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Examining Real-Road Fuel Consumption Performance of Hydrogen-Fueled Series Hybrid Vehicles

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Abstract: The use of hydrogen fuel produced from renewable energy sources is an effective way to reduce well-to-wheel CO_2 emissions from automobiles. In this study, the performance of a hydrogen-powered series hybrid vehicle was compared with that of other powertrains, such as gasoline-powered hybrid, fuel cell, and electric vehicles, in a simulation that could estimate CO_2 emissions under real-world driving conditions. The average fuel consumption of the hydrogen-powered series hybrid vehicle exceeded that of the gasoline-powered series hybrid vehicle under all conditions and was better than that of the fuel cell vehicle under urban and winding conditions with frequent acceleration and deceleration. The driving range was longer than that of the battery-powered vehicle but approximately 60% of that of the gasoline-powered series hybrid. Regarding the life-cycle assessment of CO_2 emissions, fuel cell and electric vehicles emitted more CO_2 during the manufacturing process. Regarding fuel production, CO_2 emissions from hydrogen and electric vehicles depend on the energy source. However, in the future, this problem can be solved by using carbon-free energy sources for fuel production. Therefore, hydrogen-powered series hybrid vehicles show a high potential to be environmentally friendly alternative fuel vehicles.

Keywords: hydrogen engine; series hybrid; fuel cell vehicle; electric vehicle; life-cycle assessments of CO_2 emissions; driving range

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1. Introduction

Fossil fuels, which are mainly used in vehicle engines, may be depleted in the future. Further, carbon dioxide (CO_2) emissions due to combustion are an environmental problem. The use of hydrogen fuel is a measure that is used to solve these problems. Hydrogen fuels do not contain carbon in their molecules; therefore, they do not emit CO_2. Moreover, their high ignition properties enable a leaner combustion than that of fossil fuels; hence, nitrogen oxide (NOx) emissions can be maintained at a low level [1]. Various carbon-free manufacturing and transportation methods have been established for automotive applications [2], and significant reductions in CO_2 emissions are expected compared to emissions from current internal combustion engine vehicles (ICVs). Vehicles that use hydrogen fuels include fuel cell vehicles (FCVs) and hydrogen engine vehicles. However, FCVs require large amounts of rare metals for their fuel cells [3]. Therefore, they are more expensive than vehicles that use other power sources, even with future technological developments [4]. Furthermore, ice formation occurs during a cold start in a low-temperature environment [5], which is a practical issue.

In contrast, hydrogen-engine vehicles can be developed and manufactured based on existing ICVs, which lowers their costs. Furthermore, current technologies for improving thermal efficiency can be applied to convert vehicles into hydrogen-powered hybrid vehicles (hydrogen HVs) that combine hydrogen engines and motors, and these are expected to have a high environmental performance and a widespread market [6]. However, hydrogen HVs have not yet been produced, and their performance characteristics during actual driving are not fully understood. Battery electric vehicles (BEVs) are becoming popular powertrains that do not require any liquid or gaseous fuel supply and are expected to significantly reduce CO_2 emissions owing to their high energy efficiency [7]. However, CO_2 emissions due to BEV charging using commercial electricity depend on the electricity mix in each country or region and are also strongly affected by renewable energy deployment scenarios [8]. The effective utilization of surplus electricity through the decentralized control of charging times has been proposed [9]. Moreover, the driving range of BEVs is strongly dependent on battery capacity, and the larger their capacity, the higher the CO_2 emissions during manufacturing. In addition, the establishment of an effective recycling process is being promoted because of the significant environmental footprint of batteries when disposed of or reused [10].

As each powertrain has its advantages and disadvantages, it is important to use a suitable powertrain combination for the correct application to achieve a medium- to long-term reduction in the environmental footprint. Previous studies have reported the use of various powertrains as substitutes for conventional ICVs, contributing to the reduction of CO_2 emissions [7,10–12] in addition to reducing atmospheric pollutants, such as particulate matter (PM) [13,14]. For their utilization, the practical performance, such as the driving range and acceleration performance under real-world driving conditions, is important, along with an accurate estimation of their energy efficiency. Aidin et al. [15] investigated the emissions from conventional gasoline, compressed natural gas (CNG), electric, and fuel cell vehicles under actual urban driving conditions and found that FCVs were the best in terms of reduction of CO_2 emissions. However, few previous studies have included hydrogen HVs in such evaluations.

In this study, driving simulations were conducted for various real driving patterns of several powertrains, including hydrogen HVs, to predict their fuel consumption. Life-cycle assessments (LCAs) of CO_2 emissions were conducted, and comparisons were made between FCVs and other powertrain vehicles that use hydrogen fuel.

2. Materials and Methods

The method of verifying the LCA of CO_2 emissions by real-world driving simulation using commercial software is described in detail as follows.

2.1. Analysis Method

Vehicle assessments were conducted for fuel consumption, driving range, and life-cycle CO_2 emissions. In these assessments, vehicle specifications, such as vehicle weight, motor power, and thermal efficiency, were reflected in real-world driving simulations using CarMaker 8.1.2 (IPG Auto-motive GmbH, Karlsruhe, Germany).

An overview of the real-world driving simulation by CarMaker is shown in Figure 1. The vehicle model, equipped with different powertrains, was simulated under diverse road conditions and traffic scenarios replicating real-world environments. This simulation enables the evaluation of vehicle performance, considering both the driver and vehicle models, in a manner similar to actual driving experiences. Given the significance of driver intervention in real-world driving, this approach provides a comprehensive understanding. In this study, a preset standard model, as a typical driver avoiding aggressive and overly gentle driving, was employed as the driver model while following the speed profile as closely as possible and avoiding acceleration above 0.3 G and deceleration below −0.4 G.

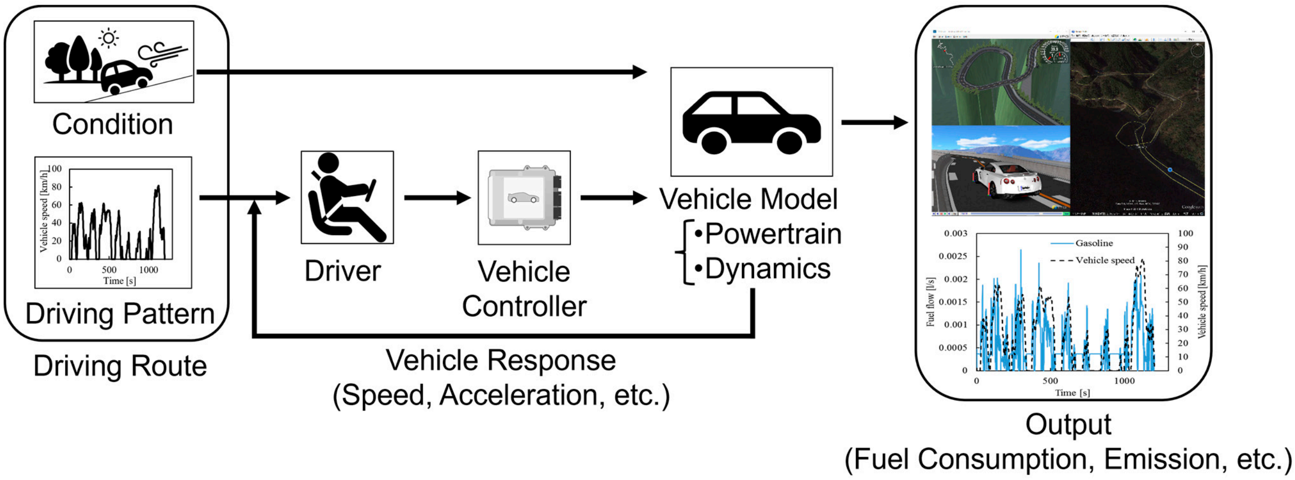


Figure 1. Real-world driving simulation by CarMaker (IPG Automotive GmbH).

2.2. *Analysis of Vehicle Models*

Vehicles with next-generation powertrains as well as hydrogen HVs were simulated, and the simulation was verified.

2.2.1. Powertrains

A series hybrid vehicle with a hydrogen engine (hydrogen S-HV), which drives the motor with the power generated by the internal combustion engine, was selected as the powertrain equipped with a hydrogen engine. In this system, the operating range of the hydrogen engine is limited to power generation; therefore, not only are the engine design and control optimized, but the coverage of the entire operating range with lean combustion also improves the fuel consumption and reduces NOx emissions [16].

The suitability of (a) a series hybrid vehicle with a gasoline engine (gasoline S-HV) and a hydrogen S-HV, (b) an FCV, and (c) an electric vehicle (EV) was examined, as shown in Figure 2, and these vehicles were compared to determine their viability as future vehicles.

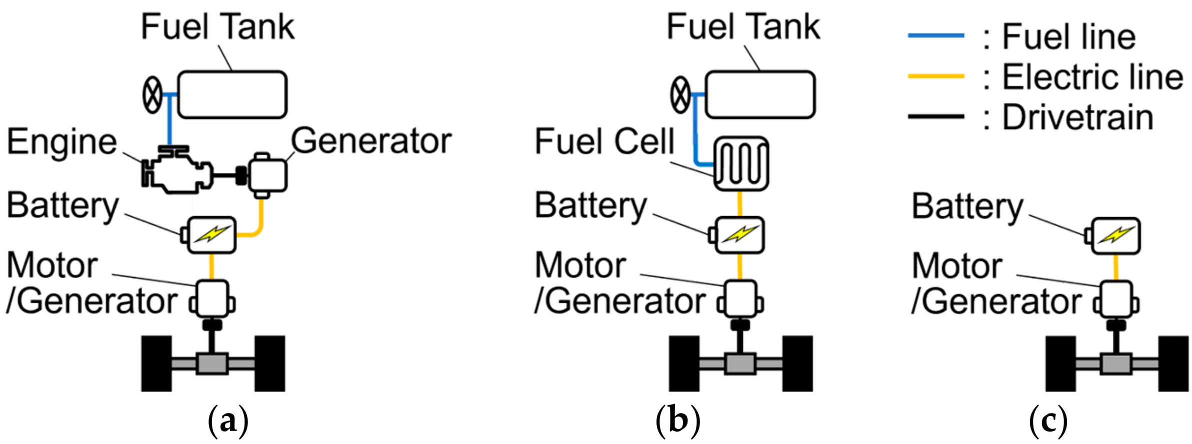


Figure 2. Powertrains to be evaluated: (**a**) gasoline/hydrogen S-HV, (**b**) FCV, (**c**) EV.

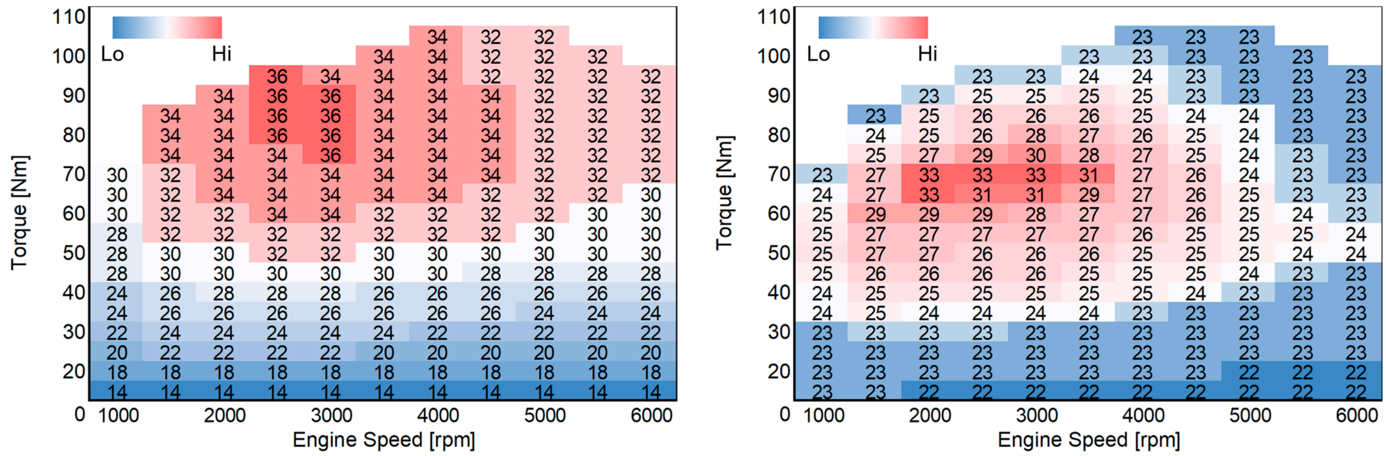
2.2.2. Comparison of Vehicle Specifications

Table 1 lists the vehicle specifications used for input simulation parameters. The vehicle specifications were set based on the specifications of production or research vehicles [1,17–22].

Table 1. Vehicle specifications.

Vehicle Type			Gasoline S-HV [17–19]	Hydrogen S-HV [1,19]	FCV [19–21]	EV [19,22]
Unloaded Weight			1170 kg	1170 kg	1850 kg	1460 kg
Energy Storage	Fuel	Type	Gasoline	Hydrogen	Hydrogen	-
		Capacity	35 L	4.6 kg	4.6 kg	-
	Battery Capacity		1.47 kWh	1.47 kWh	1.35 kWh	30.1 kWh
Engine	Displacement		1198 cm^3	1198 cm^3	-	-
	Cylinders		3	3	-	-
	Supercharging		N/A	Turbocharger	-	-
	Max. Power		58 kW	58 kW	-	-
	Max. Torque		104 Nm	104 Nm	-	-
Fuel Cell	Max. Power		-	-	114 kW	-
Motor	Max. Power		80 kW	80 kW	113 kW	80 kW
	Max. Torque		254 Nm	254 Nm	335 Nm	254 Nm

As a simulation model of the hydrogen S-HV, the fuel tank and auxiliary equipment were changed to hydrogen specifications based on the production of gasoline S-HVs. Figure 3 shows the thermal efficiency maps of the hydrogen and gasoline S-HVs. The thermal efficiency map of the gasoline S-HV is estimated based on that of a production vehicle [18], and the thermal efficiency map of the hydrogen S-HV was set based on the work of Sebastian et al. [1]. In their study, a turbocharger was added to an engine with the same displacement to obtain a power performance equivalent to that of the gasoline S-HV. The nominal fuel consumption of the gasoline S-HV in the JC08 mode [23] is 2.94 L/100 km [17]. During this verification, the fuel consumption of this vehicle model in the JC08 mode was found to be 3.42 L/100 km, which is considered an adequate reproduction.



(**a**) (**b**)

Figure 3. Thermal efficiency maps of (**a**) hydrogen and (**b**) gasoline engines.

The FCV simulation model was set with a hydrogen tank capacity of 5 kg and maximum FC stack efficiency of 58%, based on a study conducted by Kurtz et al. [24], which covered up to 100 kW, as shown in Figure 4. For the vehicles in this study, the efficiencies were extrapolated from the data provided by Kurtz et al. [24] up to a maximum power output of 114 kW.

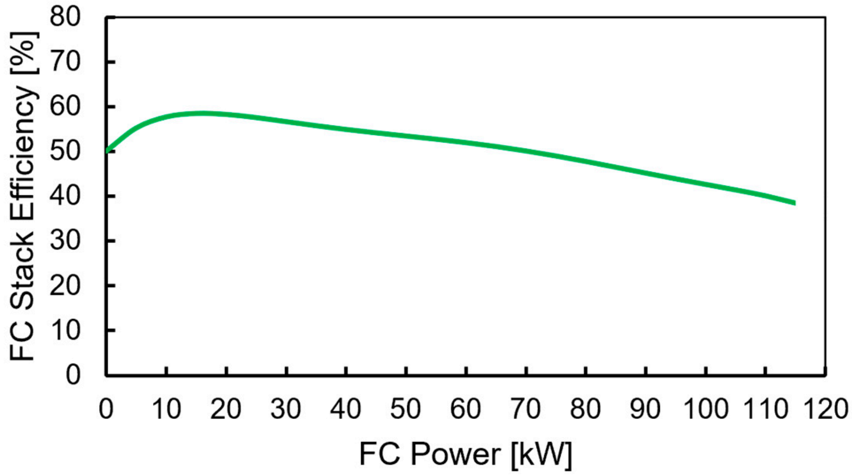


Figure 4. Fuel cell stack efficiency (up to 100 kW by Kurtz et al. [24] and extrapolated above 100 kW).

In the JC08 mode, FCVs could cover approximately 650 km with a 4.6 kg hydrogen charge, achieving a fuel consumption rate of 2.60 L/100 km, equivalent to gasoline consumption [20]. During this validation process, the FCV model exhibited a fuel consumption of 2.72 L/100 km in JC08 mode, aligning with that of the target production vehicle.

The EV simulation model used a motor and battery similar to those of the gasoline/hydrogen S-HV vehicle, with a nominal fuel consumption of 1.28 L/100 km in the JC08 mode [22]. In this verification, a fuel consumption of 1.12 L/100 km was recorded in the JC08 mode, which is equivalent to that of the target production vehicle.

For every vehicle, the overall efficiencies of the drive motor and inverter were assumed to be identical [19], and the aerodynamic drag and running resistance were calculated based on the vehicle specifications provided by CarMaker.

2.3. Driving Route

To simulate various types of actual road driving, driving analysis was conducted on the following six patterns, each with different characteristics: Highways 1 and 2, Suburban roads 1 and 2, Urban roads, and Winding roads. Figure 5 shows each course map; Figure 6 depicts each speed profile and course undulations; and Table 2 lists the course length, maximum speed, average speed, maximum gradient, and number of stops.

Table 2. Route details.

Driving Route	Distance	Average Speed	Max Speed	Max Slope Uphill	Max Slope Downhill	Number of Stops
	[km]	[km/h]	[km/h]	[°]	[°]	[-]
Highway 1	10.0	95.0	109	3.20	−1.22	0
Highway 2	20.0	107.0	113	5.86	−5.80	0
Suburban 1	13.6	51.1	75.9	4.45	−8.81	2
Suburban 2	8.79	37.1	78.2	5.23	−7.03	6
Urban	6.54	17.9	53.3	3.81	–5.02	10
Winding	6.58	35.2	43.5	10.2	–9.15	2

The difference between Highways 1 and 2 is that Highway 1 is relatively flat with a speed limit of 100 km/h, whereas Highway 2 is a section with a speed limit of 110 km/h and fast-driving speed and has more road undulations than Highway 1. The difference between Suburban roads 1 and 2 is that although the driving routes are almost identical, Suburban road 2 has more stops and a lower average vehicle speed. The Winding road has a maximum slope of 10.2°, and a route with approximately the same uphill and downhill distances was selected. The Urban roads use a speed profile that includes driving during traffic jams.

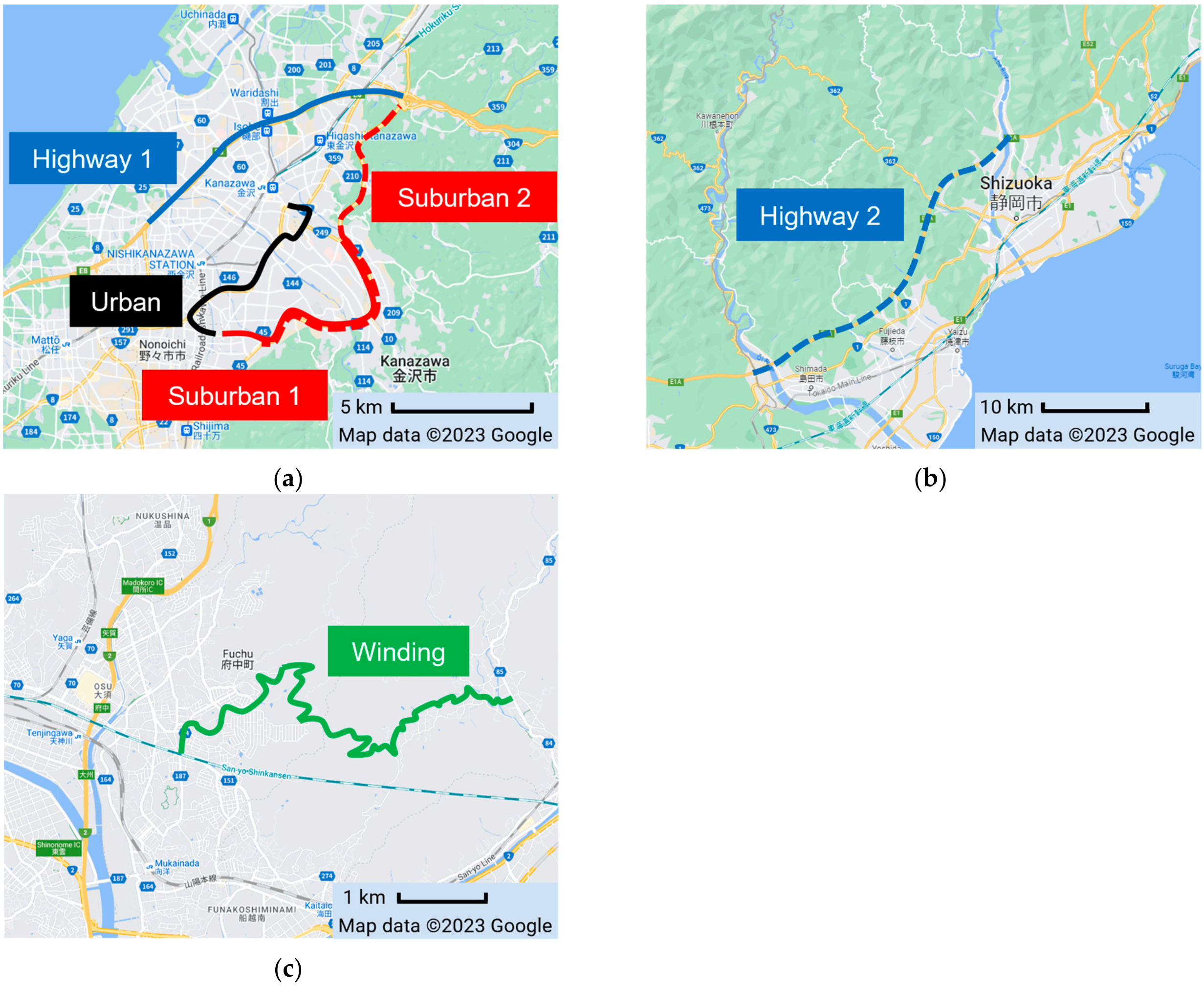


Figure 5. Route maps of (**a**) Highway 1, Suburban 1, Suburban 2, and Urban; (**b**) Highway 2; and (**c**) Winding for the virtual driving tests.

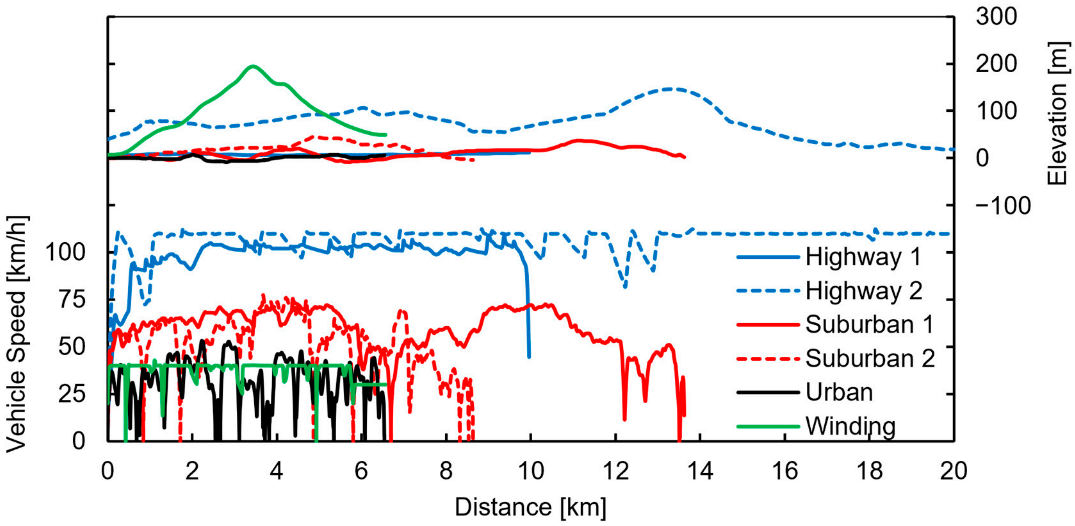


Figure 6. Speed profiles and gradients in the virtual driving tests.

2.4. CO_2 Emissions

In the LCA assessment of CO_2 emissions, the total CO_2 emissions were evaluated by considering the sum of Well-to-Wheel (WtW), which comprises Well-to-Tank (WtT) and Tank-to-Wheel (TtW) emissions, along with the CO_2 emissions incurred during the production phase. This assessment encompassed emissions generated during fuel production and transportation, extending up to the vehicle fuel tank. Additionally, the TtW emissions represented the CO_2 emissions resulting from driving the vehicle using the fuel stored in the fuel tank.

The CO_2 emissions in the WtT phase include the combined emissions from fuel production and transportation. Hydrogen fuel and electricity differ significantly depending on how they are produced or generated, as well as the power derived from them. Therefore, the current mainstream method is indicated as "Current", and the most effective method among the currently established methods that use renewable energy to reduce CO_2 emissions is indicated as "Ideal" in the results. The CO_2 emitted during fuel production was calculated as follows. For gasoline, the values were based on the emission intensity in petroleum refining [25]. Regarding hydrogen, the "Current" values represent emissions from natural gas reforming, while the "Ideal" values account solely for emissions resulting from renewable energy, including those generated through water electrolysis. In terms of electric power generation, the "Current" values were determined based on the 2017 power generation emissions in Japan. In contrast, the "Ideal" values were established solely considering emissions from hydroelectric power generation, which exhibits the lowest emission intensity among renewable energy sources [26–28]. The CO_2 emissions during transportation were based on the distance between the nearest hydrogen and gas stations from refineries in Tokyo (37.5 km) and on CO_2 emissions per commercial truck (233 g/(tkm)) [29].

The CO_2 emissions in the production phase were estimated from the studies conducted by Kawamoto et al. [30] and Ishizaki et al. [31], vehicle, 4220 kg/car; engine, 1270 kg/unit; motor and inverter, 640 kg/unit; battery, 177 kg/kWh; fuel cell, 2400 kg/unit; and hydrogen tank, 1500 kg/unit.

3. Results and Discussion

For each vehicle assessment item, comparisons were made between hydrogen S-HVs and other powertrain vehicles, and a comprehensive assessment was conducted.

3.1. Real-Road Fuel Consumption Performance

The all-vehicle models followed the target speed in each route. Figure 7 shows the fuel consumption prediction results; the obtained values were converted into equivalent gasoline consumption amounts.

Among the six driving simulation patterns, EVs showed the best average fuel consumption, followed by FCVs, hydrogen S-HVs, and gasoline S-HVs. The average gasoline-equivalent fuel consumption of the hydrogen S-HVs was 3.74 L/100 km, which was 21.9% better than that of the gasoline S-HVs for all patterns, with a maximum improvement of 32.7%. In particular, the fuel consumption improvements were remarkable on Highways and Winding roads, and the hydrogen engine had a better thermal efficiency in the high-load range than the gasoline engine on which it is based, suggesting that fuel consumption is improved in the pattern that uses this operating range on a regular basis.

When comparing the hydrogen S-HVs and FCVs, the average fuel consumption for all patterns was almost the same. However, FCVs demonstrated a distinct advantage on Highways, where steady-state driving is frequent, owing to their lower required motor power, directly enhancing their high stack efficiency. Conversely, hydrogen S-HVs exhibited lower fuel consumption on Urban and Winding roads. Notably, hydrogen S-HVs were approximately 400 kg lighter than FCVs, as indicated in Table 1. Consequently, the motor power needed for re-acceleration after stopping and decelerating was reduced, offering an advantage over the battery consumption of FCVs. A similar trend was observed on

Winding roads, with hydrogen S-HVs proving superior, particularly when ascending hills, owing to the influence of the differences in vehicle weight. Additionally, both vehicles achieved a lower fuel consumption of 3.20 L/100 km or less on Urban roads and Suburban 1 road, where regenerative braking can be actively used. Thus, hydrogen S-HVs and FCVs are highly suitable for urban and highway driving, respectively.

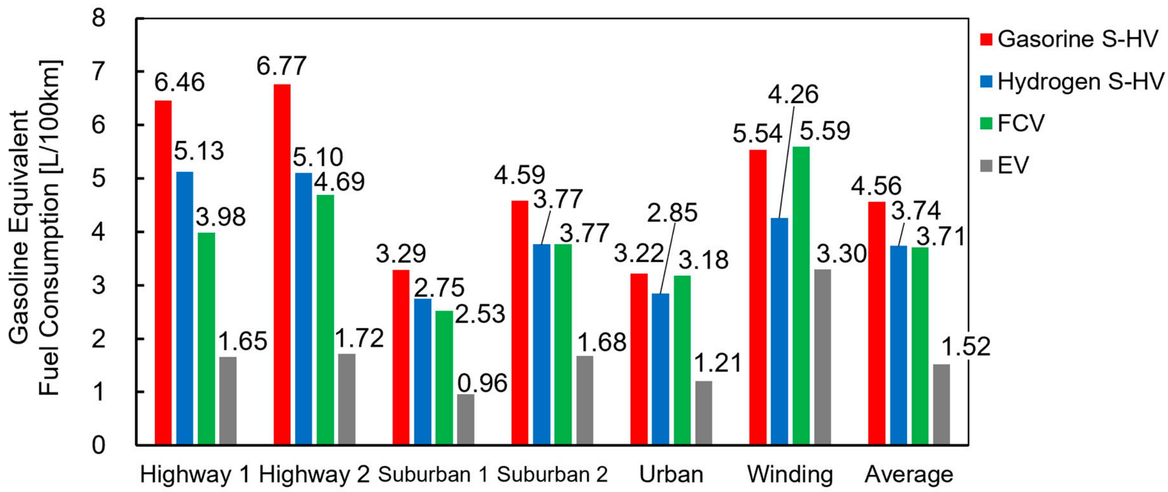


Figure 7. Fuel consumption.

3.2. Driving Range

Figure 8 presents the driving range prediction results for each route and vehicle.

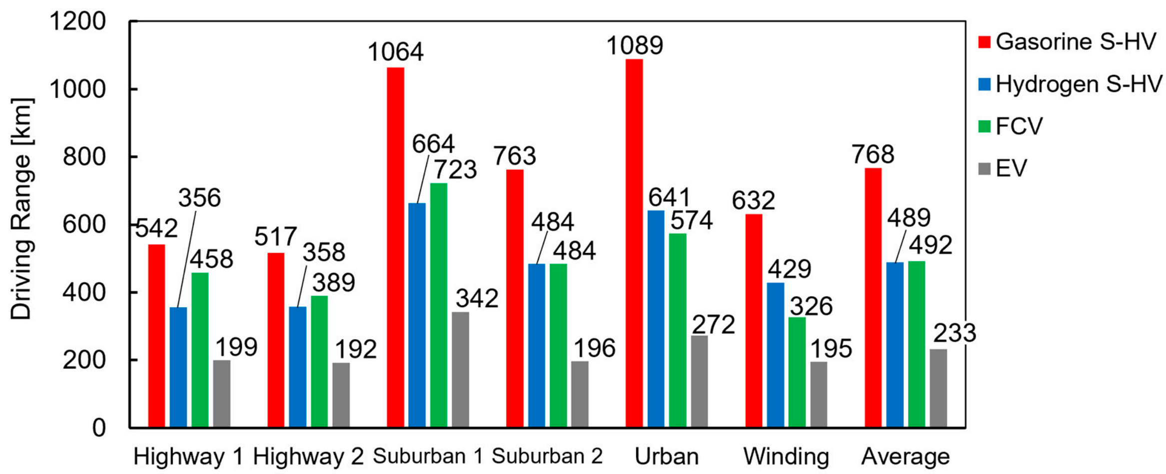


Figure 8. Driving range.

The average driving range of the six driving simulation patterns was highest for the gasoline S-HVs, followed by those of the FCVs, hydrogen S-HVs, and EVs. This superiority of gasoline S-HVs can be attributed to the substantial energy stored in vehicle tanks owing to the high energy density of liquid fuel, resulting in an extended driving range. The EVs had a good fuel consumption owing to the high efficiency of their motors; however, their driving range was the shortest because the battery capacity was a constraint. The average driving range of the hydrogen S-HVs was 489 km, 63.6% of that of the gasoline S-HVs; however, this range can be more than twice that of an EV.

3.3. CO_2 Emissions

Table 3 lists the life-cycle CO_2 emissions from manufacturing to driving. The CO_2 emissions in TtW were calculated using the average fuel consumption for the six driving simulation patterns. The results showed that during manufacturing, the CO_2 emissions were greater for the FCVs and EVs than for the other vehicles. FCVs are affected by fuel cell capacity, and EVs are affected by battery capacity. Therefore, the capacity of the installed battery must be reduced as much as possible. Owing to fuel and electric power generation, large differences in CO_2 emissions exist between hydrogen S-HVs and FCVs on the one hand, which use hydrogen fuel and thus do not have CO_2 emissions in TtW, and gasoline S-HVs on the other. However, the total CO_2 emission in WtW strongly depends on the fuel production method.

Table 3. Life-cycle CO_2 emissions.

Vehicle	Scenario	Manufacturing	WtT	TtW	WtW
		kg-CO_2/unit	g-CO_2/km	g-CO_2/km	g-CO_2/km
Gasoline S-HV	-	7461	0.56	69.62	70.18
Hydrogen S-HV	Current	7691	108.18	0.00	108.18
	Ideal	7691	0.20	0.00	0.20
FCV	Current	10,071	108.70	0.00	108.70
	Ideal	10,071	0.21	0.00	0.21
EV	Current	11,241	92.23	0.00	92.23
	Ideal	11,241	1.73	0.00	1.73

Figure 9 compares the life-cycle CO_2 emissions for each vehicle up to a mileage of 150,000 km.

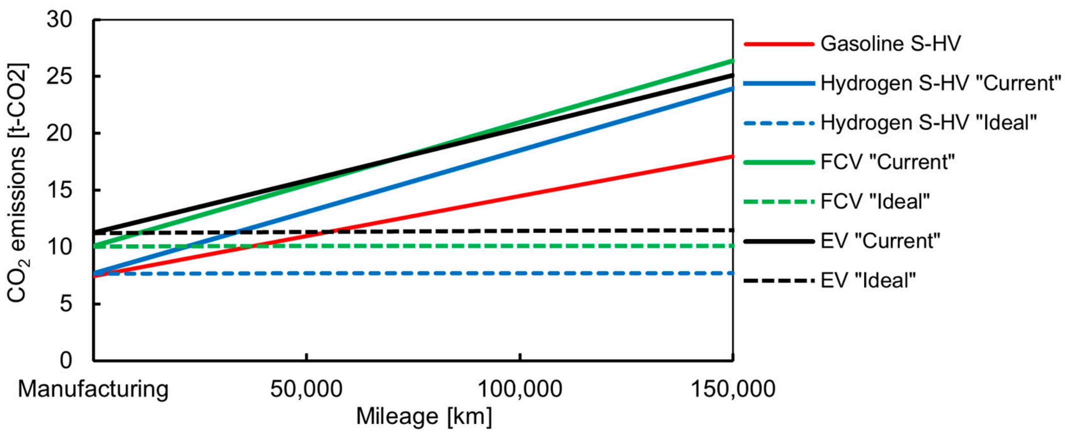


Figure 9. Life-cycle CO_2 emissions up to 150,000 km.

In the "Current" scenario, the life-cycle CO_2 emissions were higher in the gasoline S-HVs up to approximately 80,000 km, but they were better in the EVs after 100,000 km. When comparing hydrogen and gasoline S-HVs, the emissions were similar at the time of manufacturing, but the difference in CO_2 emissions owing to fuel increased as the mileage increased. Meanwhile, in the "Ideal" scenario, the life-cycle CO_2 emissions were best in the hydrogen S-HVs, which emit less CO_2 during manufacturing.

In summary, the life-cycle CO_2 emissions of vehicles using hydrogen fuel can vary considerably depending on the hydrogen production method. If derived from renewable energy, CO_2 emissions can be maintained at an extremely low level, and hydrogen S-HVs are superior to both FCVs and EVs because of their low environmental footprint. Reducing CO_2 emissions over the medium-to-long term requires establishing and actively utilizing hydrogen generation methods based on renewable energy and using vehicles that employ hydrogen fuel.

4. Conclusions

In this study, real-world driving simulations were conducted for six patterns with different characteristics and for four vehicle types (hydrogen S-HVs, gasoline S-HVs, FCVs, and EVs). The following findings were obtained:

1. The average gasoline-equivalent fuel consumption performance of the hydrogen S-HVs and FCVs was approximately 20% better than that of the gasoline S-HVs.
2. The average driving ranges of the hydrogen S-HVs and FCVs were sufficient, approximately 60% of that of the gasoline S-HVs and more than twice that of the EVs.
3. The vehicle weight of hydrogen S-HVs is lighter than that of FCVs; therefore, it can be concluded that hydrogen S-HVs are more advantageous in terms of fuel consumption and driving range on urban and winding roads, where motor power is frequently required for acceleration and deceleration. In contrast, FCVs are suitable on highways with relatively low accelerations and decelerations, owing to their high stack efficiency.
4. The life-cycle CO_2 emissions of hydrogen S-HVs are low during manufacturing; however, large differences in CO_2 emissions exist depending on the hydrogen fuel production method. In other words, hydrogen S-HVs are superior to FCVs and EVs because they emit less CO_2 during manufacturing.

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