Impact of Increased Tire Pressure on Fuel Consumption and Environment for Fuel-Cell-Assisted Shared Bicycles

Emi HOSOBUCHI※1†, Chiharu MISAKI※1, Noboru KATAYAMA※2, and Kiyoshi DOWAKI※1

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This study evaluated the use of a fuel-cell-assisted bicycle (H-bike) in bicycle sharing. Two pertinent issues arise. First, the number of start-stops and distance traveled lead to power consumption levels so high that they exceed those of households. Second, the H-bikes are 3 kg heavier than conventional bicycles. Reduction in rolling resistance due to increased tire pressures may afford a solution to these problems. The purpose of this study was to investigate whether increasing the tire pressure can reduce the amount of energy consumed and eliminate the impact of increased weight. Energy consumption was evaluated with a bicycle-riding experiment; the net impact of increased weight on energy consumption and the environment following the spike in tire pressure was assessed. Life-cycle assessment was performed using the CML model to estimate the abiotic resource depletion potential (ADP) and the global warming potential (GWP). Results showed that increasing the tire pressure reduced fuel consumption in bicycle-sharing systems by more than 10%. The 3-kg weight gain did not affect energy consumption, and the ADP and GWP were approximately 10% and 20% lower for the H-bike. Thus, H-bikes have more environmental benefits than conventional bicycles, and considering tire pressure in bicycle sharing makes sense.

Key Words
Bicycle sharing, Fuel cell, Life cycle assessment, H-bike, Increased tire pressure
1. Introduction

Owing to their functionality and eco-friendliness, various types of vehicles powered by fuel cells (FCs) are attracting attention and several of them are now being commercialized. Research and development on FC mobility in cars, trucks, ships, etc. shows promising results. In the civilian sector, assisted bicycles and/or scooters with increasing user penetration rates can make massive contributions to the reduction of CO₂ emissions by shifting to less environmental impact modes of transportation and the replacement of gas with fuel cells. In addition, a French company by the name of Pragma Industries has developed FC-assisted bicycles called alpha; these bicycles were used at the G7 summit in August 2019. Asia Pacific Fuel Cell Technology Ltd (APFCT) in Taiwan has commercialized FC-powered electric scooters that have earned the Taiwan Vehicle Safety Certification.

Given the increasing demand for bicycle-sharing in urban areas, the demand for assisted bicycles is expected to grow accordingly. Therefore, this study focuses on assisted bicycles. Bicycle-sharing provides a comfortable transportation experience and contributes to a low-carbon society, and assisted bicycles are mainly used from a management point of view. In previous research, we had demonstrated the possible environmental and functional advantages of using FC-assisted bicycles (H-bikes) over conventional assisted bicycles (E-bikes). Extending this exploration further, the current study investigated the use of H-bikes equipped with polymer electrolyte FCs and metal hydride (MH) energy storage systems. Note that a lanthanum-rich, mischmetal-nickel alloy (LmNi₄.73Mn₀.12Al₀.15) was applied to the MH; the fuel cell was powered by biogas derived from sewage sludge.

In this study, we addressed two concerns related to the use of H-bikes in bicycle sharing. The first one is the high amount of fuel consumption. The power consumed by bicycle-sharing was greater than that consumed by households. Additionally, owing to more complicated traffic conditions in urban areas (such as the increased number of traffic signals), the bike stops and starts more frequently, leading to higher energy consumption. The second problem is the increase in weight—an H-bike, with its FC and hydrogen-storage tank, weighs approximately 3 kg more than an E-bike. A 3-kg-weight-increase is found to have no effect on electricity consumption. One reason for this is that 3 kg is an insignificant weight relative to the total weights of the bicycle and rider combined; in this study, however, we will once again measure the power output at different weights and evaluate it quantitatively. Furthermore, by considering parameters other than the bike’s weight, we aimed to show that the effect of weight gain can be reasonably ignored.

We focused on tire pressure and attempted to solve these problems. The rolling resistance encountered by the tire was lowered by increasing its air pressure. This is because the pressure inside the tire determines its stiffness, which in turn significantly influences its contact area with, and pressure distribution over, the surface of the terrain on which it rides. While tire pressure and energy consumption have frequently been discussed, they are novel considerations in terms of bicycle-sharing.

The purpose of this study was to determine if increasing the tire pressure can mitigate the impact of the H-bike’s larger weight and reduce its power consumption. The experiment focusing on the increase in power consumption has, henceforth, been called the power consumption experiment herein, while the one that focuses on weight gain is called the comparison experiment; the fuel consumption of each bicycle was calculated in the latter. Based on these results, we evaluated environmental impacts using the life-cycle assessment (LCA); this impact analysis includes the calculation of the abiotic resource depletion potential (ADP) and the global warming potential (GWP), as was performed in our previous study.

2. Experimental Methodology

2.1 Driving Conditions

Driving experiments were conducted to determine the amount of energy consumed, with measuring devices installed as shown in Fig. 1. In each bicycle-travel test, the speed, battery power, and wind speed relative to the bicycle were measured. The cycling route is shown in Fig. 2, where one round constitutes a lap through each corner from Start to Goal. Riding conditions, including the type of bicycles used, are listed in Table 1. It should be noted that the weight of a rider (including the backpack he/she carries) was 47.9 kg in the power consumption experiment and 48.0 kg in the comparison experiment.

2.2 Setup of the Power Consumption Experiment

Next, to investigate if increased tire pressure can reduce the power consumed by the travel distance and the number of starts and stops, we conducted drive tests with different numbers of rounds, stops, and tire pressures. The parameters shown in Table 2 were applied in order, and all eight patterns were investigated.

2.3 Setup of the Comparison Experiment

The impact of tire pressure and the increase in weight of the H-bike on fuel consumption was investigated...
in this experiment. The fuel consumption of E-bikes and H-bikes is calculated using the following equation:

\[ P_E = \eta_{CE} \times P_{output} \times 3.6 \]

\[ V_H = \frac{P_{output} \times 3.6}{LHV \times \eta_{CE} \times \eta_{H2} \times s} \]

where \( P_E \), \( V_H \), \( P_{output} \), \( LHV \), \( \eta_{CE} \), \( \eta_{H2} \), and \( s \) are the power consumption of an E-bike [kWh/km], H\(_2\) consumption of an H-bike [Nm\(^3\)/km], energy output of the driving test [kWh], lower heating value of H\(_2\) [MJ/Nm\(^3\)], conversion efficiency of the electric and hydrogen bikes, respectively, H\(_2\) storage efficiency, and travel distance in the driving test [km], respectively.

Our driving tests were conducted in three scenarios: a tire pressure of 2.00 kg/cm\(^2\) with no weight gain, a tire pressure of 2.00 kg/cm\(^2\) with a 3.00 kg weight gain, and a tire pressure of 3.00 kg/cm\(^2\) with a 3.00 kg weight gain. Commonalities between these three cases included two rounds of travel (spanning a total distance of 2.54 km) and five stop points. Under these conditions, we set up four cases for the evaluation of fuel consumption (see Table 3).

### 2.4 Environmental Impact Evaluation

#### 2.4.1 Life-Cycle Assessment (LCA)

The environmental impacts of E-bikes and H-bikes were then evaluated using the LCA. Table 4 shows the specifications of the targeted bikes.\(^9\)\(^-\)\(^15\) Hydrogen-storage efficiency, defined as the efficiency of H\(_2\) adsorption/release, was determined based on our previous experiments.\(^15\) Energy capacity refers to the amount of energy that a fully-charged battery can provide. The energy capacity of the E-bike is based on the specifications of the bicycle, while that of the H-bike depends on the amount of H\(_2\) that can be stored in the MH storage unit. The lifetime of the MH unit was assumed to be equal to that of the fuel cell in a previous study,\(^6\) but in this study, it is defined as the number of times the unit can be recharged throughout its lifetime.\(^14\) This change in definition is because the hydrogen-storage tank can be removed from the H-bike. The lifetime of the MH unit was calculated using the following equation:

\[ LD_{tot} = \frac{s \times E \times N}{3.6 \times P_{output}} \]

### Table 3 Bicycle Cases for Experimentation

| Case | Bicycle | Weight gain [kg] | Tire Pressure [kg/cm\(^2\)] |
|------|---------|-----------------|-----------------------------|
| 1    | E-bike | Standard        | 200                         |
| 2    | H-bike | 0.00            | 200                         |
| 3    | H-bike | 3.00            | 200                         |
| 4    | H-bike | 3.00            | 3.00                        |

### Table 4 Bicycle Specifications

|                     | E-bike(Li-ion) | H-bike(FC) |
|---------------------|----------------|-------------|
| Rated Output [W]    | 240            | 240         |
| Conversion efficiency | 0.950         | 0.463       |
| H\(_2\) storage efficiency | -         | 0.930       |
| Lifetime per bicycle [km] | 24,000       | 120,000     |
| Recharging for lifetime | -             | 900 times   |
| Energy Capacity [MJ] | 1.10           | 3.03        |
| Battery Weight [kg]  | 2.12           | 0.928 (FC)  |
|                     |                | 4.15 (MH)   |

Note: H\(_2\)-LHV is 10.8 MJ/Nm\(^3\)
where $L_{\text{DMH}}, s, E, N$, and $P_{\text{output}}$ are the MH’s lifetime travel distance [km], travel distance based on the driving test in Section 2.3 [km], the energy capacity of the H-bike [MJ], the number of times the MH unit can be recharged throughout a lifetime, and the energy consumption based on a drive test in Section 2.3 [kWh], respectively.

System boundaries of the E-bike and H-bike are shown in Fig. 3. For the life-cycle impact assessment, ADP and GWP were considered based on the CML (Centrum voor Milieukunde Leiden) model developed by Leiden University. Environmental impacts were evaluated using the LCA software SimaPro ver 9.1.0.8, and background data were derived from Ecoinvent 3. The functional unit is per kilometer of the travel distance.

### 2.4.2 Battery-Manufacturing Subsystem

Background data on Li-ion batteries, FC batteries, and the MH unit in the manufacturing phase were obtained from the Ecoinvent 3 database. Based on the previous study, we applied the six-tenths factor rule to the data from Mizuho Information & Research Institute, Inc., and to the specific material data to determine the production characteristics of the FC battery. Foreground data for the manufacture of a single battery are listed in Table 5. Foreground data per km of the bicycle ride is the value obtained from the riding experiment described in Section 2.3. It should be noted here that the greenhouse gas emission factor for electricity was 0.699 kg-CO2/kWh.

### 2.4.3 Energy-Production Subsystem

The energy required to charge batteries is conventional electricity in the case of the E-bikes, and H2 gas for H-bikes. Bio-H2 produced from sewage sludge is used for H2, with inventory data based on the process design obtained from the Aspen Plus Ver9.1 process simulator. The entire system involves three processes: biogas fermentation, methane reforming, and H2 refining through the two-step pressure swing adsorption (two-step PSA) method, which reduces the energy required to perform H2 purification. The concentration of H2 was assumed to be 99.99 vol%. Additionally, inventory data pertaining to auxiliary energy consumption were considered, while material data of the plant facilities were ignored owing to their negligible impact in comparison to the energy values. Foreground data per km of the bicycle ride is the value obtained from the riding experiment described in Section 2.3.

### 3. Results and Discussion

#### 3.1 Power Consumption Experiment

Fig. 4 shows the results of the energy consumption experiment for different driving parameters. By increasing tire pressure from 2.00 kg/cm2 to 3.00 kg/cm2, fuel consumption was reduced by 12.8% over two rounds with
This drop stems from the reduced rolling resistance resulting from the increased tire pressure. This makes it clear that increasing the tire pressure can reduce the power consumed by traveling and by starting and stopping the bike. Moreover, the impact of heightened tire pressure is greater when the travel distance and the number of starts/ stops increase.

### 3.2 Comparison Experiment

Table 6 lists the fuel economy for each case. Cases 2 to 4 display the impact of the weight gain of the bike and the spike in tire pressure on fuel consumption. It should be noted that Table 6 represents the foreground data of the driving phase in the environmental impact assessment; therefore, the values for Case 1 are provided. Cases 2 and 3 indicate that the weight gain of the H-bike has no effect. This is because the effect of acceleration at the beginning of pedaling on fuel consumption is much larger in comparison to the effect of the weight gain. In cases 3 and 4, increasing the tire pressure is sufficient to deal with the effects of the H-bike's weight gain on fuel consumption. The reason for the limited decrease in fuel consumption in Case 4 is thought to be the effect of fluctuations due to air resistance caused by winds during the measurement.

Fig. 5 shows the environmental impact assessment results of the E-bikes and H-bikes. The figures indicate that using H-bikes can contribute to the mitigation of both ADP and GWP compared to E-bikes; ADP was reduced from 10.7% to 11.3%, and GWP was reduced from 19.3% to 21.8%. Case 4 has a lower environmental impact at the hydrogen production stage than Case 3; however, this can only be seen to a limited extent in the figure. This is because the environmental impact during hydrogen production is small. Because biomass-derived hydrogen is assumed, the environmental impact of the hydrogen production stage is small. Note that this study focuses on evaluating both ADP and GWP, uses Ecoinvent 3 as background data, and does not take into account the changes in values of GHG emission factors after setting.

### Table 6 Fuel Economy

| Case | Fuel Consumption |
|------|------------------|
| 1    | $1.81 \times 10^{-3}$ kWh/km |
| 2    | $1.33 \times 10^{-3}$ Nm-H2/km |
| 3    | $1.31 \times 10^{-3}$ Nm-H2/km |
| 4    | $1.27 \times 10^{-3}$ Nm-H2/km |
4. Conclusions

In this study, we focused on the fact that the rolling resistance can be reduced by increasing the tire pressure. The effect of increasing tire pressure was clarified for the practical use of H-bikes in bicycle sharing.

First, we investigated whether the increase in tire pressure can reduce the power consumption owing to the travel distance and starts/stops. As a result, tire pressure gain can mitigate power consumption, and the effect is greater when the travel distance is expanded and the number of starts/stops increases. Therefore, it is meaningful to increase tire pressure in bicycle sharing.

Next, we investigated whether raising the tire pressure could mitigate the effects of weight gain on the H-bikes. The results show that a weight increase of 3 kg has no effect on fuel efficiency. We also found that the mitigation of both ADP and GWP could be achieved by replacing E-bikes with H-bikes, even when considering the weight gain.

Thus, it is found that bicycle sharing with H-bikes has more environmental benefits than E-bikes, and it is logical to consider tire pressure in bicycle sharing.

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