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Evaluation of the Hybrid Pneumatic Vehicles According To a Standard Driving Cycle

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ABSTRACT
The world is now turning to the use of economic means of transport as a priority with lower harmful emissions. Hybrid vehicles are among important alternatives that have been used as a reasonable means of transportation. In this paper, a mathematical model of a diesel SUV equipped with a pneumatic hybridization system is designed to calculate the total fuel consumption when the vehicle crossing a whole standard driving cycle and is compared with the conventional case in which the vehicle is driven by an internal combustion engine only. The results indicated that using the pneumatic hybrid system without utilizing the brake energy recovery is uneconomic and may increase the fuel needed to cross the whole driving cycle. As for the use of the brake energy recovery to charge the pneumatic system to drive the vehicle, especially inside the city, this leads to a saving of 15% compared to the conventional case.

KEYWORDS *Driving cycles; Hybrid pneumatic vehicles; brake regenerative energy; Fuel economy*

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List of nomenclature

Vehicle speed, m/s	v	Air density, kg/m^3	r_{air}
Vehicle projected area, m^2	A	Fuel density, kg/m^3	r_{fuel}
Air resistance coefficient	c_W	Transmission ratio	i_T
Gross vehicle mass, kg	m	Transmission efficiency	h_T
Rolling resistance coefficient	f_R	Brake mean effective pressure, bar	bmep
Engine power, kW	P	Hydraulic cylinder pressure, bar	P
Engine energy, kJ	E	Hydraulic cylinder volume, m^3	V
Hydraulic cylinder energy, kJ	E_r	Hydraulic pump efficiency	h_h
Charge energy	E_c	Hydraulic pump efficiency	h_a

I. INTRODUCTION

Environmental issues have risen dramatically as a result of the massive use of fossil energy in many industries, especially transportation, leading scientists to find out more environmentally. In the transportation sector, we consume 13 TW of energy every year. It's worth noting that by 2050 and 2100, the global energy consumption is expected to be approximately 30 and 46 TW, respectively [1]. Vehicles account for roughly 19% of global energy consumption and 23% of overall greenhouse-gas emissions per year [2]. Hence, global greenhouse gas emissions must decline by 60% below the present levels by 2050 if humans are to prevent drastic climate change, according to leading climate alarmists [3, 4]. In the 21st century, renewable energy has been considered one of the most recommended alternatives to solve energy challenges. Vehicles powered by hydrogen, electricity, or synthetic fuels hold promise for a carbon-free transportation sector.

Due to the low overall efficiency of internal combustion engines, researchers have increasingly directed towards improving efficiency and thus reducing harmful emissions. One effective solution is the use of hybrid vehicles[4-6]. The primary goal of hybrid vehicles is to lower engine size to reduce fuel consumption as well as use carbon-free sources [7, 8]. Nonetheless, to reduce energy loss, power is transferred electrically rather than mechanically from energy sources to the vehicle wheels [3, 9]. In Ref. [10], different energy harvest and emission decrease technologies for hybrid electric vehicles have been illustrated and analyzed with a focus on thermoelectric generators, Rankine cycle, regenerative braking systems, renewable energy integration, and alternative fuels. Hybrid electric vehicles have the difficulties of optimization of battery and engine size, power source management, and a compact hybrid drivetrain [11].

The hybrid vehicles common systems are hybrid electric and hybrid pneumatic. Some factors favor the use of hybrid pneumatic systems, such as lightweight, low cost, and speed of recharging, in addition to the possibility of linking the system with the engine air supercharging system to increase the volumetric performance and thus increase the efficiency of the engine[12, 13]. However, there are also many disadvantages in applying this system in cars, such as the low hydraulic efficiency of pumps and actuators[14, 15].

A hybrid pneumatic vehicle is a compressed air/gas vehicle that hosts an engine fueled by compressed air [16, 17]. The necessary energy for the movement of the vehicle is generated by the expansion of compressed air within the engine. Such vehicles can be powered singly by air only, or linked with different fuels such as gasoline, diesel, compressed natural gas, or electricity [14]. The key advantages of a hybrid pneumatic vehicle were no battery discharge problems and battery degradation during the lifetime like electric vehicles. The air pressure and heat generated while braking are reused to refill the tank, improving the vehicle's overall performance and displacement distance [18]. In this regard, the compressed air is sent through a heat exchanger before being charged into an air motor to boost its energy content. After that, the air is re-pressurized and sent to the compressed air tank after expansion via a regenerative mechanism. In a pneumatic system, exhaust gas temperature or atmospheric temperature can be utilized as a heat source [19]. Generally, the driving cycles can be estimated in three classes: highway driving (80 km/h and above), acceleration (50–80 km/h), and urban driving (0–50 km/h). In city driving mode, the bus is powered by a pneumatic power system. While on a roadway with a speed of more than 80 km/h, the car is only powered by an internal combustion engine. In acceleration, the energy required is produced by both a pneumatic system and a fuel-fueled internal combustion engine[20].

Sharma and Singh [16] reviewed the effect of the capacity of the air pressure from the compressor on the air engine performance. The literature identified that an engine speed of 3000 rpm was obtained at a maximum pressure of 8 bar. Furthermore, the maximum speed was 28.9 km/h with a traveling distance of 2.5 km at a low pressure of 5 bar, whereas the maximum speed was 36.5 km/h with a traveling distance of 1.7 km at a high pressure of 9 bar. Qi et al. [21] introduced a new design for a pneumatic regenerative system hybridized in an electric car to extend the lifetime of the battery, which is only charged by the main energy in the parking. The experiments showed a satisfying conclusion in driving. Dimitrova et al. [22] performed an investigation suggesting a gasoline hybrid pneumatic powertrain for C-Segment vehicles (four-wheel vehicles). The study presented a short-term hybrid pneumatic power storage and a waste heat regeneration system to produce higher performance with a small downsized gasoline engine. The results revealed that short-term pneumatic energy storage increased the powertrain's efficiency by 100% for urban driving. An experimental investigation was undertaken by Evrin and Dincer [23] on a new hybrid compressed air-electric vehicle. According to the findings, the enhanced system had a work output of 23.12 kW and a driving range of 131 km. Rolfe et al. [24] created a pneumatic powertrain for automobile applications consisting of a compressed air tank, chassis, wheels, and an air engine fed by the compressed air and connected to wheels. Antony et al. [25] studied the performance of the hybrid pneumatic vehicle, which is powered by both an air engine and an internal combustion engine. The results showed that the fuel economy was increased, especially in cities where the vehicle encountered several starts and stops.

The hybrid pneumatic technology is relatively novel for the automotive industry. This analysis aims to show comparisons between simulated hybrid pneumatic systems and conventional systems in order to identify a technique for better predicting hybrid pneumatic system performance under a known driving cycle. Insights obtained from the simulated results of this research will shed more light on public attitudes and preferences linked to the hybrid pneumatic power system. This analysis will further guide pneumatic vehicle manufacturing design in vehicle engineering.

Hybrid vehicle system is operated at a high engine efficiency hence consumes less fuel and produces fewer pollutants than their conventional counterparts[26]. Hybrid electric or hybrid-pneumatic vehicles are examples of the systems that have an effective tangible to achieve these targets. Vehicle hybridization can be classified into many types; electric hybrid vehicle and pneumatic hybrid vehicle. Every type has advantages and disadvantages, the main advantage of a fully pneumatic hybrid vehicle that it can be easily controlled to work at the optimum fuel consumption. A pneumatic hybrid vehicle is an innovative approach similar to the so-calledelectric hybridization[27].

This study aims to evaluate the fuel consumption of a hybrid pneumatic SUV vehicle with a diesel engine using MATLAB Simulink and to compare with the conventional vehicle according to new European driving cycle NEDC. The essential vehicle resistances will be calculated as a function on NEDC time.

II. METHODOLOGY

An SUV with 1.8 liters diesel engine has been usedin this study to evaluate the total track fuel consumption when the vehicle runs whole neu European driving cycle NEDC in conventional and hybrid pneumatic conditions. The essential vehicle resistances will be calculated as a function of NEDC time. The corresponding power, energy, and brake mean effective pressure will be evaluated. Using fuzzy logic control, the engine revolutions as a first input and the brake mean effective pressure as the second input. Then the brake-specific fuel consumption is evaluated as the output of the fuzzy logic system. The overall fuel consumption during one complete cycle and then compared with the case of a conventional vehicle.

Table 1 shows the main vehicle specifications.

Max power @3600 rpm, kW	94	Rolling resistance coefficient	0.0175
Displacement, liters	1.8	Projected area, m^2	2.1
Gear ratios	3.6, 1.9, 1.2, 0.9 and 0.74	Drag force coefficient	0.33
Final drive ratio	3.2	Coefficient of rotating parts	5 %
Gross vehicle weight, kg	1800	Max. hydraulic accumulator pressure, bar	250
Gross vehicle weight (hybrid), kg	2000	Hydraulic accumulator diameter, m	0.48
Tire size	235/50 R18	Low hydraulic accumulator pressure, bar	10

The engine fuel consumption map is shown in Fig 1.

Fig 2 show the power flow diagram of the model used in this study to evaluate the total track fuel consumption. The vehicle is running according to NEDC driving cycle. The total vehicle engine power to overcome the resistances can be calculated as follow:

$$P = \frac{\left(0.5\,\rho_{air}\,c_w A v^2 + mgf_R + \delta m\frac{dv}{dt}\right)v}{\eta_t}$$

From the model data, the engine torque, brake mean effective pressure, and engine revolutions can be calculated. A Matlab Mux is used to binary the signals of engine revolutions and bmep. The two collating signals are the input of a fuzzy control system which is programmed by engine fuel map data. Through interpolation, the fuzzy control system can evaluate the brake-specific fuel consumption bsfc as a function of driving cycle time.

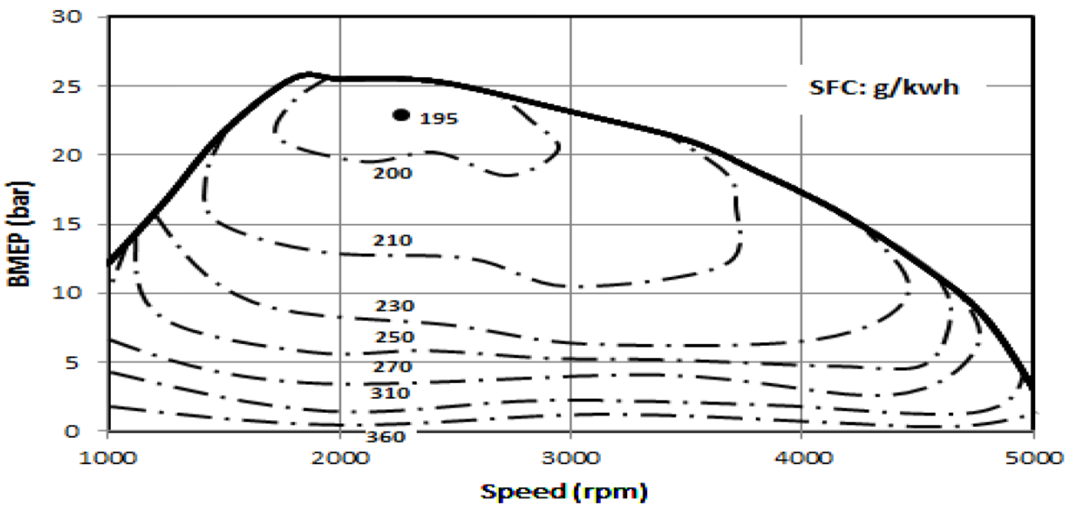

Fig 1 Engine fuel map (SUV vehicle)

The track fuel consumption can be expressed as

$$\beta(t) = \frac{bsfc.P}{\rho_{fuel}}$$

The total fuel consumption for the whole driving cycle is

$$\beta_T = \int \beta(t)dt$$

When the vehicle is driven in hybrid mode. A basic method was followed in this research by assuming 100% charged cylinders at the start of the driving cycle and the vehicle can be driven by compressed fluid until the end

of the city region of the driving cycle (0-840 seconds). During this period, the car operates at zero-emission mode. As a result, there is a decrease in the pressure of the hydraulic cylinders. The second stage is driving the vehicle on gasoline mode at the highway region of the driving cycle besides recharging the hydraulic cylinders to be fully recharged to 100%. At this stage, the engine is adjusted at maximum torque to reach satisfactory levels of the economy. The last stage is the remainder of the highway region of the driving cycle with gasoline mode, and then the fuel consumption is calculated in the second and third stages, thus an approximate calculation of the total track fuel consumption for hybrid vehicles is achieved.
High-pressure cylinder hydraulic energy can be expressed as

$$E_c = pV$$

The regenerative brake energy recovery that can be generated from negative engine power can be calculated as

$$E_r = \eta_h \left| \int_{-p}^{0} P(t)dt \right|$$

The cylinder hydraulic pressure can be formed as

$$p(t) = \frac{(E_r + E_c)}{V} \eta_a$$

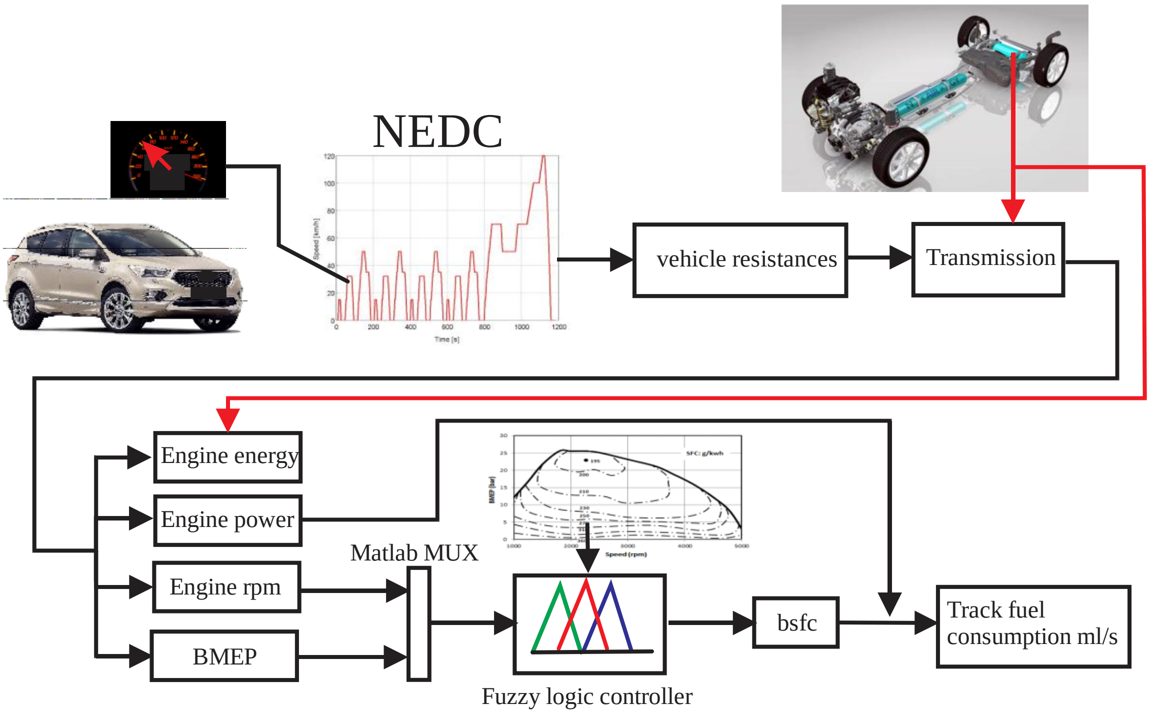

Fig 2 Layout of Matlab Simulink model

III. RESULTS AND DISCUSSIONS

Firstly, to run the conventional vehicle to cross the whole NEDC driving cycle. Fig 3 illustrates the engine brake mean effective pressure along the time of NEDC. 4 similar regions from 0 to about 840 s. Next to this region is the highway region. In the city region, the brake mean effective pressure reached a maximum of about 12 bar, in addition to that there was negative pressure due to the slowdown or deceleration. Running through highway region needs more brake mean effective pressure that devolves to about 17 bar.

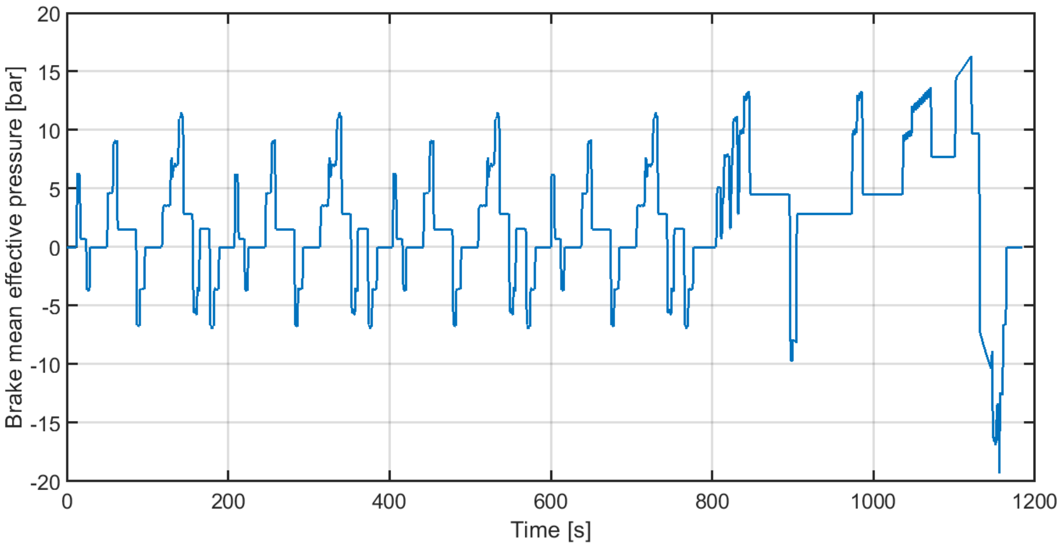

Fig 3 brake mean effective pressure variations with the NEDC cycle time

Fig 4 shows track fuel consumption of the conventional vehicle when running the whole NEDC driving cycle. It can be noticed that 4 similar city regions where, It was found that the fuel consumption reached 2 ml/s, while the fuel consumption increased to 4.8 ml/s in the highway region.

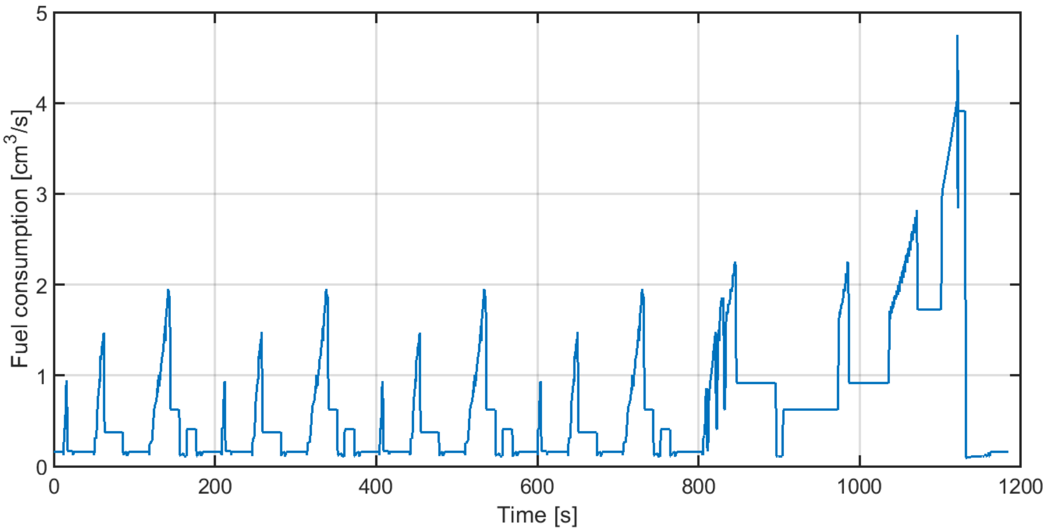

Fig 4 track fuel consumption with NEDC cycle time

The integration of the track fuel consumption in ml/s with the time is the total fuel consumption in ml that is plotted in Fig 5. At the end of the driving cycle, about 770 ml of fuel is required for the vehicle to cross the standard driving cycle. This quantity is considered reasonable for these categories of SUV vehicles when compared also with some previous studies such as [28-30]

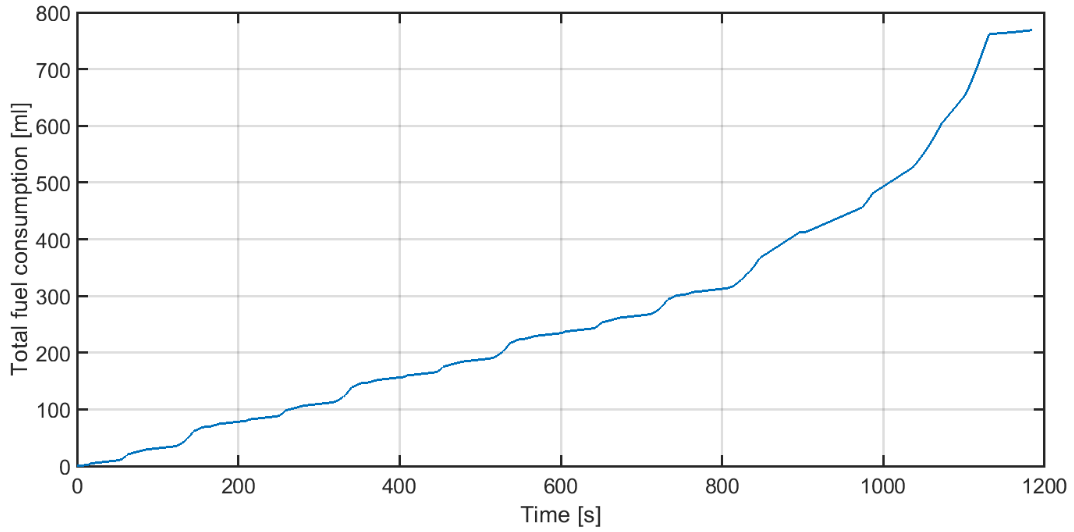

Fig 5 Total track fuel consumption of conventional vehicle running whole NEDC

As the vehicle runs in zero-emission mode (driven by the hydraulic actuator) 0-840 seconds; city region; the cylinder pressure is 100 % charged. In conjunction with the movement of the vehicle that is derived from the hydraulic energy, as a result, the cylinder pressure begins to decrease, as shown in Figure 6. This procedure was performed once without utilizing the brake energy recovery and again with the utilizing of brake energy recovery. Where about 38% of the hydraulic energy of the cylinder was consumed to enable the vehicle to run a complete city-region without utilizing the brake energy recovery, while in the case of utilizing the brake energy recovery, the hydraulic energy shortage became about 28%.

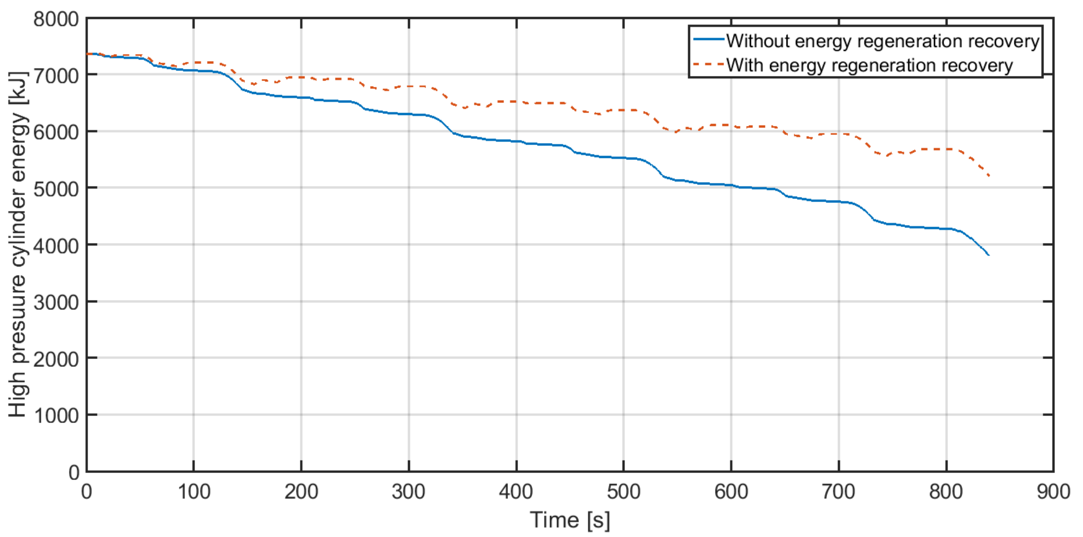

Fig 6 High pressure cylinder energy with and without brake energy recovery during city region of NEDC

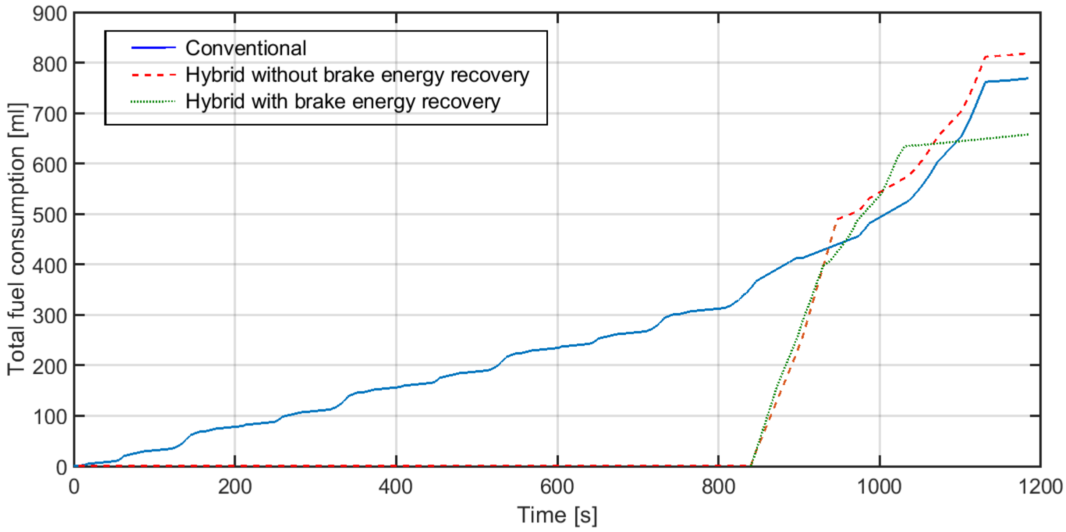

Fig 7 Total track fuel consumption during crossing whole NEDC for conventional and hybrid pneumatic vehicles

Figure 7 shows the total fuel consumption of the conventional vehicle compared to the hybrid vehicle conditions when the vehicle runs the whole standard driving cycle NEDC. It can be noted that the fuel consumption in the hybrid vehicle without utilizing the brake energy recovery has increased over the conventional vehicle by about 6%. On the other hand, there was a saving in fuel consumption in the hybrid vehicle with utilizing brake energy recovery, compared to the conventional vehicle, by about 15%. These results are in agreement with Ziming et al [21].

IV. CONCLUSION

In this research, a mathematical model was designed to evaluate the hybrid pneumatic vehicle performances. The total track fuel consumption in liters is calculated when the vehicle crossing the whole new European driving cycle NEDC. An SUV vehicle powered by a diesel engine is used in this study. It was taken into consideration; an additional 200 kg was assumed when installing the hybrid pneumatic system over the conventional vehicle. Through the results obtained, the amount of fuel required for the conventional vehicle to cross the new European driving cycle is about 760 milliliters. The hybrid pneumatic system without utilizing the brake energy recovery is not economical, as the amount of fuel needed to cross the car into the modern European driving cycle in the case of hybridization without exploiting the brake energy has increased over the traditional case by about 6%. While the amount of fuel required to cross the same driving cycle when utilizing the brake energy recovery is reduced by 15% compared to the conventional vehicle.

REFERENCES

[1]. U. Sahaym and M. G. Norton, "Advances in the application of nanotechnology in enabling a ‘hydrogen economy’," *Journal of Materials Science*, vol. 43, no. 16, pp. 5395-5429, 2008.
[2]. A. Erdemir *et al.*, "Carbon-based tribofilms from lubricating oils," *Nature*, vol. 536, no. 7614, pp. 67-71, 2016.
[3]. K. Çağatay Bayindir, M. A. Gözüküçük, and A. Teke, "A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units," *Energy Conversion and Management*, vol. 52, no. 2, pp. 1305-1313, 2011/02/01/ 2011.
[4]. M. Mourad and K. R. M. Mahmoud, "Investigation into SI engine performance characteristics and emissions fuelled with ethanol/butanol-gasoline blends," *Renewable energy*, vol. 143, pp. 762-771, 2019.
[5]. M. Mourad and K. R. M. Mahmoud, "Performance investigation of passenger vehicle fueled by propanol/gasoline blend according to a city driving cycle," *Energy*, vol. 149, pp. 741-749, 2018.
[6]. M. Mourad, K. Mahmoud, F. Mohamed, and A. Nouh, "Influence of biodiesel fuel on performance characteristics of hybrid electric vehicle according to urban driving cycle," in *2014 5th International Renewable Energy Congress (IREC)*, 2014, pp. 1-6: IEEE.
[7]. K. Song, X. Wang, F. Li, M. Sorrentino, and B. Zheng, "Pontryagin’s minimum principle-based real-time energy management strategy for fuel cell hybrid electric vehicle considering both fuel economy and power source durability," *Energy*, vol. 205, p. 118064, 2020/08/15/ 2020.
[8]. E. J. E. I. Figenbaum and S. Transitions, "Perspectives on Norway’s supercharged electric vehicle policy," *Environmental Innovation and Societal Transitions*, vol. 25, pp. 14-34, 2017.
[9]. A. Schönknecht, A. Babik, and V. J. T. R. P. Rill, "Electric powertrain system design of BEV and HEV applying a multi objective optimization methodology," *Transportation Research Procedia*, vol. 14, pp. 3611-3620, 2016.
[10]. S. Bai and C. Liu, "Overview of energy harvesting and emission reduction technologies in hybrid electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 147, p. 111188, 2021/09/01/ 2021.
[11]. F. Un-Noor, S. Padmanaban, L. Mihet-Popa, M. N. Mollah, and E. Hossain, "A comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of development," *Energies*, vol. 10, no. 8, p. 1217, 2017.

[12]. Y. Fang, Y. Lu, A. P. Roskilly, and X. J. E. S. R. Yu, "A review of compressed air energy systems in vehicle transport," *Energy Strategy Reviews,* vol. 33, p. 100583, 2021.
[13]. S. Trajkovic, *The Pneumatic Hybrid Vehicle-A New Concept for Fuel Consumption Reduction*. Lund University, 2010.
[14]. F. Wasbari, R. Bakar, L. M. Gan, M. Tahir, A. A. J. R. Yusof, and S. E. Reviews, "A review of compressed-air hybrid technology in vehicle system," *Renewable and Sustainable Energy Reviews,* vol. 67, pp. 935-953, 2017.
[15]. M. C. Naveenkumar, M. Akshai, A. Mathew, R. Balakumaran, and S. Balaji, "Design, Fabrication and Simulation of Compressed Air Hybrid Vehicle," *International Research Journal of Engineering and Technology*, 2018.
[16]. A. Sharma and M. Singh, "Parametric analysis of an air driven engine: A critical review," *International Journal Of Advanced Research In Engineering And Technology,* vol. 6, no. 4, pp. 123-131, 2015.
[17]. D. Tretsiak, T. Häberlein, and B. J. I.-P. Bäker, "Energy efficient control of the air compressor in a serial hybrid bus based on smart data," *IFAC,* vol. 49, no. 11, pp. 385-392, 2016.
[18]. A. E. Karaca and I. Dincer, "A hybrid compressed natural gas-pneumatic system as a powering option for buses: A comparative assessment," *Energy,* vol. 230, p. 120865, 2021/09/01/ 2021.
[19]. R. A. Evrin and I. Dincer, "Experimental investigation of a compressed air vehicle prototype with phase change materials for heat recovery," *Energy Storage,* vol. 2, no. 5, p. e159, 2020.
[20]. R. Mohammadali Zadeh, "Development and investigation of compressed air only and hybrid powering options," Master thesis, University of Ontario Institute of Technology, 2016.
[21]. D. Hawkins, Z. Qi, and V. J. I. J. o. R. E. V. Liang, "Pneumatic regeneration system in an electric car," *International Journal of Renewable Energy Vehicles,* vol. 1, pp. 14-18, 2010.
[22]. Z. Dimitrova, P. Lourdais, and F. Maréchal, "Performance and economic optimization of an organic rankine cycle for a gasoline hybrid pneumatic powertrain," *Energy,* vol. 86, pp. 574-588, 2015.
[23]. R. A. Evrin and I. Dincer, "Experimental performance study of a hybrid compressed air-electric vehicle prototype," *Energy Storage,* vol. 2, no. 6, p. e195, 2020.
[24]. B. F. Rolfe *et al.*, "Pneumatic powertrain for an automotive vehicle," Deakin University, 2010.
[25]. F. Antony, P. Albert, P. Rimin, R. Disney, M. Sooraj, and S. S. Menon, "Design and development of pneumatic hybrid vehicle (PHV)," *Department of Mechanical Engineering, Jyothi Engineering & College, Thrissur, India,* 2014.
[26]. Ł. J. E. Bartela, "A hybrid energy storage system using compressed air and hydrogen as the energy carrier," *Energy,* vol. 196, p. 117088, 2020.
[27]. M. Hannan, F. Azidin, A. J. R. Mohamed, and S. E. Reviews, "Hybrid electric vehicles and their challenges: A review," *Renewable and Sustainable Energy Reviews,* vol. 29, pp. 135-150, 2014.
[28]. Z. Wang, J. Zhang, P. Liu, C. Qu, and X. J. E. P. Li, "Driving cycle construction for electric vehicles based on Markov chain and Monte Carlo method: A case study in Beijing," *Energy Procedia,* vol. 158, pp. 2494-2499, 2019.
[29]. J. Cao, J. Peng, and H. J. E. P. He, "Modeling and simulation research on power-split hybrid electric vehicle," *Energy procedia,* vol. 104, pp. 354-359, 2016.
[30]. K. Hereijgers, E. Silvas, T. Hofman, and M. J. I.-P. Steinbuch, "Effects of using synthesized driving cycles on vehicle fuel consumption," *IFAC,* vol. 50, no. 1, pp. 7505-7510, 2017.

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