

PERFORMANCE COMPARISON OF HYDROGEN FUEL CELL AND HYDROGEN INTERNAL COMBUSTION ENGINE RACING CARS

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Abstract: Students from RMIT University and the University of Applied Sciences Ingolstadt have collaborated to build a hydrogen-powered racing car. As part of the initial conceptual design, a lap simulation was developed to compare performance and fuel usage of hydrogen internal combustion engine and hydrogen fuel cell vehicles. For the vehicle and track specifications analyzed, it was found that fuel cells require a power density of 5kg/kW to be competitive with the hydrogen internal combustion engine. The study also highlighted the complex nature of the alternative fuels debate.

1 Introduction

1.1 The case for hydrogen vehicles

Mankind's dependence on personal transport is increasing as economies grow and as emerging nations move towards a more Western lifestyle. However the transport sector relies heavily on petroleum products as a fuel source, resulting in the production of large quantities of greenhouse gases, and exposure of the transport sector to great uncertainty in the face of diminishing oil supplies.

A possible alternative fuel is hydrogen. When hydrogen reacts with oxygen in the air the only product of reaction is water, and therefore it offers the potential of carbon-free transport. Two available power units for hydrogen vehicles are the fuel cell (H₂FC) and the internal combustion engine (H₂ICE). Of the two options, the fuel cell offers advantages in potential efficiency as the chemical reaction energy is directly harnessed as an electric current to drive a motor. In comparison,

the H_2ICE cycle includes an intermediary heat phase, restricting potential efficiency to ideal heat cycle limits. From these efficiency considerations, fuel cell vehicles are often seen as the ideal “end-goal” for hydrogen powered transport.

However fuel cells can be heavier and more expensive than internal combustion engines, and require high purity hydrogen to prevent the cell from being poisoned. Hydrogen internal combustion engines are less efficient, but offer weight and cost advantages and can be run on multiple or impure fuels.

A motor vehicle is a dynamic system and therefore a vehicle’s powertrain must use some of its available power to accelerate itself. This leads to the question: in an automotive situation, how much is the potential efficiency advantage of a fuel cell offset by the additional mass of the fuel cell itself?

1.2 *Formula H*

RMIT University (Australia) and Hochschule Ingolstadt (Germany) have collaborated to build a hydrogen powered racing car. Known as Formula H, the objectives of the project were to prove that alternative fuel vehicles are achievable with existing technologies, and to expose the student team to a real-world multinational design project. The project delivered a fully functioning LeMans prototype style racing car, powered by a BMW 800cc motorcycle engine running on hydrogen fuel, and featuring a 200bar compressed gas hydrogen supply system.

2 Vehicle Comparison Methodology

2.1 *Lap Simulation*

Early conceptual design process required the Formula H team to assess the relative performance of internal combustion engines and fuel cells for racetrack use. A preliminary study was undertaken in the form of a quasi-static lap simulation, based on the 3 km long Winton racetrack in Victoria Australia. A vehicle model representing a benchmark H_2ICE vehicle was simulated, with predicted lap time and fuel consumption results recorded. These results were then compared against fuel cell vehicle models of varying powers and weights.

The simulation was constructed as follows:

- The vehicle path was modeled as a string of straight lines and constant radius arcs, broken into 1 metre increments.
- Each vehicle was modeled as a point mass with representative tyre grip and power output characteristics.

- Vehicles travelled at constant speed through corners, at the tyre grip limit. Cornering speed defined entry and exit speeds for each straight.
- Forward acceleration was calculated as a function of engine power (P_{ENGINE}), driveline efficiency (η), resistance power ($P_{RESISTANCE}$, the combined aerodynamic drag and rolling resistance), velocity (v) and vehicle mass (m):

$$\eta P_{ENGINE} - P_{RESISTANCE} = mav \quad (\text{Gillespie, 1992})$$

- Velocity under braking was calculated using combined wind resistance and maximum tyre grip force.
- Vehicle power was assumed constant and independent of engine speed.
- Aerodynamic drag was calculated as a function of velocity (v), frontal area (A), drag coefficient (C_D) and air density (ρ), as described in [1]:

$$F_{DRAG} = 0.5 \rho A C_D v^2$$

- Vehicle energy requirements were calculated by summing kinetic energy changes, air resistance and rolling resistance energies across each track increment.
- Relative fuel used was calculated as a function of the total energy required, and overall thermodynamic efficiency. Thermodynamic efficiency of the H_2 ICE was estimated at 25%, and the fuel cell at 40%.

The modeling of detailed vehicle dynamics such as cornering transients, weight transfer, or suspension dynamics were considered unnecessary for this preliminary study.

2.2 Tyre Grip

A critical modeling requirement was to capture the effect that varying vehicle weights would have on tyre performance. Whilst a tyre's grip force increases with vertical load, the relationship is not linear and the grip coefficient actually falls with increasing normal force [2]. This is known as tyre load sensitivity, and published test data [3] for Goodyear tyres similar to those used on the Formula H vehicle confirms this characteristic. The grip coefficient is seen to fall by approximately 0.03% per Newton of load (Fig. 1).

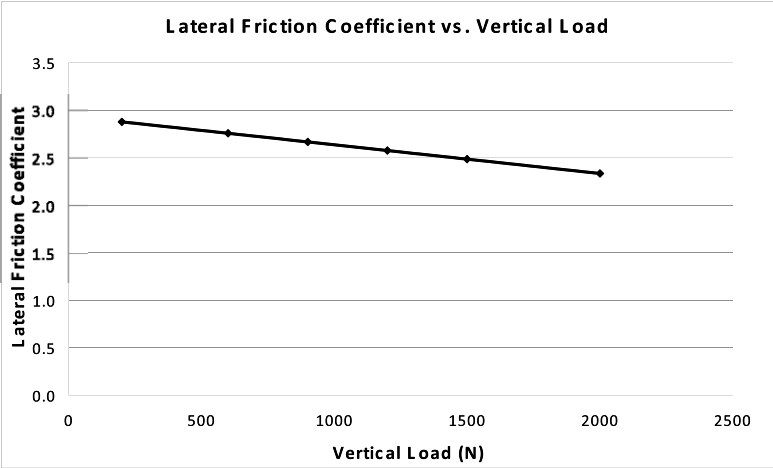


Fig. 1 Friction data, Goodyear 20.0-7.0x13 D2509 FSAE tyre ([3]).

Note that the above data were taken in controlled laboratory tests on a rolling drum tyre testing machine, and are believed to overestimate absolute friction coefficient values. A more representative value of friction coefficient is estimated at approximately 1.4-1.5, based on observations of the cornering performance of the RMIT Formula SAE vehicle using similar tyres. Tyre load sensitivity is expressed in terms of percentage variance per Newton of load, so is unaffected by this adjustment of scale.

2.3 Vehicle Specifications: *H₂ICE Benchmark Vehicle*

The benchmark H₂ICE vehicle was modeled on the Formula H vehicle, with the following specifications:

Table 1. H₂ICE vehicle specifications.

Specification	Value
Total vehicle mass (including driver and engine)	600kg
Engine system mass (not including H ₂ supply system)	80kg
Tractive power (rear wheels)	30kW
Tyre grip coefficient (all directions)	1.4
Frontal area	1.2m ²
Drag coefficient (CFD estimate)	0.62
Rolling resistance (assumed constant)	200N
Thermodynamic efficiency	25%

The above vehicle model completed one lap of the circuit in 105.1 seconds, with a maximum speed of 129.8kmh. Note that the top speed of the actual Formula H car has been measured at 133kmh, confirming that the simulation is of reasonable accuracy.

2.4 Vehicle Specifications: Fuel Cell Vehicle

Fuel cell vehicles were simulated by replacing the IC engine system mass and output in the baseline vehicle model with each combination of the following fuel cell attributes:

- Power output: 30-80kW, in 10kW increments.
- Fuel cell unit power to weight ratio: 5-10 kg/kW, in 1kg/kW increments.

It was assumed that the compressed gas hydrogen supply system would be common to fuel cell and H₂ICE vehicles. In each case a modified tyre friction coefficient was calculated, using a tyre load sensitivity of 0.03% reduction in friction coefficient per Newton of total vehicle weight (relative to the baseline vehicle).

3 Vehicle Comparison Results

Inspection of the results highlights the importance of fuel cell weight reduction. The only fuel cell vehicles to achieve equivalent or faster lap times than the H₂ICE vehicle were those with a fuel cell mass to power ratio of 5kg/kW, and only those with power outputs of around 45kW or greater (Fig. 2). The effect of additional mass of the heavier vehicles slowed them sufficiently in the corners that any advantage on the straights was negated. This was despite the fact that in many cases the higher powered fuel cell vehicles had a greater overall power to weight ratio than the benchmark H₂ICE vehicle.

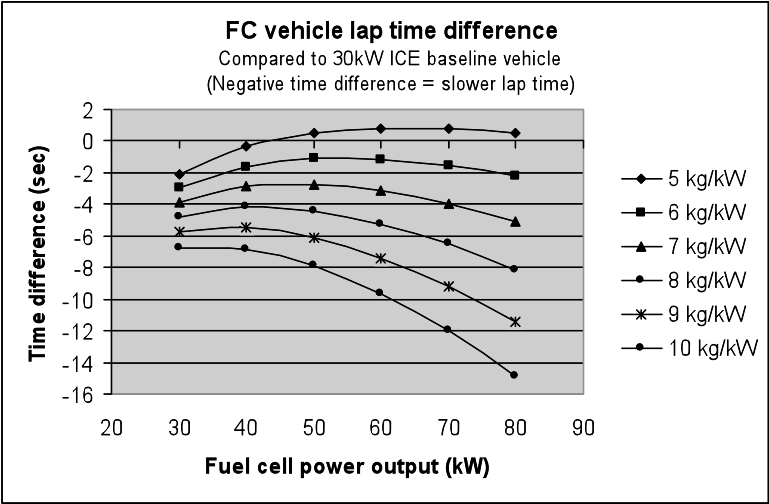


Fig 2. Comparative lap times.

All fuel cell vehicles showed a similar trend of increased fuel usage at higher power outputs, as lesser cornering speeds and higher top speeds created greater kinetic energy and aerodynamic drag energy demand (Fig. 3). Of the variants tested, only the 50kW and 60kW fuel cell design options of 5kg/kW power density were calculated to offer faster lap times and lower fuel consumption.

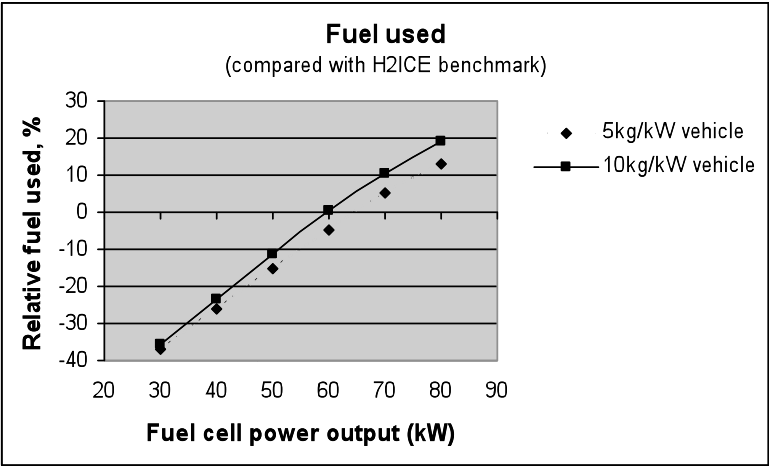


Fig. 3 Comparative fuel used

It is interesting to note that lap times show a distinct negative trend at higher power outputs. The vehicle designer would need to be aware that increasing pow-

ertrain output in an attempt to gain competitiveness can in fact result in both worse lap times and greater fuel consumption. This is particularly dependant on the tyre's load sensitivity characteristics.

4 Conclusions

The above work is a preliminary study only, and the presented results are relevant only to the particular vehicle, tyres and racetrack used in the study. Moreover, the results presented are for race conditions at the limits of a vehicle's performance, and would not be representative of common passenger vehicle usage.

However the study highlights the danger of focusing on individual parameters when assessing vehicle performance. A motor vehicle is a complex system, and decisions made on the basis of isolated criteria such as thermodynamic efficiency or power density may be poorly informed when observed at a system level. It is recommended that further investigation be undertaken into the relative merits of hydrogen fuel cell and hydrogen internal combustion engine vehicles.

References

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