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Recent advances on the energy management of a Hybrid Electric Vehicle

D. S. Efstathiou, A. K. Petrou, P. Spanoudakis, N. C. Tsourveloudis, and K. P. Valavanis

Abstract—**This paper presents new innovative subsystems of the ER11 prototype urban vehicle which is powered by hydrogen fuel cells and ultra-capacitors. The subsystems described here are: 1) the energy management system, which is responsible for the optimization of the fuel efficiency and the increased mileage of the vehicle, 2) the driver's monitoring and control panel and 3) the power transmission system, which offers the possibility of continuous change of gear. The powertrain of the test-bed vehicle consists of an electric motor, a fuel (H_2) cell system, an ultra-capacitor bank and a DC/DC converter. Testing verified that the proposed energy management system is benefitted by the variable transmission of power leading to less fuel consumption**.

I. Introduction

In the last decades, due to emissions reduction policies, research has focused on alternative powertrains, among which hybrid electric vehicles (HEVs) powered by fuel cells and –sometimes- supported by supercapacitors (also known as ultracapacitors, UCs) are becoming an attractive solution [1]. One of the main research issues of HEVs is their energy management system [2] in order to improve the overall fuel efficiency. Indeed, energy management systems are crucial for the performance of vehicles powered in whole or in-part by non-conventional energy sources. Several control strategies have been proposed in the literature concerning energy management controllers, and can be grouped into several broad categories; based on static optimization methods [3], numerical dynamic optimization methods [4-7], closed-form dynamic optimization methods [8], state prediction and predictive control [9]. In hybrid fuel cell/supercapacitor electric vehicles, an overall management of the power is needed in order to achieve a balance between fuel consumption and desired speed. In [10], an energy management control system has been suggested for the ER11 (Eco Racer 2011) prototype urban vehicle, which is a HEV powered by a hydrogen fuel cell and a set of supercapacitors.

The urban vehicle ER11 is the latest version of the vehicles that are fully designed and constructed by the Machine Tools Laboratory and the Intelligent Systems and Robotics Laboratory (IS&RL) of the Technical University of Crete, Greece [11]. ER11 is the continuation of our research and development efforts in studying aspects regarding low consumption, driving safety and future unmanned navigation of vehicles. Figure 1 shows the evolution and the performance, in terms of energy consumption and safety levels, of the urban vehicles prototypes built till 2011.

The ER11 prototype power system consists of a commercially available H_2 Fuel Cell system (FC), a set of rechargeable ultra-capacitors (UC), a DC/DC converter, a motor controller and an electric motor. The FC is the Nexa Power Module 1.2 KW and the UC bank consists of six Maxwell BPAK0052 P015 B01 modules. The FC generates the power of the system and the UC can be utilized when the electric motor demands extra power to overcome situations with increased energy needs. The parallel operation of FC and UC enhance the driving performance and the fuel economy. A DC/DC converter is responsible for the simultaneous operation of the two energy sources.

The present investigation aims at presenting new mechanical and software components which will aid in achieving an overall configuration and control strategy in order to reduce fuel consumption and further increased the safety level of the vehicle. Beyond the presentation of the new systems, this study focuses on the coupling of the energy management system with a first time suggested continuously variable gearbox for a vehicle powered by hydrogen and equipped with a super-capacitor bank as a secondary energy source. The goal of this study remains the further reduction of hydrogen consumption while maintaining a desired mean velocity.

The structure of this paper is the following. Initially the energy management system and its architecture is discussed. Then a novel driver's software interface is presented. Through this software the driver interacts with the car and also receives and stores crucial info for its state and the route that follows at every time instant. The component which is then discussed is a variable transmission system, which transfers the torque from the electric motor to the wheel. The variable transmission when integrated in the energy management system allows for gear rates that contribute in lowering the fuel consumption. The test cases presented at the end of this paper verify that the dynamically changing gear rate increases the mileage of the vehicle for a given velocity.

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D. S. Efstathiou is with the Intelligent Systems and Robotics Lab, Technical University of Crete, Chania, Greece (phone: 0030-2821037314; fax: 0030-28210 69410,e-mail: defstathiou@isc.tuc.gr).

A. K. Petrou is with the Intelligent Systems and Robotics Lab, Technical University of Crete, Chania, Greece (e-mail: apetrou@isc.tuc.gr).

P. Spanoudakis is with the Machine Tools Laboratory Technical University of Crete, Chania, Greece (e-mail: hroniss@dpem.tuc.gr).

N. C Tsourveloudis is with the Intelligent Systems and Robotics Lab, Technical University of Crete, Chania, Greece (e-mail: nikost@dpem.tuc.gr).

K. P. Valavanis is with the Department of Electrical and Computer Engineering, University of Denver, Denver, CO 80208 USA (e-mail: kimon.valavanis@du.edu).

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II. SYBSYSTEMS DESCRIPTION

A. Energy Management System

The Energy Management System (EMS) controls the distribution of the power among FC and UC in order to minimize the fuel consumption and maintaining the desired average speed [10]. It receives information from all subsystems of the ER11 and interacts with them. The overall information and command flows are presented in Figure 2. The EMS includes both hardware devices and software.

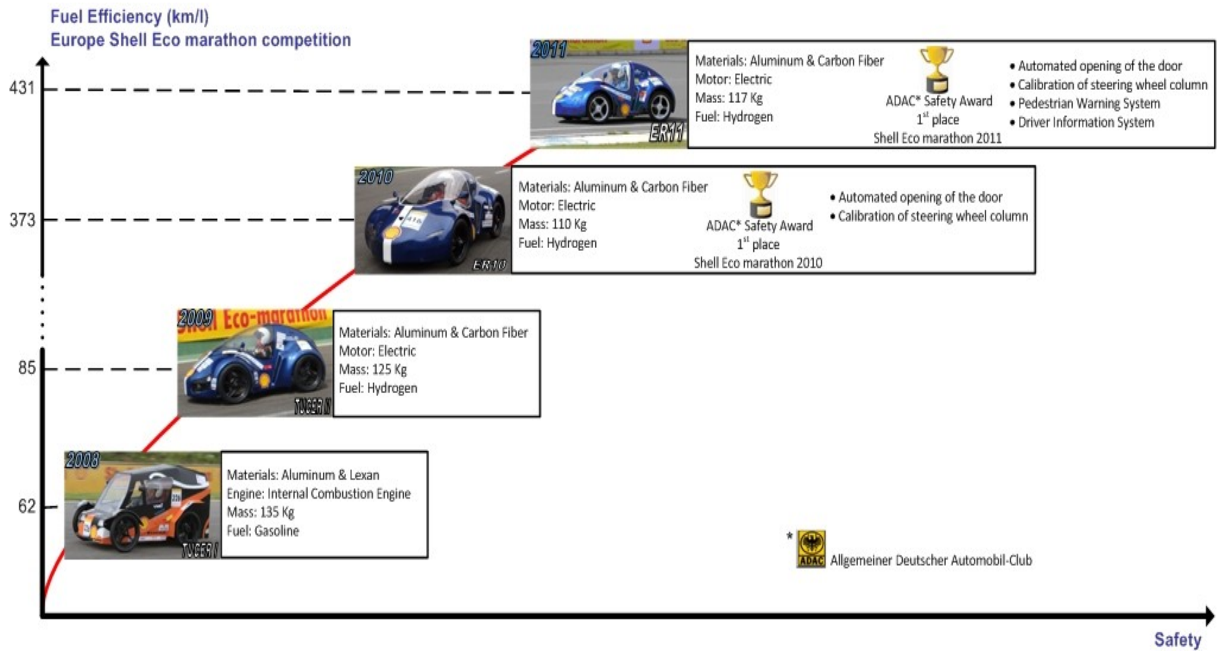

Figure 1: Fuel efficiency and safety levels for the prototype urban vehicles built so far (2008-2011) at the Technical University of Crete, Greece

The hardware are a PIC microcontroller, a computer unit based on a VIA EPIA-P700-10 Pico-ITX main board (we will refer to it as CPU), four sensors (tilt, velocity, acceleration and voltage) and a custom electronic board. The PIC microcontroller communicates via its serial port with the CPU in real time and sends the data received from the vehicle sensors. The CPU executes the control program (described immediately after) which has as inputs 1) the data from sensors, 2) the current hydrogen level and returns the output data to the PIC microcontroller. Then the microcontroller sends the control output to the electronic board, which converts them to the voltage demanded by the FC, the voltage demanded by the UC bank and controls the rotational speed (rpm) of the electric motor. The control program that is executed by the CPU consists of two fuzzy logic controllers [10].

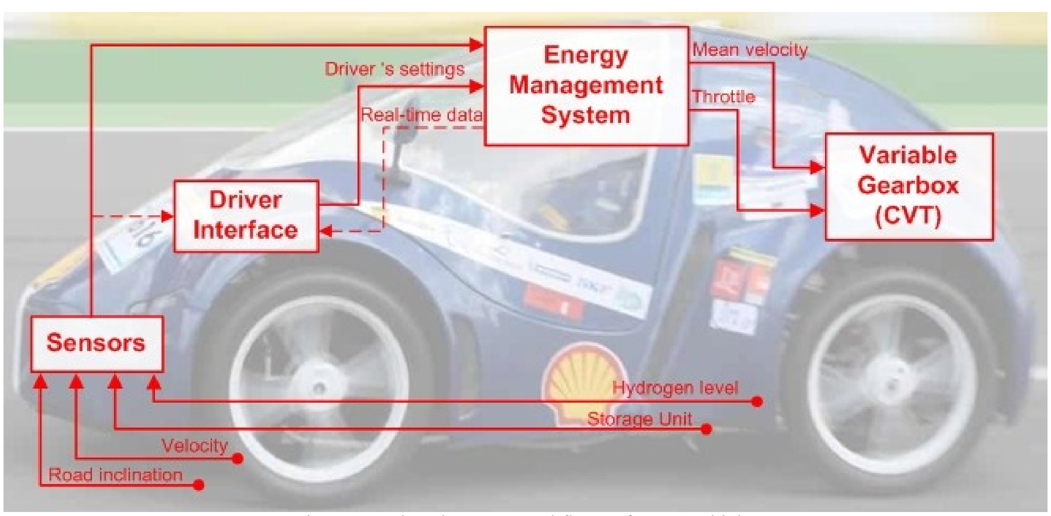

Figure 2:Main subsystems and flows of ER11 vehicle

The main fuzzy controller has four inputs and three outputs. The input variables are 1) the *Road Inclination* (*RI*), the ultracapacitors *Stage-of-Charge* (*UC-SOC*), the *Hydrogen Level* (*H_2L*) and vehicle's *Average Velocity* (*AV*). This controller reads the input variables and adjusts the power demand required from the FC and UC, in order to maintain the desired speed. The output variables are the *rotational speed* (rpm) of the electric motor, the *power required from the FC* (*FC-power*) and the *power required from the UC* (*UC-power*). The generic rules that used in this controller has the following type:

IF *road inclination* is *RI* AND *SOC-level* is *UC-SOC* AND *hydrogen-level* is H_2L AND *average velocity* is *AV* THEN *power required from FC-level* is *FC-power* AND *power required from UC-level* is *UC-power* AND *rotational speed* is *rpm*

A second fuzzy logic controller has been created in order to distribute the produced by the fuel cell power directly to the motor, or to charge the ultracapasitors (as we don't use any other energy source, as for example, regenerative braking [12] for charging the UCs). The input variables of this controller are the ultracapacitors *Stage-of-Charge* (*UC-SOC*), the *Hydrogen Level* (H_2L) and the *output current* (*I*) of the fuel cell. The output variable is the *percentage of the fuel cell current* (*I-OUT*) needed to charge the UCs. The rules that used in this controller have the following type:

IF *SOC level* is *UC-SOC* AND *hydrogen-level* is H_2L AND *output current from FC* is *I* THEN *the percentage of fuel cell current which charge UC* is *I-OUT*.

Mathematically the output of this set of rules is given by:

$$I\_OUT^* = \frac{\sum I\_OUT \cdot \mu_R^*(I\_OUT)}{\sum \mu_R^*(I\_OUT)} \qquad (1)$$

where

$$\mu_R^*(I\_OUT) = \max_{I,H_2L,UC-SOC} \min[\mu_{AND}^*(I,H_2L,UC-SOC), \mu_{FR^{(k)}}(I,H_2L,UC-SOC,I\_OUT)] \qquad (2)$$

and denotes the membership function of the aggregated current percentage of power that is used to charge the ultracapacitors. The terms in (2) are as follows:

$$\mu_{FR^{(k)}}(I,H_2L,UC-SOC,I\_OUT) = f_{\rightarrow}[\mu(I), \mu(H_2L), \mu(UC-SOC), \mu(I\_OUT)],$$

and

$$\mu_{AND}^*(I,H_2L,UC-SOC) = \mu^*(I) \wedge \mu^*(H_2L) \wedge \mu^*(UC-SOC)$$

where $f_{\mapsto}$ is the fuzzy implication, which is min for the Mamdani type of rules. Also, μ (*x*) denotes the membership grade of *x*.

B. Driver's monitoring and control panel

The interface and control panel, shown in Figure 3, is especially studied and developed to assist the driver and support the energy management system of the ER11 vehicle. The software provides a friendly and functional graphical user interface (Figure 3) to allow the user interact with the hardware devices and control the whole system in general. So the user-driver can watch the whole information and the same time can react with the system and also make the necessary settings. The graphical interface is ergonomically designed for maximizing it's functionality. It consists of several gauges and legible indicators. In the main area of the screen the driver can see the values of the measured data. In the right side of the screen several control buttons are provided to be used by the driver.

Figure 3: The driver 's monitoring and control panel

The user-driver has the possibility of activating the Pedestrian Sound Warning System, the Data Logging System and the EMS described in the previous section. The Pedestrian Sound Warning System (PSWS) is a system created to face the European and international rules of adding sounds in electric cars for the warning of pedestrians and bicyclists. The specific sub-system helped Technical University of Crete Eco Racing team to win the ADAC safety award, for a second consecutive year (2010 and 2011), at the Shell Eco Marathon Europe 2011 [13]. The software amplifies and transmits through speakers the motor sound according to vehicle's speed so as to be noticeable by the pedestrians and cyclists in urban areas. This necessary for safety purposes as the vehicle produces almost no sound by itself.

The Data Logging System (DLS) software communicates through a serial port with the PIC microcontroller and receives information about the inclination of the track, the x-axis acceleration and the distance travelled. Also, the DLS software communicates through a serial port with the FC and receives the cumulative hydrogen consumption, the hydrogen pressure, the fuel cell's stack temperature. The driver has the option to activate or deactivate the DLS through the graphical user interface and the 7.5 inches touch screen. Furthermore, the user has the option to set or reset the value of several variables (such as the fuel volume, timer, vehicle's point, etc.), to upload new routes, to load custom sound file for the PSWS, and to create new serial port settings, among others. Due to the need of multiple calculations and the simultaneous communication with two different hardware devices the software developed is a multithreading application.

C. Continuous variable transmission system

The drive train system of the prototype vehicle includes a *Continuous Variable Transmission* (CVT) system, which transfers the torque from the electric motor to the wheel. A cone based type CVT is used along with a linear actuator, which changes the ratio of the transmission. This transmission system has a gear ratio of that can be varied continuously within a certain range, thus providing an infinity of gear ratios. The continuous variation allows for the matching of virtually any engine speed and torque to any wheel speed and torque. It is therefore possible to achieve an ideal torque–speed profile (constant power profile) because any engine power output to the transmission can be applied at any speed to the wheels [14].

In general CVT's were mostly used –until now- in cars with internal combustion engines where they can cover a wide range of ratio's, which make possible to operate a combustion engine in more efficient working points than stepped transmissions [15]. This decreases the fuel consumption of the engine and can be achieved by cooperative control of the motor and the CVT [14,15].

Vehicle drive cycles typically involve numerous stops and starts and uneven terrain. Drive trains with CVT can benefit the growing market of such vehicles that operate over these dynamic speed and load conditions, by allowing the motor to operate closer to its peak power or peak efficiency over a broad range of a given duty cycle. Additionally, the CVT changes the effective inertia seen at the motor to increase acceleration of the vehicle. Since there are no fixed gear ratios, the system is able to control component speeds precisely, allowing them to operate exactly at their optimal speed for the desired performance [16].

A CVT controller is developed as a subsystem of the Energy Management System (EMS) so as to adjust the transmission ratio. The CVT controller changes transmission ratio so that motor *rpm* are regulated in order to minimize the required driving torque and target minimum motor power. This corresponds to minimum fuel consumption. When the vehicle accelerates then higher ratio is used in order to use less motor power and at the same time achieve target mean speed more quickly. On the other hand, when the vehicle moves in constant speed and target mean velocity is achieved then transmission ratio is selected closer to maximum motor efficiency. Specifically, the inputs of the CVT controller are 1) the *average speed (AV)*, 2) the *throttle* position *(TP)* along with 3) the *transmission ratio* at the present time instant. The controller's output is the *required/target transmission ratio* (i_{target}). The targeted ratio corresponds to the specific voltage required to upshift or downshift the ratio via a linear actuator. The present ratio value (i_{real}) obtained from the linear actuator position, is the feedback in the CVT control loop. The generic control rule of the CVT operation is the following

GENERIC RULE

IF *average velocity* is *AV* AND *Throttle* is *TP* AND *transmission ratio* at the present time is *PR* THEN *Transmission Target Ratio is TR.*

As an example consider the following rule:

IF *average velocity* is *Low* AND *Throttle* is Low AND *transmission ratio* at the present time is Low THEN *Transmission Target Ratio is High, thus more torque is requested in order to accelerate the vehicle.*

III. TESTING

The aim of these tests is the evaluation of the EMS coupled with the variable transmission gearbox. The objective in these tests is to maintain the average speed constant (here we set it to 25km/h as this speed is directed as the minimum average speed in the Shell Eco marathon competition). The main criterion of the comparisons we perform is the fuel consumption. Two test cases were used in order to examine and compare the proposed energy management system with two different gearboxes. The first gearbox has constant gear ratio and was used in ER11 vehicle in Europe Shell Eco marathon 2011 competition while the second gearbox is the proposed Continuous Variable Gearbox which will be used in the 2012 Eco Shell Marathon competition. The first gearbox has constant gear ratio 1/13 while the second can change the gear ratio from 1/17 to 1/10.

In the first test case, a zero inclination track is used. In the second test case, a real test track with various degrees of inclination is reflected. It resembles the Eurospeed racing field at Lausitz, Germany. As may be seen, the hydrogen consumption of the vehicle is better when the Continuous Variable Transmission gearbox is used.

During the test case with zero ground inclination, the two gearboxes achieve the desired average speed. This is an expected result because of the action of the Energy Management System. The fuel level dropped to 192 liters with the constant gear ratio approach, while Continuous Variable Transmission gearbox kept 194.5 liters in the tank.

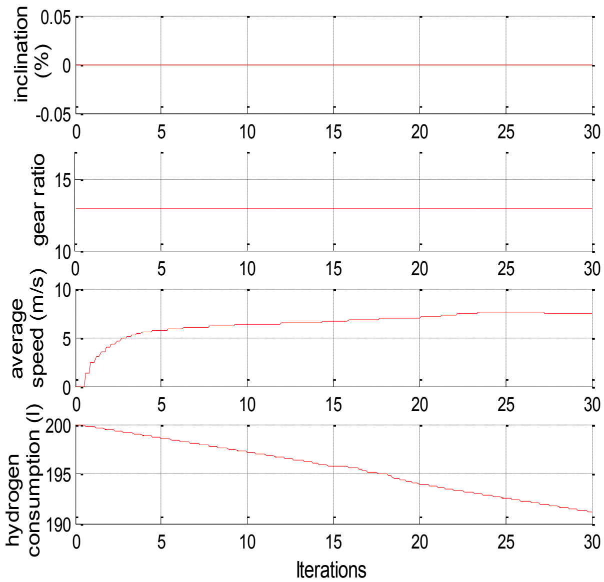

Figure 4: Test case 1: Constant gear ratio in zero inclination track

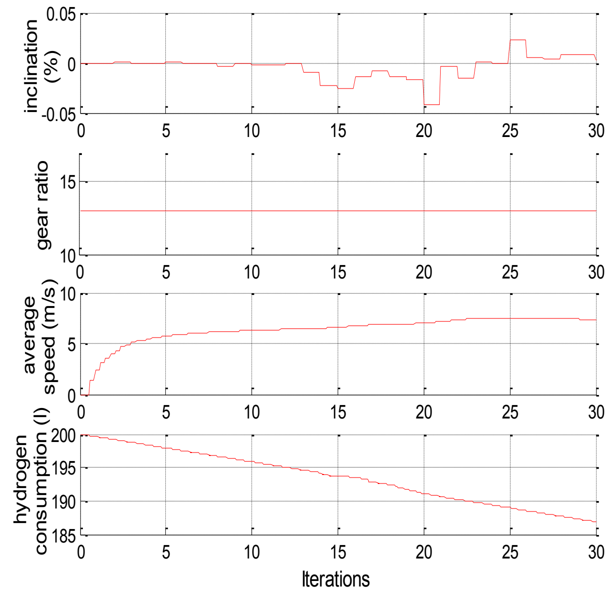

Figure 6: Test case 2: Constant gear ratio in real track

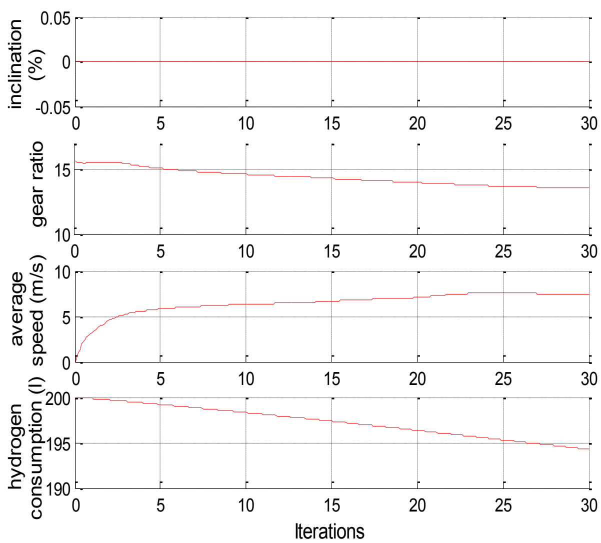

Figure 5: Test case 1: Variable transmission in zero inclination track

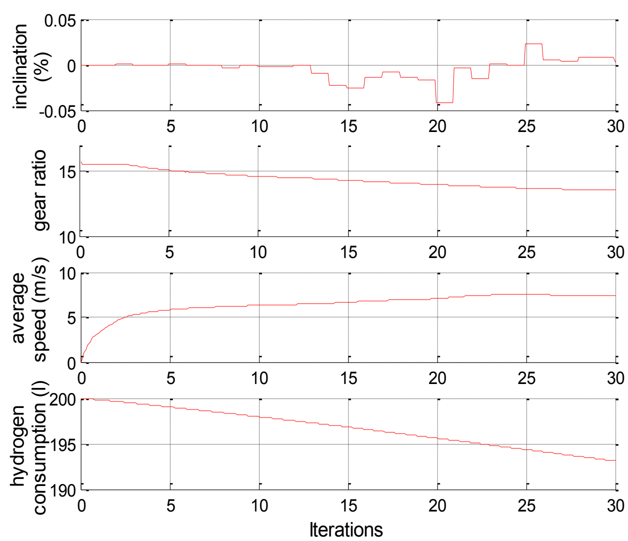

Figure 7: Test case 2: Variable transmission in real track

Similarly, when the ground slopes (inclination pattern) were close to reality, the desired average speed is achieved by both gearboxes. In this test case the Continuous Variable Transmission gearbox needed about 5% less hydrogen to accomplish the mission by also keeping the average car speed within the desired levels. It is observed that in the real track the improvement of fuel consumption by the use of Continuous Variable Transmission is 5% while in the zero inclination track is 1.5%. This is an expected result because in the zero inclination track the gear ratio 1/13 has calculated in order the electric motor has its best efficiency.

IV. Conclusion

In this paper, three new innovative subsystems are presented, namely, the energy management system, the driver's monitor and control panel and the continuous variable transmission system. These systems are important for the improvement of the ER11 vehicle fuel consumption. Two test cases are presented in order to evaluate the performance of the energy management when coupled to the variable gearbox. The performance of the variable gearbox is also compared to a fixed-ratio one. In the first test case a zero inclination track is used against a real multi value inclination track that used in the second test case.

In both test cases (in zero and realistic inclination), the desired speed was achieved. However, the continuous variable transmission gearbox, which allows the motor to operate closer to its peak power or peak efficiency, showed a lower fuel hydrogen consumption in all test cases compared to the constant gear ratio for the same track.

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