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The environmental and cost performance of current and future motorcycles

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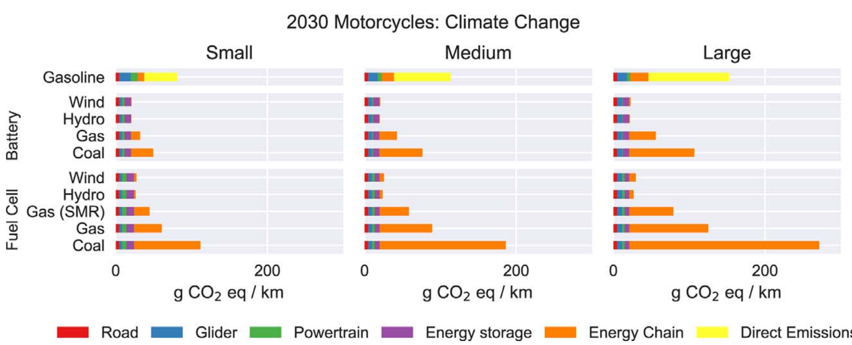
HIGHLIGHTS

- LCA and cost assessment of motorcycles including battery and fuel cell powertrains.
- Battery motorcycles already cost competitive with large environmental benefits.
- Motorcycle environmental performance most strongly dependent on driving speed.
- Extensive supporting information including calculation files and life cycle inventories.

GRAPHICAL ABSTRACT



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ABSTRACT

This work presents an integrative approach to environmental and cost assessment of current and future motorcycle technologies for four motorcycle size categories, three powertrain types, and a variety of fuel supply chains. We consider conventional gasoline (ICEV), battery electric (BEV) and fuel cell electric (FCEV) motorcycles with production years from 1990 to 2030. Motorcycle energy consumption is modelled based on the world harmonized motorcycle test cycle and calibrated with data measured from existing motorcycles. We model the potential future performance of motorcycles by adapting the model input parameters according to historic trends and future component performance predictions. We find that smaller motorcycles have much better environmental performance than larger motorcycles, though this is mostly due to the fact that larger motorcycles have different driving patterns: urban driving is found to have much lower environmental impact per kilometer than highway driving. Current BEV are found to have similar ownership costs to ICEV. They also have reduced climate change potential by roughly 60% when they are powered by electricity from natural gas, 80% when powered by renewables, and they still offer advantages over conventional motorcycles when charged with electricity from hard coal. Next generation BEV are found to have similar environmental performance advantages, though with a definite cost advantage. FCEV climate change reduction potential is found to depend strongly on the source of the hydrogen fuel, with climate benefits being substantial with hydrogen originating from renewable energy sources. Future cost competitiveness of FCEVs is linked closely to the development of fuel cell costs.

1. Introduction

Motorcycles and scooters (hereafter referred to as motorcycles) typically have lower operating costs and fuel consumption than passenger cars and contribute less to traffic congestion while still providing the personal freedom that is not available with public transportation. For these reasons, motorcycles are viewed as a technology with the potential to reduce the impacts of passenger transportation, especially in

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urban areas [1–3]. In some countries, such as Vietnam, India, Indonesia, Thailand, Taiwan, and China, motorcycles make up over 60% of the passenger vehicle fleet [4]. Although they offer benefits in terms of energy consumption compared to cars, combustion motorcycles have also been shown to cause significant emissions of many air pollutants responsible for public health problems [5–7]. However, motorcycle tailpipe emissions have decreased drastically in the past two decades and are expected to continue to do so in the near future [8–10].

Advanced technologies such as electric powertrains may have the potential to further reduce motorcycle energy consumption and greenhouse gas (GHG) emissions while nearly eliminating the impact of motorcycle travel on urban air quality [3,11]. Advanced powertrain motorcycles have rapidly gained in popularity in recent years, and there are already several manufacturers offering battery electric motorcycles in all size categories [12–21]. Moreover, several concepts for fuel cell electric motorcycles have been published to date [22–24]. While advanced powertrain motorcycles have no direct tailpipe emissions and thus perform well in terms of direct urban air pollution, the environmental impacts of producing the motorcycle and the electricity or hydrogen used to power it can be significant from a life cycle assessment perspective [3,11,25].

It seems likely that motorcycles will play a role in future urban transport solutions, though their environmental benefits are strongly dependent on powertrain type, energy chain and motorcycle size. Thus, decision makers and modelers require more information regarding the environmental performance and costs of different types of future motorcycles. Ideally, this information should be life cycle based to allow a complete comparison of the powertrain types and avoid burden shifting. It should also include variations in key performance parameters such as motorcycle size and fuel production chains. The goal of this paper is to provide this information using a consistent framework and a neutral technology point of view.

1.1. Previous work

There are several excellent resources available that tabulate the fuel consumption and exhaust emissions of internal combustion motorcycles, often including different motorcycle sizes, driving patterns, and emission standards [10,26–28]. These sources show that motorcycle emissions and fuel consumption are strongly dependent on motorcycle size and production year (indicated by Euro category). However, these studies consider only conventional motorcycles and do not include the whole life cycle of the motorcycle or cost information.

A number of studies do consider motorcycles with battery or fuel cell electric powertrains, and some even perform LCA of these motorcycles and compare them to conventional motorcycles [3,11,25,29–33]: Cherry et al. [33] examined lead battery based electric bicycles in China and compared them to competing modes of transport, such as conventional bicycles, motorcycles, cars and buses. Del Duce and Gauch [11] evaluated the environmental impacts of different transport technologies for Swiss Post and included combustion and electric scooters in their analysis. Leuenberger and Frischknecht [31] created detailed datasets for electric and combustion scooters which are now included in the ecoinvent database. Hofmann et al. [29] analyzed the potential of small electric cars and scooters for the Swiss Federal Office of Energy in 2013. They based their life cycle inventories for motorcycle production on ecoinvent, but carried out detailed measurements and modelling of electric scooter energy consumption. Hwang and Chang [30] studied the well-to-wheel greenhouse gas emissions from combustion, fuel cell and battery scooters. Walker and Roser [32] modelled cost and energy consumption of gasoline, battery electric and hybrid motorcycles. Mellino and Petrillo [25] performed LCA comparing battery and fuel cell electric bicycles to a conventional scooter. Weiss and Dekker [3] consider the life cycle environmental impacts of several size classes of electric motorcycles and compare them to bicycles, motorcycles, passenger cars and buses, also including cost information.

In general, these studies find that electric and fuel cell powered motorcycles have higher tank-to-wheel efficiencies than combustion motorcycles and thus have the potential to reduce greenhouse gas emissions. The energy consumption values for motorcycles are rather consistent across all studies, though they vary significantly according to motorcycle size. Life cycle impacts per kilometer (where reported) are found to vary, mostly due to differences in assumptions regarding the lifetime distance travelled and the source of electricity and hydrogen. This makes it very difficult to draw general conclusions about the performance of different motorcycle powertrains and sizes. Furthermore, as all of these technologies seem to be improving quite rapidly due to emission standards for conventional motorcycles and battery and fuel cell technology development for advanced powertrains, it is highly unclear how these technologies might compare in the mid-term future, which is the time horizon of interest for decision makers. Finally, it seems that all of the above studies that considered lithium ion battery based electric bicycles and motorcycles in their assessment used the lithium ion battery life cycle inventory from the ecoinvent database, which in turn is taken from Notter and Gauch [34]. However, the energy consumption assumptions for battery production contained therein are very optimistic, likely leading to an underestimation of the impacts of producing lithium ion batteries in these studies [35,36].

1.2. Research goals

Although many conclusions may be drawn from the studies discussed above, we feel that the literature still lacks a single study that considers the environmental and cost performance of all relevant motorcycle powertrain types and sizes, a wider selection of energy production chains, as well as past, current, and future technology performance. We provide a comparison of the cost and environmental performance of both conventional (gasoline combustion) and advanced powertrain (battery electric and fuel cell electric) motorcycles. We believe that such a comparison will not only be of use to persons interested in purchasing a motorcycle, but also helpful for decision makers and model developers in the areas of energy and transport. To this end, we also provide model results for historic motorcycles starting with production year 1990, and future motorcycles with production year 2030. We include four different motorcycle sizes in order to better understand the impact that size has on the cost of a motorcycle and its environmental performance. We focus on motorcycles produced globally, but operated in Western Europe.

As our goal is to provide input information for decision makers and modelers, we also include all calculation files, input assumptions, and results in supporting information (SI) so that others may build on our work. We hope that our results will be used to more accurately include different motorcycle sizes and powertrains in transportation, economic and energy models as well as life cycle databases.

2. Methods and calculation

2.1. Motorcycles considered

This study models the environmental and cost performance of internal combustion (ICEV), battery electric (BEV) and fuel cell electric (FCEV) motorcycles. Four different motorcycle size classes that represent the entire range of motorcycles commonly found in the fleet are included (see Table 1). ICEV motorcycles are modelled for production years 1990–2030, while BEV and FCEV motorcycles are modelled for production years 2015–2030. We include FCEV motorcycles in the base year of 2015 to represent their performance as if they had been commercially produced, thus allowing their comparison with other motorcycle types.[1] However, it seems unlikely that fuel cell powered motorcycles will be common before 2020.