COMPARISON OF DIFFERENT VEHICLES DRIVEN BY ALTERNATIVE FUELS AND HYBRID DRIVELINE FOCUSING ON EMISSION, EFFICIENCY AND ECONOMY

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Abstract

Air pollution is becoming an important issue in big towns, in particular in city centres, where the density of traffic is high. Both, passenger cars and commercial vehicles are responsible for air quality. In the last decades more and more transportation companies changed their conventional vehicles into any kind of alternative vehicles. The aim of this paper is to investigate the economic and environmental effects of introducing alternative fuels and powertrains in cargo vans.

All of the simulated vehicles were equipped with internal combustion engines, but they are operating with different fuels. Gasoline, methane, ethanol and hydrogen fuels are used in these engine models. Conventional and hybrid powertrains are compared too. Only the gasoline fuelled engine is simulated with hybrid driveline besides the conventional ones. Both micro- and full-hybrid vehicles are modelled. Instead of dynamical analysis we focused on efficiency and emission therefore tests drive cycles were simulated. There were cycles defined by standards, like NEDC drive cycle. An individual cycle was recorded on a given route at different times of the day; the vehicle was driven along the planned path and the speed profile was recorded. As a result we could compare the different vehicles from the point of view of emission, fuel consumption and efficiency. In order to validate the simulation results laboratorial measurements were carried out.

We also aimed at developing a business model capable of analysing the economical effects of alternative fuel and powertrain use. Generally it can be stated that the application of any alternative technology means additional costs (investment) at the beginning for the user. The investment is just worth the money if lower operational costs can be achieved. Achieved savings were calculated with our model and a sensitivity analysis was also performed.

Keywords: *hybrid vehicles, alternative fuels, payback time*

1. Introduction

The purpose of this paper is to investigate the benefits and drawbacks using vehicles powered by any kind of alternative method. We are focusing on vehicle fleets, single users are of no consideration. Transportation companies can have fleets with enormous number of vehicles. These companies are much more responsible for air pollution than single users. Vehicles with alternative drivelines exist more than a century, although the conventional ones were more efficient, had more performance; therefore alternative methods could not come into general use. This was the past, but now two facts advance them to be widespread used. First, the social requirements on emissions of vehicles, second, new, better technologies have arrived, and consequently alternative vehicles can compete with conventional ones in performance and efficiency.

The aspects of the comparison of the different types of vehicles are the consumption, emission and economical rate of return. The consumption and the emission are evaluated by simulation data, and vehicle measurements.

2. Vehicle simulations

Several types of vehicles driven by an alternative way exist on the market. From these vehicles we selected some on which simulation could be carried out. The parameters were not based on real vehicles, the only purpose of the models was comparability. The vehicle models were built from three main parts: an internal combustion engine, a driveline, and the chassis.

The internal combustion engine was fuelled with gasoline, natural gas (substituted with methane), hydrogen and ethanol. All the engines were 4 cylinder inline engines with 1.6 litre displacement volume. All the engines were spark ignited.

Since we were focusing on emission and consumption the engine model had to be accurate, therefore detailed engine models were built up (Fig. 1). The intake and the exhaust pipelines were modelled with one-dimensional fluid dynamics. In the cylinder we used predictive combustion model with which we were able to calculate the different emission values as well.

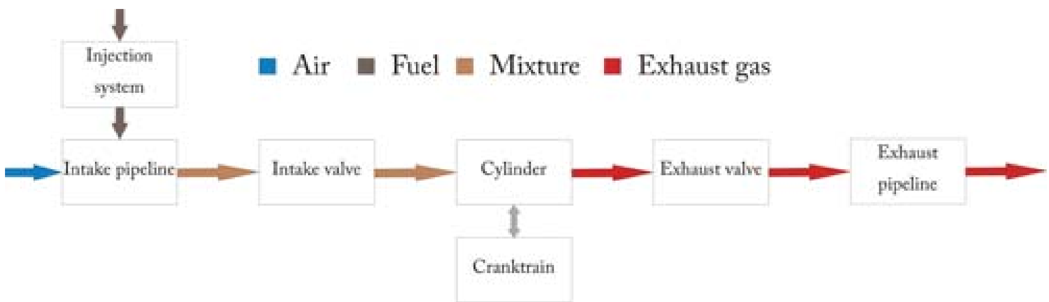

Fig. 1. Block diagram of the engine model

The engines were not totally same, because they were optimised for the used fuel. The different alternative fuel types have advantages compared to the conventional gasoline, but for this an optimised engine is needed. There are several during construction optimised parameter on the engine, which should be modified, varied for a given fuel type. The most relevant parameters are the air-fuel ratio, the ignition timing, and the compression ratio. The fuels used in spark ignition engine have different octane numbers which determine how resistive they are against knocking phenomena. The maximum torque of the engine is determined by the effective mean pressure, which depends on the compression ratio. The higher the compression is, the higher is the torque but certainly the maximum torque depends on the heat value as well. However, the compression cannot be increased boundless, because knocking may occur during combustion. The higher the octane number of a fuel is, the higher compression can be set. The air-fuel ratio determines both the torque and the fuel consumption. Using a lean mixture the consumption and the emission can be reduced, but the power of the engine will be lower as well. As an agreement we decided to apply a stoichiometric mixture. Tab. 1. shows the properties of the different fuel types and the optimal compression ratio. [1]

Tab. 1. Fuel properties

	Density [kg/m^3]	Heat value [MJ/kg]	Octane number [-]	Theoretical air-fuel ratio [kg/kg]	Compression ratio [-]
Gasoline	755	43.9	95	14.7	10.5
Methane	0.72	50	140	17.2	12.8
Ethanol	789	28.6	111	9	15
Hydrogen	0.09	120	130	34	11

The second part of the vehicle is the driveline. Two main powertrains were used: a conventional (totally mechanical) and hybrid electric powertrain. The conventional driveline contains the general elements: clutch, manual transmission, differential gear, axle shaft and driven wheels (Fig. 3.).

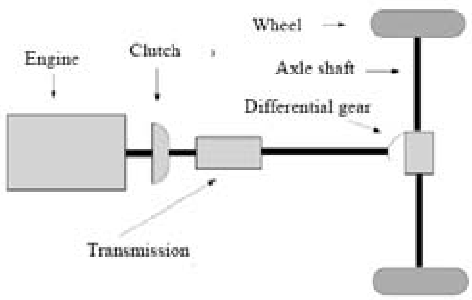

Fig. 2. Schematic diagram of the conventional driveline

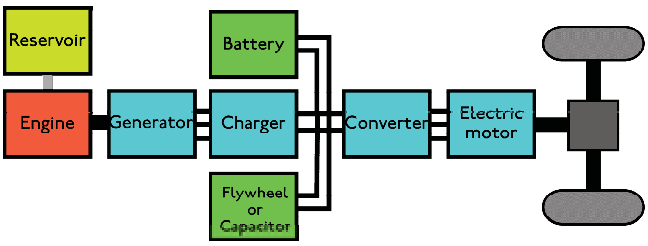

Fig. 3. Parallel hybrid powertrain

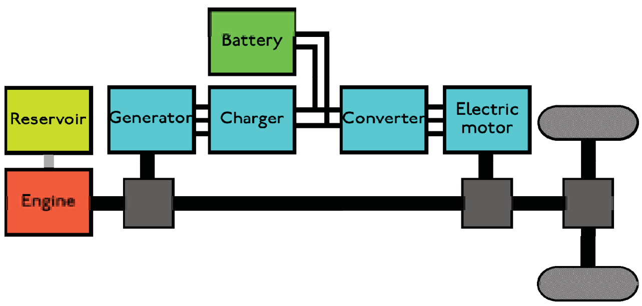

Fig. 4. Power split combined hybrid powertrain

In hybrid electric vehicles the mechanical powertrain is extended with electric motor-generator devices. During acceleration the electric motor helps the engine accelerate the vehicle, during deceleration the generator operates, so the braking energy will be recuperated. Between acceleration and braking the energy is stored in batteries. Different types of hybrid powertrains exist, depending on the location of the electric devices. Series, parallel and combined hybrids are differentiated. Other classification is the power. Three different classes exist: micro-, mild- and strong hybrids. Micro hybrids are equipped with stronger alternator and starter (these two devices may be substituted with one electric machine), and they operate with 12 V voltage. It operates as a start-stop system, regenerative braking is unusual. Mild hybrids are equipped with a medium size electric motor generator object, with a voltage of 40-120 V. It is able to recuperate the braking energy and able to accelerate the vehicle together with the internal combustion engine. Strong or full hybrids have high power electric motor-generator machines (usually more). It operates with high voltage, more than 150 V. They have the possibility to drive with electric motor without engine. Fig. 3. shows the structure of a parallel and Fig. 4. a power split combined hybrid vehicle driveline. [2]

The last part of the vehicle to be modelled is the chassis. During tests only longitudinal dynamics were taken into account. Therefore the chassis has mass and wind drag coefficient, the axles, and the brake were modelled. Gasoline, natural gas, ethanol and hydrogen fuelled vehicles were simulated with conventional powertrain, furthermore a micro- and a full hybrid gasoline vehicle was tested as well.

The input of the simulations was the speed profile, the velocity of the vehicles in function of time. Three profiles were used: NEDC and two urban profiles. NEDC (New European Drive Cycle: Fig. 5.) is a test cycle, which is used to carry out vehicle measurements on roller test benches, during which the fuel consumption and the emissions are measured. Drive cycles are created for making vehicle tests more similar to the real use of vehicles; moreover the drive cycles make the tests repeatable.

The other two urban profiles were created with traffic simulator software in a previously chosen route in Budapest (Fig. 5.) the total distance of which was approximately 5 km. The route was the same for both profiles, but they were created at different times, consequently the density of the traffic was different. One of them was simulated on a weekday at 8 o'clock in the morning; the other at 11 o'clock in the morning (Fig. 6.).

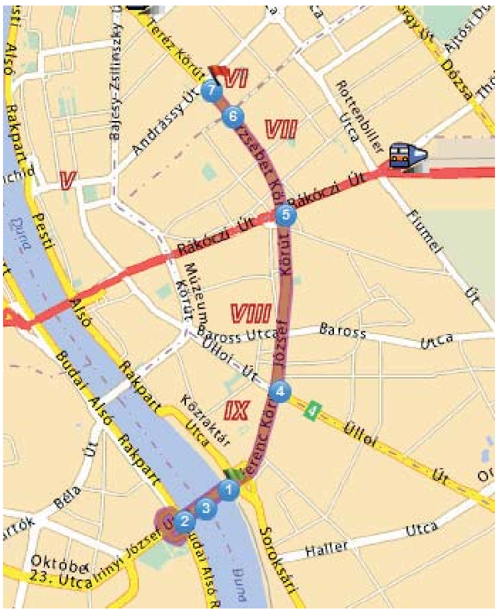

Fig. 5. Route for simulation in Budapest

At 11 o'clock less time is needed to take the chosen distance (i.e. the average speed is higher), than at 8 o'clock, because in the early morning hours the traffic is heavier. During the simulations we focused on the emissions and the fuel consumption, the following diagrams represent the result of the different situations.

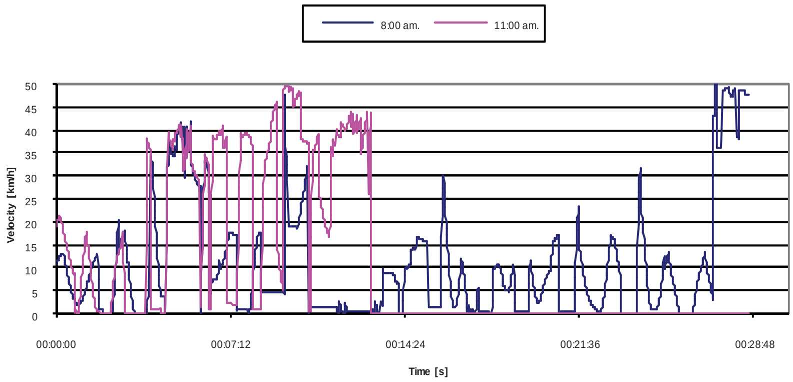

Fig. 6. Simulated urban speed profile

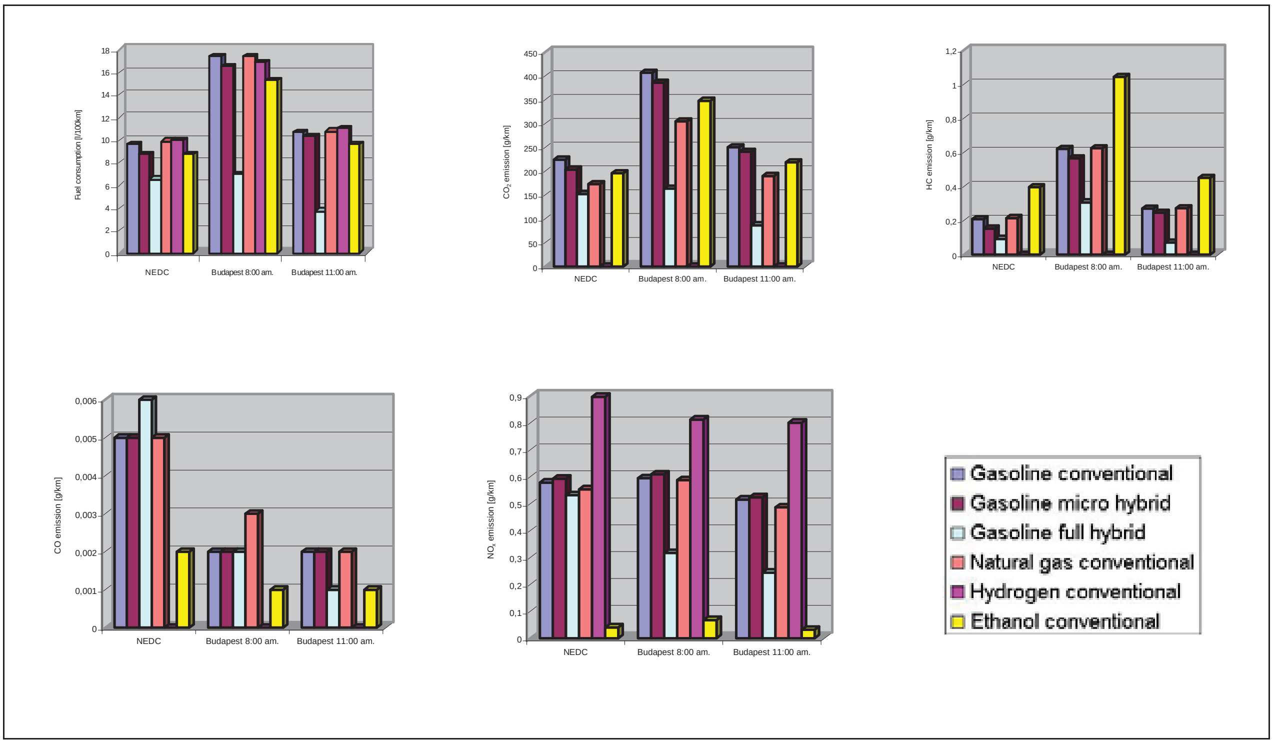

Fig. 7. Gasoline equivalent fuel consumption and emissions during simulations

In all the three cases, the hybrid vehicles (even the micro hybrids) have the lowest gasoline equivalent fuel consumption. Natural gas and hydrogen have larger heating values than conventional fuels, however, natural gas and hydrogen fuelled vehicles have higher consumption because these fuels are in gaseous state; their density is very low compared to the other ones.

Concerning emissions hydrogen vehicles have quite good results, since hydrogen gas does not contain any carbon, no carbon-monoxide, no carbon-dioxide and no hydro-carbon can be found in the exhaust gas. The hybrid vehicles have also lower emission values compared to the gasoline vehicles with conventional driveline. The reason is that the engine is switched off frequently when no or low drive torque is needed. Only the nitrogen-oxide emission is higher in case of micro hybrids. In case of natural gas vehicles the results show that their exhaust gas contains less carbon-dioxide, less carbon-monoxide, less hydro-carbon and the same amount of nitrogen oxide. Using ethanol fuel, only the hydro-carbon has higher emission value, all others are lower.

3. Measurements

To validate the results of the simulations, measurements have to be carried out. All the above chosen vehicle types have to be tested, but we do not have the possibility to test all of them. Three cars were chosen for measurements: an Opel Astra 1.6 gasoline vehicle, an Opel Zafira 1.6 CNG and a Toyota Prius which has power split hybrid driveline. For the measurements we chose a laboratorial roller test bench. The purpose of these tests was to realise the result of the simulations. During the laboratorial test the vehicle was placed in a room on a roller with its driven wheels. The speed profile was projected on a monitor, and the driver could follow the speed profile as accurate as he could. The rollers could be retarded to simulate the braking effect of the wind drag. The exhaust gas was collected into bags, from which samples were taken and the composition was determined.

Only two tests from the three above demonstrated speed profiles were measured: the NEDC and Budapest urban speed profile at 8 o'clock. Fig. 8. shows the fuel consumptions, emissions are plotted as well.

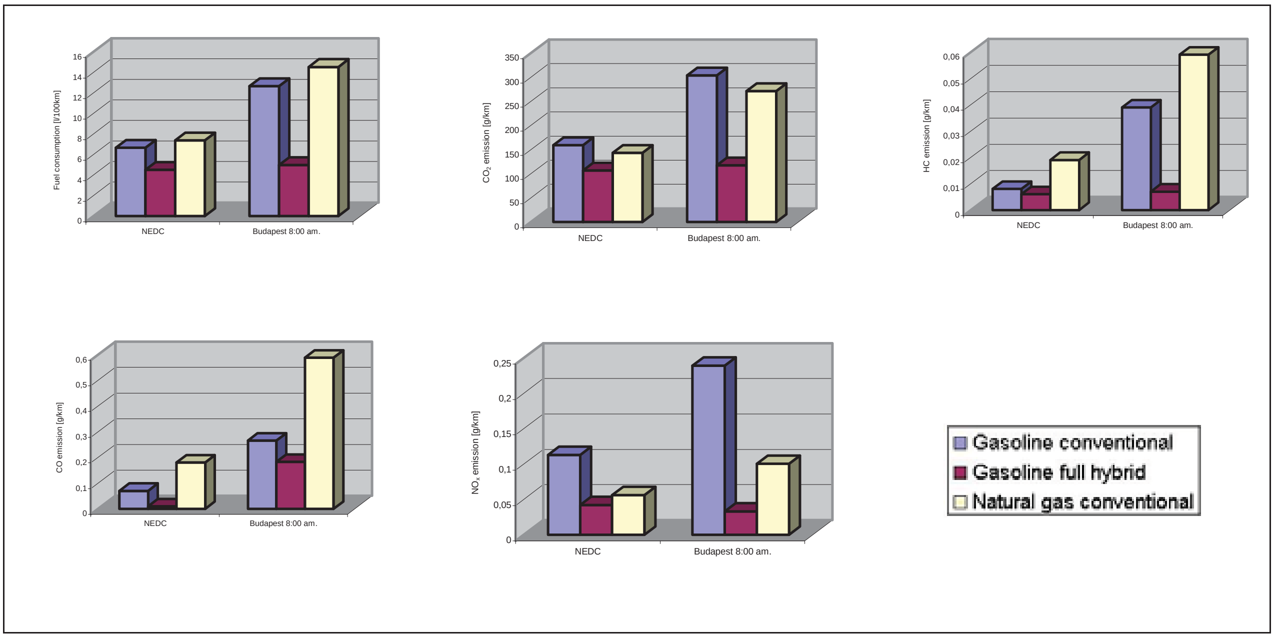

Fig. 8. Gasoline equivalent fuel consumption and emissions during laboratorial measurements

During both tests hybrid vehicle's gasoline equivalent fuel consumption is lower, the consumption of the CNG car is higher than in case of the conventional gasoline vehicle. From the simulation we become the result that at urban profile at 8 o'clock both the conventional gasoline and the natural gas powered vehicles consume about 80% more fuel than during the NEDC test cycle. Although the full hybrid vehicle needs approximately 10% more fuel under urban circumstances. We got the same results from laboratorial tests.

Concerning emissions the simulation results seem to be verified. Just like in computations, the hybrid vehicle's emission was lower than it was of the other cars. The only difference was the carbon-monoxide, which was a bit higher during NEDC simulations. This could be explained with the difference on the control strategy. The advantage of a hybrid vehicle depends on the control strategy, which could not be modelled perfectly in simulation since several parameters were unknown. However the fuel consumption of the vehicle powered by methane was the highest, the carbon-dioxide emission of the CNG car was lower compared to the gasoline vehicle since natural gas contains less carbon atoms, than gasoline. The natural gas vehicle had higher carbon monoxide and higher hydrocarbon emission than the gasoline vehicle, but its exhaust gas contained less nitrogen-oxide. The explanation for the low nitrogen-oxide is the low heating value: because the combustion temperature will be lower. Gas fuelled engines have perfect homogenous mixture of the methane and air so combustion shut-off may occur, consequently the carbon-monoxide and hydrocarbon emission will be higher.

4. Economical analyses

During our investigation different alternative fuels (LPG, CNG, bioetanol, biodiesel) and an alternative propulsion system (hybrid) were compared from an economic point of view. Generally it can be stated that the application of any alternative mode means additional costs (investment) at the beginning for the user. The investment is just worth the money, if during the use lower operational costs can be achieved, which can compensate for the additional investment at the beginning.

We aimed at calculating the payback period of the additional investment costs that occur when alternative fuels are applied. Different types of costs were taken into consideration; achieved savings were calculated and a sensitivity analysis was performed.

Input parameters of the model were operational characteristics (duration, fleet size, average travelled distance), fuel consumption, variable costs (fuel price, maintenance costs, maintenance interval), annual costs (vehicle tax, liability insurance, other costs such as for example entrance fees, environmental tax), single costs (costs of purchasing and conversion, registration tax), depreciation time, interest rate.

Certain advantages and disadvantages caused to the user due to change in engine characteristics are not taken into account, because it is difficult to reflect them as costs. Such a disadvantage is for example the loss in enjoyment caused by performance reduction. However, disadvantages occurring due to the lack of infrastructure or occurring during the operation of the infrastructure can be taken into account by considering the staying period as a cost.

At low temperatures alternative fuels might not be able to start the engine and operate it until the engine temperature is not reached. The cold start distance can also be an input parameter in the model. The relative increased consumption of conventional fuels (petrol, diesel) in the cold start period can also be added to the model. This might be of importance in particular if the engine is optimised to the alternative fuel. In the model a cold start distance of 1 km and an increased consumption of 3.5-4.5% were assumed.

Urban consumptions of cargo vans were modelled and a sensitivity analysis was performed in order to determine the sensitivity of the model. The effect of changing the different costs (fuel price, maintenance costs, annual costs, purchasing costs) by 20% was examined.

Base case

Input Parameters were chosen to correspond to the operation conditions and to reflect the actual Hungarian price conditions. The mileage was set at 15 000 km and the average distance travelled at 30 km. The relation of the different costs (fuel price, maintenance costs, annual costs, purchasing costs) is shown in Fig. 9.

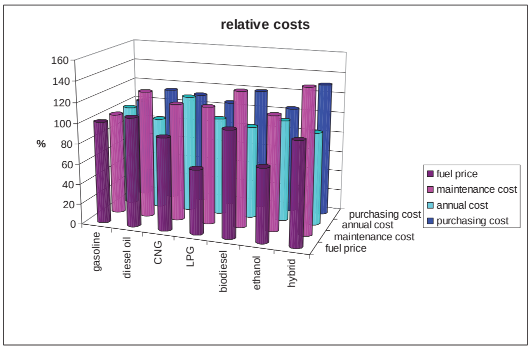

Fig. 9. Relative costs. Input cost parameters of the model were expressed as relative costs (Costs were in all cases proportioned to the cost of gasoline)

Petrol, diesel and LPG prices were chosen according to the prices set by the Hungarian Tax and Financial Control Administration. CNG prices were in accordance with the prices of a Hungarian gas company. Ethanol prices were chosen from a fuel station, biodiesel prices were taken from Germany, and were changed to Hungarian forints according to exchange rates.

We assumed that the operation costs of diesel vehicles are higher due to the more expensive technology. In the case of alternative fuels we assumed extra maintenance costs (compared to petrol and diesel engines) because of the complementary equipment. Furthermore it must be taken into consideration that in the case of modern internal combustion engines the service interval can reach 30000 km, but in the case of vehicles fuelled by alternative fuels this is not allowed by the manufacturers.

Just currently existing annual costs were taken into account. For this reason we assumed lower costs for diesel vehicles with usually lower performance. In the case of CNG vehicles higher costs were assumed because of the lack of appropriate fuel-station network that causes staying periods and extra distances to reach the special fuel station. Lower annual costs were taken into consideration in the case of hybrid vehicles, due to the fact that they are environment friendly and as a consequence of this mostly no entrance fees have to be considered.

In the case of CNG, gasoline, diesel and hybrid vehicles purchasing costs were calculated according to vehicle category and were taken from catalogues. In the case of other fuels purchasing prices were taken from German data and were proportioned to Hungarian circumstances. The interest rate was set at 5%. We assumed that the examined vehicles mostly run in urban areas, therefore urban consumption rates were applied for calculating the payback period. In the case of CNG, gasoline and diesel vehicles consumption rates were taken from catalogues, in the other cases consumption rates were taken from the literature and from other studies. For these input parameters the payback period is shown in Fig. 10.

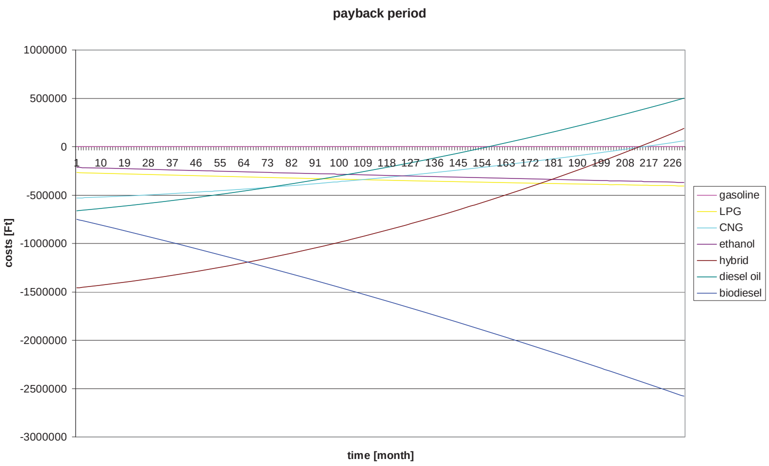

Fig. 10. Payback time taking urban consumption rates into consideration

As it can be seen in Figure 10 the payback period of CNG and hybrid vehicles is very long at current prices in Hungary. The investment returns after 215 months (18 years) in the case of CNG vehicles and after 214 months in the case of hybrid vehicles. The reasons for this are on the one hand the high purchasing costs and on the other hand the high gas prices. Gas prices (relative to traditional fuel prices) are relative high in Hungary compared to other European countries. Fig. 10 also shows that with these input parameters the investments in diesel vehicles also return, but ethanol, biodiesel and LPG vehicles do not return under such conditions, because of their high consumption and price.

Sensitivity analysis

A sensitivity analysis of the base case was performed. The aim was to examine how a 20% reduction of the costs influences the payback period. The business model is the most sensitive to that parameter, the reduction of which causes the biggest change in the payback period.

A reduction of 20% in the CNG fuel price decreases the payback period by 63% (to 80 months). In practice this may occur, if the tax rate of the fuel price is moderated. A 20% reduction of annual costs reduces the payback period by 28% (to 155 months) in the case of CNG vehicles and by 11% (to 192 months) in the case of hybrid vehicles. In practice this may occur if the vehicle taxes are reduced in order to promote the wide-spreading of environment friendly vehicles. However, the reductions of fuel taxes have a bigger influence. A 20% reduction of single costs reduces the payback time to 1 month in the case of CNG vehicles and to 25 months in the case of hybrid vehicles. In practice this could mean the reduction of the registration fee, which already exists in Hungary for hybrid vehicles. Under these conditions the purchasing cost of the CNG vehicle can be lower than that of a gasoline fuelled vehicle, which means that the CNG vehicle provides from the beginning on benefits. In addition the favourable operation costs raise these benefits further compared to vehicles using traditional fuels. The non-linearity of the cost curves is caused by the fact that the interest rate was also taken into account. A 20% reduction in the interest rate reduces the payback time to 206 months in the case of CNG vehicles and to 205 months in the case of hybrid vehicles.

5. Conclusions

The technical results from simulations and measurements show that it is worth to turn our attention to vehicles with alternative powertrains. The simplest way to reduce emissions is the application of alternative fuels. Using natural gas or ethanol are already available technologies. Hydrogen as fuel is not ignorable either, since it has the benefit of almost zero emission (only nitrogen-oxides are emitted), but the problem of storing hydrogen onboard is not solved yet. Hybrid technologies are also considerable to apply, but these technologies are a bit expensive nowadays. For future trends the combination of alternative fuelled engines (or fuel cells) might be combined with hybrid technologies.

With the economical analysis of alternative fuels and propulsion systems we aimed at determining the conditions needed for making the application of alternative vehicles more attractive. Emphasis was put on the determination of the payback time of CNG and hybrid vehicles. We found that single costs and fuel costs are the main factors influencing payback time. Reduction of annual costs and of the interest rate have a smaller influence. In order to make the application of alternative vehicles more attractive a wide cooperation is need, in which national gas companies and the government have to be involved in the future.

References

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[2] Miller, J. M., *Propulsion Systems for Hybrid Vehicles*, 2004.