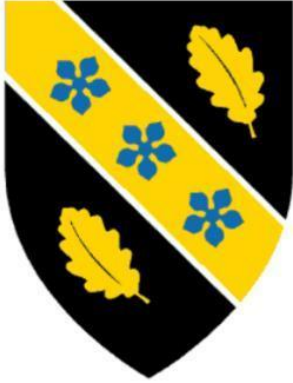


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***Hydrogen Internal Combustion Engines in Motorcycles and
Passenger Vehicles***

Academic Skills (ACHA4005)

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1. Introduction

Earlier this year in 2024 Kawasaki as a member of the HySE Group (Hydrogen Small-mobility & Engine technology) unveiled a Hydrogen ICE (Internal Combustion Engine) powered motorcycle, based off of their popular H2 Sports Tourer motorcycle. (Duke 2024)

Similarly Toyota are working on Hydrogen technologies in the automotive sector, with a history of both Hydrogen ICE vehicles and Hydrogen Fuel Cell Electric Vehicles, such as the Toyota Mirai II. (Clifford 2020)

In recent years there has been more research conducted into the possible use of Hydrogen as an energy carrier to power vehicles, with the two most common routes for which being a Hydrogen Fuel Cell Vehicle, or a Vehicle powered by an ICE that burns hydrogen as fuel.

The purpose of this report is to explore the current technologies in the market of Hydrogen powered vehicles, specifically motorcycles and speculate on the future of the industry.

2. Contextual/Background Information

2.1. History of Hydrogen Vehicles

The idea of running motor vehicles off Hydrogen gas is not a new idea – the first design of a Hydrogen combustion engine is from Switzerland, by François Isaac de Rivaz in 1807. The use of hydrogen as a fuel source in a combustion engine proved promising, however was not as widely implemented or researched as the Otto or Diesel cycle fossil-fuel powered engines due to the problems associated with storing hydrogen and the wide availability of petrol and Diesel fuel. (Wróbel et al. 2022)

The struggles with the supply of traditional hydrocarbon fuels in the early and mid 20th Century led to a few developments in converting vehicles to Hydrogen power. One example of this is a small truck converted by a Norwegian hydropower plant to run on hydrogen in 1933. Another example is in 1941 the Soviet army had 200 GAZ-AA military trucks converted to use hydrogen, which proved very effective compared to their regular hydrocarbon burning variants. (Wróbel et al. 2022)

Since the Second World War research has continued on hydrogen vehicles. Both German and Japanese companies have developed vehicles of both Fuel Cell and Hydrogen Internal Combustion power, such as the 2003 BMW Hydrogen 7 (bi-fuel petrol and hydrogen) or 2005 Toyota Quantum Prius. (Wróbel et al. 2022)

2.2. Modern Hydrogen Vehicle Development

In recent years development of hydrogen powered vehicles has gained more attention, with multiple companies making commercially available four-wheeled vehicles. As of 2014 Toyota have been producing the Toyota Mirai, a Hydrogen Fuel Cell Electric vehicle, and updated the model in 2021. (Clifford 2020) The Mirai was the world's first mass produced and publicly available hydrogen powered vehicle and has proved itself to be effective in its goals, achieving about 400 miles of range on a charge of hydrogen, while delivering zero tailpipe emissions.

In terms of motorcycle development, 2024 has been an exciting year. Kawasaki revealed and publicly tested a version of their H2 motorcycle powered by onboard hydrogen storage cells, burning the hydrogen in a similar way to a hydrocarbon. It is burned in a modified version of the 998cc engine used in their standard H2 motorcycle. (Kawasaki UK 2024)

3. Discussion

In their study Georgescu, Pană et al. (2024) researched the possibility of using a mixture of a conventional hydrocarbon fuel and hydrogen gas to improve the efficiency, power and emissions characteristics of an Internal Combustion Engine. As well as utilising the research of others, they performed an experiment where a setup of injecting hydrogen gas alongside atmospheric air was utilised alongside a series of sensors to evaluate engine performance.

3.1. CO₂ Emissions

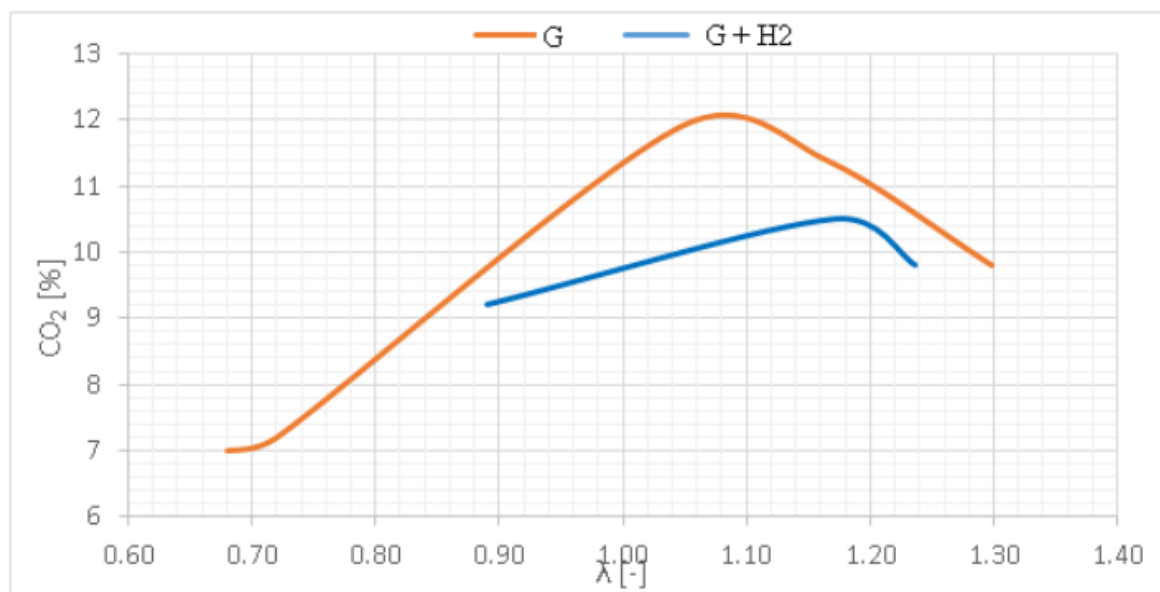


Figure 1 - CO₂ Emissions against Lambda (Georgescu et al. 2024)

One of the main benefits of hydrogen fuel in either an ICE or as a Fuel Stack is that there are no Carbon Dioxide emissions. In this case the hydrogen is used supplementary to a regular hydrocarbon fuel, so there are still CO₂ emissions present. Figure 1 shows that when supplementing Hydrogen gas alongside the hydrocarbon fuel, CO₂ emissions are noticeably reduced across a range of air-fuel ratios supplied to the engine, and by 16% at around the stoichiometric ratio.

3.2. Battery Usage

In their study Pipitone, Caltabellotta & Occhipinti (2021) found that while Battery Electric Vehicles over their entire lifecycle have a lesser impact on the environment, there are some

negative aspects to their usage. The typically used Lithium-Ion batteries require a lot of energy and expensive material to manufacture, and the electricity to power the vehicle is not usually produced from a renewable source of energy. The Hydrogen Fuel Cell Electric approach does not completely eradicate this problem, as the Fuel Stack used to convert the chemical energy in the hydrogen to electrical energy does not react well to changes in demand. They usually change their power output slowly, so the demand from an electric motor is challenging. To use the power from the Fuel Stack, a Lithium Ion battery is generally used as a capacitor to manage the demand and supply of power to the motors of the vehicle. This battery, while not as large as a traditional Battery Electric Vehicle battery, still burdens the environment with its creation and is not ideal. A hydrogen ICE does not require this to operate, as the battery for operation would be the same size and type as a conventional ICE vehicle's.

3.3. Retrofitting Existing ICEs

Another benefit with the development of hydrogen burning ICEs is the possibility of retrofitting existing ICEs to burn hydrogen. The rewards of this are multi-faceted, including energy & material costs of scrapping and remanufacturing new vehicles, protection of jobs in maintenance and manufacturing of ICEs, and the ability to continue using heritage vehicles with little impact on the environment.

There is possibility to convert both petrol and Diesel engines to burn hydrogen as all of the processes and parts in storing and burning the hydrogen are functionally the same as in a hydrocarbon vehicle. (Onorati et al. 2022) This does not only apply to passenger cars, but also motorcycles. The Kawasaki H2 concept demonstrated at the 8 Hours of Suzuka race this year is based on the chassis and engine of the normal road-going H2 motorcycle, with certain adaptations to allow for direct injection of hydrogen and the storage of the fuel in canisters on the rear of the vehicle. (Duke 2024)

3.4. NOx Emissions

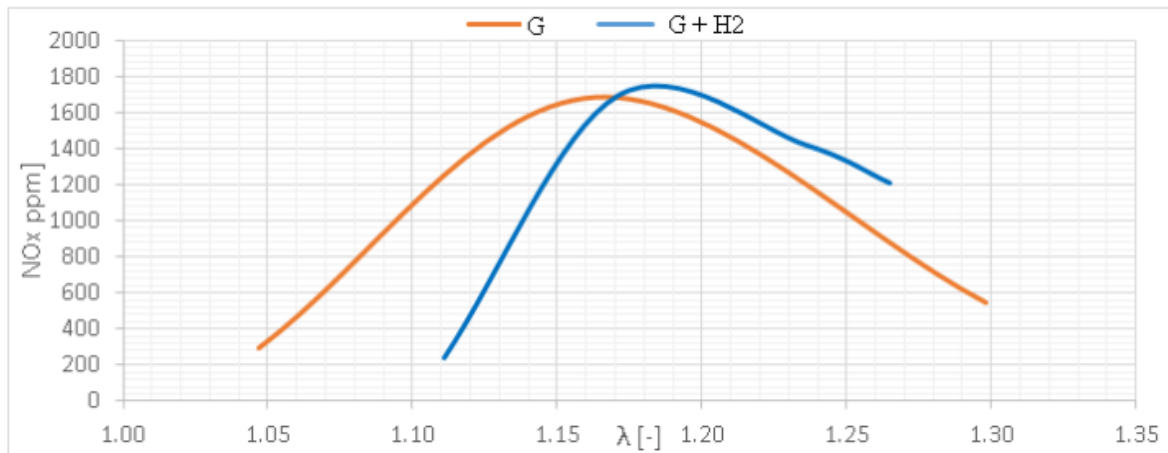


Figure 2 - NOx Emissions against Lambda (Georgescu et al. 2024)

There are however challenges associated with the usage of hydrogen as fuel. Nitrous Oxide (NOx) Emissions pose a great threat to the environment, and the higher combustion temperatures when burning hydrogen cause Oxygen and Nitrogen present in the atmospheric air to react and form Nitrous Oxides. Figure 2 shows that when supplementing hydrogen alongside the hydrocarbon fuel there are conditions in which NOx emissions are increased. In their study Onorati et al. (2022) suggest some methods for combatting the issues with Hydrogen ICEs, including NOx emissions. One of these methods is via water injection, where water is injected as a fine mist alongside the air charge entering the combustion chamber. As it is converted into steam it consumes a large amount of energy and reduces the temperature in the cylinder. This is effective at controlling NOx emissions because, as mentioned, NOx emissions are worsened when cylinder temperatures are high. This is a similar approach as it taken in some hydrocarbon engines already.

3.5. Hydrogen Production and Storage

Another challenge to overcome with the use of hydrogen is the production and storage of the chemical. There are three main methods for producing hydrogen gas suitable for a passenger vehicle. The first of these is steam methane reforming, however this process produces a large amount of CO₂ gas, which is detrimental to the environment and counteracts the reason for producing a hydrogen powered vehicle. The second method is coal gasification, which has a efficiency than steam methane reforming and still produces CO₂ emissions. The final method is

through the electrolysis of water, however this is incredibly energy consuming and the electricity required is not necessarily produced in an environmentally friendly manner. (Onorati et al. 2022) When storing hydrogen, it is required to either store it in a liquid state – which requires very low temperatures and is not convenient for on-vehicle storage – or to store it at extremely high pressures – as much as 700 bar is required in current applications. The vessels for storage with current technology are very expensive and not always practical for use in any passenger vehicle, nevermind a motorcycle. (Onorati et al. 2022) The Kawasaki H2 test model that is previously mentioned had been fitted with large panniers to house the hydrogen storage tanks, as the space dictated by a traditional motorcycle layout was not sufficient.

4. Conclusions

While there are numerous drawbacks associated with the production, storage and usage of hydrogen gas in either a fuel cell or ICE vehicle, the industry is investing in a large amount of research to make mass-production of hydrogen vehicles feasible. Many individuals and companies are leaning towards hydrogen as a preferred method of running both passenger and commercial vehicles because of the benefits of it over battery electric and conventional ICEs, with a backdrop of an international mandate of carbon neutrality.

It is entirely possible that the next decade will see further development of not only new fuel cell and ICE vehicles, but allow for the conversion of existing ICEs to hydrogen power.

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