Enhancing HCCI Engine Performance through AI Integration: Addressing Ignition Timing and Emission Challenge

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Abstract. This article explores the integration of artificial intelligence (AI) with Homogeneous Charge Compression Ignition (HCCI) engines to address the inherent drawbacks of traditional spark-ignition (SI) and compression-ignition (CI) engines. It highlights how HCCI technology mitigates issues such as higher emissions and lower efficiency associated with SI and CI engines. However, HCCI also faces challenges, particularly in ignition timing control. The article delves into the detrimental impact of diesel emissions on engines and underscores the critical role of precise ignition timing in HCCI performance. To overcome these challenges, the potential of combining AI, specifically through the Internet of Things (IoT) and deep learning within the realm of machine learning, is examined. The integration of AI technologies with HCCI engines promises significant improvements in thermal efficiency and fuel economy by optimizing ignition timing. This synergy between AI and HCCI engines represents a promising avenue for enhancing engine performance while reducing environmental impact.

Keywords: HCCI Engine, fuel type, thermal efficiency, artificial intelligence, AI development.

1. Introduction

The concept of the Homogeneous charge compression ignition (HCCI) engine emerged in the 1990s as a response to increasing environmental degradation, leading to a reduction in the use of finite energy sources like fossil fuels. HCCI involves using a homogeneous mixture of air and fuel for combustion within the cylinder, employing compression ignition like diesel engines rather than spark ignition used by gasoline engines. However, both the gasoline and diesel engines utilized in this system have certain limitations. Despite sharing a similar ignition method with diesel engines, the HCCI engine also incorporates microprocessor control to achieve emissions comparable to those of gasoline engines while maintaining the efficiency of diesel engines or even surpassing it.

HCCI engines have the potential to effectively reduce exhaust emissions and demonstrate impressive efficiency in terms of vehicle emissions. It is important to recognize that achieving emission reduction with HCCI engines requires proper utilization techniques and fuel selection, as different types of fuel can have varying impacts on vehicle exhaust emissions. The thermal efficiency of an HCCI engine is influenced by two primary factors, one being the impact of combustion timing on the engine.

As engine load increases, manual operation faces challenges due to a narrower ignition angle window. How can people achieve optimal combustion timing? Is it currently feasible to integrate AI technology into engines and how to get involved with engines?

2. HCCI Engine Operation Process

2.1. HCCI Compared with Homogeneous Charge Spark Ignition (HCSI)

HCCI is a promising engine technology that has been extensively researched due to its potential for reducing emissions of nitrogen oxide (NOx), carbon monoxide (CO), hydrocarbon (HC), and particulates while maintaining high thermal efficiency. HCCI engines distinguish themselves from gasoline and diesel engines by eliminating the need for spark plugs in SI engines or fuel injectors in CI engines during the HCCI cycle. Unlike diesel engines, which also rely on compression combustion processes, microprocessors are employed to control HCCI engines. By combining the advantages of both the Otto cycle and the diesel cycle while mitigating their drawbacks, the HCCI cycle enables emission levels comparable to those of a gasoline engine and efficiency like that of a diesel engine. For applications requiring high power density like those commonly found in gasoline engines, HCSI processes are widely utilized as power sources for passenger vehicles, commercial vehicles, power generation systems, and other industrial sectors. Table 1 provides a visualization of different types of ignition.

Table 1. Three types of ignitions

Engine type	SI	CI	HCCI
Ignition Method	Spark Ignition	Compression-Ignition	Compression ignition
Throttle Loss	Yes	No	NO
Compression Ratio	Low	High	High
Fuel Economy	Good	Better	Best
Max Efficiency	30%-40%	40%-45%	>50%
Major Emissions	HC, CO and NOx	Nox, HC and PM	HC, CO and NOx

In internal combustion engines, the combustion process plays a pivotal role in energy conversion as it directly converts the chemical energy of fuel into heat. In combustion in spark ignition (SI) at ignition, a homogeneous mixture comprising air and vapor is formed. Initiates at the upper part of the flame ignited by the spark plug and gradually propagates towards the lower region where the piston is situated. In conventional spark ignition engines, both fuel and air are simultaneously drawn into the combustion cylinder, enabling combustion to take place within a specific range characterized by an optimal fuel-to-air ratio in a gaseous phase.

However, this process leads to throttle losses, resulting in reduced thermal efficiency. Despite the widespread utilization of gasoline engines, compared with HCCI, they are accompanied by several inherent limitations that cannot be overlooked. Two primary drawbacks are associated with gasoline engines: firstly, their thermal efficiency is relatively low, typically ranging from 30% to 40%, which can be attributed to various factors encompassing different types of losses. The adoption of natural intake during each cycle leads to a reduction in overall efficiency, not only due to insufficient utilization of combustion gas from the previous cycle during exhaust but also causing a substantial and noteworthy decline in efficiency. Furthermore, when compared with diesel engines, although thermal efficiency can reach 40 to 45%, and because it is compressed combustion, fuel economy is better than SI. It is important to note that emissions cannot be overlooked as they have had a considerable impact on our lives and health, particularly NOx and PM particles [1].

2.2. Advantage of HCCI Engine

Firstly, during the ignition process, fuel is injected into the cylinder via a direct injection nozzle when the compression stroke of the engine nears completion. The HCCI engine possesses a higher compression ratio than a typical gasoline engine, allowing sufficient time for small oil droplets to disperse uniformly within the cylinder once the compression stroke concludes. Upon reaching the ignition point temperature, all fuels ignite simultaneously, thus optimizing fuel utilization efficiency. In contrast, conventional gasoline and diesel engines. Experience non-uniform diffusion combustion, leading to energy wastage during diffusion [2]**.** Second, The HCCI's fuel utilization efficiency is significantly enhanced by employing compression ignition, enabling an exceptionally high compression ratio, obviating the necessity for a throttle.

Thirdly, HCCI demonstrates both positive and negative effects. On the one hand, the low combustion temperature in the HCCI engine effectively minimizes heat transfer to the combustion chamber wall, thereby reducing radiant heat transfer. And it significantly mitigates nitrogen oxide formation. On another hand, The HCCI engine operates at a relatively low combustion temperature, resulting in minimal convective heat transfer to the walls of the combustion chamber and consequently leading to self-extinguishing conditions. The fourth advantage stems from its remarkable adaptability as a parameter for the HCCI engine, facilitating extensive variations in fuel octane numbers. It can utilize diverse sources such as gasoline, natural gas, dimethyl ether, and other high-octane fuels, either individually or through different fuel blends during combustion processes.

The technical structure of the engine with HCCI technology is more intricate compared to that of a conventional engine, thereby enhancing thermal efficiency and minimizing heat loss through various means. Moreover, fine-tuning the proportion between high and low-octane fuels offers an efficacious approach to regulating both ignition timing and load range within HCCI combustion. However, prior to achieving global implementation of the HCCI engine, there exist certain corresponding challenges that can be categorized into two crucial aspects. Firstly, the precise control and manual operation required during high load conditions pose a significant hurdle for ignition timing. Secondly, external factors exacerbate engine emissions beyond anticipated levels. Moreover, prolonged high-load scenarios result in reduced thermal efficiency owing to inaccurate prediction of ignition position and timing.

2.3. Insights and Recommendations from Mazda HCCI Engine

Compared to the conventional internal combustion engines utilized in HCSI systems, HCCI engines present advancements on multiple fronts. A notable example is Mazda's Skytatic-X engine which deviates marginally from traditional HCCI designs by amalgamating spark plug and compression-based combustion methodologies. Distinguishing itself with an impressive 16:1 compression ratio, this Mazda-engineered innovation leads to a substantial reduction in fuel intake within the combustion chamber during the compression phase while effectively eradicating any potential occurrence of fuel gas detonation. In addition to its exceptionally high compression ratio, resulting in outstanding fuel efficiency, Mazda's engine also presents a solution to another challenge: the cold start issue. The combustion process of Mazda's engine is referred to as spark controlled compression ignition (SPCCI). Due to the overpressure combustion in the HCCI engine, the temperature within the combustion chamber remains relatively low, potentially leading to incomplete combustion and self-extinguishing.

The Mazda engine combines the gasoline engine's spark plug ignition with diesel's compression ignition, resulting in a unique combustion process. After compressing the air-fuel mixture to its optimal ratio within the combustion chamber and reaching the top dead center during the compression stroke, an additional spark ignites this mixture from a nozzle, thus increasing core temperature in turn. As a result, this elevated temperature enables efficient burning and ignition of both oil and gas dispersed throughout due to an increased compression ratio. Due to Mazda's high compression ratio of 16:1, the HCCI engine demonstrates remarkable work generation capabilities even under extremely poor fuel conditions, leading to significantly reduced fuel consumption in comparison with gasoline engines.

Furthermore, the HCCI engine exhibits a notable increase in emissions while presenting several disparities in thermal efficiency when compared to diesel and gasoline engines. When diesel enters the combustion chamber, the diesel engine exhibits insufficient mixing of diesel fuel and air, leading to notable emissions of particulate matter and NOX. Despite the presence of a filter, it still falls short in comparison to the superior mixing achieved through direct injection in HCCI. Conventional diesel engines emit around 2000-2500 ppm of nitrogen oxide. However, using diesel in HCCI engines can significantly reduce this emission. When natural gas like hydrogen is used in the HCCI engine, the emission drops to as low as 10 ppm, making it almost negligible compared to nitride emissions [3]**.**

3. HCCI engine's Emissions

3.1. Different Types of Fuel

3.1.1. Diesel

The impact of natural gas, methanol, ethanol, and diesel on engine performance in HCCI engines has been compared. When the engine uses diesel, The exhaust emissions of HCCI engines may not exhibit lower levels of CO and HC compared to diesel engines [2]. Compared to diesel engines, HCCI engines emit less NOx emissions. The reason for the lower burning temperature of HCCI is less nitrogen oxide stuff, which makes for fewer emissions under equivalent external conditions, including the employment rate of EGR and the temperature of the intake air. Traditional diesel engines emit around 2000-2500 ppm (parts per million) of NOx; nevertheless, using diesel in HCCI engines lowers this level to just 70-400 ppm [3].

In terms of exhaust emissions, the implementation of exhaust gas recirculation (EGR) has a significant impact on NOX emissions and other substances, with the extent of EGR implementation being inversely proportional to the level of exhaust emissions. The combustion, emissions, and performance characteristics of the two engines were analyzed with and without 15 % EGR. Upon examination of the emission data, it was observed that in the non-EGR group, the diesel engine exhibited a maximum CO emission level of 5 g/kWh, while shown in Fig. 1, the HCCI engine demonstrated a CO emission level of 7 g/kWh. Diesel engines emitted NOx at a rate of 8.9 g/KWH. The NOx emissions of HCCI engines are measured at 3.9 g/kW, while the CO emissions from these engines surpass those emitted by diesel engines. When utilizing a 15 % EGR rate in a diesel engine, the CO emissions exhibit a further increase to 13 g/kWh. Conversely, as shown in Fig. 1, when employing the same EGR rate of 15 % in the HCCI engine, there is a notable reduction observed in NOx emissions to 2.9 g/kWh. It is noteworthy that, in Fig. 1, the employment of EGR resulted in a reduction in NOX emissions from HCCI engines, albeit concurrently leading to a notable increase in CO emissions.

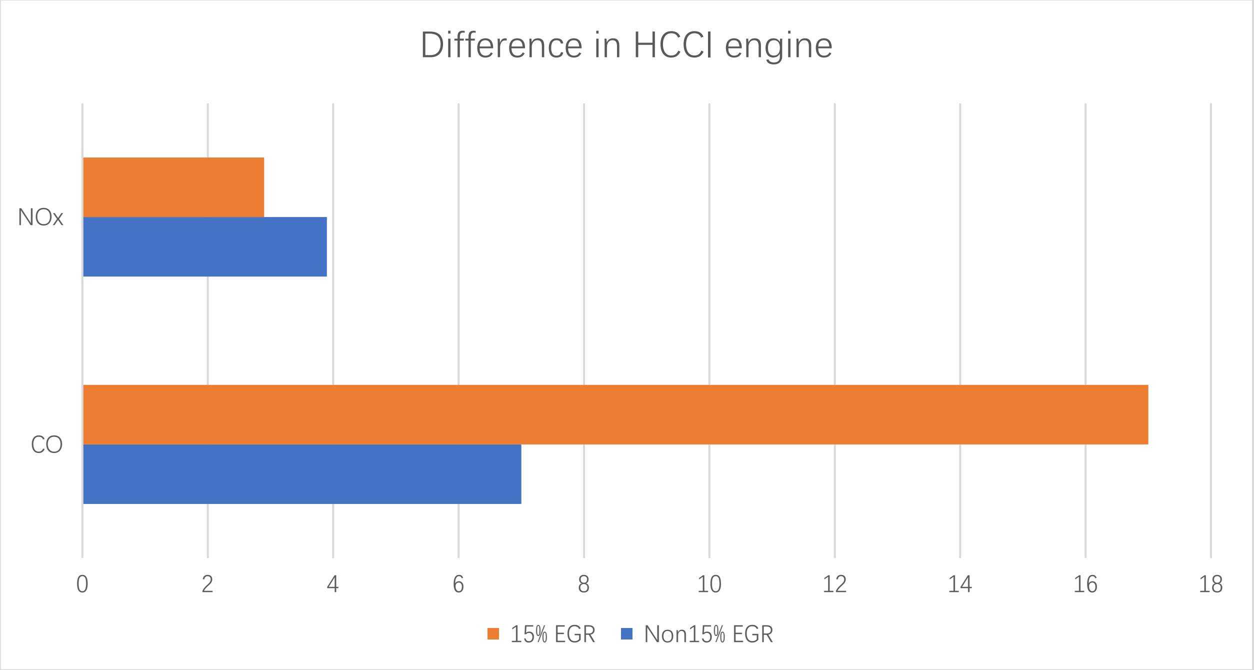

Fig. 1. Application with EGR in HCCI (Photo/Picture credit: Original)

In addition to employing EGR, the intake temperature of an HCCI engine also exerts a significant influence on emissions. Results shown in Fig. 2, specifically, elevating the intake temperature by 40 °C, 50 °C, and 60 °C leads to corresponding increases in NOx emissions by approximately 2 %, 5 %, and 9 %, respectively, with an increase in the HCCI engine's intake temperature, In Figure 2 shows that HCCI engine smoke emissions rise by increments of 2 %, 4 %, and 5 %, respectively. At an intake temperature of 50 degrees Celsius and an injection pressure of 4 bar, HCCI engines reach a maximum smoke level of 32 HSU (Hatridge smoke units), while conventional diesel engines exhibit a range of smoke levels ranging from 36 to 73 HSU. However, in a diesel engine operating at an intake temperature of 50°C and an injection pressure of 4 bar, HC emissions are measured at 50 ppm, while HCCI engines exhibit approximately 100 ppm. Diesel engines have CO emissions at a level of 0.2 %, whereas HCCI engines range from about 0.34 % to 3.7 %.

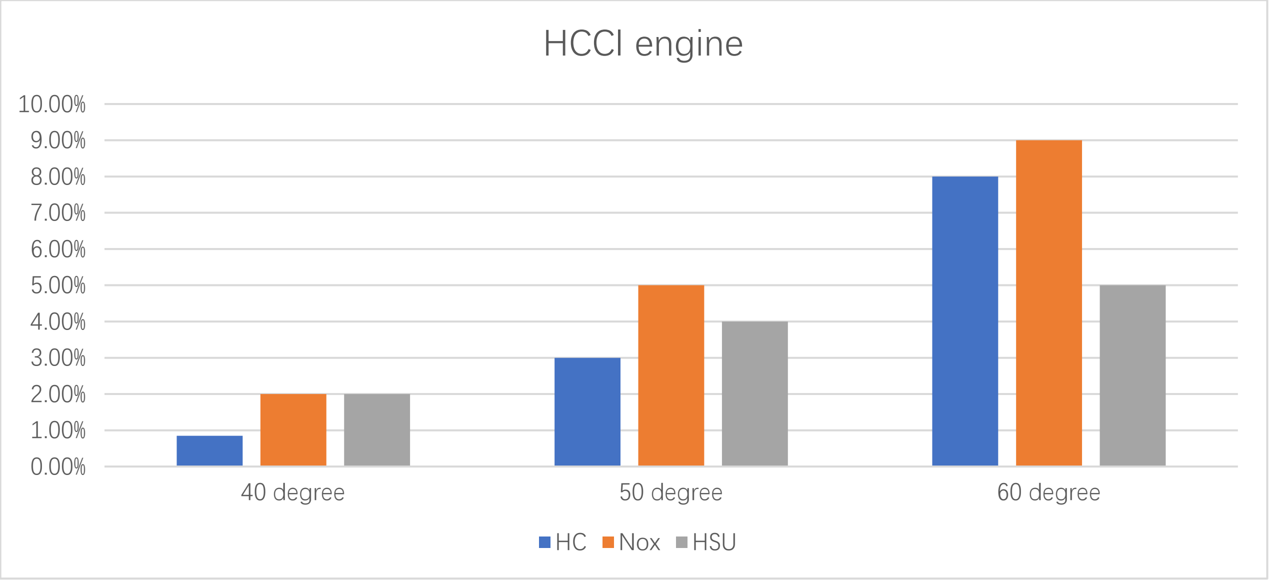

Fig. 2 HCCI performers in different Temperature (Photo/Picture credit: Original)

In 2005, Shi et al. conducted a study on the impact of exhaust gas recirculation on emissions from both internal combustion and external combustion HCCI engines [4]. Compared with the exhaust gas cycle of the internal combustion engine, the external combustion cycle shows a higher efficiency in reducing the emissions of the HCCI engine. The highest level of smoke opacity, reaching up to 50 %, was ascertained within a diesel engine employing an external combustion cycle at an EGR rate of 40 %. Conversely, within the HCCI engine, a reduction in smoke opacity ranging between 10 - 30 % was achieved. However, it should be noted that CO and HC emissions remain elevated compared to conventional engines across both cycles. Specifically, diesel engines exhibit a maximal CO emission level of merely 0.15 %, which stands lower than that recorded for HCCI engines, amounting to approximately 0.4 %. The utilization of diesel in HCCI engines leads to a reduction in NOX emissions, albeit accompanied by an elevation in CO and HC emissions relative to conventional diesel engines.

3.1.2. Hydrogen and Natural Gas

When hydrogen or natural gas is introduced into the engine, it expands the operating range compared to other fuel oil types. The addition of hydrogen content to the fuel shows a positive correlation with combustion time and peak combustion efficiency. A significant improvement in peak combustion efficiency is observed when a certain threshold of hydrogen is reached. Hydrogen enables rapid, nearly constant volume combustion, resulting in high efficiency and reduced emissions. Substituting gasoline with natural gas in HCCI engines can increase combustion efficiency by 5-10 %. Additionally, using hydrogen allows for virtually eliminating carbon monoxide and unburned hydrocarbon emissions. EGR and DME have notable effects on both the performance and emissions of HCCI engines.

Hydrogen can potentially fuel CI engines in HCCI mode despite its high heat release rate and lower ignition energy compared to traditional hydrocarbon fuels. However, precise control of ignition timing is necessary due to the requirement for a significantly higher temperature for spontaneous combustion. Exhaust emissions were measured during engine operation in hydrogen-fueled HCCI mode at 2200 rpm and 100 °C, with the test results shown in **Fig. 3**.

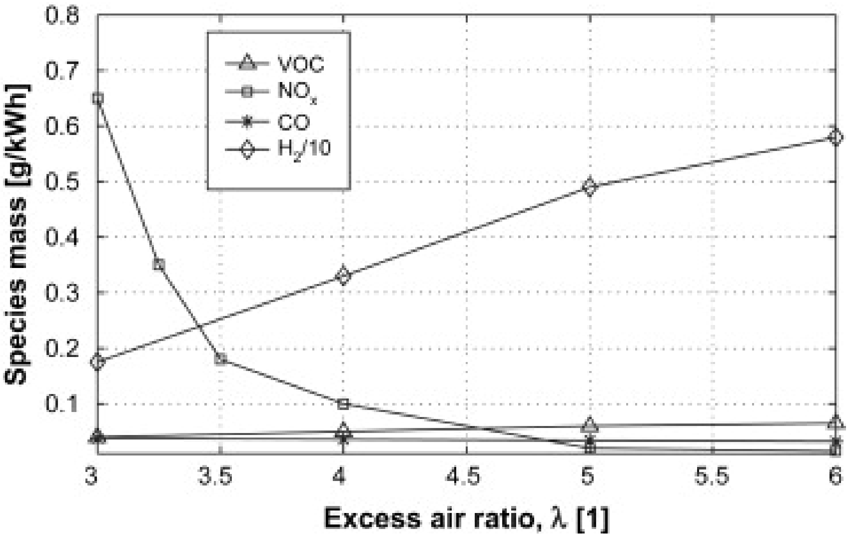

Fig. 3 H2 HCCI engine exhaust gas emissions levels [5].

The increase in NOx emissions is significantly influenced by the temperature rise in the gas cylinder when λ is less than 3.5, while a proportional relationship exists between λ and NOx emission for values greater than 3.5. At an excess air ratio of 6, NOx emission becomes negligible. When hydrogen is used as engine fuel, regardless of speed and intake temperature, NOx levels are considerably lower compared to those expected from conventional diesel engine operation [5].

3.2. Impact of Hydrogen in Engine

One crucial consideration when using hydrogen fuel is the significantly high-pressure rise rate and peak pressure in the cylinder of an HCCI hydrogen engine. It is important to consider the mechanical load on the engine's crankshaft mechanism and piston rings in such situations. Prolonged exposure to high-temperature and high-pressure environments can lead to material degradation, which must be considered for maintaining engine reliability. As a practical guideline, it is recommended to keep the P max/P comp ratio below 1.5 for standard diesel engine piston rings. This suggests that hydrogen-fueled HCCI engines may require broader crankshaft bearings and thicker piston rings. As mentioned earlier, hydrogen has a lower ignition energy compared to conventional hydrocarbon fuels.

However, achieving spontaneous combustion requires significantly higher temperatures. Therefore, precise control of ignition timing is crucial in HCCI engines and necessitates preheating the intake air for automatic ignition. This challenge has been a major obstacle faced by HCCI engines since their inception in the late 1970s when limited advancements in electronic control components hindered progress. Currently, with the emergence of more sophisticated electronic components and innovative technologies, along with the integration of artificial intelligence machine learning and the SPCCI process, it is now possible to achieve meticulous control over ignition timing and potentially overcome major hurdles encountered by contemporary HCCI engines.

4. Artificial Intelligence Development

4.1. Start Point about Artificial Intelligence

The origins of artificial intelligence can be traced back to 1954 when Alan Mathison Turing proposed the "Turing test," which marked the inception of machine-generated intelligence. Ever since the domain of artificial intelligence research has emerged, it has been a widely acknowledged perspective that the fundamental logic of AI is intrinsically related to the decision tree architecture, exemplifying a conventional approach for crafting interpretable models [6]. As AI develops, the contemporary determination of artificial intelligence necessitates the integration of specific philosophical tenets. Given computers' immense speed, memory capacity, and logical units, it becomes challenging to distinguish between a computer-generated idea that is truly "self-originated" or just an intricate "simulation," potentially overriding any indications of self-generation. To resolve the longstanding philosophical dispute on cognition's definition, Turing proposed a practical yet subjective criterion: if a computer behaves, reacts, and interacts indistinguishably with a conscious individual, then it should be considered conscious.

4.2. Milestones of Different Eras

In the 1960s, symbolic logic emerged in artificial intelligence, primarily focusing on sorting and reorganizing logical information. For example, applications were developed to help chemists deduce molecular structures from mass spectrometry data. In the late 1970s and early 1980s, non-monotonic logic was introduced in AI research through robot logic for playing board games by inferring potential moves based on board configurations. The computer, developed by Hans Berliner, defeated the backgammon world champion in 1980, and AlphaGo interchanges against the international Go champion and won in 2016. These instances effectively showcase the capabilities of AI machine learning algorithms [7]. The onset of the 21st century has witnessed a momentous progression in artificial intelligence, with deep learning being initially posited by Geoffrey Hinton and his colleagues in 2006. In 2014, the accuracy of face recognition using DL has reached more than 97 %. In 2023, ChatGPT was coming out. The emergence of generative artificial intelligence has revolutionized AI technology and applications, expedited the human-AI interaction process and marked a significant milestone in the history of AI.

In the field of artificial intelligence algorithms, most belong to parallel computing. For example, in the renowned game of Go in 2016, AlphaGo analyzed its opponent's moves from different positions and calculated the most likely winning moves based on the board. By 2019, the AI industry bid farewell to an era characterized by mere rhetoric and superficial packaging of concepts, transitioning into a trajectory of steadfast development. The integration of AI technology and its application across industries has surged, resulting in numerous accomplishments. In 2020, the global pandemic outbreak. AI is set to play a pivotal role in information gathering, data aggregation, real-time updates, epidemic investigation, vaccine development research, and new infrastructure construction. For example, AI-driven automated CT image analysis tools are used for coronavirus detection and tracking [8].

5. The Potential of AI in the HCCI Engine

5.1. Application in the Automotive Industry

The integration of AI in the automotive manufacturing process has great potential to reduce operational costs for global automakers. The conventional car production process typically includes five stages: press shop, body shop, paint shop, assembly, and finish. The first three stages of the procedure can now be 90 % mechanically operated, achieving a significantly higher level of automation [9].

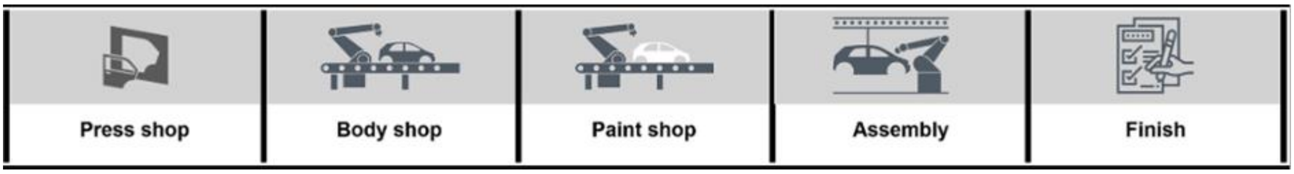

Fig. 4 AI applies in Industry [9]

The field of AI includes many branches, with Machine Learning (ML) being a prominent subfield in current research(Fig. 4). Deep learning (DL), a subset of ML, has applications beyond automotive technology and is relevant to everyday life. ML applications in the automotive industry can be broadly categorized into non-visual and visual quality control. Visual quality control utilizes AI to assess high-resolution visual input data, specifically through camera-based observation, information collection, and component control. Non-visual quality control involves indirect or direct vehicle management using electric currents, force feedback, wireless signals, etc.

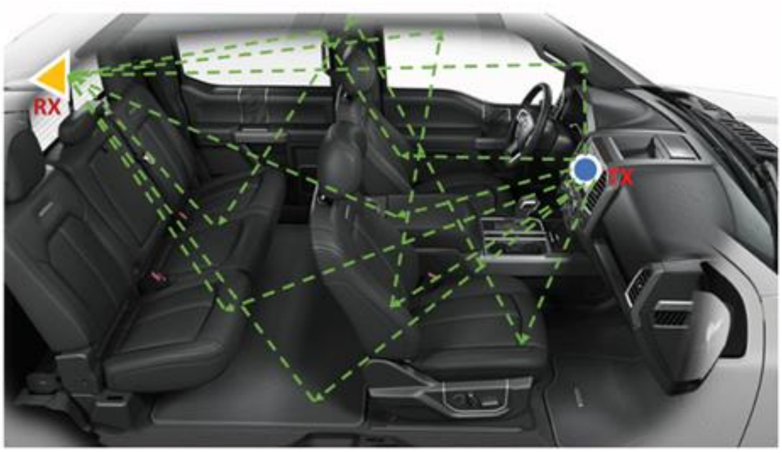

Fig. 5 IoT connect [10]

The term 'Internet of Things (IoT)' refers to the expansion of machine learning through wireless signals (Fig. 5). Smart devices and sensors are strategically placed in the environment, interconnected to gather, share, and integrate information. The fundamental principle underlying IoT is the use of radio waves for data acquisition and analysis. The radio analysis relies on time inversion (TR) technology and extracts various features using Radio Channel State Information (CSI), allowing for the interpretation of environmental information. Changes in the indoor environment cause variations in multipath propagation, resulting in a weakened TR resonance [10].

5.2. The AI Software Analyzing Combustion Processes

HCCI uses flameless combustion, which makes it very difficult to control the ignition timing for each cycle precisely. Certain individuals employ simulation software to optimize control through the simulation of the combustion process in HCCI engines. In the simulation software, natural gas is used as fuel, and the cylinder pressure varies over time during compression and ignition of the natural gas-air mixture. Increasing the initial pressure in the simulation leads to a higher concentration of product components in the fuel-air mixture. Each outcome can be treated as a dataset, enabling AI to acquire knowledge through DL while assimilating substantial amounts of simulation software data. The precise ignition timing is analyzed from amounts of simulation software data, in combination with Mazda's Skyactiv engine the SPCCI mode. Leveraging the advantage of IoT, non-visual quality control is utilized for identifying diverse road conditions, and real-time adjustments are made to internal ignition timing based on throttle actions to sustain thermal efficiency.

6. Conclusions

This study investigates emissions resulting from various fuel types in HCCI engines. Compared to conventional internal combustion engines, the HCCI process offers significant advantages in terms of improving thermal efficiency and economy. A comparative analysis reveals that with appropriate fuel types and EGR external cycle ratios, HCCI remission shows lower levels of HC, CO, and NOx emissions. While the utilization of diesel in HCCI engines leads to reduced NOx emissions compared to traditional diesel engines, it also results in significantly higher HC and CO emissions; hence, diesel is considered unsuitable as a fuel for HCCI engines. Compared to traditional internal combustion engines, the HCCI process offers significant advantages in enhancing thermal efficiency and economy. A comparison reveals that with the appropriate fuel type and EGR external cycle ratio, HCCI reemission results in lower levels of HC, CO, and NOx compared to conventional internal combustion engines. Subsequently, this paper delves into the historical background of AI and explores its current role in the automotive industry. After discussing the potential integration of AI with HCCI engines, it further examines the concept of leveraging "IoT" principles and employing DL methods of AI to address issues related to HCCI combustion timing. The "Internet of Things" can combine with ML's AI model analysis data to adjust the compression ratio and spark plug ignition time, maintaining better thermal efficiency and economic effects when speed and load are high.

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