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Research Paper

A proposed fuel cell vehicle for reducing CO_2 emissions and its contribution to reducing greenhouse gas emissions

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Abstract

Because of their high efficiency and low emissions, fuel cell vehicles are undergoing extensive research and development. When considering the introduction of advanced vehicles, a complete evaluation must be performed to determine the potential impact of a technology on carbon dioxide (CO_2) and greenhouse gases emissions. However, the reduction of CO_2 emission from the vehicle became the most important objective for all researches institutes of vehicle technologies worldwide. There interest recently to find unconventional methods to reduce greenhouse gas emission from vehicle to keep the environment clean. This paper offers an overview and simulation study to fuel cell vehicles, with the aim of introducing their main advantages and evaluates their influence on emissions of carbon dioxide from fuel cell vehicle and compares advanced propulsion technologies on a well-to-wheel energy basis by using current technology for conventional and fuel cell. The results indicate that the use of fuel cells, and especially fuel cells that consume hydrogen, provide a good attempt for enhancing environment quality and reducing greenhouse gas (GHG) emissions. Moreover, the emission reduction percentage of fuel cell vehicle reaches to 64% comparing to the conventional vehicle.

Keywords: *Fuel Cell Electric Vehicle, Performance, Simulation, Driving Cycle, CO_2 Emissions, Greenhouse Gas Emissions, Fuel Consumption.*

1. Introduction

Road vehicle is one of the main causes of the environmental pollution. According to latest researches it is responsible for about 30% on the total emissions of carbon dioxide (CO_2) into the surrounding air [1]. Research and development of currently technologies for the vehicles field has been growing at transportation is a major source of energy consumption and pollutants emission worldwide. The energy consumed by several vehicles contributes to the majority of petroleum usage, and mean- while billions of tons of airborne pollutants are emitted into the environment. The global greenhouse gas emissions come from vehicles. The effects of greenhouse gas (GHG) emissions on global warming and the ozone layer are well known, and regulations around the world are giving a concentrated effort to reduce the overall emissions of CO_2 [2]. Carbon dioxide can be considered the great face of greenhouse gas. Motor vehicle CO_2 emissions are part of the enormous contribution to the growth of CO_2 concentrations in the atmosphere to participate a considerable part in climate change.

The most researches of vehicle emission focus on three ways to decrease the greenhouse gas emission [3]. The first way is the reduction of vehicle weight and size. This is a tendency which is even today clear, with all ordinary manufacturers extending the range of smaller cars presented. Downsizing reduces emissions as a result of less fuel or energy required to drive small and lighter vehicles.

The second method is hybrid electric vehicle. Hybrid vehicle advantages from the combined operation of an internal combustion engine and an electric batteries which assist the vehicle during accelerations phase and high load condition. The third direction is the use of pure electrical energy source. It considered the introduction of electric vehicles or fuel cell vehicle, i.e. vehicles where power to the wheels is produced by an electric motor throughout the electric batteries and which can be charged directly from external source i.e. power grid. The electric vehicle gives zero emission into environment therefore it can be considered the optimum solution if the two big problems; range wide of vehicle and charging of batteries could be solved.

Multi ways to minimize greenhouse emission is through the introduction of new technologies [4]. Fuel cell vehicles (FCV) are one of the new methods options that has the main advantage of zero fuel consumption and therefore from indirect view reducing the amount of CO_2 into the environment. Electric vehicles and hydrogen fuel cell vehicles are expected to become more important in the longer term to help power growing numbers of vehicles. They offer the potential to reduce CO_2 emissions from road transport since they emit zero CO_2 in use – but actual CO_2 emissions depend on how the energy is produced. FCV are being developed because they promise to meet the requirements expected of automobiles in a market increasingly constrained by environmental and resource limitations [5]. Moreover, electric propulsion has its attractive features of quiet, precisely controllable operation and high efficiency for both powertrain and accessories. What makes fuel cell vehicles attractive is their promise for affordably addressing the multiple design requirements likely to be faced by future automobile propulsion systems.

The current study investigates the influence of use fuel cell in vehicles on the emission of carbon dioxide under different road conditions. Comparing fuels and propulsion systems require a comprehensive, quantitative, life cycle approach to the analysis [6]. It must be more encompassing than 'well-to-wheels' analysis. Well-to-wheels is comprised of two components, the 'well-to-tank' (all activities involved in producing the fuel) and 'tank-to-wheel' (fuel consumption during driving of the vehicle) [7]. In this study, the conventional vehicle was simulated according a driving cycle to know the behavior of vehicle emission especially CO_2 pollutant. The investigation was divided into two fields, the first field is the production phase and the second field is the use of fuel in vehicle.

However, this work offers an overview and simulation study to fuel cell vehicles, with the aim of introducing their main advantages and evaluates their influence on emissions of carbon dioxide from fuel cell vehicle and compares advanced propulsion technologies on a well-to-wheel energy basis by using current technology for conventional and fuel cell.

2. Fuel cell vehicle technology

A fuel cell is an electrochemical device that directly converts a fuel such as hydrogen to electricity by means of reactions on the surfaces of electrodes and transfer of ions through an electrolyte [8]. Intermediate conversions of the fuel to thermal and mechanical energy are not required. All fuel cells consist of two electrodes (anode and cathode) and an electrolyte usually retained in a matrix. They operate much like a battery except that the reactants and products are not stored, but continuously fed to the cell. Fuel is fed to the anode (negative electrode) and an oxidant is fed to the cathode (positive electrode). Electrochemical oxidation and reduction reactions take place at the electrodes to produce electric current [9]. Figure 1 illustrates a schematic diagram of a hydrogen PEM fuel cell. Pure hydrogen gas is supplied to the anode where it diffuses to a catalyst layer.

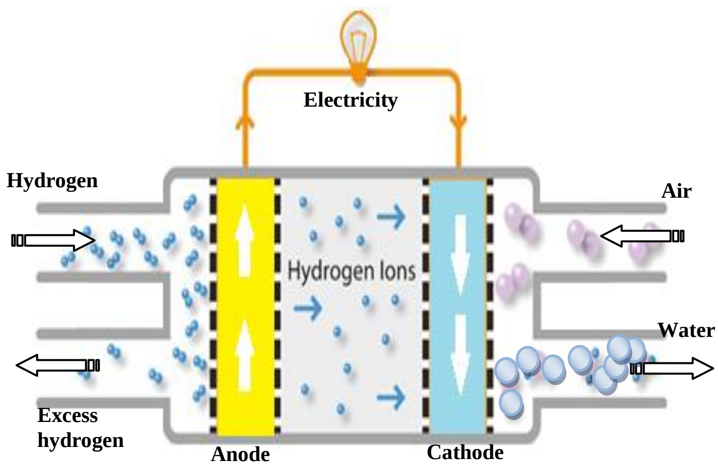

Fig. 1: Schematic Diagram of PEM - Fuel Cell

Firstly, the hydrogen gas flows to the anode. Here, a platinum catalyst is used to separate the hydrogen molecule into positive hydrogen ions and negatively charged electrons [10]. The polymer electrolyte membrane (PEM) allows only the protons to pass through to the cathode, while the electrons pass through an external circuit to the cathode. The flow of electrons through this circuit creates the electric current used to power the vehicle motor. On the other side of the cell, oxygen gas, usually drawn from the atmosphere air, flows to the cathode. When the electrons return from the external circuit, the positively charged hydrogen ions and electrons react with oxygen in the cathode to form water, which then flows out of the cell. At the cathode, electrons from the returning current and oxygen from the air complete the reaction at another catalyst layer, forming water vapor that is exhausted from the fuel cell.

The primary electric drivetrain components for fuel cell vehicles are the same as those for any electric vehicle: traction motors, power electronics, and batteries. Electric drive components require their own sets of auxiliaries and management systems, for control and cooling of the equipment. A fuel cell vehicle may have a hybrid powertrain, in which the fuel cell is sized at less than the vehicle's peak power requirement and additional power is supplied from an electricity storage device, such as a high-power battery. The electric drive system for a fuel cell vehicle is comparable to that for a battery electric vehicle, with the traction motor and power electronics scaled to meet the full power needs of the vehicle.
The use of hydrogen in a fuel cell with an electric motor is an alternative and a complementary solution to the storage of electricity in batteries for EV. It provides longer range and faster recharging compared to the storage of electricity in batteries for EV. As shown in Figure 2 the fuel cell and battery electric vehicles both use electric drivetrains, but where battery electric vehicles feed their motors only with batteries, fuel cell vehicles are hybrids, derived by hydrogen fuel cell which need to a small battery. Both vehicle types benefit

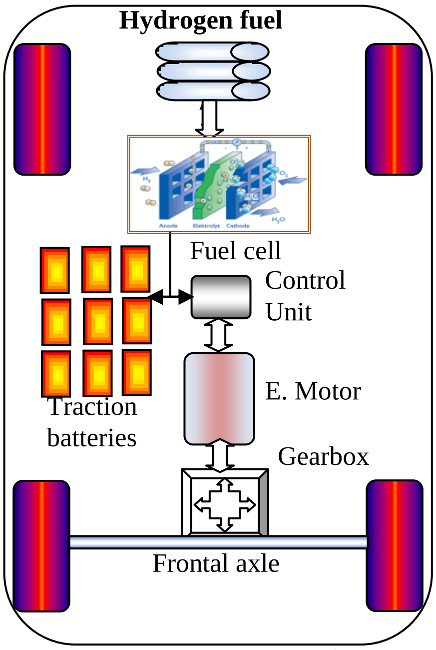

Fig. 2: Schematic Diagram of FCV

As shown in Figure 2, the fuel cell vehicle uses electric drivetrain, where, fuel cell vehicles are hybrids, derived by hydrogen fuel cell which need to a small battery. This type of vehicle benefits from near-silent operation, excellent drive ability and no tailpipe emissions. On the other hand, FCV offers all of the advantages of electric vehicles combined with the utility of conventional vehicle with internal combustion engine. A great amount of road fuel is used in large travelled distance by vehicles and only fuel cells are verified as a zero-emission power source for this type from vehicles.

3. Modeling and theoretical study

To carry-out the main objective of the present study, the Advisor model, AVL's vehicle and powertrain simulation tool, was used to simulate vehicle maneuver over certain driving cycles 'New European Driving Cycle (NEDC)'. Advisor considers a vehicle simulator. In principle, a vehicle simulator is giving all different types of powertrain characteristics (electric motor type, batteries, ICE, wheel size, gearbox, differential, etc.). Then an engine fuel consumption map and CO_2 emission map are given, where the engine characteristics are provided as a function of the engine torque and its revolution per minute. Then the vehicle is allowed to operate over different road conditions and the software of Advisor simulates the vehicle and engine operation by which it can produce total fuel consumed and total emissions produced. The success in the simulation depends on the quality of input data delivered both on the vehicle and engine fronts [11].
For this study, the main variables which were used as an input to the model were fuel consumption engine maps, rated engine power, frontal area and aerodynamic drag, vehicle mass, rolling resistance coefficient, wheel diameter and dimensions and weight of various components as shown in Table1.

Table 1: Technical Data of Vehicle

Description	Data
Wheel base	1600 mm
Height of gravity centre	0.50 m
Cross-section area,	1.37 m^2
Drag coefficient	0.26
Rolling coefficient	0.02
wheel diameter	0.34 m
Maximum vehicle weight	1000 kg
Type of Fuel	Diesel
Compression ratio	23
Max. Power	50 kW
Max. Torque	134 Nm
Fuel cell power	50 kW

Fig 3 shows the flow chart of the simulation program of the vehicle. There are three basic tasks that the software must perform:

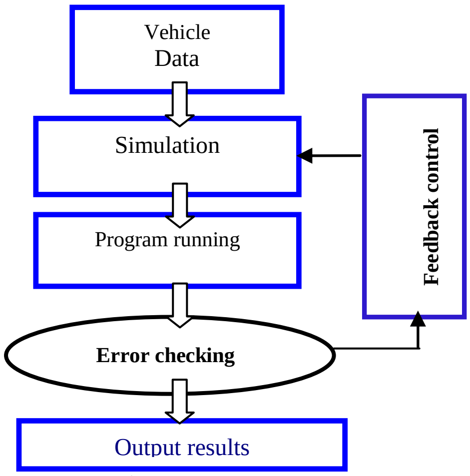

Fig. 3: Outline of Simulation Program

- The data distinguish this run from other runs are read as input. Inputs sort include parameter values, initial conditions, and specifications for predetermined functions of time (i.e., forcing functions from controllers and disturbances). This activity is shown by the block labeled Input Script in the Figure.
- Computations are made to prepare the simulation by setting initial conditions and constants computed from parameter values. An output file is started, in which values of the output variables will be written. Also, the input values might be "echoed" by writing them into a file. These activities are identified by the block labeled Block Diagram.
- The simulation is performed. The equations of motion for the multimode system are used to compute values of state variables at discrete points in time. The power output from the power source can be calculated as [12]:

$$P_{average}=1/t\int_0^t \left(m_{veh}\left(\frac{dv}{dt}\right).\ \delta_{rot}+0.5\ .\ \rho_{air}.A.\ c_d\ .\ v^2+m_{veh}\ .\ g.\ f_{roll}\right)\ v\ dt \quad (1)$$

Where:

A cross sectional area of vehicle, m^2
c_d drag coefficient of vehicle,-
dv/dt vehicle acceleration, m/s^2
ρ air density, kg/m^3
g gravity acceleration, m/s^2
m_{veh} vehicle mass, kg
v vehicle speed, m/s
δ_{rot} coefficient of rotating mass
f_r. rolling resistance coefficient

These values may also be written into one or more output Matlab files. This task involves operations that are repeated for each point of driving cycle in time, using a program loop [13].

4. Estimating method of CO_2 emissions

Carbon dioxide is the principal component of greenhouse gas which emitted by the combustion of fossil fuels in internal combustion engines of vehicles and so in power plant. CO_2 is a stable product of combustion. There are two other components common in fuel combustion emissions that also demonstrate a global warming potential: methane (CH_4) and nitrous oxide (N_2O). From the literature review, it can be observed that every mole of hydrogen produces four mole of CO_2. If all gases were treated as ideal, this would lead to 5.46 kg of CO_2 produced for every kilogram of hydrogen. Furthermore, for the internal combustion engine gives 3.17 kg of CO_2 for each kilogram of Diesel fuel [14]. However, these values just illustrate inefficiencies in the production of hydrogen, so the CO_2 emissions are further increased by 12.5% to represent upstream inefficiencies from the transportation and collection of methane, resulting in production phase that so-called well-to-tank emissions of 10.8 kilograms of carbon dioxide per kilogram hydrogen [15].
Once again, beginning with a projection of the total vehicle traveled distance; it is straight forward to project the annual levels of CO_2 outlet from small vehicles and light duty trucks. The following equations represent the method of calculation of CO_2 mass in case of fuel production (well – to - tank).

CO_2 (kg) = traveled distance of vehicle (km) * Fuel consumption (kg/km) × 10.8 (kg CO_2 per kg H_2) (2)
CO_2 (kg) = traveled distance of vehicle (km) * Fuel consumption (kg/km) × 2.5 (kg CO_2 per kg fuel) (3)

There are two main approaches are used by the calculators to estimate greenhouse gas (GHG) emission from internal combustion engine of vehicle, one of them depend on the amount of fuel used and the other based on the amount of vehicle travelled distance in kilometer [15]. Figure 4 shows the predictable raise of vehicle CO_2 emission in unit Mega tones in worldwide (non-OECD, Eastern Europe, OECD “Organization for Economic Co-operation and Development”, western Europe and north America fin the period from 2010, 2015 to 2020 years.
Fuel use for estimating CO_2 emissions from mobile combustion, the most accurate method is to estimate by the volume of fuel used, the measured carbon content of the fuel per unit of energy (or per unit of volume or mass), and the measured heat content (or density) of the fuel used, represented as [14].

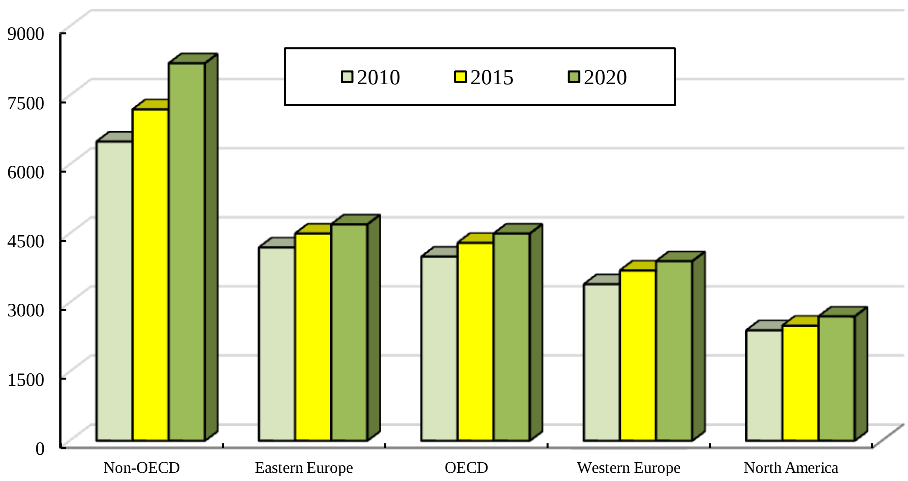

Fig. 4: Predictable Raise of Vehicle CO_2 Emission in Mt

$ECO_2 = F * R * K * (44/12)$ (4)
Where ECO_2 = emissions of CO_2 [kg]
F = fuel use [liter]
R = fuel density [kg/liter]
K = carbon content [kg C / kg fuel]
The estimation of the CO_2 emissions for a bus fleet merely requires fuel consumption and fuel emission factor data for the fleet as a whole. However, the evaluation of the CO_2 emissions of various bus propulsion technologies within a transit fleet requires either segmented fuel consumption data for each vehicle type, or both vehicle-specific fuel economy and vehicle traveled distance data for estimating each vehicle type’s fuel consumption.
The emissions forecasting models developed at national levels are often based on the fact that CO_2 emissions from road transport are closely matched with fuel consumption. Actuality CO_2 emissions based on the carbon content of the fuels [14]. Hence, high-quality estimates of the emissions (g CO_2) from a vehicle can be calculated as the product of an emission factor (g CO_2/g fuel) and the amount of fuel consumption, (g fuel). The average carbon content of some fuel types is illustrated in Table 4.

Table 2: Emission factors of different fuel types [10]

Fuel type	Factor of emission (g CO_2/g fuel)
Gasoline	3.13
Diesel	3.17
CNG	3.00
LPG	2.67

5. Results discussion

Figure 5 shows the results of the engine fuel consumption. The maximum torque was measured at different engine speeds. It is considered as a full load line of engine map of fuel consumption and hence carbon dioxide map. The engine vehicle operates with pure Diesel fuel at different road conditions. With increasing road resistances such as aerodynamic, rolling, gradient and accelerating resistance, the CO_2 emissions are decreasing. These phenomena occurs due to, the efficiency increases with an increasing road resistances. Second, the combustion efficiency enhances with an increasing engine load. The engine map of fuel consumption and CO_2 emission are considered an input data for the simulation program, where it calculates the total road resistances to apply it on the engine map as shown in Figures 5 and 6. The simulation program has the ability to determine the position of operation points throughout the driving cycle second by second. Therefore it could determine the sum of road resistance and hence calculate the load acted against the vehicle motion. By simulation's process can be recorded the correlated values of fuel consumption and CO_2 emission during the time of driving cycle.

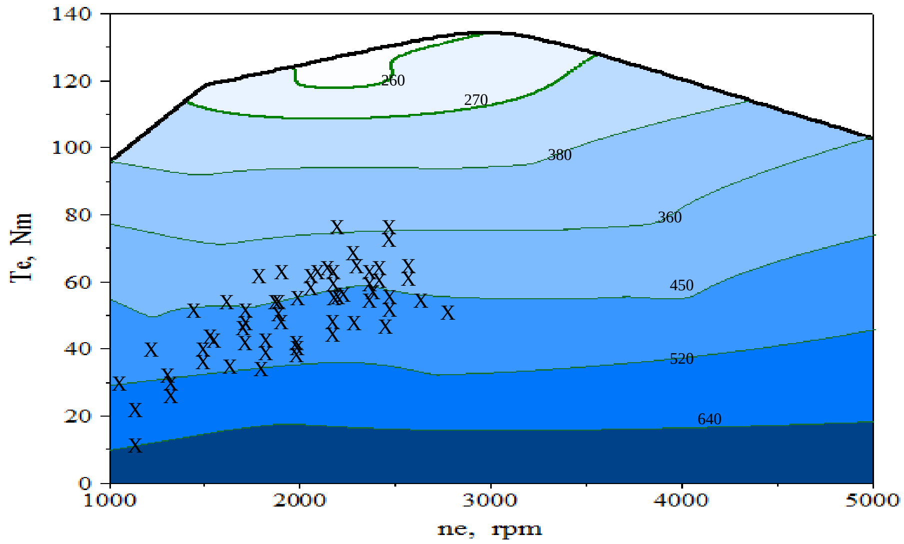

Fig. 5: Fuel Consumption Engine Map

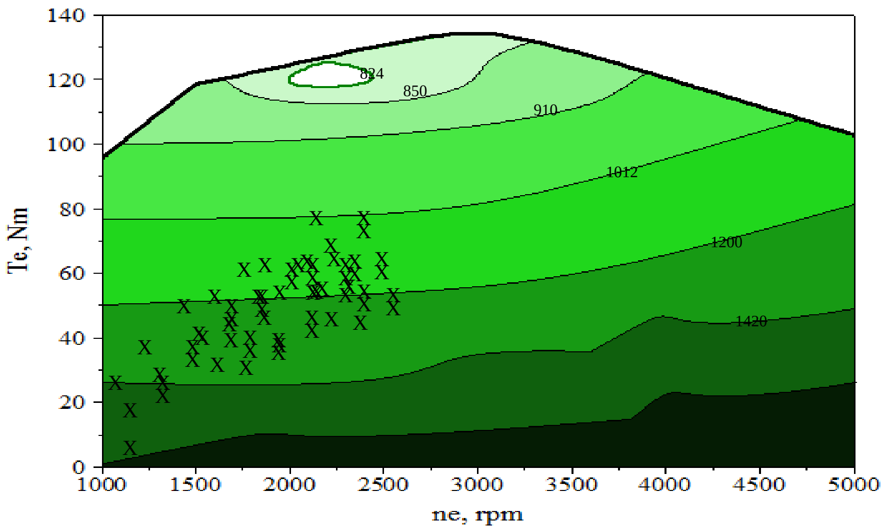

Fig. 6: Carbon Dioxide CO_2 Emission of Engine

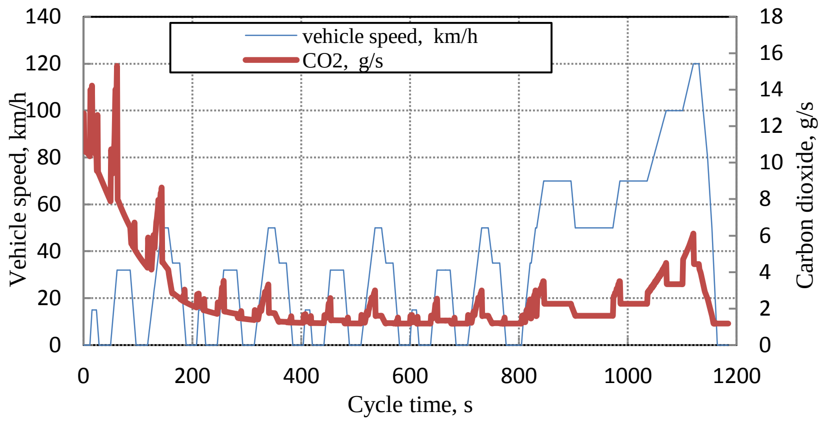

Fig. 7: CO_2 Emission of Vehicle during Driving Cycle

The simulation results for the Diesel vehicles are summarized in Figures 7, 8 and 9. Figure 7 shows the CO_2 emission during driving cycle NEDC in unit of g/s. It was observed that CO_2 increases with the increase of road resistance especially at the phase of vehicle acceleration. Figure 8 presents the out wheel torque of the vehicle along the driving cycle, where the vehicle torque ranges between the positive side and the negative side. The positive torque means that the effort come from the engine throughout the transmission line into the driving wheels, otherwise during the deceleration phase, the vehicle movement comes from road.

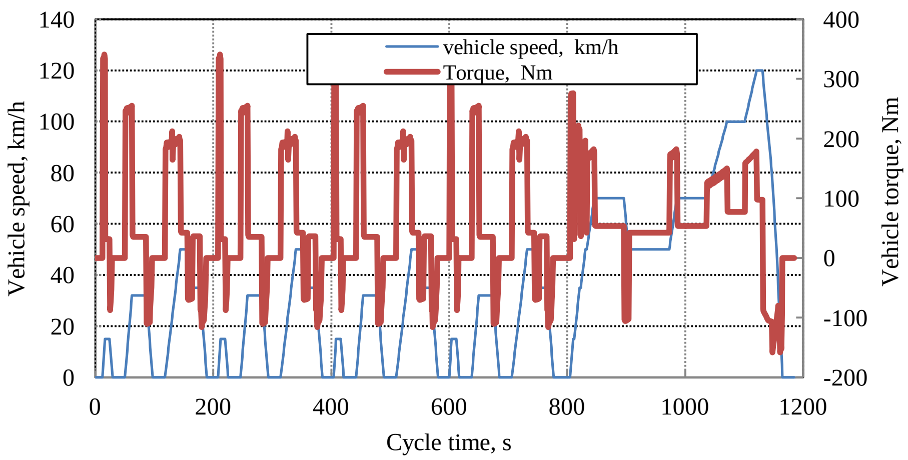

Fig. 8: Vehicle Torque during Driving Cycle

Figure 9 shows the integrated CO_2 emission and fuel consumption during the driving cycle which its values can be reached to 172.7 g/km and 7.3 l/100km respectively.

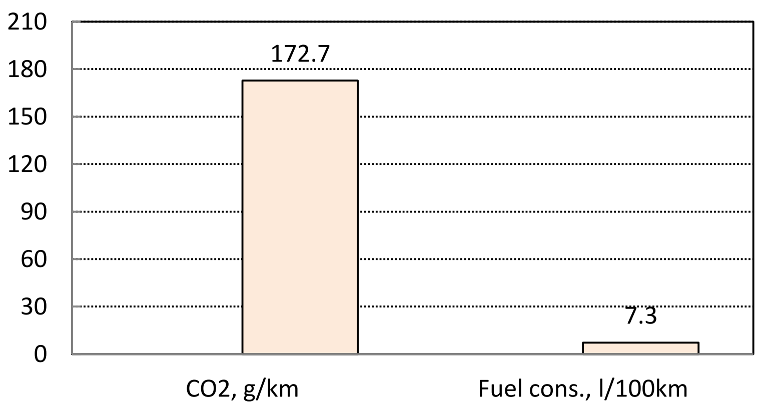

Fig. 9: Mean Value of CO_2 and Fuel Consumption

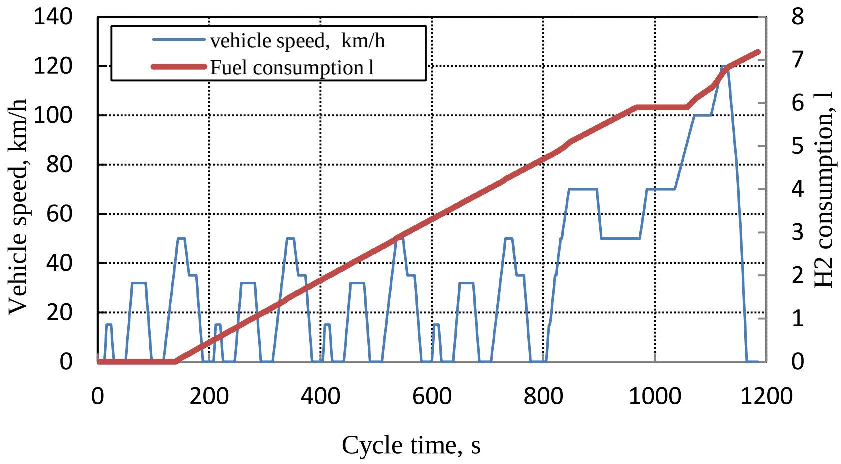

Fig. 10: H_2 Consumption of Fuel Cell Vehicle

Figure 10 illustrates H_2 consumption of FCV. The consumption of H_2 rises along the driving cycle to complete the process in fuel cell to generate the electricity for FCV. Figure 11 shows State of Charge (SOC) of electrical batteries of FCV during the time of NEDC driving cycle. First of all SOC refers to a battery's residual charge capacity on a range from 0 level to 1 full level. When the current flows from fuel cell into the battery, the battery's state of charge increases. . It can be observed in Figure 11 that the level of SOC decreases with the time and reaches to 0.80. In this case the batteries feed the electric motor with the power without charge from the fuel cell therefore SOC will initiate to decrease as shown in Figure.

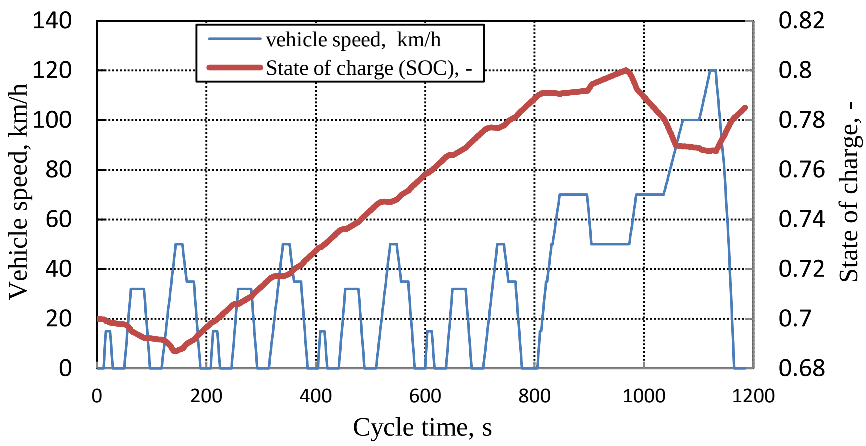

Fig.11: SOC of Fuel Cell Vehicle

As shown in Figure 12 and 13, environmental impacts of FCV were compared with the conventional vehicle on emission during full fuel cycle so-called well-to-wheels. This study takes into account all emission outlets due to the extraction, processing, distribution, and final use of the energy used to propel the different types of FCV and compares them with those of the corresponding Diesel conventional vehicle [17]. The Diesel conventional vehicle emits all emissions that outcome from extracting basic oil, processing oil into a vehicle fuel, distributing the fuel, fuel the vehicle and finally, the vehicle's tail pipe emissions during operation. For the FCV, the analysis of full fuel cycle 'well-to-wheels' must take into account the emission produced during the production of hydrogen for complete the process into fuel cell. It can be observed in Figure xx that well-to-wheels CO_2 emission of conventional vehicle is greater than the CO_2 emission of FCV. Table 2 shows the CO_2 emission full cycle 'production and combustion' for FCV and Diesel vehicle. In Well-to-tank or production phase, the FCV emits zero emission but the Diesel vehicle gives 182.6 g/km. The total CO_2 emission is present in Well-to-wheel phase that shows the significant difference between the FCV and Diesel vehicle as reported in the following Table 3 and Figures 12 & 13.

Table 3: CO_2 Emission in g/km

	Fuel cell vehicle	Diesel vehicle
Well-to-tank	127.7	182.6
Tank-to-wheel	0	172.7
Well-to-wheel	127.7	355.3

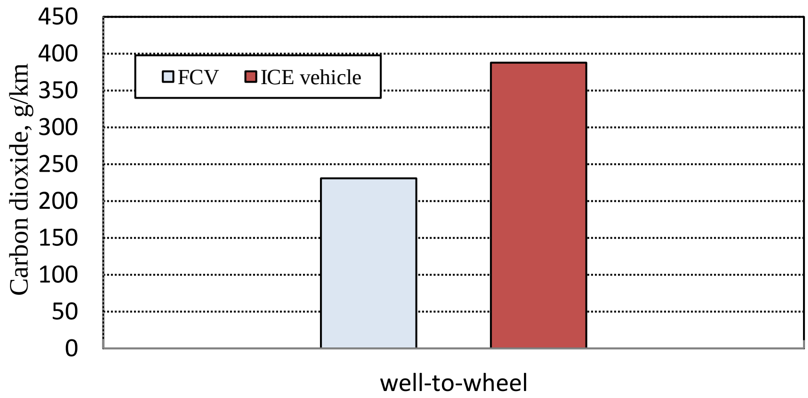

Fig. 12: CO_2 Emission for Both Types of Vehicle

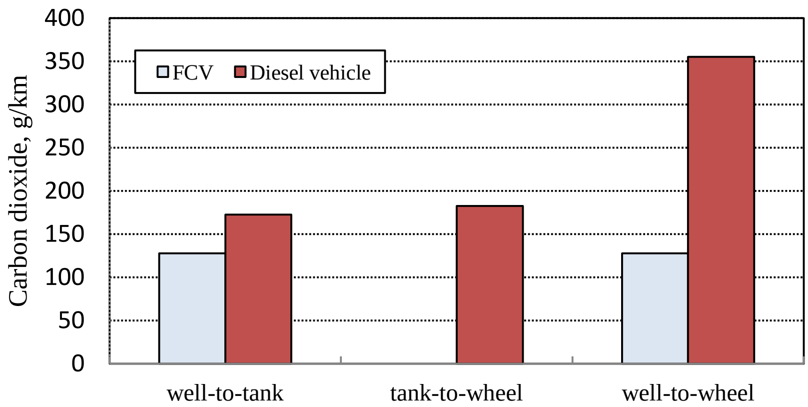

Fig. 13: CO_2 Emission for FCV and Diesel Vehicle

6. Summary and conclusion

1)The use of fuel cells, and especially fuel cells that consume hydrogen, provide a good attempt for enhancing environment quality and reducing GHG emissions.

2)FCV is the endpoint technology for the direct path scenario for a fuel cell transition. In Worldwide CO_2 emissions are gradually decreasing from passenger vehicles in an effort to reduce the influence of road transport upon greenhouse gas emissions and climate change.

3)According to the results, it clears that FCV technology has a significant role in efforts to reduce carbon dioxide (64 %) causing the greenhouse effect, which is strongly related to the fuel consumption, with the most important purpose of FCV is to have greater energy efficiency.

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