

Evaluation of the efficiency of hybrid drive applications in urban transport system on the example of a medium size city

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Abstract. Unconventional drive systems of the urban buses become more and more popular. The reason is clear: reduction of the harmful emissions as well as the fuel consumption reduction. Environmental aspects are becoming of the great importance. Local governments of large cities are “pushing” conventional buses away from city centres, trying to substitute them by the other more environmentally friendly urban vehicles. The goal of the contribution is to present a comparison of the selected types of the urban buses equipped with alternative drive systems under conditions of medium size city. The first part of the paper presents the methodology and construction of urban bus driving cycles prepared for Kielce city (Poland). The next part shows fuel economy and energy consumption obtained from simulation of urban buses powered by conventional diesel engine and hybrid electric drive under the developed driving cycles. The last part presents results of the Total Cost of Ownership (TCO) calculations estimated for selected urban buses.

1 Introduction

To evaluate the efficiency of the hybrid drive for urban public transport applications some most popular alternatives of the hybrid drives have been taken into account. The most attractive alternatives for the classical Diesel engine drive system are pure electric drives and hybrid drives. Pure electric autonomous vehicles are still very expensive although the price ratio of the conventional vehicles and electric vehicles has become more acceptable lately. Great progress has been taken place in the field of batteries offered, whose capacities and life time have increased significantly and the price has decreased. Recently, there has been a great deal of interest from the self-governments of the Polish cities manifesting itself in that they have already bought or are preparing to purchase a significant number of electric vehicles in Poland. More popular option is hybrid drive urban buses, which are offered in some different options by some Polish bus manufacturers. Among them the most typical are parallel and series hybrid vehicles, which have been chosen for the further consideration. Evaluation of the hybrid bus effectiveness has been conducted by use of the simulation model developed by the US National Renewable Energy Laboratory within the program “Partnership for a New Generation of Vehicles” (PNGV), co-financed by the US Department of Energy and the biggest American car manufacturers [4]. The model was developed in Matlab/Simulink simulation environment. The ADVISOR packages used to be able to download free of charge from the Program web site. The model can be used for alternative drive systems of the different types of the vehicles, including

urban buses. To accommodate the model to local conditions of the medium-size city some driving cycles have been worked out.

2 Driving cycles

The driving cycle – Is a record of vehicle movement, represented as its speed vs. time. It does not provide detailed information about driving style, but illustrates the communication conditions of a given city and gives the basis for energy analysis of vehicle traffic [1, 2]. The first driving cycle was developed in the 50s of the 20th century in Los Angeles to investigate the impact of emissions on the formation of smog. The cycle consisted of 11 modules, including the acceleration phase, driving at constant speed, braking and staging [3]. Standardized road cycles are currently used to estimate emissions of harmful emissions and fuel consumption.

In the EU, the NEDC cycle is now in use, in the USA the FTP-75 cycle is used, in Japan there are J10 or J15 cycles, in India – it is IDC cycle. Standardized On-Road Tests (SORT) have been developed to standardize mileage fuelling procedures for buses and public transport. They include three types of tests [4, 5]:

- SORT 1 (Heavy Urban), which reflects the operating conditions in the centre of large cities (average speed 12 km/h);
- SORT 2 (Easy Urban Cycle), which reflects the operating conditions for a typical urban route (average speed is 18.0 km/h);
- SORT 3 (Easy Suburban Cycle), which reflects traffic conditions in the suburbs of large cities and on inner routes of smaller cities (average speed is 25.3 km/h).

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The complete cycle consists of a number of speed profiles that group basic cycles, with the following values: acceleration (decelerations), driving at constant speed, stopping time [2, 6, 7]. Standardized road cycles do not, however, reflect the actual communication conditions of a particular city. Therefore, in order to carry out an energy analysis of a particular vehicle and the emission of harmful exhaust particles, many researchers have undertaken to develop a driving cycle for specific cities [8-14]. This contribution presents the method of creating Kielce cycles of driving, which reflect the actual traffic conditions of urban communication vehicles in Kielce.

Two urban bus driving cycles have been worked out for the medium-size city (Kielce), the first one for a flat route (driving cycle I) and the second - for a route with a varied vertical profile (driving cycle II), both of them are based on the measurements conducted on the real bus routes in Kielce (Fig. 1).

Kielce driving cycle I reflects the route of line 13 that runs from the east to the west side of the city and has 39 bus stops. Its total length is 20.2 km. The Kielce II cycle was built on the basis of line 30, which runs from the north to the southern part of the city. There are 36 bus stops in the route and its length is 19.5 km.

Kielce is characterized by uplifting terrain, with the absolute height of between 260 and 400 m, therefore one of the route selection criteria was its vertical profile. Route 13 is characterized by a relatively flat vertical profile with a maximum slope of 1%. Line 30 runs along the hilly route and the highest slope of the route is 4%.

During the measurements of the Kielce cycles, the public transport bus of 12 meters in length. The vehicle was equipped with a Diesel engine of 209 kW (284 HP), its own weight was 10400 kg, while the maximum allowable weight was 18000 kg. Real-time traffic records were recorded using Kiestler GPS CDS Data Logger, installed by the authors on the vehicle. The data sent from the bus on-board GPS system to the ZTM

Kielce (bus provider) monitoring system was also taken into account.

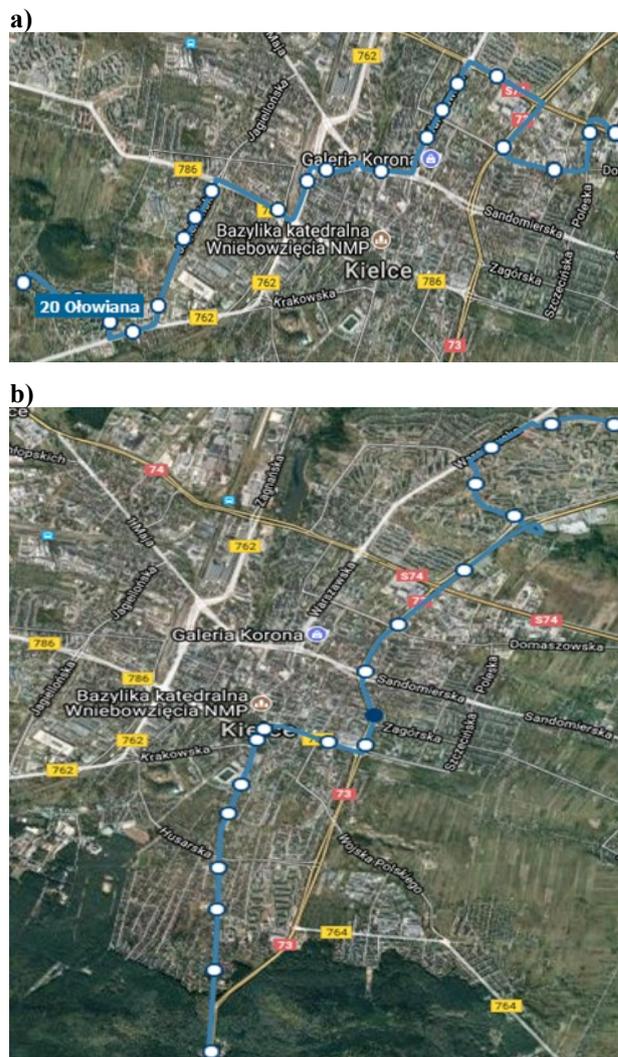


Fig. 1. Bus routes utilized for driving cycles construction: a) bus route No. 13; b) bus route No. 30.

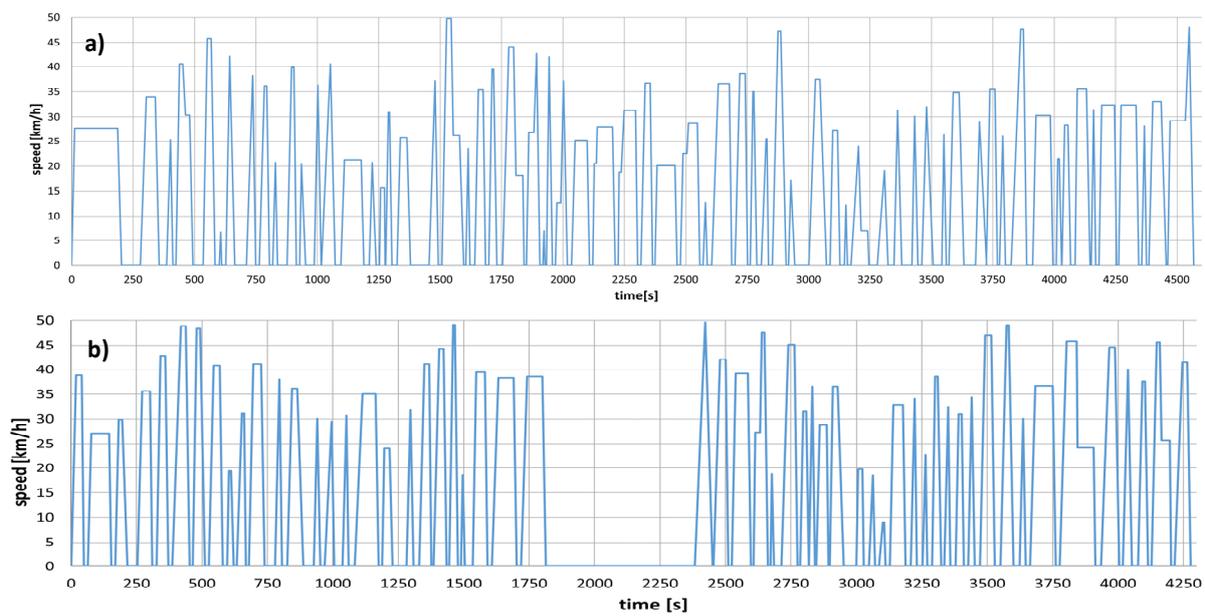


Fig. 2. Kielce driving cycle: a) driving cycle I; b) driving cycle II.

When compiling the actual driving cycles, the following vehicle performance parameters were selected: instantaneous speed, instantaneous acceleration, driving time, distance travelled, and vehicle momentary. On the basis of the available data, journeys with similar stop counts and average speeds and similar cycles were identified. Then one of them was selected for each of the routes studied. These journeys were taken as actual driving cycles, recorded as instantaneous velocity distributions as a function of time (Fig. 2).

The actual driving cycles were divided into short runs between the following stops. For each of them the average speed, acceleration and deceleration were calculated, and delay. The mean value of the real cycle velocity is equal to the average speed of the representative cycle, and the mean acceleration of the actual cycle is equal to the average acceleration of the representative cycle.

Both routes run in urban areas, so the maximum speed should not be higher than 50 km/h. The representative Kielce driving cycle I lasts 4568 s and its length is 20,25 km, its average speed is 15.95 km/h. This route is characterized by high variations in speed values and high variability of acceleration. The average acceleration is 0.55 m/s² and the average deceleration is 0.67 m/s². The total number of stops on the route was 66. The basic parameters of both cycles were presented in Table 1.

The driving cycle II is shorter by about 700 m and is characterized by a higher average speed (16.44 km/h). Average acceleration is 0.54 m/s² and average deceleration is 0.81 m/s². The route is also characterized by a smaller proportion of congestion, which results in fewer stops. In the middle of the cycle, according to the actual timetable for this line, there a stop lasting 568 s.

Most of the time of the two cycles were stops. For the driving cycle I it was 46%, and for the driving cycle II it was 52% of the total cycle time. Since the both worked out representative cycles show the urban bus

driving cycles, the total stoppage times included stopping times at stops and stopping times due to traffic conditions. For the driving cycle I, the percentage of times of the two types of stops differed only 2% whereas for the driving cycle II the differences were much higher – total stop time caused by traffic conditions was 38% higher than total bus stop time.

Table 1. Basic parameters of the driving cycles.

Parameter	Driving test I	Driving test II
Test cycle time [s]	4568	4276
Cycle length [km]	20,25	19,53
Maximum speed [km/h]	49,89	49,79
Average speed [km/h]	15,95	16,44
Maximum acceleration [m/s ²]	1,34	1,24
Maximum deceleration [m/s ²]	1,49	1,66
Average acceleration [s/s ²]	0,55	0,54
Average deceleration [m/s ²]	0,67	0,81
Number of stops	66	55

3 The urban bus variants

Three types of vehicles have been chosen for simulations: the parallel hybrid bus, the series hybrid bus and the “classical” Diesel engine urban bus. The last one has been chosen to enable the comparison of the fuel consumption as the main parameter describing the bus usage efficiency.

Table 2. Technical parameters of the drive components of the analysed vehicles.

	SHEV1	SHEV2	PHEV1	PHEV2	Conventional
Engine:					
Maximum power:	140 kW	170 kW	190 kW	200 kW	205 kW
Engine displacement:	7,3 dm ³	7,3 dm ³	6,7 dm ³	6,7 dm ³	6,7 dm ³
Mass:	476 kg	476 kg	404 kg	443 kg	443 kg
Electric motor:					
Power max:	150 kW	180 kW	40 kW	55 kW	-
Mass:	82 kg	88 kg	48 kg	66 kg	-
Generator:					
Power max:	150 kW	180 kW	-	-	-
Mass:	82 kg	88 kg			
Energy storage device:					
Storage capacity:	9,4 kWh	10,6 kWh	5,6 kWh	5,6 kWh	-
Nominal voltage:	362 V	362 V	335 V	335 V	
Mass:	193 kg	231 kg	73 kg	73 kg	
Transmission:	BAE HDS200	BAE HDS200	ZF 5HP590	ZF 5HP590	ZF 5HP590
Mass:	31 kg	31 kg	30 kg	30 kg	30 kg
Gear ratio of the main gear:	5,857	5,857	4,33	4,33	4,33

vehicle. We should add that these amounts of energy were calculated for one driving cycle only, so to evaluate the real energy effectiveness SOC level for ESD must be taken into account.

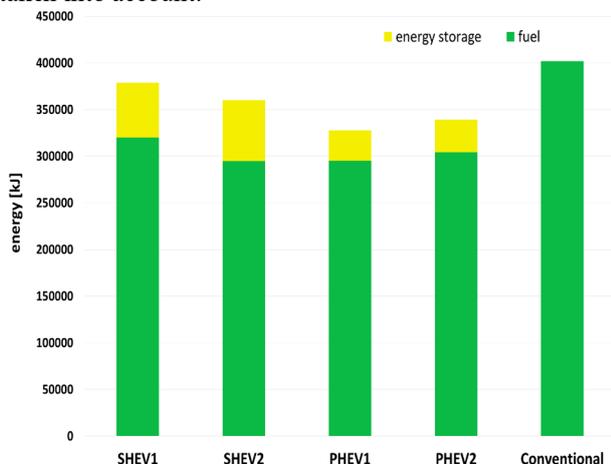


Fig. 6. Amounts of energy [kJ] coming from the fuel combustion (green) and returned from the storage tank (yellow) in total amount of energy consumed in the cycle I.

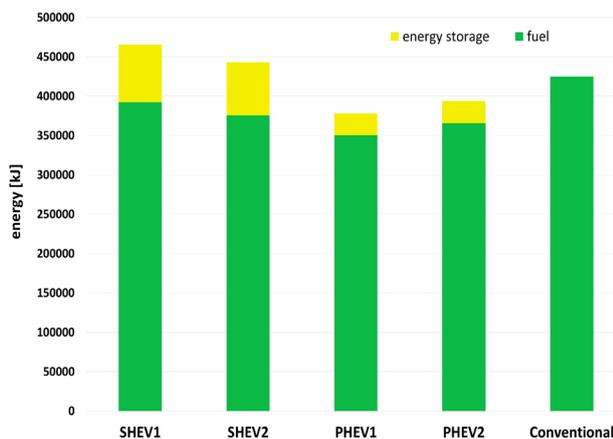


Fig. 7. The amounts of energy [kJ] from the fuel (green) and from the ESD (yellow) in total energy amounts consumed in both driving cycle II.

Our investigations show that hybrid vehicles require about 11% less energy than conventional vehicles. The estimated share of energy from batteries for parallel hybrid vehicles was 7%. For SHEV1 and SHEV2 these ratios were 16% and 15% respectively. The amount of energy from the fuel and from the ESD in total energy consumed in second driving cycle can be seen on Fig. 7.

For both driving cycles we have stated that the lowest energy values were observed for vehicles with parallel hybrid drive. For the driving cycle II, vehicles with series hybrid powertrain needed 19% more energy than for the driving cycle I. In the case of parallel hybrid vehicles, PHEV1 needed 13% and PHEV2 14% more energy for the driving cycle II than for driving cycle I. The share of the energy returned from the storage tank was higher for the driving cycle II. The biggest differences were observed for SHEV2.

5 The TCO (Total Cost of Ownership) evaluation

The TCO has been used for a vehicle total cost of ownership estimation for a specific period of time. It includes all the expenses spent on fuel, insurance, maintenance, repairs, service, interest on loan payments as well as the losses incurred due to depreciation of the car at the end of the same period [18-23].

The life cycle costs, calculated for the three types of buses mentioned, including fuel costs, service costs, the battery exchange costs, show that the hybrid drive buses can be the cost effective alternative for a classical bus, even having taken into account the actual hybrid drives and batteries prices.

Total Cost of Ownership (TCO) is the sum of all costs of a vehicle, from its purchase, through use, to disposal. TCO analysis allows to evaluate the direct and indirect costs associated with vehicle usage and possession. In addition to the purchase cost, the total costs of living are included (fuel and/or energy costs, insurance, maintenance and repair costs).

The total cost of ownership can be written as follows:

$$K_{TCO} = K_Z + N_P \cdot (K_f + K_u) + N_W \cdot K_A \quad (1)$$

where K_{TCO} – total vehicle cost [PLN], K_Z – vehicle purchase cost [PLN], N_P – vehicle operating period, K_f – cost of fuel [PLN/year], K_u – cost of maintenance [PLN/year], N_W – number of battery exchanges during the life of the vehicle, K_A – purchase cost of the battery [PLN].

Calculating TCO for a vehicle equipped with a hybrid drive some additional costs connected with the battery exchange must be taken into account. The vehicle life time is as a rule longer than the battery usage time, so the battery must be exchanged a few times. A very important factor, determining the cost of the purchase of a new vehicle, the battery exchange cost as well as the energetic effectiveness of the bus is a battery capacity.

Three city buses with a length of 12 meters were selected for the analysis. The annual mileage for each selected bus is 70 200 km. The life time of each bus is 18 years. The first one has a conventional combustion engine, which complies with the European Euro 6 emission standard. According to the producer data it has been assumed that the average fuel consumption of this vehicle is 43.3 dm³/100 km. The second vehicle is the Solaris Urbino 12, equipped with a hybrid Eaton hybrid drive. The bus has a lithium-ion battery with a capacity of 3.6 kWh. Average fuel consumption is 33.7 dm³/100 km. The third vehicle is the next-generation Solaris Urbino 12 Hybrid (launched in 2016), equipped with a hybrid BAE HybriDrive. According to the bus manufacturer data, average fuel consumption is 27 dm³/100 km. The bus has a lithium-ion (LFP type)

battery with a capacity of 11.6 kWh. It was assumed that the battery life time is 6 years. Therefore, the battery pack replacement is required two times during vehicle lifetime. The cost of lithium-ion battery is 900 PLN per kilowatt-hour. The following purchase prices were assumed: the conventional vehicle – 950,000 PLN, the parallel hybrid – 1,200,000 PLN, the series hybrid – 1,300,000 PLN. According to [24] the average maintenance cost assumed for conventional bus – is 35 000 PLN per year, for hybrid buses – 48 000 PLN per year. The fuel price is 4.4 PLN per dm³. It should be noted that the TCO analysis was carried out for current prices of fuel and lithium-ion battery per kWh. These prices are variable and it is difficult to predict their level in the future. It should also be noted that the changes of money value over time has not been taken into account in these calculations.

The conducted analysis has shown that the total cost of ownership of a conventional bus, referenced to 1 km, is PLN 3.12. The TCO of the parallel hybrid bus is 3.09 PLN/km, and the TCO for the series hybrid drive system is 7% lower – it has been estimated as 2.89 PLN/km. As it has been mentioned before the TCO has been calculated as the sum of fuel costs, maintenance costs and battery replacement costs. Hybrid buses have lower operating costs (TCO) than conventional vehicles. These differences are respectively about 10% for parallel hybrids and 22% for serial hybrids.

The costs of fuel accounts for the largest share of total vehicle ownership. In the case of TCO of a conventional drive vehicle, their share is 61%. For hybrid vehicles, the cost of fuel is lower – it is 48% for parallel hybrids and 41% for serial hybrids.

The share of the purchase cost in TCO of hybrid buses is more than 30%. They have a much higher production costs. Additional costs stem mainly from the use of electric drive components such as batteries, electric motors and electronic components for energy management and thermal balance. Electric auxiliaries improve energy efficiency, but since the market for these items is still small, their costs are quite high.

6 Conclusions

The results of investigations, presented in the paper, show, that hybrid buses are becoming an attractive alternative for urban public transport, especially in medium size cities. However, presented results have not taken into account the environmental aspects of the vehicles' operation. Hybrid buses offer better energy efficiency and fuel efficiency in comparison with conventional buses. They have also a significantly lower Total Cost of Ownership (TCO) than buses equipped with conventional drive.

The trends of reducing air pollution caused by exhaust gases emitted by the urban buses and the tendency to add to TCO some additional costs connected with the environmental effects will have a positive effect on evaluating the effectiveness of the utilizing hybrid drive technology. The authors have shown, that even

taking to account only TCO proves a profitability of implementation hybrid buses in cities.

The purchase cost of buses equipped in hybrid drive is still much higher than for the conventional bus. It is possible that the difference in the purchase costs between hybrid and conventional buses will decrease in the future. The advantages of hybrids is that they do not require additional and expensive infrastructure and bring additional environmental and social benefits.

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