gasoline fuel is often limited by knock. In high load conditions, the engine combustion phasing is often delayed to a suboptimal timing in order to avoid knock. While this allows harmful premature combustion to be avoided, it also leads to reductions in efficiency.

Alternatively, knock can also be prevented by using a fuel with a higher octane number (typically described by the research octane number (RON), motor octane number (MON) or anti-knock index (AKI)). Fuels with a high octane rating will be able to operate at the optimal combustion phasing even at high loads, but are more expensive. If high octane fuels are used in dual-fuel engines, they can enable a technique known as “octane-on-demand”. Octane-on-demand strategies are often implemented on engines with dual-fuel capabilities by using both a low RON fuel and a high RON fuel simultaneously [2–5]. With dual-fuel capabilities, the fuel mixture’s knock resistance can be changed in real time to avoid knock while maintaining optimal combustion phasing. Such methods also allow fuel cost to be minimized since a less expensive, low RON fuel can be used in the lower operating conditions and the high RON fuel can be used only in knock-prone conditions.

On CI engines, dual-fuel injection methods have historically been used for retrofitting old diesel engines with a cheaper fuel. In addition to the utilization of an alternative power source, the implementation also enabled reductions in PM emissions. More recently, dual-fuel injection methods have been used to promote the utilization of less reactive fuels and facilitate more advanced combustion strategies. Some dual-fuel combustion modes have shown significant promise and operate with high efficiency and low pollutant output. This is often achieved over a wide operating range by simultaneously utilizing two fuels with differing reactivities to promote premixing of the fuel or create stratification of the reactivity of the in-cylinder mixture [6, 7].

While these dual-fuel combustion modes show promise, they are not currently utilized in many production vehicles, due to a variety of challenges including difficulties with controlling combustion phasing and combustion stability with the more complex combustion strategy as well as consumer acceptance and infrastructure limitations. Currently, most of these dual-fuel combustion strategies are studied in closely monitored laboratory environments on single cylinder engines. Once removed from the laboratory and implemented on multi-cylinder engines, combustion variations and phasing challenges begin to dominate [8–10]. One such challenge is the occurrence of more significant cylinder-to-cylinder variations that can lead to inconsistent power production and potentially damaging engine conditions. In addition, on CI engines, many dual-fuel combustion strategies leverage a more premixed combustion and as such, the timing of the combustion event is controlled by the chemical kinetics. This makes it more challenging to properly time the combustion event. More advanced control methodologies are required to reduce these combustion variations and ensure an optimal combustion phasing.

Dual-fuel engines have the potential to be highly efficient and clean, but their usage may also be limited by consumer acceptance and infrastructure challenges. Users will have to fill two fuel tanks and will need access to the needed fuels in a broad enough region. This chapter will discuss the technological developments that led to today's dual-fuel engines, and the advancements that have been made on dual-fuel CI and SI engines.

## 2. Technology overview

The concept of the dual-fuel engine has been around almost as long as the Gasoline (Otto) and Diesel engine. Following the development of Nikolaus Otto's spark-ignited engine, the desire to improve the thermal efficiency by increasing the engine compression ratio led to the development of Rudolf Diesel's compression-ignited engine. Subsequently, interest in better controlling the ignition and regulating the combustion led Rudolf Diesel, himself, to propose a dual-fuel combustion strategy and patent his invention in 1901 [11]. Today, the idea has been leveraged to promote the use of gaseous fuels such as natural gas in diesel engines and for the development of advanced combustion strategies that take advantage of the ability to dynamically optimize the properties of the fuel mixture (by controlling the proportion between the injected fuels) based on the operating conditions. Such implementations of the dual-fuel combustion strategy promise significant gains in fuel efficiency as well as reductions in toxic emissions. Nevertheless, most of the benefits associated with dual-fuel combustion have been primarily explored in academic and research institutions under strictly regulated conditions; the technology currently still faces significant challenges and limited acceptance, which restricts its market penetration.

This section aims to provide an overview of the development of the dual-fuel engines by specifically reviewing the history behind the technology and discussing examples of current and past dual-fuel engines in production. The subsequent sections will discuss ongoing research on dual-fuel engines and its expected role in the near and far future.

### 2.1 Brief history

In a patent application filed on April 6, 1898, Rudolf Diesel proposes that “if a given mixture is compressed to a degree below its igniting-point, but higher than the igniting-point of a second or auxiliary combustible, then injecting this latter into the first compressed mixture will induce immediate ignition of the secondary fuel and gradual combustion of the first mixture, the combustion after ignition depending on the injection of the igniting or secondary combustible” [11]. This patent entitled *Method of Igniting and Regulating Combustion for Internal Combustion Engines* was accepted in 1901 and marks one of the initial efforts to introduce and successfully ignite a less reactive gaseous fuel in a 4-stroke internal combustion engine using a second fuel. Similarly, today, the ability to ignite a premixed charge (ex: air and a low reactivity fuel such as natural gas) with a secondary high reactivity fuel (such as Diesel) or interchangeably solely operating on the high reactivity fuel is one of the important characterization of a dual-fuel combustion strategy.

For several years, the dual-fuel engine was not used commercially due to its mechanical complexity and rough running caused by auto-ignition and knocking. The first commercial dual-fuel engine was only produced in 1939 by the National Gas and Oil Engine Co. in Great Britain. The engine, fueled by town gas or other types of gaseous fuels, was relatively simple to operate and was mainly employed

in some areas where cheap stationary power production was required [12]. During the Second World War, the shortage of liquid fuels attracted further interest in dual-fuel engines from scientists in Great Britain, Germany and Italy. Some diesel engine vehicles were successfully converted to dual-fuel and the possible application of dual-fuel engines in civil and military areas were also explored. Different kinds of gaseous fuels, such as coal gas, sewage gas or methane, were employed in conventional diesel engines during this time [13]. After the Second World War, due to economic and environmental reasons, dual-fuel engines have been further developed and employed in a very wide range of applications from stationary power production to road and marine transport, including long and short haul trucks and busses [12].

In 1949, Crooks, an Engineer at The Cooper-Bessemer Corporation—one of the main engine manufacturers during World War II, presented experimental work with a dual-fuel engine that claimed to have led to the most efficient engine known with a thermal efficiency of 40% at full load. He further highlights that the dual-fuel engine has led to “an extremely economical source of power having an extremely low maintenance cost” [14]. The potential of utilizing relatively cheap gaseous fuel resources and simultaneously benefitting from high thermal efficiencies have promoted the conversion of a conventional compression ignition engine to dual fuel operation. Nevertheless, important limitations still persist: (1) at high loads, the power output and efficiency was limited by the onset of autoignition and knock with most common gaseous fuels, (2) the combustion process in dual-fuel engine is highly sensitive to the type, composition, and concentration of the gaseous fuel being used, and (3) at light load operation, the dual-fuel engine exhibits a greater degree of cyclic variations in performance parameters such as peak cylinder pressure, torque, and ignition delay [13].

A great deal of research is still being undertaken to understand and overcome the challenges associated with the operation of dual-fuel engines. A promising endeavor consists of successfully harnessing the benefits of the dual-fuel engine in the automotive industry.

## **2.2 Dual-fuel in the modern automotive industry**

In a book chapter entitled ‘The Dual-fuel Engine’ published in 1987, Ghazi A. Karim who had previously conducted several studies [15–20] on the topic of dual-fuel engines suggests that although dual-fuel engine has been employed in a wide range of stationary applications for power production, co-generation, compression of gases and pumping duties; the implementation in mobile applications “remain a field of urgent long term research that can have the potential for opening widely the market for the dual-fuel engine and the increased exploitation of gaseous fuel resources, particularly in the transport sector” [21].

Indeed, the implementation of dual-fuel technology has been more favorable in stationary and heavy-duty applications as opposed to mobile and light-duty applications. Yet, the opportune long-term research proposed by Karim for the transportation sector is still on-going. More recently, efforts to diversify the energy resources of the transportation industry have motivated researchers and engine manufacturers alike to investigate opportunities to leverage the dual-fuel combustion strategy. Furthermore, government imposed regulations on engine-out emissions and fuel efficiency targets have propelled the search for innovative engine technologies including novel implementations of the dual-fuel concept.

In more recent years, a research group at the University of Wisconsin-Madison proposed the implementation of a dual-fuel combustion strategy to reduce Nitrogen Oxide (NO<sub>x</sub>) and Particulate Matter (PM) emissions [6, 7, 10, 22]. The combustion

strategy called Reactivity Controlled Compression Ignition (RCCI) promises significant pollutant reductions as well as impressive fuel efficiency gains. RCCI uses in-cylinder fuel blending with at least two fuels of different reactivity and multiple injections to control in-cylinder fuel reactivity to optimize combustion phasing, duration and magnitude. The process involves introduction of a low reactivity fuel into the cylinder to create a well-mixed charge of low reactivity fuel, air and recirculated exhaust gases. The high reactivity fuel is injected before ignition of the premixed fuel occurs using single or multiple injections directly into the combustion chamber [22].

Kokjohn et al. [6] compared the performance of a conventional diesel combustion and a dual-fuel RCCI combustion. Their study showed the implementation of a dual fuel combustion strategy yielded a reduction in NO<sub>x</sub> by three orders of magnitude, a reduction in soot by a factor of six, and an increase in gross indicated efficiency of 16.4%. Splitter et al. [7] demonstrated on a dual-fuel RCCI engine that optimizing in-cylinder fuel stratification with two fuels of large reactivity differences achieved gross indicated thermal efficiencies near 60%. Furthermore, they showed through simulations studies that a dual-fuel combustion strategy rejected less heat, and that ~94% of the maximum cycle efficiency could be achieved while simultaneously obtaining ultra-low NO<sub>x</sub> and PM emissions.

Similar motivations to boost the thermal efficiency of engines have led to the implementation of a dual-fuel strategy in light duty-spark ignited engines as well. Initially proposed as an engine concept in 2005 by Cohn et al. [3], the dual-fuel spark-ignited engine featured two fuel injections systems—one for conventional gasoline and another for ethanol. The engine would promote the utilization of alternative fuels such as ethanol reducing the dependence on fossil fuels, and it was an alternative knock suppressing strategy which allows for higher load and higher efficiency operations. A high octane rating fuel such as ethanol is used in conjunction with the conventional fuel, gasoline, to dynamically adjust the fuel mixture's resistance to auto-ignition based on the operating conditions.

The studies by Cohn et al. [3] suggested dual-fuel combustion could potentially increase an SI engine's drive cycle efficiency by approximately 30%. Similar studies by Daniel et al. [4] demonstrated that dual-injection showed benefits to the indicated efficiency and emissions at almost all loads compared to a single fuel gasoline direct injection (GDI) strategy. Furthermore, Chang et al. [77] showed a maximum 30% Well-to-Wheels (W-t-W) CO<sub>2</sub> equivalent reduction can be achieved by utilizing a dual-fuel injection system. Numerous studies, such as [23–25], continue to explore the benefits that can be achieved through the introduction of dual-fuel combustion in the modern automotive engines.

In the next sections, the application and benefits of dual-fuel combustion are separately discussed for compression-ignition and spark-ignited engines followed by concluding remarks.

### **3. Dual-fuel compression-ignition engines**

Diesel or compression-ignition engines dominate the medium and heavy-duty markets due to their higher efficiency and high torque production capabilities. Such engines require a more reactive fuel that will auto-ignite at high pressures and temperatures. This limits the fuels that can be leveraged on CI engines. Dual-fuel engines provide a way to use less reactive fuels since they can leverage a second more reactive fuel to produce ignition. In addition, dual-fuel concepts have also been investigated as a way to reduce engine emissions. Conventional diesel combustion is diffusion controlled and is typically accompanied by high nitrogen oxide

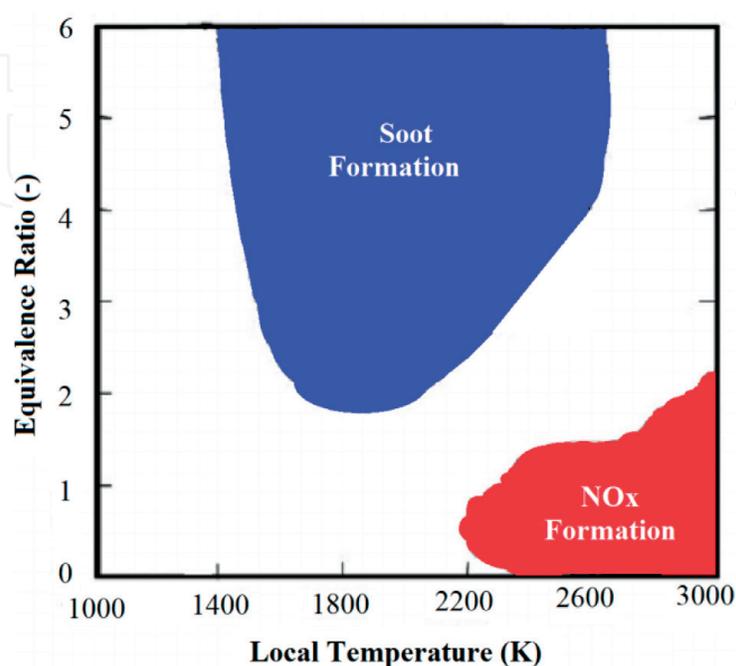
(NO<sub>x</sub>) and particulate matter (PM) emissions [26]. Nitrogen oxide emissions result from high in-cylinder temperature conditions which promote the combination of nitrogen (carried in with the fresh air) with excess oxygen [27]. Meanwhile, particulate matter or soot is produced in fuel rich regions when hydrocarbon species agglomerate [27, 28]. As such, high local equivalence ratios can lead to soot formation and high local temperatures can lead to NO<sub>x</sub> formation as shown in **Figure 1**. In order to avoid these problematic regions, many dual-fuel, heavy-duty CI engines attempt to operate in conditions which promote premixing of the fuel and air and/or achieve in-cylinder stratification in order to reach high efficiencies and low emissions. By enabling a more premixed combustion, rich regions where PM would be produced can be nearly eliminated and shorter combustion durations are achieved which reduces local temperatures and thereby, NO<sub>x</sub> emissions [6, 7, 29–33].

As such, dual-fuel engines have been pursued in the heavy-duty market for two main reasons:

1. As a way to leverage more readily available but less reactive fuels as the primary power source and use a high reactivity fuel to initiate combustion.
2. As a way to introduce fuels of varying reactivities and create a more complex combustion mode that can be more efficient and produce less NO<sub>x</sub> and PM.

### 3.1 Conventional dual-fuel compression-ignition engines

As the world seeks to become less reliant on conventional diesel and gasoline, there has been increasing interest in using fuels such as natural gas in engines. Some of these fuels are less reactive than conventional diesel fuel and therefore, are more challenging to use on compression-ignition engines where auto-ignition of the fuel is needed. Dual-fuel systems are one way to leverage less reactive fuels on heavy-duty engines [34–38]. One such fuel is natural gas and it will be focused on here as an example of the benefits and challenges of this type of engine operation.



**Figure 1.**  
*Emissions with respect to local temperature versus local equivalence ratio.*

Natural gas is more difficult to ignite than conventional engine fuels so it is more easily integrated into spark-ignited engines. On heavy-duty engines, natural gas needs an ignition source so it is typically port-injected and diesel is direct injected and serves as a pilot. Fuels that are port-injected become premixed with the air and typically exhibit a rapid combustion event that is dominated by the chemical kinetics of the combustion reaction, but fuels that are direct injected and have to mix with the air tend to have a longer combustion event that is dominated by the time taken for the air and fuel to mix adequately. Since dual-fuel engines have a fuel that is port-injected and one that is direct-injected, they often exhibit a two-stage combustion process. The portion of combustion that occurs in a premixed vs. a diffusion mode will be strongly dependent on the amount of each fuel that is used [39]. While this makes the combustion process more complicated, dual-fuel injection can provide stable combustion of a less reactive fuel like natural gas in CI engines. However, fuel economy reductions around 10% have been observed when operating in this type of mode [34].

Not only is fuel economy or efficiency impacted, but emissions are also altered with dual-fuel combustion. In natural gas-diesel dual-fuel engines, up to 60% reductions in NO<sub>x</sub> and PM have been observed [34]. However, these emissions are dependent on the fuels used as well as the amounts of each fuels used. For example, particulate matter emissions and the particle size distribution of the particulates have been shown to strongly depend on the properties of the direct-injected fuel and level of natural gas substitution. Direct injected fuels with lower densities and viscosity and higher volatility produce lower amounts of particulates [40]. However, higher natural gas substitution rates can increase soot levels since they decrease the local oxygen availability [41].

As with many natural gas engines, higher CO and UHC emissions are typically encountered. Various natural gas substitution rates have been explored in [42] and showed that only lower amounts of natural gas could be used at low load conditions due to emissions constraints, but higher fractions of natural gas could be used at high loads. Direct injection of both fuels [43], higher fuel injection pressures, and adapted engine control units [44, 45] have been implemented to avoid these emissions constraints. After treatment systems including diesel oxidation catalysts [35] as well as diesel particulate filters and urea-selective catalytic reduction systems [46] have also been introduced on dual-fuel engines to reduce emissions. However, to enable efficient use of high amounts of natural gas, more advanced combustion methods and optimization methods are likely needed [47, 48].

A majority of conventional dual-fuel engine studies have focused on natural gas, but this approach of using diesel as a pilot fuel can also be leveraged with a variety of fuels that are not reactive enough to be used as the sole fuel on a compression-ignition engine. Dual-fuel concepts have also been explored with fuel combinations including on methanol and diesel [49], biogas and biodiesel and biogas and diesel [50].

### **3.2 Advanced dual-fuel compression-ignition engines**

In order to push engines to higher efficiencies, there has been a great deal of exploration into more complex combustion modes. Many of these advanced combustion strategies attempted to premix the fuel and air in order to achieve a more efficient and clean combustion, but were only able to be leveraged in lower torque ranges [51, 52]. One strategy for expanding the operating region of these more advanced techniques is to simultaneously utilize two fuels with differing reactivities in order to further increase the combustion delay period and promote premixing in higher operating regions [53]. This strategy is known as reactivity-controlled

compression ignition (RCCI). In RCCI, a fuel with low reactivity such as gasoline is injected separately from a high reactivity diesel-type fuel. The quantities of each respective fuel can be modified so that the combustion event can be delayed to provide adequate mixing time and the desired shape of the combustion event can be achieved. Recent work in RCCI has shown that fuel properties that differ from those of conventional fuels can be leveraged to shape the combustion process and increase engine efficiency from 45% to near 60% [6, 7] in this mode. While the efficiency benefits can be significant, high CO and UHC emissions as well as high pressure rise rates can still limit the use of RCCI.

### *3.2.1 Reactivity controlled compression ignition*

RCCI-type combustion was originally studied at the University of Wisconsin-Madison using gasoline as the port-injected low reactivity fuel and diesel as the direct-injected, high reactivity fuel [7]. By leveraging two fuels with varying properties stratification of the in-cylinder mixture reactivity could be achieved leading to longer ignition delays and increased time for premixing. Diesel fuels with lower reactivities were shown to be advantageous in these operating conditions as they increase the local reactivity gradient [54, 55]. In such modes, the more reactive fuel components are consumed at a faster rate and the slower burning competent make up a larger portion of the UHC emissions [56].

The use of alternative fuels such as ethanol and natural gas in such RCCI-type operation conditions has also shown promising results and appears to better take advantage of these alternatives. Research by Navistar, Argonne National Laboratory and Wisconsin Engine Research Consultants found that using E85 as the low reactivity fuel could allow higher loads and efficiencies to be achieved with RCCI. While more traditional gasoline and diesel dual-fuel operation achieved a BMEP of 11.6 bar and brake thermal efficiency (BTE) of 43.6%, using E85 with diesel allowed operation to be extended to 19 bar BMEP with a BTE of 45.1% [57]. Later studies led by RWTH Aachen University and FEV GmbH showed that when using diesel and ethanol, higher ethanol quantities could be leveraged in lower load conditions and would provide a more stable combustion and lower UHC emissions. However, as the load was increased higher amounts of diesel were required in order to keep the cylinder pressure rise rate to an acceptable level [58].

Some of these detrimental impacts on CO and UHC emissions are able to be counteracted by more complex fuel injection strategies [59]. For example, more recent work has explored the use of ethanol port-injection with a multi-pulse direct-injection of diesel. A double pilot injection was able to reduce the UHC and CO emissions in RCCI-type conditions [60]. Other methods such as leveraging higher injection pressures have also been shown to be able to increase efficiency and provide further decreases in emissions of NO<sub>x</sub>, CO, UHC, and PM [61].

### *3.2.2 Challenges with reactivity controlled compression ignition*

While RCCI methods are promising, these modes suffer from several technical challenges. First, cycle-to-cycle and cylinder-to-cylinder variations can be more dramatic than in conventional diesel combustion [62, 63]. Since fuel and air mixing are critical and high amounts of recirculated exhaust gas are typically leveraged in these modes, small variations in the in-cylinder fuel quantities and gas mixture can lead to significant variations in the combustion process. Combating such variations is likely to require more complex control strategies and additional engine sensors [62].

Second, control of the combustion phasing of these modes is challenging since the combustion process is controlled by chemical kinetics and not directly triggered

by an injection event. Control techniques must try to maintain an optimal combustion phasing while ensuring that pressure rise rate and combustion variations do not exceed acceptable limits by monitoring the fuel blend ratio [64] and direct-injection timing [65]. Successful use of RCCI may also require switching between traditional diesel combustion at lower load and dual-fuel operation at higher load [65]. Intermediate modes such as “premixed dual-fuel combustion” and “partially premixed compression ignition” may provide clean and efficient intermediate combustion strategies that can be used on their own or in transitions from conventional diesel combustion to RCCI [66].

As discussed previously, UHC and CO emissions are often higher in RCCI modes. This is believed to be because local equivalence ratios can drop below the flammability limit of natural gas and lead to unburned hydrocarbon emissions [67], but may necessitate the development of new after treatment systems for these engines. Consumer acceptance is also a concern with dual-fuel engines. Since users may not want to fill two fuel tanks, Splitter et al. explored a method of enabling RCCI by using gasoline and the cetane improver di-tert-butyl peroxide (DTBP) [22]. This study leveraged port injected gasoline as the low reactivity fuel, but used gasoline mixed with varying amounts of DTBP as the high reactivity fuel. A peak gross ITE of 57% was achieved and emissions were similar to standard dual-fuel RCCI levels.

#### **4. Dual-fuel spark-ignited engines**

The implementation of dual-fuel combustion strategies on medium and heavy-duty engines have primarily been discussed in the preceding section. These utilizations of dual-fuel combustion strategies are generally restricted to compression-ignition engines where Diesel is the conventional fuel. Nevertheless, in recent years, light-duty spark ignited engines have also been configured to feature a dual-fuel combustion system. This section will discuss the implementation and utilization of dual-fuel combustion on light-duty SI engines.

In SI engines, a dual-fuel combustion strategy is also leveraged to promote the utilization of alternative fuels such as ethanol and methanol. There are increasingly numerous government imposed legislations promoting the use of biofuels in transportation [68]. Current legislation requires EU member states to conform to a 10% minimum target on the use of alternative fuels (biofuels or other renewable fuels) in transportation by 2020 [69]. In the US, tax incentives have been used to promote the use of ethanol in gasoline [70], in order to replicate the success seen in Brazil [71]. The quest to benefit from incentives or conform to legislations has led engine manufacturers to explore the implementation of dual-fuel combustion on spark-ignited engines with the utilization of biofuels and other renewable fuels.

Additionally, one of the primary motivations for the implementation of dual-fuel combustion in SI engines has also been for the development of better engine knock control techniques. Engine knock, the inadvertent auto-ignition of the fuel in localized high pressure and temperature regions inside the cylinder [72, 73], can result in significant engine damage and marks one of the main obstacles in SI engines. The conventional approach to avoiding knock in spark-ignited (SI) engines consists of delaying the combustion phasing by retarding the spark timing [74]. A combustion event occurring later in the combustion stroke (further away from top dead center) has a lower tendency to knock since the combustion pressure and temperature are lower. However, delaying the combustion phasing also reduces the fuel efficiency since less work can be extracted by the late combustion [75].

A dual-fuel combustion strategy provides SI engines with an alternative way to avoid knock without sacrificing fuel efficiency. The tendency of the fuel to

auto-ignite is not only dependent on the in-cylinder conditions, but also on the knock resistance (octane rating) of the fuel. As such, increasing the fuel's octane rating helps avoid knock without compromising fuel efficiency. Engines with dual-fuel capabilities can use a low RON fuel and a high RON fuel simultaneously to optimize the fuel mixture's knock resistance by controlling the proportion of each injected fuel. Many studies have explored the implementation of a dual-fuel strategy to suppress knock [2–5, 72–75].

The studies by Cohn et al. [3] and Bromberg et al. [76] at Massachusetts Institute of Technology proposed an ethanol boosted engine concept, which provides suppression of engine knock at high pressure through the use of direct ethanol injection. Their studies conclude that the implementation of the secondary fuel injection system could allow engine operation at much higher levels of turbocharging and could potentially increase the drive cycle efficiency by approximately 30%. Daniel et al. [4] implemented a dual-fuel strategy for knock mitigation on a single cylinder SI research engine. The study shows that dual-injection strategy (using either ethanol or methanol as the high RON fuels) showed benefits to the indicated efficiency and emissions (HC, CO, CO<sub>2</sub>) at almost all loads compared to a single fuel gasoline direct injection (GDI) strategy. Furthermore, Chang et al. [77] conducted a Well-to-Wheels (W-t-W) greenhouse gas emissions assessment to estimate the overall emissions benefits of a knock mitigating dual-fuel system. Their study showed a maximum 30% W-t-W CO<sub>2</sub> equivalent reduction can be achieved by utilizing a dual-fuel injection system.

A dual-fuel SI configuration provides three main benefits: (1) engine can be further downsized and operated in high pressure conditions (2) the fuel knock resistance can be adjusted based on operating point while maintaining an optimal combustion phasing (maximizing engine efficiency), and (3) operating points with low knock propensity can be operated with a low octane fuel, eliminating the waste of RON, which generally translates into cheaper fuel cost and lower CO<sub>2</sub> emissions [5, 77]. A team at Saudi Aramco, in collaboration with IFP Energies nouvelles, demonstrated these benefits on a production passenger vehicle [23, 78, 79]. The dual-fuel technology is identified as “an opportunity to improve fuel efficiency by using the octane only when you need it.” The researchers outline that the technology will improve fuel efficiency while reducing overall energy requirements to manufacture gasoline fuels in the future [79]. The researchers at Aramco Fuel Research Center (AFRC) identify the development of the production car as only the start, and outline the near-term objective of going from a vehicle with two tanks with two different fuels to one that only uses only one fuel and process it with an on-board fuel upgrading system.

Similar to the efforts of Saudi Aramco, there is currently a growing interest to harness the benefits of a dual-fuel combustion strategy on conventional SI engines. A study at Massachusetts Institute of Technology by Jo et al. [24] investigates the use of dual-fuel for a passenger vehicle and a medium-duty truck. Their simulation studies, coupled with experimental testing, conclude that significant gains in engine brake efficiencies can be achieved: 30% for the Urban Dynamometer Driving Schedule (UDDS) cycle and 15% for the US06 cycle. Studies by Marchitto et al. at Istituto Motori, CNR [25] demonstrate the port injection of ethanol as a secondary fuel showed a significant increase in thermal efficiency (~10%) and significant reduction in particle number emissions as well as particulate mass (60–80%).

Dual-fuel combustion provides a promising path to boost the thermal efficiency of spark-ignited engines. The opportunity to leverage alternative fuels such as ethanol and methanol, as well as the ability to suppress knock without compromising thermal efficiency, has garnered interest in the technology. Nevertheless, the

challenges associated with multiple tanks and multiple fuels require researchers to seek paths that will make the technology more accessible to everyday consumers.

## 5. Conclusion

Since the inception of the dual-fuel combustion strategy as a tool to better control combustion, its application has been most vital in stationary and heavy-duty applications. The integration of the dual-fuel combustion in the transportation industry promises great benefits both in terms of fuel efficiency improvement as well as toxic emissions reduction. Significant efforts are undertaken to implement this technology in the automotive industry for heavy-duty, as well as medium and light-duty engines. The on-going research on dual-fuel combustion promises encouraging paths that will allow the utilization of more readily available gaseous fuels and renewable fuels. The observed benefits on both compression-ignition and spark-ignited engines warrants further investments, research, and efforts to better exploit these gains on a larger scale.

In compression ignition (CI) engines, dual-fuel combustion presents an effective approach to control combustion timing and extend engine load limitations. This is achieved by injecting both a high reactivity and low reactivity fuel, adjusting the concentration of one relative to the other, and thereby optimizing the fuel mixture's reactivity (on a cycle-by-cycle basis) for different operating conditions. In spark ignited (SI) engines, the optimization of the fuel's octane rating presents an alternative approach to avoid abnormal combustion (engine knock due to auto-ignition). The conventional SI engine relies on delayed spark timings to avoid knock, which results in degraded efficiency and higher emissions. With dual-fuel combustion techniques, two fuels with high and low octane ratings can be used to adjust the fuel mixture's octane as needed to avoid knock without sacrificing the engine's efficiency.

While dual-fuel operation has many potential benefits, the implementation of these strategies on CI and SI engines also involve significant challenges. These challenges are exacerbated when dual-fuel combustion is implemented in conjunction with other advanced combustion strategies including varying valve timing, and high EGR circulation. The underlying challenges include increased combustion variations and difficulties in properly adjusting fuel mixture for effective control of combustion timing (in CI engines) and effective knock control (in SI engines). While the technology has successfully been used in stationary applications, the implementation of dual-fuel strategy on mobile applications, specifically in the transportation sector, still faces limiting challenges. In addition to the technical challenges associated with the dual-fuel engine, a primary concern for its integration in the automotive industry consists of the social resistance to the requirement of having and filling two fuel tanks. In order for the technology to successfully penetrate the automotive market, the benefit in the terms of fuel efficiency improvement and toxic emissions reduction need to clearly outweigh the technical and social challenges.

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## References

- [1] Heywood J. Not dead yet: The resilient ICE looks to 2050. Automotive Engineering, SAE International. April 2018
- [2] Baranski J, Anderson E, Grinstead K, Hoke J, Litke P. Control of fuel octane for knock mitigation on a dual-fuel spark-ignition engine. SAE Technical Paper 2013-01-0320. 2013
- [3] Cohn DR, Bromberg L, Heywood JB. Direct Injection Ethanol Boosted Gasoline Engines: Biofuel Leveraging for Cost Effective Reduction of Oil Dependence and CO<sub>2</sub> Emissions. Cambridge, MA: Massachusetts Institute of Technology; 2005
- [4] Daniel R, Wang C, Xu H, Tia G, Richardson D. Dual-injection as a knock mitigation strategy using pure ethanol and methanol. SAE International Journal of Fuels and Lubricants. 2012;5:772-784
- [5] Viollet Y, Abdullah M, Alhajhouje A, Chang J. Characterization of high efficiency octane-on-demand fuels requirement in a modern spark ignition engine with dual injection system. SAE Technical Paper 2015-01-1265. 2015
- [6] Kokjohn S, Hanson R, Splitter D, Reitz R. Fuel reactivity controlled compression ignition (RCCI): A pathway to controlled high-efficiency clean combustion. International Journal of Engine Research. 2011;12(3):209-226
- [7] Splitter D, Wissink M, Del Vescovo D, Reitz R. RCCI engine operation towards 60% thermal efficiency. SAE 2013-01-0279. 2013
- [8] Beatrice C, Avolio G, Beroli C, Del Giacomo N, et al. Critical aspects on the control in the low temperature combustion systems for high performance DI diesel engines. Oil & Gas Science Technology. 2007;62(4):471-482
- [9] Bittle J, Zheng J, Xue X, Song H, Jacobs T. Cylinder-to-cylinder variation sources in diesel low temperature combustion and the influence they have on emissions. International Journal of Engine Research. 2014;15(1):112-122
- [10] Klos DT, Kokjohn SL. Investigation of the effect of injection and control strategies on combustion instability in reactivity controlled compression ignition engines. Journal of Engineering Gas Turbines Power. 2015;138(1)
- [11] Diesel R. Method of igniting and regulating combustion for internal combustion engines. U.S. Patent 673,160, April 1901
- [12] Sahoo BB, Sahoo N, Saha UK. Effect of engine parameters and type of gaseous fuel on the performance of dual-fuel gas diesel engines—A critical review. Renewable and Sustainable Energy Reviews. 2009;13:1151-1184
- [13] Liu Z. An Examination of the Combustion Characteristics of Compression Ignition Engines Fuelled with Gaseous Fuels. Ph.D, University of Calgary; 1995
- [14] Crooks WR. The dual-fuel engine and its application to sewage treatment plants. Sewage Works Journal. 1949;21:957-961
- [15] Karim GA, Klat SR, Moore NPW. Knock in dual-fuel engines. Proceedings of the Institution of Mechanical Engineers. 1966;181:453-466
- [16] Karim GA, Khan MO. Examination of effective rates of combustion heat release in a dual-fuel engine. Journal of Mechanical Engineering Science. 1968;10:13-23
- [17] Karim GA. The ignition of a premixed fuel and air charge by pilot

- fuel spray injection with reference to dual-fuel combustion. SAE Technical Paper Series; 1968. DOI: 10.4271/680768
- [18] Karim GA. A review of combustion processes in the dual fuel engine—The gas diesel engine. *Progress in Energy and Combustion Science*. 1980;6:277-285
- [19] Karim GA, Burn KS. The Combustion of Gaseous Fuels in a Dual Fuel Engine of the Compression Ignition Type with Particular Reference to Cold Intake Temperature Conditions. SAE Technical Paper Series; 1980. DOI: 10.4271/800263
- [20] Karim GA. The Dual Fuel Engine of the Compression Ignition Type - Prospects, Problems and Solutions - A Review. SAE Technical Paper Series; 1983. DOI: 10.4271/831073
- [21] Karim GA. The dual fuel engine. In: Evans RL, editor. *Automotive Engine Alternatives*. Boston, MA: Springer US; 1987. pp. 83-104
- [22] Splitter D, Reitz R, Hanson R. High efficiency, low emissions RCCI combustion by use of a fuel additive. *SAE International Journal of Fuels and Lubricants*. 2010;3(2):742-756
- [23] Morganti K, Viollet Y, Head R, Kalghatgi G, Al-Abdullah M, Alzubail A. Maximizing the benefits of high octane fuels in spark-ignition engines. *Fuel*. 2017;207:470-487
- [24] Jo YS, Bromberg L, Heywood J. Optimal use of ethanol in dual fuel applications: Effects of engine downsizing, spark retard, and compression ratio on fuel economy. *SAE International Journal of Engines*. 2016;9:1087-1101
- [25] Marchitto L, Tornatore C, Costagliola MA, Valentino G. Impact of Ethanol-Gasoline Port Injected On Performance and Exhaust Emissions of A Turbocharged SI Engine. SAE Technical Paper Series; 2018. DOI: 10.4271/2018-01-0914
- [26] Heywood J. *Internal Combustion Engine Fundamentals*. New York, NY, USA: McGraw-Hill; 1998
- [27] Turns S. *An Introduction to Combustion: Concepts and Applications*. New Dehli, India: McGraw Hill; 2013
- [28] Mansurov ZA. Soot formation in combustion processes (review). *Combustion, Explosion and Shock Waves*. 2005;41(6):727-744
- [29] Akihama K, Takatori Y, Inagaki K, Sasaki S, Dean AM. Mechanism of the smokeless rich diesel combustion by reducing temperature. SAE International Paper 2001-01-0655. 2001
- [30] Neely GD, Sasaki S, Huang Y, Leet JA, Stewart DW. New diesel emission control strategy to meet US tier 2 emissions regulations. SAE International Paper 2005-01-1091. 2005
- [31] Caton JA. The thermodynamic characteristics of high efficiency, internal-combustion engines. *Energy Conversion and Management*. 2012;58:84-93
- [32] Ma J, Lu X, Ji L, Huang Z. An experimental study of HCCI-DI combustion and emissions in a diesel engine with dual fuel. *International Journal of Thermal Sciences*. 2008;47:1235-1242
- [33] Leermakers C, Luijten C, Somers L, Kalghatgi G. Experimental study of fuel composition impact on PCCI combustion in a heavy-duty diesel engine. SAE 2011-01-1351. 2011
- [34] Addy JM, Bining A, Norton P, Peterson E, Campbell K, Bevillaqua O. Demonstration of Caterpillar C10 dual fuel natural gas engines in

commuter buses. SAE Technical Paper 2000-01-1386. 2000

[35] Mittal M, Donahue R, Winnie P, Gillette A. Combustion and gaseous emissions characteristics of a six-cylinder diesel engine operating within wide range of natural gas substitutions at different operating conditions for generation application. SAE Technical Paper 2014-01-1312. 2014

[36] Taritas I, Kozarac D, Sjeric M, Aznar MS, Vuilleumier D, Tatschl R. Development and validation of a quasi-dimensional dual fuel (diesel-natural gas) combustion model. SAE International Journal of Engines. 2017;10(2):2017-01-0517

[37] Wurzenberger JC, Katrasnik T. Dual fuel engine simulation—A thermodynamic consistent HiL compatible model. SAE International Journal of Engines. 2014;7(1):2014-01-1094

[38] Hountalas RPD. Combustion and exhaust emission characteristics of a dual fuel compression ignition engine operated with pilot diesel fuel and natural gas. Energy Conversion and Management. 2004;45(18-19):2971-2987

[39] Ahmad Z, Aryal J, Ranta O, Kaario O, Vuorinen V, Larmi M. An optical characterization of dual-fuel combustion in a heavy-duty diesel engine. SAE Technical Paper 2018-01-0252. 2018

[40] Zhang Y, Ghandhi J, Rothamer D. Effects of fuel chemistry and spray properties on particulate size distributions from dual-fuel combustion strategies. SAE International Journal of Engines. 2017;10(4):2017-01-1005

[41] Srna A, Bruneaux G, Rotz BV, Bombach R, Herrmann K, Boulouchos K. Optical investigation of sooting propensity of n-dodecane pilot/lean-premixed methane dual-fuel combustion in a rapid

compression-expansion machine. SAE Technical Paper 2018-01-0258. 2018

[42] Garcia P, Tunestal P. Experimental investigation on CNG-diesel combustion modes under highly diluted conditions on a light duty diesel engine with focus on injection strategy. SAE International Journal of Engines. 2015;8(5):2015-24-2439

[43] Fasching P, Sprenger F, Eichlseder H. Experimental optimization of a small bore natural gas-diesel dual fuel engine with direct fuel injection. SAE International Journal of Engines. 2016;9(2):2016-01-0783

[44] Yang B, Wei X, Zeng K, Lai M-C. The development of an electronic control unit for a high pressure common rail diesel/natural gas dual-fuel engine. SAE Technical Paper 2014-01-1168. 2014

[45] Xu S, Anderson D, Singh A, Hoffman M, Prucka R, Filipi Z. Development of a phenomenological dual-fuel natural gas diesel engine simulation and its use for analysis of transient operations. SAE International Journal of Engines. 2014;7(4):2014-01-2546

[46] Besch MC, Israel J, Thiruvengadam A, Kappanna H, Carder D. Emissions characterization from different technology heavy-duty engines retrofitted for CNG/diesel dual-fuel operation. SAE International Journal of Engines. 2015;8(3):2015-01-1085

[47] Mattson JMS, Langness C, Depcik C. An analysis of dual-fuel combustion of diesel with compressed natural gas in a single-cylinder engine. SAE Technical Paper 2018-01-0248. 2018

[48] Kozarac D, Sjeric M, Krajnovic J, Sremec M. The optimization of the dual fuel engine injection parameters by using a newly developed quasi-dimensional cycle simulation

combustion model. SAE Technical Paper 2018-01-0261. 2018

[49] Saccullo M, Benham T, Denbratt I. Dual fuel methanol and diesel direct injection HD single cylinder engine tests. SAE Technical Paper 2018-01-0259. 2018

[50] Yoon SH, Lee CS. Experimental investigation on the combustion and exhaust emission characteristics of biogas-biodiesel dual-fuel combustion in a CI engine. *Fuel Processing Technology*. 2011;92(5):992-1000

[51] Keeler B. Constraints on the operation of a DI diesel [PhD thesis]. The University of Nottingham; 2009

[52] Kulkarni AM, Stricke KC, Blum A, Shaver GM. PCCI control Authority of a Modern Diesel Engine Outfitted with Flexible Intake Valve Actuation. *Journal of Dynamic Systems, Measurement, and Control*. 2010;132(5)

[53] Kokjohn SL, Hanson RM, Splitter DA, Reitz RD. Experiments and modeling of dual-fuel HCCI and PCCI combustion using in-cylinder fuel blending. *SAE International Journal of Engines*. 2010;2(2):24-39

[54] Ickes A, Wallner T, Zhang Y, Ojeda WD. Impact of Cetane number on combustion of a gasoline-diesel dual-fuel heavy-duty multi-cylinder engine. *SAE International Journal of Engines*. 2014;7(2):2014-01-1309

[55] Benajes J, Garcia A, Monsalve-Serrano J, Boronat V. Influence of direct-injected fuel properties on performance and emissions from a light-duty diesel engine running under RCCI combustion mode. SAE Technical Paper 2018-01-0250. 2018

[56] Puduppakkam KV, Liang L, Naik CV, Meeks E, Kokjohn SL, Reitz RD. Use of detailed kinetics and advanced chemistry-solution techniques in CFD to investigate dual-fuel engine

concepts. SAE Technical Paper No. 2011-01-0895:2011

[57] Zhang Y, Sagalovich I, Ojeda WD, Ickes A, Wallner T, Wickman DD. Development of dual-fuel low temperature combustion strategy in a multi-cylinder heavy-duty compression ignition engine using conventional and alternative fuels. *SAE International Journal of Engines*. 2013;6(3):2013-01-2422

[58] Heuser B, Kremer F, Pischinger S, Rohs H, Holderbaum B, Körfer T. An experimental investigation of dual-fuel combustion in a light duty diesel engine by in-cylinder blending of ethanol and diesel. *SAE International Journal of Engines*. 2015;9(1):2015-01-1801

[59] Nithyanandan K, Hou D, Major G, Lee C-F. Spray visualization and characterization of a dual-fuel injector using diesel and gasoline. *SAE International Journal of Fuels and Lubricants*. 2014;7(1):2014-01-1403

[60] Yu S, Dev S, Yang Z, Leblanc S, Yu X, et al. Early pilot Injection strategies for reactivity control in diesel-ethanol dual fuel combustion. SAE Technical Paper 2018-01-0265. 2018

[61] Mobasheri R, Seddiq M. Effects of diesel injection parameters in a heavy duty iso-butanol/diesel reactivity controlled compression ignition (RCCI) engine. SAE Technical Paper 2018-01-0197. 2018

[62] Kassa M, Hall C, Ickes A, Wallner T. Modeling and control of fuel distribution in a dual fuel internal combustion engine leveraging late intake valve closings. *International Journal of Engine Research*. 2016;18(8):797-809

[63] Dong S, Ou B, Cheng X. Comparisons of the cyclic variability of gasoline/diesel and ethanol/diesel dual-fuel combustion based on a diesel engine. SAE Technical Paper 2017-01-5001. 2017

- [64] Han X, Divekar P, Reader G, Zheng M, Tjong J. Active injection control for enabling clean combustion in ethanol-diesel dual-fuel mode. *SAE International Journal of Engines*. 2015;**8**(2):2015-01-0858
- [65] Divekar P, Han X, Tan Q, Asad U, Yanai T, Chen X, et al. Mode switching to improve low load efficiency of an ethanol-diesel dual-fuel engine. *SAE Technical Paper 2017-01-0771*. 2017
- [66] Martin J, Boehman A, Topkar R, Chopra S, Subramaniam U, Chen H. Intermediate combustion modes between conventional diesel and RCCI. *SAE Technical Paper 2018-01-0249*. 2018
- [67] Sprenger F, Fasching P, Kammerstätter S. Experimental investigation of CNG-diesel combustion processes with external and internal mixture formation for passenger Car applications. In: *Proceedings of the Conference on the Working Process of the Internal Combustion Engine*. Austria: Graz; September 2015. pp. 24-25
- [68] Wu X, Daniel R, Tian G, Xu H, Huang Z, Richardson D. Dual-injection: The flexible, bi-fuel concept for spark-ignition engines fuelled with various gasoline and biofuel blends. *Applied Energy*. 2011;**88**:2305-2314
- [69] Union E. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *Official Journal of the European Union*. 2009;**5**:2009
- [70] Curtis B. *US Ethanol Industry: The Next Inflection Point*. 2007 Year in Review. San Francisco, CA: BCurtis Energies & Resource Group; 2008. p. 52
- [71] Goldemberg J. The challenge of biofuels. *Energy & Environmental Science*. 2008;**1**:523-525
- [72] Haskell WW, Bame JL. Engine Knock—An End-Gas Explosion. *SAE Technical Paper Series*; 1965. DOI: 10.4271/650506
- [73] Zhen X, Wang Y, Xu S, Zhu Y, Tao C, et al. The engine knock analysis—An overview. *Applied Energy*. 2012;**92**:628-636
- [74] Guzzella L, Onder C. Control of engine systems: Engine knock. In: *Introduction to Modeling and Control of Internal Combustion Engine Systems*. Berlin: Springer Berlin; 2014. pp. 199-209
- [75] Ayala FA, Gerty MD, Heywood JB. Effects of combustion phasing, relative air-fuel ratio, compression ratio, and load on SI engine efficiency. *SAE Technical Paper Series*; 2006. DOI: 10.4271/2006-01-0229
- [76] Bromberg L, Cohn DR, Heywood JB. Calculations of knock suppression in highly turbocharged gasoline/ethanol engines using direct ethanol injection. *Massachusetts Institute of Technology*; 2006
- [77] Chang J, Viollet Y, Alzubail A, Abdul-Manan AFN, Al Arfaj A. Octane-on-Demand as an Enabler for Highly Efficient Spark Ignition Engines and Greenhouse Gas Emissions Improvement. *SAE Technical Paper Series*, 2015. DOI: 10.4271/2015-01-1264
- [78] Saudi Aramco—A Step Forward in Fuel Technology [Online]. 2017. Available from: <http://www.saudiaramco.com/en/home/news-media/news/a-step-forward-in-fuel-technology.html> [Accessed: June 10, 2018]
- [79] Green Car Congress [Online]. 2017. Available from: <http://www.greencarcongress.com/2017/08/20170810-aramco.html> [Accessed: June 10, 2018]