LATEST TRENDS IN NEW INTERNAL COMBUSTION ENGINES

Abstract: Internal combustion engines have been used for the last one hundred fifty years as the main power source for many vehicles, most notably automobiles. These engines are characterized by a cycle that ignites a compressed air-fuel mixture, generating a combustion event which produces mechanical power. Despite their prominence in society, the depleting supply of oil, coupled with global warming issues related to carbon emissions, will limit their usage in the near future. Alongside government regulations on fossil fuels and newer technologies paving the way for more competitive vehicle models, these drawbacks foster a transition away from traditional internal combustion engine vehicles to alternative powertrains. Although the automotive community is moving towards electrification, the supply chain, power grid, and charging infrastructure will not be able to support a drastic change in the foreseeable future. As such, internal combustion engines will remain relevant and new technologies are offering large advances in fuel efficiency and emissions. In this paper, the prospect of utilizing hybridization, homogeneous charge compression ignition and hydrogen fuel are explored and examined in their efforts to ensure the future of the internal combustion engine.

1. Introduction

Responsible for being the powerhouse of many modern day vehicles, the internal combustion (IC) engine has proved an invaluable resource in allowing passengers to get to where they desire. Over the last one hundred fifty years, the IC engine has evolved from its initial designs, resulting in increased efficiency and performance. These improvements often may change the design or specific components of the engine, but the main purpose of the machine, converting chemical energy into mechanical energy, remains constant.

Much of the world is moving towards electrification for their automobile sector. Likewise, electric vehicles (EV) are an evolution from IC vehicles as the IC engine is replaced entirely with an electric traction motor and a battery which can be recharged through a charge port [1]. With these components, these EVs can potentially use electricity as a clean fuel source without the harmful greenhouse gas (GHG) emissions of their predecessor, given that the grid power is produced from renewable sources. This advantage has prompted many governments to put regulations in place which promote a transition to EVs by banning the future sale of IC cars. The most notable of these endeavors being the state of California's decision to phase out these vehicles by 2035 in hopes of having only EVs on the market; a decision of which has since been echoed by various automakers who are also striving for the same goal [2].

Despite the recurring sentiment, however, the likeliness of an all EV future in the near term appears to be rather low. According to industry estimates, as seen in Figure 1, only 18% of new cars sold in 2030 would be completely electric, with the remaining vehicles being an even split of pure IC engines and hybrid engines [3]. Consumer choice appears to be the main driving force behind these statistics, despite government regulations, due to the high costs of purchase associated with the expensive value of these batteries [4]. Among other factors listed in Table 1, most commercially-viable EVs have significant range limitations compared to their IC engine powered counterparts. In addition, the limited availability of charging stations in certain neighborhoods would put drivers in a dangerous situation had they run out of electricity on the road and could not recharge, further decreasing consumer confidence [5].

For the time being, the drawbacks of EV's far outweigh the advantages, causing consumers to go for the cheaper and more convenient IC vehicles. However, as the costs of the

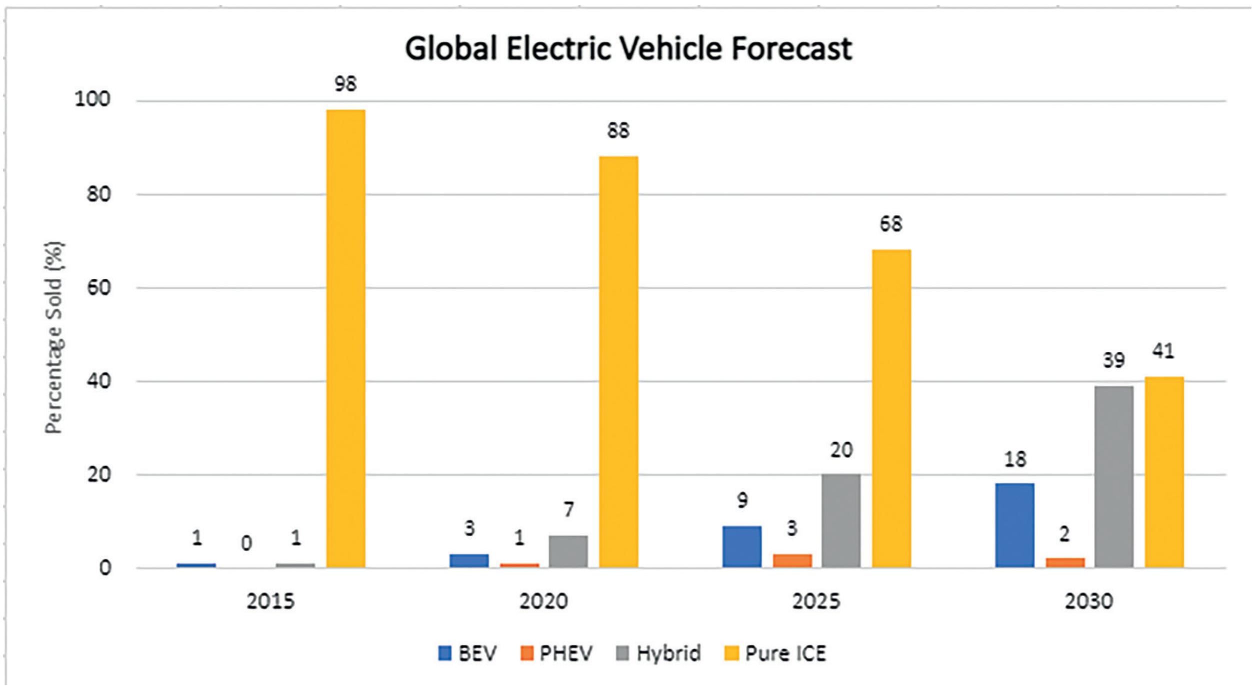

Fig. 1: Global electric vehicle forecast by 2030, according to industry estimates [3].

Table 1: Selected comparisons among IC engine-based vehicles and electric vehicles [4].

Internal Combustion Engine	Electric Vehicle
High energy density	Low energy density
Emits greenhouse gasses	No tailpipe emissions
Travels >300 miles before refueling	Travels <100 miles before recharging
High maintenance costs	Low maintenance costs
Can't recover braking energy	Can recover braking energy
30% engine efficiency	80% motor efficiency
Gradually produces torque	Produces maximum torque

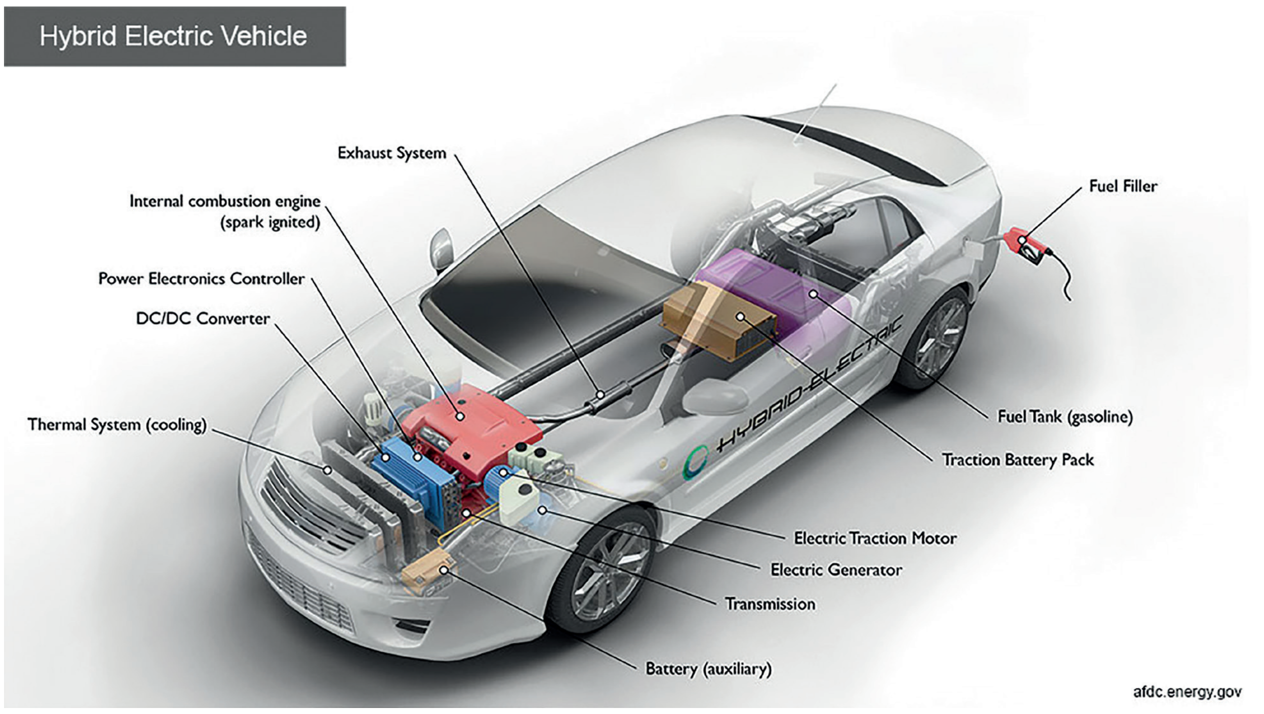

Fig. 2: Diagram of an hybrid electric vehicle, as depicted by the U.S. Department of Energy [9].

battery continue to decline, EVs gradually become more cost and performance competitive with IC vehicles. For IC engines to compete, they must evolve and adopt new technologies including hybridization, homogeneous charge compression ignition, and/or hydrogen fuel.

2.1. Hybridization

In order to upgrade any piece of equipment, one must first examine the base product and see how it can be improved. The IC engine is a machine that utilizes a four-step cycle of intake, compression, power, and exhaust to create energy for most vehicles. The pistons of the engine are able to compress an intake of an air-fuel mixture via a rotating crankshaft allowing the ignitor to spark the air into a combustion. This releases an explosion of chemical energy which is converted into work and allows the vehicle to drive, with the piston pushing out excess burned gas as exhaust [6]. Two-stroke engines also exist for smaller vehicles and simpler machines, but the general mechanics of compressing and igniting air-fuel mixtures for power remain constant [7]. There are currently two main types of IC engines: a spark ignition for gasoline and a compression ignition engine for diesel. While each type has their respective efficiencies and ignition strategies, the general four-stroke cycle remains constant for both engines and can also be powered through alternative fuels or be combined with hybrid electric powertrains to increase fuel economy [8].

If hybridized, the traditional IC engine would be combined with an electric motor that can store and use electricity, as seen in Figure 2, to combine the benefits of EVs with traditional vehicles. Since it is a hybrid, the IC engine would continue to be the main power source of the car and will have the battery supplement additional power whenever needed [4]. The main reliance on the IC engine would allow hybrids the power and range of conventional vehicles which is much further than a traditional EV. With support from the battery, the hybrid can benefit from powered auxiliary loads and reduced engine idling. Moreover, the IC engine could afford being downsized to a smaller model without a sacrifice in performance [9].

Normal IC engines are very heavy and add tremendous weight to the vehicle, consequently requiring that the engine is worked more to move the mass. This is very fuel inefficient and releases unnecessary GHG into the atmosphere. With a smaller engine the weight of the vehicle would be reduced and thus require less horsepower needed for operation. In turn, hybrids are granted low tailpipe emissions as the smaller engine runs more efficiently and mostly when needed, resulting in minimal pollution of nitrogen oxides (NOx), particulate matter, and carbon dioxide (CO2) emissions. Sequentially, this would help reduce global warming and conserve the near-depleted fossil fuel supply, ultimately complying with legal standards and satisfying the goals governments are trying to meet [9]. Together, the engine and battery would be able to provide hybrids with high fuel economies alongside the efficiency and range of conventional vehicles, all while cutting fuel consumption and conserving energy.

With the electric motor being one of the main components of a hybrid vehicle, the omission of any external charging ports to keep the battery charged on full-hybrids, as seen in Figure 2, would seem very surprising. As it turns out, the IC engine is primarily responsible for charging the battery of these full-hybrids throughout the normal operation of the vehicle. The electric motor can assist the charging through the technique of Regenerative Braking (RB), where the energy normally lost during braking is captured by the electric motor who then generates and stores the captured energy in the battery as electricity [9].

A group of Italian researchers led by Gianfranco Rizzo looked to quantify the amount of energy recovered by RB in an average hybrid vehicle. By calculating the amount of kinetic energy the vehicle possessed when at a certain speed and comparing it to how much energy the battery was found to store after each brake, the researchers came up with the graph in Figure 3. They noted that their lower speeds were able to let the battery recover up to 40% of the car's energy, but could not at very high speeds due to an increased difficulty in extracting energy from faster cars. The team believes that the hindrance could be related to various factors relating to the mechanical braking along with limitations of the battery pack [10].

Drag may also be a leading culprit in this hindrance as the force presents friction into the system proportional to the increased velocity. As drag reduces the total mechanical energy of the system, RB would also be lessened since there would be less energy that could be recovered; ultimately leading to their observed results. Nonetheless, their data indicates that hybrids are best for lower speeds and stop-and-go traffic for them to attain the full potential benefit of the electric motor. Hybridization is a feasible option that can help progress IC engines into the future alongside EVs, with minimal environmental impact.

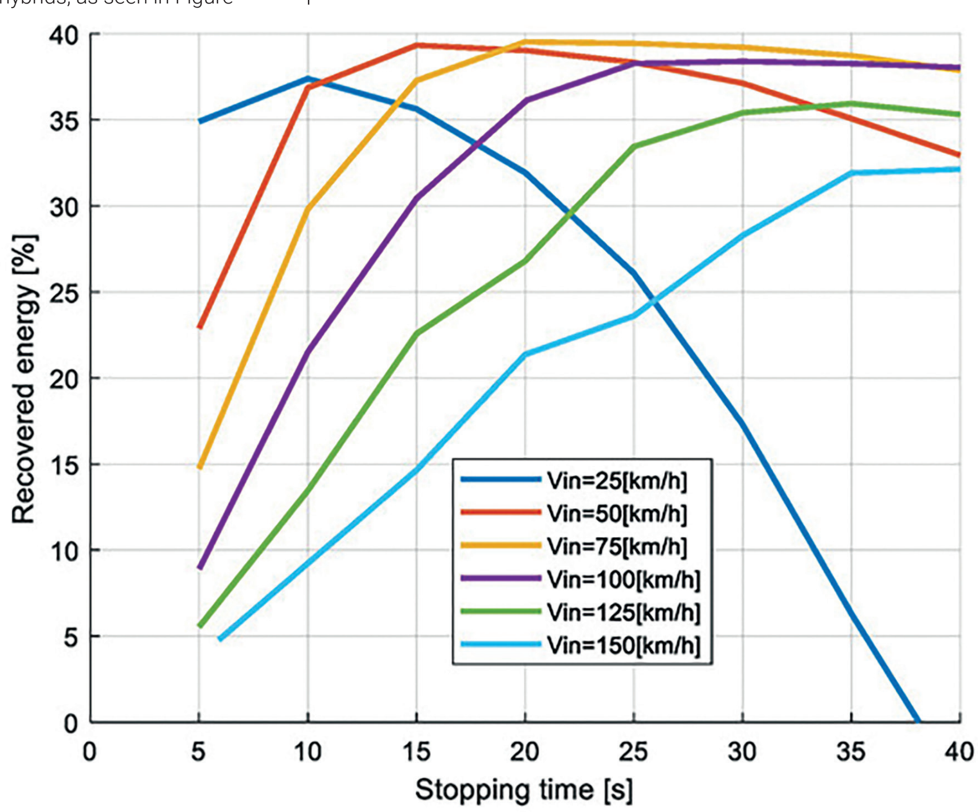

Fig. 3: Recovered energy percentage against stopping time at various speeds, as determined by Rizzo's team [10].

2.2. Homogeneous Charge Compression Ignition

While hybrid electric vehicles are best suited for slower stop-and-go traffic, IC engines must also be well equipped for faster highway traffic to best stand against EVs. In order to accomplish this, many developers have turned to the low temperature combustion system of homogeneous charge compression ignition (HCCI). The HCCI operates with gasoline under a compression ignition system commonly used for diesel engines, where an air-fuel mixture is inducted in the intake stroke. An auto-ignition system engine then compresses the mixture until it gets hot enough for all of the blend to ignite simultaneously and uniformly. This is a significant improvement over spark ignition systems for gasoline engines that mix fuel and air together during the intake stroke and normal diesel engines [8].

When using a stronger diesel engine system, HCCI is able to obtain max work for the car pistons without soot forming from gasoline or exorbitant levels of NOx or CO2 being released in the process, keeping in line with government emission regulations [11]. This is due to a more uniform distribution of the fuel around the engine cavity, so that localized pockets of lean/rich mixtures do not form. Furthermore, HCCI has the potential to allow a greater fuel efficiency than traditional spark and compression engines thanks to higher compression ratios, as well as offer significant power density over EV batteries [12].

Despite the astounding performance and environmental benefits this system produces, HCCI is reportedly very difficult to control with fine-tuned precision on intake temperatures and ignition timing needed for maximum benefit, as indicated in Figure 4 [12]. According to insiders in the industry, if HCCI combustion were to occur too early when the piston was moving up then the engine could be severely damaged and if it happened too late when the piston was moving down then overall engine efficiency would be lost [11]. These conditions would only allow for a restricted range of stable combustion and thus a limited window of operation. Having said that, HCCI could still prove to be great future technology for IC engines if the right automakers can harness it properly.

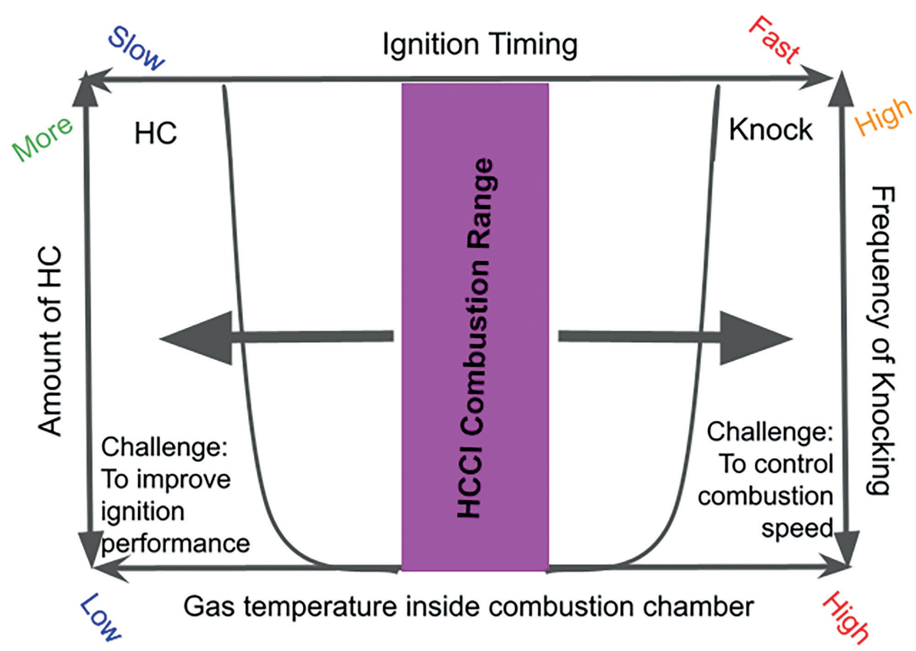

Fig. 4: Graph indicating the fine-tuned combustion range of HCCI combustion [12].

2.3. Hydrogen Internal Combustion Engine

If HCCI implementation is undesired due to its precise requirements, then the use of alternative fuels in IC engines may also be considered. The alternative fuels an IC engine could use is natural gas, propane, biodiesel or ethanol [8]. Hydrogen is a common gas and presents an enticing prospect for an alternative fuel source due to its efficiency and reduction of harmful emissions.

Commercial hydrogen for these vehicles in the US mainly comes from the process of steam reforming where superheated steam is combined with natural gas to extract hydrogen. Steam reforming is relatively easy but produces carbon monoxide and trace CO2 as byproducts, harming the environment. Electrolysis methods is an alternative method that uses renewable energy sources and would not release harmful GHG in the process. Although this is ideal, electrolysis is more energy intensive and thus has rarely been executed on a massive scale [13].

No matter the source, commercial hydrogen is versatile and very cooperative with the IC engine. Hydrogen IC engines work similar to the traditional gasoline spark ignition system, where it uses a normal four-stroke cycle but uses hydrogen instead of gasoline [14]. Unlike the IC engine, however, the hydrogen IC engine does not emit CO2 or particulate matter, but water vapor as only hydrogen would be combusted. Trace amounts of NOx may also be produced, but it could be cleaned via exhaust aftertreatment systems [13].

In practical use, hydrogen IC engines should prove to be reliable and economical in the long-run, but would require expensive upgrade costs to the IC engine in order to successfully allow it to run on hydrogen. Most of these upgrades would relate to the storage of hydrogen onboard the vehicle. Hydrogen has a very low-volumetric energy density and would need storage tanks that can compress the onboard element at high pressure loads of 5,000 or 10,000 psi to greatly increase its energy density of the element. It is only through this high-pressure compression that can allow hydrogen-based IC vehicles to achieve and possibly exceed the mileage range of conventional vehicles before refueling [13].

Along with the installation of hydrogen tanks on the vehicle for storage, high pressure fuel lines and injectors that connect the tank to the fuel filler and the engine are also needed for drivers to refill and provide hydrogen fuel for their vehicle [13]. Despite the effort required to install these components, only heavy duty trucks and buses would be able to efficiently use these engines as those vehicles have enough volume to store these heavy tanks onboard and drive [14].

Even if only heavy duty trucks are able to be converted in the short-term future, the transformation of these vehicles would still offer great environmental benefit. According to industry estimates in Figures 5 and 6, the transportation sector emits the most GHG into the atmosphere with a great portion belonging to trucks. By converting only heavy duty trucks into hydrogen vehicles, approximately 26% of this sector's emissions would be eliminated assuming that the hydrogen was produced through electrolysis powered by renewable energy [14,15]. Additionally, heavy duty trucks would have increased cargo capacity, as compared to their EV counterparts, since the hydrogen fuel tanks are smaller in size than electric batteries, freeing up space in the vehicle. This would allow each truck to carry more freight than normal and thus reduce the need and amount of trucks on the road, furthering environmental benefits [16].

However, these vehicles may have the same issue as EVs where drivers can only drive where hydrogen is present and could cause a difficult situation if a driver is running low and a refueling site is nowhere to be found [14]. Nevertheless, hydrogen IC engines have the flexibility, power, and range that long haul heavy duty trucks need which EVs cannot provide, all without releasing any additional harm to the environment.

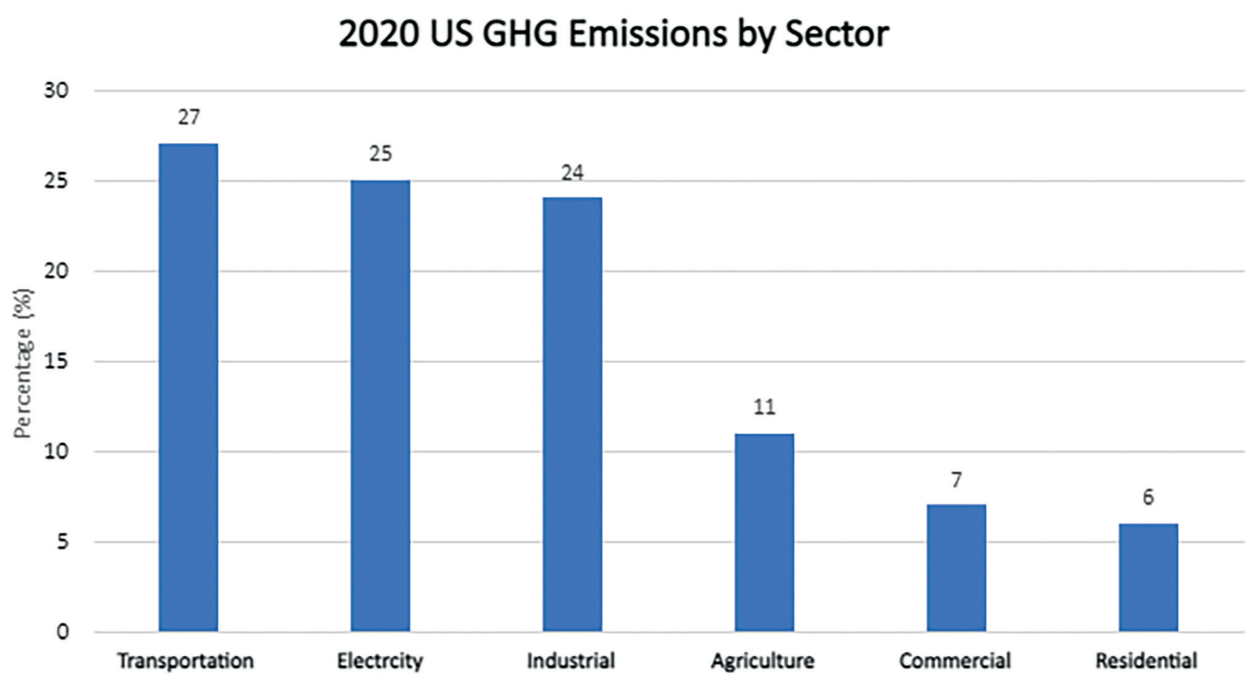

Fig. 5: Column graph of recent US greenhouse gas emissions by sector in 2020, according to the U.S. Environmental Protection Agency [15].

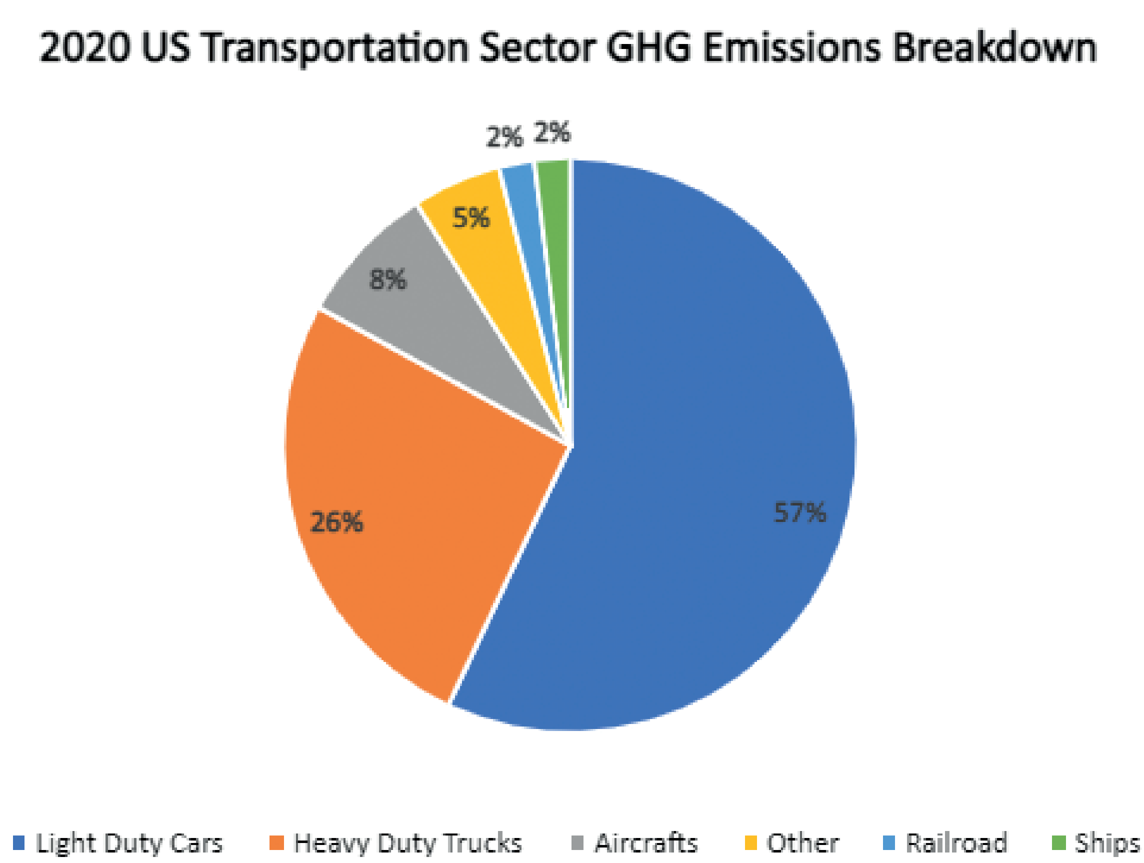

Fig. 6: Breakdown of the sources releasing the most greenhouse gas emission in the U.S. transportation sector in 2020, according to the U.S. Environmental Protection Agency [15].

4. Conclusion

The IC engine will need to utilize hybridization techniques, homogeneous charge compression ignition, and/or hydrogen fuel in order to meet government regulations on emissions and ensure a long-term future against the rise of EVs. Hybridization allows for vehicles to reap the benefits of conventional gasoline engines with those of an electric battery, helping to increase efficiency and save fuel. The HCCI system allows vehicles increased power density with minimal emission released. Hydrogen IC engines allow for great fuel efficiency at near-zero emissions. No matter which route these machines will take, their future is bright in every respect and, with the right automakers, will allow the IC engines to survive well into the future amongst EVs and laws.

5. Future Work

As true with any type of machine, IC engines will go through a multitude of iterations in history as research and development progresses alongside advanced technology. For the near future, resources on these engines should focus on the discussed trends and how best to implement them in subsequent models. Researchers should focus on how to allow the car to move in more heavy traffic and increase energy recovery from regenerative braking. On the other hand, experimenters should study the HCCI system on how best to widen the precision range needed for operation without sacrificing performance. Additionally, automakers should focus on the feasibility of introducing hydrogen fueling pumps into local towns, similar to EV charging stations; as well as finding a way for smaller vehicles to properly store and compress the hydrogen at the right pressure in limited available space. Altogether, continued support of research efforts in any area can allow the IC engine to thrive well in a cleaner and more efficient future.

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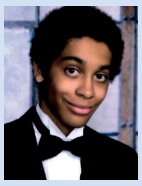
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