Preliminary Design of a Series Hybrid Pneumatic Powertrain for a City Car

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***Abstract*— The need for service passenger cars, like taxies and governmental vehicles, to work in central Tehran that can produce less emission has been the main drive behind this research. A series hybrid pneumatic vehicle based on Iran manufactured Samand Passenger car was developed using commercially available components. The idea is to use as much standard parts as possible to reduce the development and manufacturing costs of the developed hybrid car. The vehicle space and weight limitations and the fixed geometry have been the main constraint in adoption of the components. The calculations show that the designed vehicle succeeds to satisfy the requirements set by driving cycle, but requires further component development to become competitive from the view point of maximum speed and gradeability.**

Keywords-Hybrid car; Hybrid pneumatic power system; Series hybrid system;Hybrid Pneumatic Vehicle; Driving cycle

I. Introduction

The achievements in automotive industry have been enormous in recent years. The largest portion of this advancement can be owed to the development of more efficient engines and power trains. In principal engines are to convert the chemical energy of fuels such as gasoline or fuel oil into mechanical energy with highest possible efficiency. They also have to satisfy acceleration and deceleration requirements during different driving demands. This fact causes the engine not to work in its sweet spot. As a result of incomplete combustion, engines generate three main toxic exhaust emissions, which are Nitrogen oxides (NO_x), Carbon monoxides (CO) and unburned hydrocarbons. The exhaust toxic emissions cause environmental damages and bring about air pollution, global warming and faster depletion of fossil fuel resources.

According to Schwarz [1], as shown in “Fig. 1”, about 70 to 80% of the fuel energy burnt in an engine cannot be converted to mechanical Energy. The wasted energy is turned into heat, which is transferred to the environment or lost through exhaust gases. In fact, about 15% of the fuel energy leads to run the vehicle.

To solve the aforementioned engines deficiency, most of major automobile manufacturers have invested in the development and research for new power sources. As a first attempt, electric cars were introduced as the zero emission vehicles. Electric vehicle driving range seems to be the main drawback of this technology. In the next stage, hybrid electric vehicles were designed and manufactured by American and Japanese main car makers. Low charging capacity of batteries, slow charging, inaccurate indication of remaining electrical power and chemical pollution made by used batteries, are the bottlenecks of this technology.

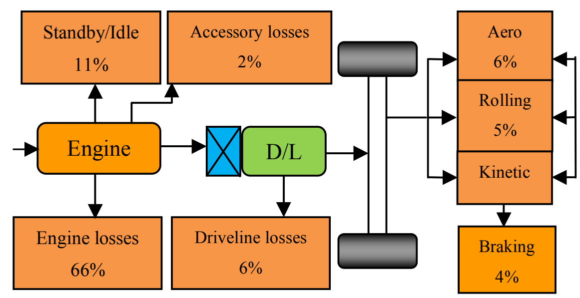

Fig 1. Engine power efficiency diagram [1]

Other designs such as bi-energy engine by Guy Negre [2] incorporating gasoline and compressed air, or HPPS by Hung [3] that stored “flow work” as compressed air instead of electromechanical energy in batteries were other attempts to reach to alternative solutions. The latter design recycles the heat lost in exhaust in addition to employing an engine that works in its optimal point. In this concept model electric motor, generator and batteries are replaced by air motor, compressor and high pressure air storage tanks. The optimization of ICE and recycling of exhaust energy can increase the vehicle efficiency from an original 15% to 33% [4]. Their experiments in 2008 and 2009 concluded that the storing capability of flow energy, exhaust gas energy recycling and merger flow energy are strongly depend on operating pressure (P_{air}) in the system and contraction of cross section area (*CSA*) [5]. Under the optimal adjustment of *CSA* and P_{air} recycling efficiency reach to about 75 to 80%. Therefore, the system energy efficiency will reach to about 45% [6, 7].

Despite apparent advantages to HPPS system, The Idea has not yet been commercialized. Therefore our team decided to evaluate the idea by trying it on an Iranian platform (Samand).

II. Hybrid Vehicle Design

A. Hybrid Electric Vehicles

Hybrid electric vehicles are classified from different aspects. The most common classification is based on drive-train arrangement. In this classification the architecture of a hybrid vehicle is defined on the basis of the connections between the components that define the energy flow routes and control ports. In this arrangement HEVs are categorized into three major groups; series, parallel and series-parallel groups. In year 2000 new HEVs were introduced which changed the classification into four group including series, parallel, series-parallel and complex hybrid [8].

Series hybrid drive train is a drive train where two power sources feed a single power plant (electric motor) that propels the vehicle. The most commonly found series hybrid drive train is the one shown in "Fig. 2". The main components of this configuration are the engine, batteries and traction motor. The traction motor can be controlled either as a motor or a generator, in forward or reverse motion [9]. Batteries can be charged from engine or plug-in device or regenerative braking equipment. Series HEV can work in different operation modes. In pure electric and pure engine modes vehicle is propelled only by batteries or engine, whereas in hybrid mode, both of them are engaged. Batteries are charged via generator in engine traction and regenerative braking modes, also, when traction motor receives no power [10]. In addition, batteries can charge with combination of aforementioned methods, which is called hybrid charging mode. Operation modes of series HEV are indicated in "Fig. 2" with dash and solid arrows. Simple control strategies, mechanical decoupling of engine from driven wheels, maximum efficiency of engine on speed-power characteristic, which is illustrated in "Fig. 3" and simplicity of drive train are some of the advantages of series HEV systems [8].

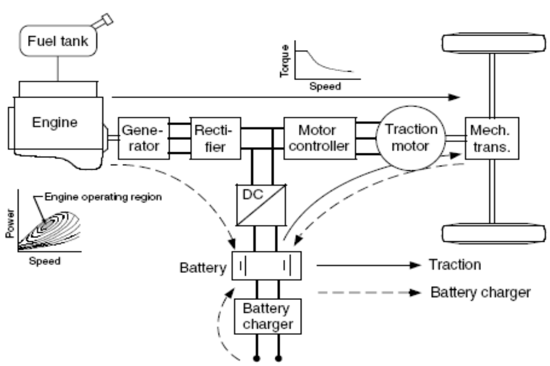

Fig 2. Configuration of a series hybrid electric drive train [8]

The advantages of series HEV lead the research group to select this configuration as their first attempt in designing the conceptual Hybrid pneumatic vehicle (HPV) power train. Aside from the engine, electric components of HEV are to be replaces by pneumatic components of similar function in HPV.

B. Methodology

According to Newton's second law in vehicle movement, vehicle acceleration can be written as "(1)", where V is vehicle speed, $\sum F_t$ is the total tractive effort of the vehicle, $\sum F_{tr}$ is the total resistance, M_v is the total mass of the vehicle, and δ is the mass factor, which is an effect of rotating components in the power train.

$$\frac{dV}{dt} = \frac{\sum F_t - \sum F_{tr}}{\delta M_v} \quad (1)$$

The mass factor, δ for a passenger car would be estimated using the "(2)", where δ_1 and δ_2 is measured about of 0.04 and 0.0025 respectively.

$$\delta = 1 + \delta_1 + \delta_2 i_g^2 i_o^2 \quad (2)$$

Acceleration power of the vehicle can be calculated by "(3)", where a is the acceleration of the vehicle.

$$P = M_v a V \quad (3)$$

1) Vehicle Resistance: Vehicle resistance is against its movement direction. The resistance of the vehicles include rolling resistance, aerodynamic resistance and grading resistance. Equations "(4)", "(5) " and "(6)" show the rolling resistance, aerodynamic drag and grading resistance respectively.

$$F_r = M_v g f_r \cos\alpha \quad (4)$$

$$F_w = \frac{1}{2}\rho A_f C_D (V + V_w)^2 \quad (5)$$

$$F_g = M_v g \sin\alpha \quad (6)$$

Where f_r is the rolling resistance coefficient, α is the road angel, ρ is the air density, A_f is the vehicle front area, C_D is aerodynamic drag coefficient and V_w is the component of the wind speed in moving direction of the vehicle.

2) Power Rating Design: On a flat road and at a constant speed, the power output from the power source (engine/generator) can be expressed as "(7)", where η_t and η_m are the efficiency of the transmission and traction motor respectively.

$$P_{e/g} = \frac{V}{1000\eta_t\eta_m}\left(M_v g f_r + \frac{1}{2}\rho C_D A_f V^2\right) \quad (7)$$

In addition, the traction power of the motor drive can be estimated as "(8)". V_f is the final speed and V_b is the vehicle speed. Also t_a is the expected acceleration time.

$$P_t = \frac{\delta M_v}{2t_a}(V_f^2 + V_b^2) + \frac{2}{3}M_v g f_r V_f + \frac{1}{5}\rho_a C_D A_f V_f^3 \quad (8)$$

3) Torque and Rotational Speed: The maximum speed of the vehicle can be determined by "(9)", where N_m, $i_{g\min}$ and r_d are the maximum speed of the engine (air motor), the minimum gear ratio and radius of tire of the transmission, respectively.

$$V_{\max} = \frac{\pi N_m r_d}{30 i_o i_{g\min}} \quad (9)$$

The torque on the driven wheels, transmitted from the power plant, is expressed as "(10)". T_p is the torque output of the power plant.

$$T_w = i_g i_o \eta_t T_p \quad (10)$$

C. Hybrid Pneumatic Vehicle

The series hybrid pneumatic power system is shown in "Fig. 4".

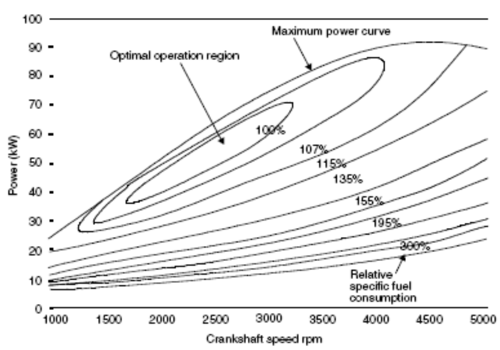

Fig 3. Example of engine characteristics and optimal operating region [8]

Compared with series HEV the main difference lies in that an air compressor replaces the generator, a pneumatic motor replaces the electric motor, a high-pressure air tank replaces the battery, and flow work replaces the electrical energy [4].

A gasoline engine is combined with an air compressor, which works with full throttle in a fixed rotational speed characteristic zone. High-pressure air, after being stored in a tank, flow through the regulator and control valves and activate the pneumatic air motors on each wheel. The framework and the major components of the series HPPS is shown schematically in "Fig. 5". In this arrangement, the opening throttle valve determines the speed of the wheels. In addition, a gearbox converts the rotational speed of the air motor to the rotational speed of the wheels.

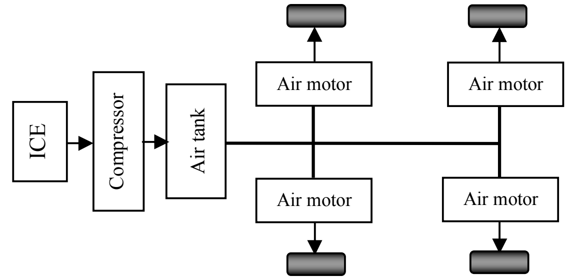

Fig 4. Schematic of a series HPPS

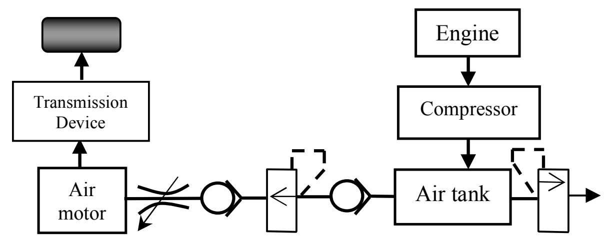

Fig 5. The arrangement of the series HPPS

III. BASIC ASSUMPTIONS

To evaluate HPPS working condition, Tehran driving cycle was used [11]. "Fig. 6" illustrates Tehran driving cycle with maximum cruising speed of 40 km/h. In addition, the specifications of the National Iranian car, Samand, was used to generate power graphs for Tehran driving cycle. Table I indicates Samand main features. Moreover, the design parameters are shown in Table II.

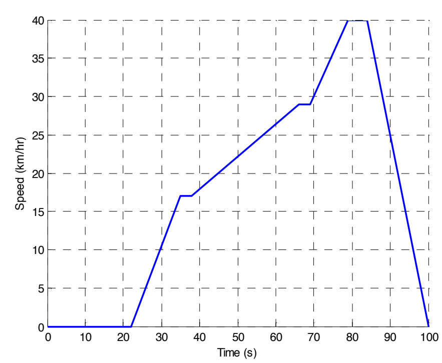

Fig 6. Tehran driving cycle in traffic zone

The system is simulated based on Tehran driving cycle. Furthermore, we checked the system with 60 (Km/h) and 70 (Km/h) maximum cruising speeds to study the ability of the system.

TABLE I. SAMAND CAR DATA SHEET

Parameter	Type/ Value
Engine	Linear
Cylinders/valves	4/8
Capacity	1761cc
Max. output	75 KW (6000 rpm)
Max. torque	151 Nm (3000 rpm)
Weight	1500 Kg
0-100 Km/hr	13 S
Starting torque Engine	100 Nm
Width	1735 mm
Height	1448 mm

TABLE II. HPPS DESIGN PARAMETERS

Parameter	Value
Aerodynamic coefficient	0.4
Rolling resistance coefficient	0.013
Front area	2.2611 m^2
Air density	1.3 Kg/ m^3
Transmission efficiency	0.9
Air motor efficiency	0.5
Radius of the tire	0.34 m

IV. RESULTS AND DISCUSSION

The performance of a vehicle is usually described by its maximum cruising speed, gradeability, and acceleration [8]. In order to analyze the ability of this system we checked these characteristics. The equations governing the dynamic behavior of the vehicle are omitted here due to space limitations. The simulation results presented here are the results of the vehicle dynamic simulation.

A. *Acceleration and Traction Power for Driving Cycle*

The acceleration and power during the driving cycle are illustrated in "Fig. 7" and "Fig. 8". Furthermore, the values of acceleration power, resistance power and traction power are shown in Table III.

B. *Engine/Compressor Power*

The engine/compressor power of the system was calculated. The engine/compressor power of the system for 40 Km/hr and 60 Km/hr are denoted in "Fig. 9".

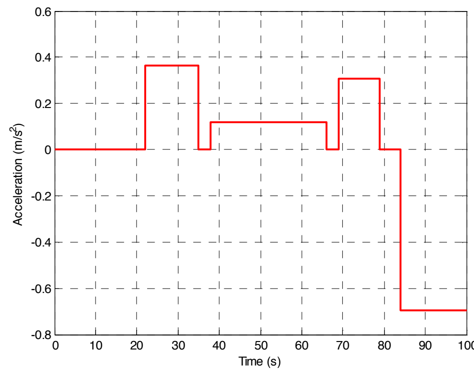

Fig 7. Acceleration of the system based on Teharn driving cycle

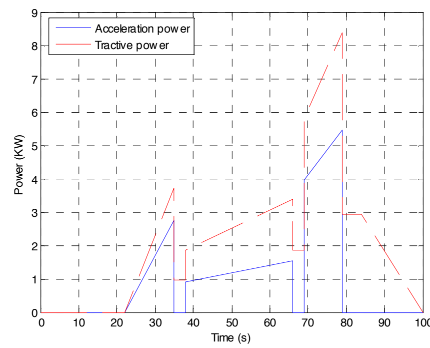

Fig 8. Powers of the system based on Tehran driving cycle

TABLE III. POWER OF THE SYSTEM BASED ON TEHRAN DRIVING CYCLE

Parameter	Value (KW)	
	Average Power	*Maximum Power*
Acceleration power	0.912	5.4505
Resistance power	1.4364	2.913
Traction power	2.3484	8.3824

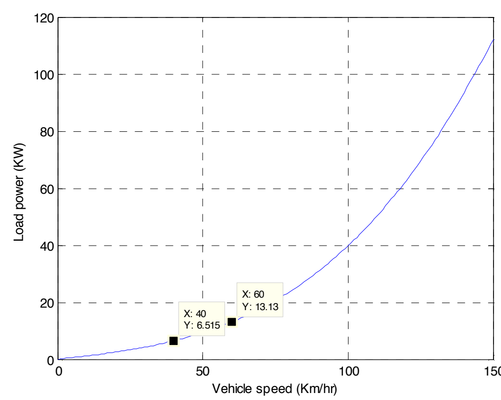

Fig 9. Engine/compressor power of a car at constant speed

C. *Traction Power for Different Maximum Speed*

Table IV shows the traction power for different speed in expected acceleration time 13(S). Calculating in different maximum speed ensure us that the system can works in other maximum speed.

TABLE IV. TRACTION POWER BASED ON DIFFERENT MAXIMUM SPEED

Maximum Speed (Km/hr)	Traction Power (KW)
40	9.069
60	19.342
70	25.914

D. *Starting Torque and Gradeability*

In order to increase the torque of the air motor for starting torque of the vehicle and transform the rotational speed of the air motor to the desired rotational speed of the wheel we used a gearbox. To check the starting torque and calculating the gear ratio, we selected an appropriate air motor, which its characteristics are shown in "Fig. 10" and "Fig. 11". Moreover, the air consumption of the air motor is illustrated in "Fig. 12". With respect to the calculated demanded powers and in order to satisfy different conditions based on characteristic graphs of the air motor, the system's operation pressure is considered 7bar.

Based on the first gear ratio and differential ratio the starting measured torque of Samand is about 775 (Nm). The torque output of the air motor is calculated from the wheels necessary torque. Furthermore, the gear ratios of the system in different maximum speed are shown in Table V.

Gradeability is usually defined as the grade (or grade angle) that the vehicle can overcome at a certain constant speed [8]. The different resistance powers in accordance with different maximum speeds and Tehran maximum grade (17.6%) are shown in Table VI. Also maximum gradeabilty of the system based on selected air motor are shown in Table VII.

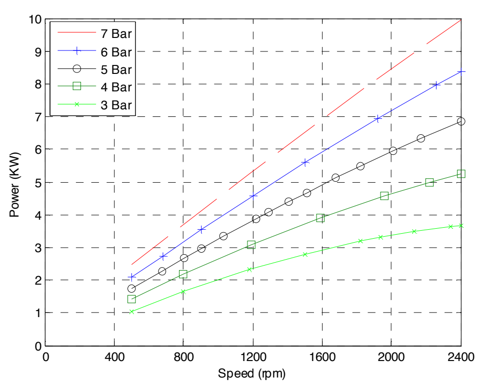

Fig 10. Power of the air motor

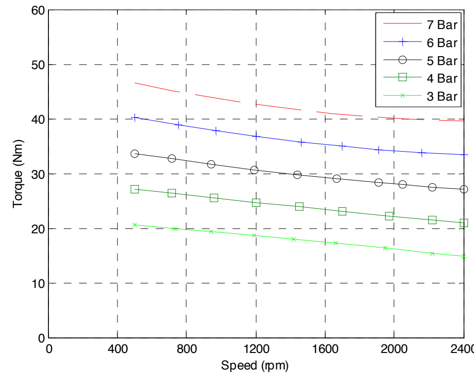

Fig 11. Torque of the air motor

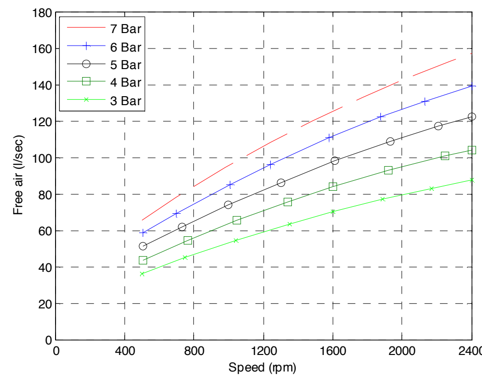

Fig 12. Air consumption of the air motor

According to the maximum output power of each air motors (10KW), the designed system cannot reach the maximum speeds 60 (Km/h) or 70 (Km/hr). Moreover, in order to satisfy the starting torque the minimum gear ratio must be 4.5, which will provide a maximum speed of about 68 (Km/hr). This can be solved by selecting an air motor with higher output power and torque, but the main problem in our design is air consumption of the air motor. Table VIII shows the total amount of air required by the air motor.

In current industrial compressor, free air delivery increases the necessary motor power, noise, weight and dimensions. With increasing the power of the air motors to satisfy the requirement for higher maximum speeds and torque, the air consumption and the free air delivery of the compressor will increase.

TABLE V. GEAR RATIO AND STARTING TORQUE FOR DIFFERENT MAXIMUM SPEED

Maximum Speed(Km/hr)	Starting Torque (Nm)	Gear Ratio
40	1301	7.69
60	867	5.12
70	743	4.39

TABLE VI. POWER RESISTANCE BASED ON TEHRAN MAXIMUM GRADE

Maximum Speed (Km/hr)	Resistance Power (KW)	
	Without Gradeability	*With Gradeability*
40	2.93	31.32
60	5.90	48.49
70	8.04	57.72

TABLE VII. MAXIMUM GRADEABILITY ACCORDING TO THE SELECTED AIR MOTOR

Maximum Speed (Km/hr)	Resistance Power (KW)	Maximum Gradeability
40	31.32	13.10
60	48.49	7.99
70	57.72	6.41

TABLE VIII. TOTAL AIR CONSUMPTION IN DIFFERENT SPEEDS

Parameter	Maximum Speed (Km/hr)		
	40	*60*	*70*
Traction power	9.069	19.343	25.914
Power of an air motor	2.267	4.835	6.478
Output power of compressor	6.5154	13.1332	17.87
Air motor air consumption (Lit/s)	65	100	120
Total air consumption (m^3/min)	15.6	24	28.8

V. CONCLUSION

A series Hybrid-Pneumatic vehicle based on Samand car platform and Tehran driving cycle was designed in this research. The aim was to evaluate the idea and to develop a service car for commutation in the city central area. The results show that although the design satisfies the basic requirements of the driving cycle, but fails to show a satisfactory performance in gradeability and maximum speed. To solve this problem using commercially available compressors, larger air compressor and engine are required, which are limited by available space and total vehicle weight. If lighter and more efficient compressors for the vehicle geometry be designed the idea will be feasible for developing a city service car.

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