

# The Application of HCCI Technology in the Automotive Industry: Technical Analysis and Future Prospects with Mazda as an Example

Hongduo Yan

Department of Engineering, Oakland University, Rochester, 48309, United States

yanhongduo@oakland.edu

**Abstract.** Homogeneous Compression Combustion Ignition (HCCI) engine is a new type of combustion engine technology that realizes fuel combustion through compression ignition. It combines the benefits of gasoline and diesel engines to improve fuel efficiency and reduce emissions significantly. Its huge advantage of improving efficiency is widely used in the automotive field. This paper summarizes the achievements and challenges of HCCI engines and their application in automotive industries especially in Mazda. Mazda uses its SkyActiv-X engine to produce the car model to achieve high efficiency and low emissions. Another company, General Motors, has its own Ecotec engine to ensure the stability of combustion conditions, thus applying the HCCI technology. HCCI technology faces challenges such as ignition control and stable combustion conditions, but through continuous technological innovation and optimization, HCCI is expected to become one of the mainstream internal combustion engine technologies in the future. It solved the problem of high efficiency and being environmentally friendly, which could help the global warming caused by too much fossil fuel use.

**Keywords:** HCCI engine, Mazda, general motor, automotive.

## 1. Introduction

Nowadays, the use of fossil energy continues to increase, resulting in an increasing emission rate, which is not a good sign for the environment. Therefore, low-emission and high-efficiency internal combustion engine technology is the direction that the world is currently studying. In order to address the efficiency and environmental issues in the field of internal combustion engines, scientists first proposed the HCCI concept by researchers in the 1970s [1]. HCCI engine is a kind of combustion engine that incorporates the best features of both spark ignition (SI) engine and compression ignition (CI) engine. SI engines could mix the air and fuel well to minimize emissions. CI engines could lower the losses and have higher efficiency. As for the gasoline engines, they are SI engines. The air and fuel are mixed in the cylinder and ignited by the spark plug. Diesel engines are CI engines, which compress the air to meet with the injected fuel and then ignite in high-pressure and high-temperature conditions. HCCI engines inject fuel mix with air before CI, which leads to high efficiency and low emissions. This effectively solves the problem of energy use in our lives, which is energy saving and emission reduction.

The advantages of the HCCI engine are high efficiency, low emissions and fits all kinds of fuels. Although the HCCI engine has lots of advantages in combustion, it also has challenges. The first one is the control of temperature and the precise timing of the CI to make higher efficiency. Second is the control of the air-fuel ratio to decrease emissions. Also, scientists have been studying the use of HCCI engines. However, they have not been able to achieve the standard of use. Engines like Mazda's Spark Controlled CI (SPCCI) have been built as close as possible to the aim of the research, through CI with lean burn. However, the challenges of improving the compression ratio, maintaining a thin mixture, and ensuring no spontaneous combustion through secondary injection of the fuel are ongoing.

The most important part of HCCI engines is the control of combustion conditions, which need a very precise technology to do that. HCCI engines burn at a high temperature and high pressure, and the precision of the control is very high, which is a very important step. The mix of the fuel and air and the control of ignition determine the results of emissions. The mixture of fuel and air is the basis

of efficient combustion of HCCI engines, and uneven mixing will lead to incomplete combustion and increased emissions. In the future, people may try to use the sensor to control the conditions accurately and to improve the technic to mix the air and fuel more evenly.

## 2. Achievement and Challenges of HCCI Technology

HCCI engine is a kind of combustion engine which have lots of achievements. The first one is increasing combustion efficiency. The working process of HCCI engines has four parts. The first step is to open the intake valve, let the fuel and air go inside, and mix the homogeneous air and gasoline in the cylinder chamber. Second, the piston compresses the homogeneous charge as it rises. Then, the compressed homogenous charge ignites and drives the piston down.

At last, the exhaust valve will open, and the piston rises again and makes the exhaust escape. Achieve high efficiency is the even mix of step one. The research done by Verma et.al (2022) shows that lean combustion in HCCI increases the fuel efficiency by 15% over the conventional engine [2]. The fuel and air are evenly mixed before compression so that the combustion is uniform, reduces energy loss, and obtains high efficiency. However, this method creates challenges for research and development. That means it needs a higher compression ratio and many other premises, such as a lean mixture and no spontaneous combustion. Research from Puskar et al. (2017) shows that when the compression ratio rises higher, the engine-indicated efficiency goes higher [3]. The HCCI engines has the highest efficiency of the three engines. The equation shown in Fig. 1 could prove that when the  $\gamma$  is lower, the efficiency is higher, and the HCCI engines use air and fuel mixture to do the ignition, so it has a higher efficiency than other engines that ignite with air only.

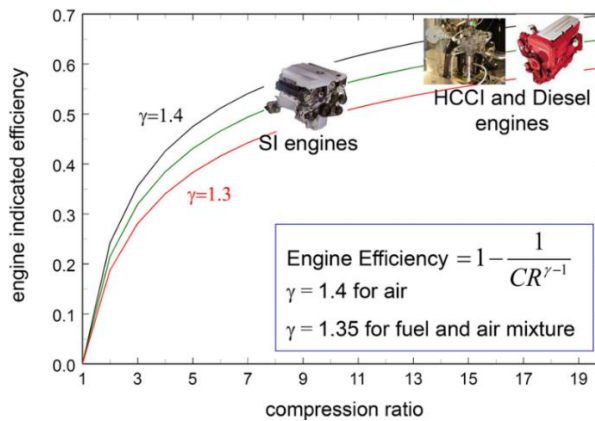


Figure 1. The efficiency of different compression ratios [3]

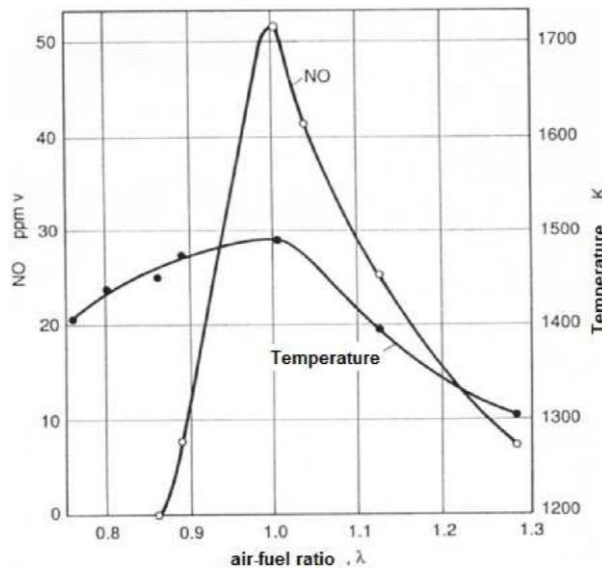


Figure 2. NO emissions of air-fuel ratio [4]

The next achievement of HCCI engines is the low emission. Moreover, that means it needs an air-fuel ratio closer to the CI engine. Popescu and Ionel (2010) provide a detailed figure of NO emissions. [4]. When the air-fuel ratio is below 1, the emission rate of NO increases significantly (Fig. 2). When  $\lambda$  is approximately 1.02, the emissions of NOx are the highest. However, when the ratio exceeds 1, the emission rate of NO decreases and the combustion temperature is also decreasing. To control the air-fuel ratio exceeding 1 as much as possible is one of the solutions to solve the large amount of nitrogen oxides produced by lean burn. However, this chart is not completely accurate to show the emission trend of nitrogen oxides because it only shows the emission of NO and does not show all types of nitrogen oxides, so this is still a study that needs to be improved.

NavyGhost (2020) discusses the specific air-fuel ratio needed for HCCI engines [5]. In Fig. 3, it shows that when the air-fuel ratio is higher than 35, the NOx emissions almost become 0. So, keeping the higher air-fuel ratio for combustion is a good way to reduce the emissions of NOx.

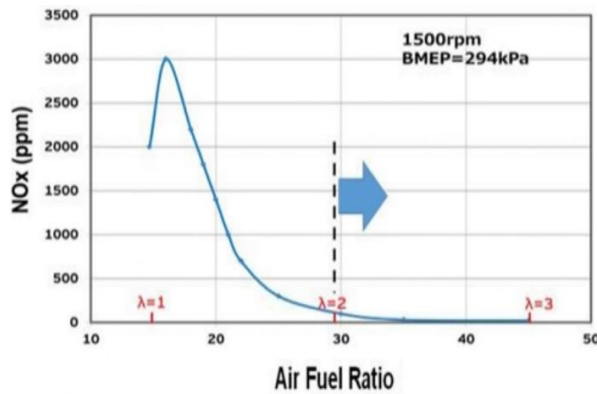


Figure 3. NOx emissions with different air-fuel ratio [5]

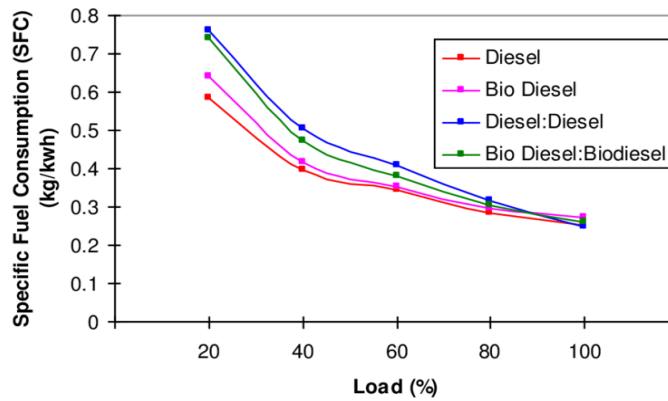


Figure 4. Different fuel consumptions of different loads [6]

The third achievement of HCCI engines is that they are not picky with the fuels when ignition. It has lots of abilities to control the fuel uses such as gasoline, diesel and biofuels, which could increase the use range of this technology. In order to further explore the HCCI engine fuel and emissions more accurately, Sendilvelan (2011) examined the emission and combustion characteristics of different fuels in HCCI engines [6]. It can be seen in Fig. 4 that as the load percentage increases, the fuel consumption of both ordinary internal combustion engines and HCCI decreases, and the fuel consumption trend of each type is basically the same. With the increase in load percentage, the value of SFC is more clustered, that is, the fuel consumption is basically the same under higher load conditions. In the case that the load percentage is difficult to improve, through a reasonable selection of fuel, it is possible to optimize the performance of the HCCI engine further, reduce emissions, and achieve a more efficient and environmentally friendly internal combustion engine technology.

### 3. Specific Development of HCCI in Mazda

In Mazda's second-generation study, they use HCCI engines to become efficient and environmentally friendly. They try to use their patent research SPCCI engine to control the combustion time in order to control the precise temperature for the HCCI engines, which is a very small range to achieve this. In principle, they required a very high compression ratio; research by Lee, Schenk, and McDonald (2016) shows that the compression ratio was changed from 13:1 to 14:1 [7]. This is a good improvement, but the compression ratio still needs to be improved. Conway (2019) provides a detailed analysis of the Mazda Skyactiv-X market and technology [8]. His research shows the advantages and challenges of using SPCCI engine technology for Mazda.

The SPCCI engine is a similar engine designed by Mazda using the technology of the HCCI engine. The Mazda Skyactiv-X mentioned in Conway's research tries to control the temperature range. If the temperature is too high, it will explode. If it is too low, it will affect ignition performance. However, the HCCI engine has a higher compression ratio than other combustion engines, which means the change of knocking will be more frequent. Although, in principle, compression combustion is detonation, if the detonation time is not required by the design time, it will seriously damage the engine. One of the best ways to reduce the knock is to control the combustion temperature of the mixture, so Mazda uses a partial injection of fuel on the intake so that the mixture is very small and does not form a compression combustion. In the compression process, the fuel is injected again because the time is shorter; the heat of the latter fuel is not much, so that it can form a controlled compression combustion. Kitchen, in 2016, researched the combustion range of HCCI engines [9]. Fig. 5, researched in their paper, very clearly shows the range of HCCI ignition. It is in the middle of other kinds of combustion, so it is not very easy to achieve this. This means the oil atomization and mixing time is very short, and the combustion temperature will become very difficult to control, so this control technology still needs to be improved.

General Motors also researched the HCCI engine and tried to use it in real production. Research in 2007 by Neff showed that there are two kinds of type of HCCI technology cars, Saturn Aura and Opel Vectra. They all use a 2.2L Ecotec engine with valves on two sides. They control combustion through a single-cylinder pressure sensor as well as an electric camshaft phaser [10]. They use a sophisticated controller that uses cylinder pressure sensors and control algorithms developed by General Motors to manage the HCCI combustion process and the transition between HCCI combustion and traditional SI combustion. Thus, a more stable combustion process is achieved. However, this technology and the HCCI engines of General Motors are still in the development phase. More experiments are needed for research and development.

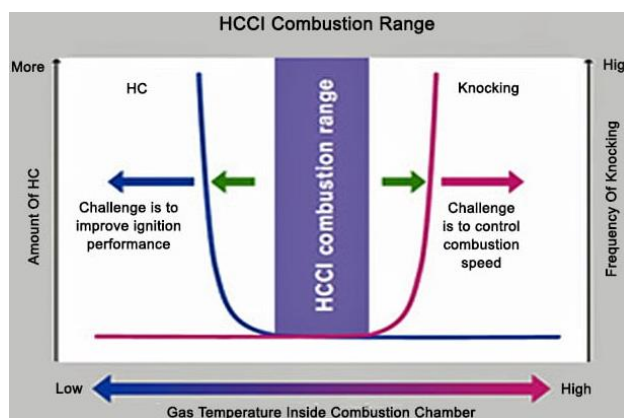


Figure 5. Range of HCCI combustion [9]

### 4. Future Development of HCCI

As for the prospect of future development, Ramana, Maheswar, and Gowd (2013) mentioned in their research that General Motors (GM) has launched a prototype vehicle equipped with a gasoline

HCCI engine, which can reduce fuel consumption by about 15% [11]. This means that its engine's NO<sub>x</sub> emissions can be significantly reduced and increase efficiency, making it more environmentally friendly. Mazda also continues to make breakthroughs in fuel efficiency and emissions reduction with its third-generation SKYACTIV engine. As the use of fossil fuels has made global warming a serious problem this year, more scientists have chosen different ways to overcome the challenges of HCCI engines.

In the study, Hamid et al. stated that when the physicochemical properties of syngas are fully studied, and numerical models are established, it has great potential as an alternative to traditional fossil fuels [12]. His research gives us a very good idea for developing HCCI engines that control temperature and emissions more precisely.

## 5. Conclusion

HCCI engine has a different ignition method from ordinary diesel and gasoline engines. It uses CI to increase the efficiency and mix the air and fuel well before ignition to reduce the emissions of NO<sub>x</sub>. The achievements it made are high efficiency, low emissions and not picky for fuel kinds. However, it also has improvements. It needs to raise the compression ratio to achieve the CI and control the air-fuel ratio at a specific range to reduce the NO<sub>x</sub> emissions.

This technology is already used in some companies. In Mazda, this is almost a mature technology in the research process. Their second generation of the SKYACTIV-X engine improves the compression ratio to a higher scale and uses twice injected to control the combustion temperature to have a good ignition condition. In General Motor Company, their Ecotec engine is now possible to use HCCI technology while running at high speeds, and to use precise sensor control technology to ensure the operation of the most basic HCCI combustion. Including other companies of automotive, it all starts to research HCCI engines to achieve high efficiency and environmentally friendly.

For future experiments and applications, efforts are being made to develop more advanced techniques to control temperature and combustion conditions. Moreover, for fuel options, HCCI is not limited to gasoline and diesel; researchers are also exploring the use of biofuels, natural gas and other alternative fuels in HCCI engines. This can promote the popularity of HCCI engines in different markets and application scenarios to further achieve the goal of low carbon and sustainable development.

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