Reducing Fuel Consumption of Hybrid Vehicles by Replacing Diesel Engines with Gas Turbine Engines

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Abstract – This paper is devoted to assessing the prospects of reducing fuel consumption in hybrid vehicles by replacing diesel engines with gas turbine engines, taking into account the progress made in recent years in improving the efficiency of gas turbines possibly. Reduction in fuel consumption was estimated separately for each of the classes of vehicles in accordance with their total mass: light, medium and heavy, and in each class subclasses based on differences in engine power were considered separately. Estimates were obtained by calculations utilizing a model which incorporates specified design parameters of vehicles. The results of the calculations presented in this paper show that for light vehicles of any engine power and mid-sized vehicles whose engine power does not exceed 50 kW, transition to gas turbine engines would lead to a substantial reduction in fuel consumption (more than 20%), and for heavy vehicles whose engine power does not exceed 50 kW transition to gas turbine engines would lead to a less substantial, but still significant (more than 10%) reduction in fuel consumption.

Keywords - gas turbine, efficiency of gas turbine, hybrid vehicle, urban driving cycle, fuel economy

1 Intrduction

One of the options being examined in last decades in the development of environmentally sustainable, energy-efficient and lightweight vehicles is the replacement of piston engines by gas turbine engines, especially in hybrid vehicles. A lot of effort has been consistently put in design and production of concept hybrid automobiles powered by gas turbine engines by leading automobile producers such as Toyota, Chrysler, Jaguar, Rover, General Motors and many others in recent decades (see [1-8]), and the application of gas turbine engines in commercial hybrid buses operating in different parts of the world which started 15 years ago has been very successful (see [8]).

The Design Line EcoSaverIV [7], a hybrid transit bus operating globally, uses a diesel-fueled micro gas turbine instead of a diesel engine to generate electricity. The stored electricity is used to power traction motors. Design Line boasts a 100% improvement in fuel economy over diesel buses, and can achieve seven to eight miles per gallon compared to traditional hybrid buses which achieve 3 to 4 miles per gallon. Note that in the past the main obstacle to wide application of gas turbine engines in different types of vehicles was their relatively weak performance in terms of fuel consumption. In the paper we show that in view of significant progress made in development of highly efficient micro gas turbines in recent years, and the potential progress which is expected in the near future, this obstacle has completely lost its actuality. Moreover, the reduction in fuel consumption can be achieved by replacing diesel engines by gas turbine engines in different types of hybrid vehicles in the coming years, and therefore the wide replacement of piston engines by gas turbine engines should be considered very seriously as a viable option.

In a recently published article [9] it was shown that replacing diesel engines by gas turbine engines in hybrid vehicles whose mass does not exceed 1200 kg could reduce fuel consumption (the effective efficiency of gas turbines used for replacement was assumed to be 0.26, which was a feasible estimate for gas turbines available a few years ago). Since the publication, gas turbines have been in the process of very rapid development, and the effective efficiency of gas turbines developed to date is much higher than the effective efficiency of gas turbines that were available a few years ago. The effective efficiency of diesel engines, on the other hand, has already nearly reached its maximum (saturation level), and significant growth is not expected in the near future.

The graph presented in [10], (Fig. 1) illustrates the fact that for Wärtsilä's engines the saturation level of 0.5 had been almost reached 15 years ago. For automotive diesel of 0.4 has been almost reached.

As shown in [11], [12], [13] no significant progress has been observed in improving instances in recent Volkswagen Jetta TDI and Toyota Prius years the efficiency of diesel engines which are currently the most advanced automotive diesel engines.

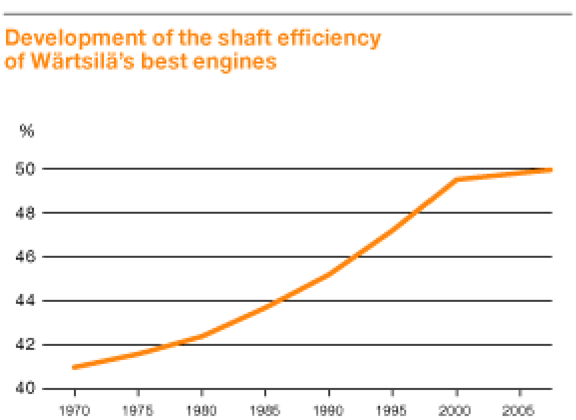

Fig. 1 The dynamics of change in shaft efficiency of Wärtsilä diesel engines for the period between 1970-2005

The indicator 0.5 for the efficiency of diesel engines in this figure describes stationary diesel engines. However, the same tendency is also observed regarding the changes in efficiency of automotive diesel engines, the only difference being that the level of their efficiency is 0.4. This is evidenced by the fact that in recent years there has been almost no change in the efficiency of diesel Volkswagen Jetta TDI [12] and the Toyota Prius [11]. In [8] , [11] and [12] it is shown that currently the most advanced automotive diesel engines are found in Volkswagen Jetta TDI and Toyota Prius, whose efficiency is about 0.40, while the results of [11] indicate that the predicted efficiency of automobile diesel engines for 2015 is also at the level of 0.40.

The efficiency of gas turbines, on the other hand, is growing rapidly. Already, there are reports about levels of efficiency of the order of 0.29-0.42. For instance, in 2010 Capstone Turbine Corporation [14, 18] received an assignment from the U.S. government to develop a microturbine with capacity of 370 kW and effective efficiency of 42%. The Tesla company [15,16] has already announced the development of a microturbine with capacity of 14 h.p. and effective efficiency of 42%. The Israeli firm R-Jet Engineering Ltd [17] has also reported development of a relatively high efficiency microturbine with capacity of 90 kW and effective efficiency of 34%.

All of the above allowed us to assume that replacement of diesel engines by currently available gas turbines would reduce fuel consumption not only for light vehicles, but also for other classes of vehicles. Estimating the expected reduction in fuel consumption as a result of replacing diesel engines by currently available gas turbine engines for vehicles of different is the aim of this work. The estimates were obtained by a model for estimating fuel consumption described below.

In the calculations using our model we assume that the effective efficiency of diesel engines at engine power $P \leq 50$kW is 0.3, and at $P > 50$ kW is 0.4, and that the effective efficiency of gas turbine engines is 0.35. As shown below in this article, reduction in fuel consumption with gas turbines is achieved to a very considerable degree via mass reduction, and the percentage of mass reduction is different for different classes of vehicles. It is most significant for light vehicles, and least significant for heavy vehicles. Therefore, it is advisable to consider reduction in fuel consumption separately for each of the following three classes of vehicles: light (whose mass is about 1000 kg), mid-sized (mass about 4000 kg) and heavy (mass about 10,000 kg), as is done in this article.

In addition, for vehicles of the same class the reduction in fuel consumption as a result of switching to gas turbines differs substantially depending on the power-to-weight ratio R. For that reason, in this article estimation of fuel reduction for light and mid-sized vehicles is made separately for three subclasses: for light vehicles - subclasses with power-to-weight ratio of 40, 55 and 70, and for mid-sized vehicles - subclasses with power-to-weight ratio 8, 11.5 and 15.

Remark 1. Fuel consumption calculations are performed for driving in urban areas. This is due to the fact that the benefits of hybrid systems over traditional ones are manifested primarily in urban environments, and that is where their use is most appropriate. The rest of the article is organized as follows. The description of the model utilized for estimating fuel consumption for different classes of vehicles is presented in Section 2. Results of calculations by the model and their analysis are presented in Section 3, and the main conclusions are presented in the last, fourth section.

2 Model For Estimating Fuel Consumption

A formula for estimating hybrid vehicle fuel consumption (in liters) per 100 km distance, which takes into consideration fuel economy assessment technologies, as stated in EU Directives and norms and regulations of the UN ECE was presented in [9]. The formula is based on dividing the 100 km distance into I subintervals and on the assumption that there are J accelerations per 100 km. It looks as follows:

$$Q_S = \frac{1}{\eta_e \cdot \eta_t \cdot H_c} \left[\sum_{i=1}^{I} \int_{T_i} \left(m_v \cdot g \cdot f_r \cdot \frac{v_i(t)}{3.6} + K \cdot A_f \cdot \left\langle \frac{v_i(t)}{3.6} \right\rangle^3 \right) dt + \frac{m_v \cdot \gamma_m}{26} \sum_{j=1}^{J} \frac{(v_2^2 - v_1^2)_j}{s_j} \right], \quad (1)$$

where

$v_i(t)$ is the instantaneous vehicle speed at subinterval i, [km/h];

T_i is the i-th subinterval duration [sec];

m_v is the total mass of the vehicle, [kg];

f_r is the rolling resistance coefficient;

K is the aerodynamic resistance coefficient of the car [Ns^2/m^4];

A_f is the vehicle frontal area, [m^2];

s_j is the acceleration distance, [m];

v_2 is the speed after acceleration, [km/h];

v_1 is the speed before acceleration, [km/h]

γ_m is the mass factor of the car,

g is the acceleration of gravity, [m/s^2].

η_e is the engine effective efficiency;

η_t is the mechanical drive train efficiency;

H_c is the fuel calorific value, [J/l].

Some of the parameters used to calculate fuel consumption by formula (1) are in turn calculated by formulas taken from the literature, which is listed below.

The total mass of the vehicle, m_v, is calculated by the formula:

$$m_v = m_w + m_e + m_g, \quad (2)$$

where m_w designates total mass of all parts of the vehicle except the engine and the generator, m_e designates the mass of the engine and m_g designates the mass of the generator.

m_e is estimated by the formula $m_e = \frac{P}{1000\,\mu}$, where μ designates specific mass of the heat engine [kW/kg], P designates the engine power.

m_g is estimated by the formula [19,20]:

$$m_g = 0.09 \frac{P\rho_g}{C \cdot n}, \quad (3)$$

where ρ_g designates the average density of ratio materials, [g/cm^3]; C is the torque-per-volume constant $[N \cdot m / cm^3]$, N is the entire rotational speed, [rpm].

Remark 2.1. In equality (2) the first term m_w is the same for a vehicle before and after the replacement of diesel engine by gas turbine engine. However, the replacement makes m_e many times less since the specific mass μ of a gas turbine (5-7 kW/kg) is 10 times greater than the specific mass of a diesel engine (0.5-0.62 kW/kg), and m_g after the replacement is many times less since the rotor speed n of a gas turbine is 90000 rpm compared to 3960 rpm for diesel.

Thus the total mass of vehicles and consequently fuel consumption is reduced significantly by the replacement.

The vehicle frontal area A_f for vehicles with mass in the range between 1000 – 2500 kg is calculated using an empirical formula [21,22]:

$$A_f = 1.6 + 0.00056 \cdot (m_v - 765)$$

The frontal area A_f for vehicles with mass >2500 kg is calculated using an empirical formula [22]:

$$A_f = 0.75 \cdot H \cdot B$$

where:

H is overall height of the vehicle [m], B is overall width of the vehicle, [m].

The mass factor of the car γ_m was calculated using an empirical formula [21, 22]:

$$\gamma_m = 1.04 + a \cdot \xi_0^2,$$

where:

ξ_0 is overall gear reduction ratio of the transmission, and a is a coefficient. For cars, $a = 0.0025$, and for trucks $a = 0.0015$.

It is easy to show that ξ_0, and consequently γ_m depend on the mass of the vehicle [22]:

$$\xi_0 = \frac{\Psi \cdot r_d \cdot W}{M_{\max} \cdot \eta_t},$$

where:

$\psi = f_r + i$ is the combined resistance of the road. i is the gradient of the road, and it is assumed that $i = 0.12$ [22],

W is the total weight of the vehicle, $W = m_v g$, [N],

r_d is the wheel radius [m] ,

$M_{\max}$ is the maximum moment of engine [Nm].

This formula can be transformed as follows, taking into account that:

$$M_{\max} = kM_P,$$

$$M_P = 9550\, P / n_P,$$

where:

M_P is engine moment at maximum power, Nm,

k is a coefficient, and for diesel engine $k = 1.05 - 1.10$ [22],

n_P is engine speed at maximum power [min^{-1}].

Thus we obtain:

$$\xi_0 = \frac{(f_r + i) \cdot r_d \cdot n_P \cdot m_v \cdot g}{9550 \cdot k \cdot P_{\max} \cdot \eta_t}$$

or

$$\xi_0 = \frac{(f_r + i) \cdot r_d \cdot n_P \cdot g}{9550 \cdot k \cdot R \cdot \eta_t}$$

From this formula it can be seen that ξ_0 is directly proportional to the weight of the vehicle and inversely proportional to the engine power.

Initial input parameters were determined in accordance with design characteristics of vehicles based on experimental data given in various literature sources [9, 21 and 22]. These parameters are summarized in Table 2.

Table 2. Input parameters used in calculations

m_v [kg]	K $\left[\frac{N \cdot s^2}{m^4}\right]$	η_t	r_d[m]	n_P [min^{-1}]	H [m]	B [m]
1000	0.3	0.95	0.3	4500	1.8	1.4
4000	0.4	0.95	0.4	4500	2.0	2.1
10000	0.6	0.95	0.5	4500	2.0	2.5

The fuel calorific value H_l was set to $36 \cdot 10^6\ J/l$ for gas turbines and to $34 \cdot 10^6\ J/l$ for diesel engines [22].

3 Results of Calculations and Their Analisis

The main results of calculations using our model are shown in Table 4. This table shows the reduction in mass and fuel consumption for different classes of vehicles after replacement of diesel engines by gas turbine engines under the conditions of the elementary urban driving cycle. The two columns on the left show the total mass m_v of diesel vehicles and power-to-weight ratio. The third column shows the total mass m_v' after the transition to gas turbines. The fourth column shows the percentage of reduction of vehicle mass after the transition to gas turbine engines, which is calculated by the formula

$$\Delta m_v = \frac{m_v - m_v^{'}}{m_v} \cdot 100.$$

The fifth and sixth columns show fuel consumption before and after the transition to gas turbine engines, respectively. The seventh column shows the percentage of reduction of fuel consumption ΔQ_s as a result of the replacement, which is calculated by the formula:

$$\Delta Q_s = \frac{Q_s - Q_s^{'}}{Q_s} \cdot 100.$$

Table 4. Total mass and fuel consumption before and after replacement.

m_v [kg]	R [W/kg]	$m_v^{'}$ [kg]	Q_s $\left[\frac{l}{100km}\right]$	$Q_s^{'}$ $\left[\frac{l}{100km}\right]$	ΔQ_s %
1000	40	877	3.65	2.75	24.7
	55	831	3.62	2.59	28.5
	70	785	3.62	2.46	32.0
4000	20	3755	14.37	11.40	20.7
	25	3693	14.23	11.17	21.5
	30	3622	10.73	10.87	-1.3
10000	8	9755	38.96	34.75	10.8
	11.5	9647	32.00	32.42	-1.3
	15	9540	28.00	29.98	-7.1

Figure 2 illustrates the effect of replacement of diesel engines by gas turbine engines on fuel consumption, which depends on total mass and power -to -weight ratio.

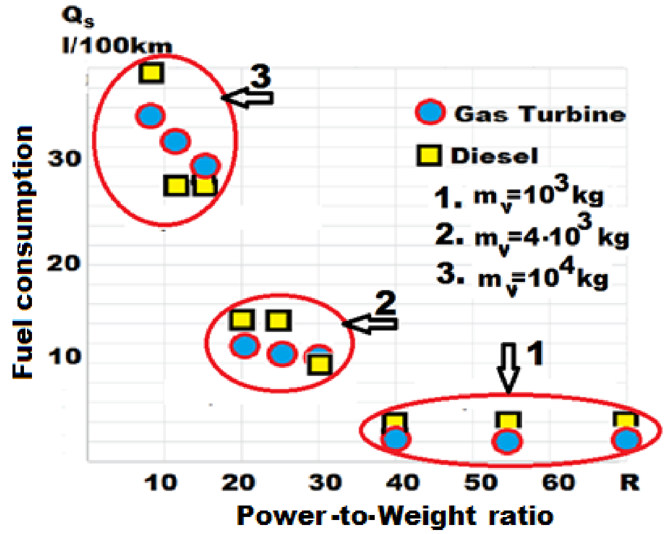

Fig. 2. Fuel consumption of hybrid vehicles with diesel and gas turbine engines

The obtained results allow for the following analysis:

1. When the mass of the vehicle is small (1000 kg), replacement of diesel engines by gas turbines leads to a very significant reduction in fuel consumption for any R. This is due, firstly, to the fact that for vehicles with such total mass the power of the heat engine does not exceed 50 kW, and accordingly the effective efficiency does not exceed 0.3 [23], and, secondly, to the fact that the relative reduction in the mass of the vehicle after the transition to gas turbines for any R is very significant: 12.3, 16.9 and 21.5% for R = 40, 55 and 70, respectively.
2. For mid-sized buses and trucks with mass of 4000 kg and R in the range of 20-25 the replacement of diesel engines by gas turbines also leads to a decrease in fuel consumption. This is due firstly to the fact that the effective efficiency of diesel engines in this case does not exceed 0.3, secondly, to the fact that γ_m in vehicles with diesel engines is 2% greater than in vehicles with gas turbines, and thirdly, that the relative reduction in the mass of the vehicle after the transition to gas turbines is quite significant: 6.1 and 7.7% for R = 20 and 25, respectively. When R = 30 for vehicles of this class fuel consumption after the transition to gas turbines increases slightly due to the fact that the power of the heat engines for this subclass is greater than 50 kW, and therefore the effective

efficiency of diesel engines equals 0.4. The 9.5 % reduction in the mass of the vehicle as a result of the transition to gas turbines leads to a decrease in fuel consumption, but this is offset by a decrease in effective efficiency from 0.4 to 0.35.

3. When the mass of the vehicle is 10,000 kg (large buses and trucks), reduction in fuel consumption after replacing diesel engines by gas turbines occurs only if $R \leq 10$. This is due to the fact that in this case the power of the heat engine is no greater than 50 kW, and therefore the effective efficiency of diesel engines does not exceed 0.3. When $R > 10$, the effective efficiency of the diesel engine is higher than that of the gas turbine, and this outweighs the influence of the slight (3-4%) mass reduction which results from replacing the diesel engine by a gas turbine.

4. Conclusive remarks

Let us summarize the main conclusions.

Remark 4.1. When assessing the feasibility of replacing diesel engines by gas turbines for different classes of vehicles, the most important design parameters of the vehicle that should be considered are: effective efficiency, mass and power of the heat engine.

Remark 4.2 Calculations show that for all light vehicles with mass of 1000 kg and mid-sized vehicles with R in the range between 20-25 W/kg, replacing diesel engines by gas turbines leads to a very significant (more than 20%) reduction of fuel consumption. For heavy trucks with mass of about 10 tons whose R = 8, transition to gas turbines will also lead to a reduction in fuel consumption, although a less significant one (about 10%). Thus, the widespread transition to gas turbines in such vehicles is highly desirable, since it will lead to a very significant reduction in the total fuel consumption in transportation, given that these classes represent a large percentage of all vehicles.

Remark 4.3. Even though for vehicles with mass of 4000 kg whose R = 30 and those with mass of 10000 kg whose R = 15 transition to gas turbines will result in a slight (approximately 1%) increase in fuel consumption, this transition is nonetheless advisable in view of the important advantages of gas turbine engines compared to diesel engines in terms of emissions, noise and vibration [8, 24], compactness and operating costs

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