PUBLIC BUS ENERGY CONSUMPTION INVESTIGATION FOR TRANSITION TO ELECTRIC POWER AND SEMI-DYNAMIC CHARGING

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Abstract. The research paper is devoted to the research results of public bus energy consumption and potential transition to electric drive, as well as to the development requirements of semi-dynamic charging for bus additional energy supply. The research object – bus Ambassador 200 produced in Latvia was chosen, and the research in energy consumption took place during January…March – the months with potentially highest energy consumption (winter – spring). Energy consumption investigation revealed high efficiency of the bus in the city cycle – just 2.86 kWh per kilometer. Simulation of bus transit to electric drive was provided, and introduction of different energy recuperation strategies allowed to reduce the energy consumption in electric drive to 0.42-0.99 kWh·km^{-1}. Bus equipped with such electric driving system can cover 200-300 m distance using the energy received from semi-dynamic charging system.

Keywords: bus energy consumption, electric drive, recuperation, semi-dynamic charging.

Introduction

Transition to transport energy supply using electric and combined (hybrid) solutions is a vital way for Latvia to meet the programme "Europe 2020" [1] criteria. Latvia targets are defined in the programme [2], which determines the need to reduce CO_2 emissions by 17 %, and 40 % of the energy used should be obtained from renewable sources, as well as the request to reach at least 10 % transport energy consumption provided using renewable energy [3]. At the same time EU experts evaluating Latvia results in reaching "Europe 2020" goals mentioned that "low energy efficiency is a problem in the transport sector" [4].

Bus producers all over the world are investigating a possibility to produce electric buses and hybrid buses. The current approach is to use ordinary buses, and to install the electric system – either trolley bus type, without any energy storage for driving, or accumulator backed electric drive, or hybrid systems, which include the internal combustion engine driven generator, accumulator battery, and electric drive. As the infrastructure for charging is on the development stage, the main direction of electric energy driven bus development is devoted to hybrid buses, and buses with extensive accumulator batteries. At the same time researchers are developing systems which could allow additional energy supply of a public bus, which is repeating the same route and the same short stops for passengers boarding – the system called semi-dynamic charging [5].

Semi-dynamic energy supply is being used for electric and hybrid buses energy supply during short stops, thus reducing the battery size. The development of the semi-dynamic charging system depends on the bus energy consumption, and power available from the public network. The most challenging question for the developers and scientists is linking together the bus energy consumption, electric driving system parameters and requirements for semi-dynamic charging. These aspects, and in particular the power parameters of bus Ambassador 200 produced in Latvia, were the aim of this study.

Energy consumption of public transportation buses - review

Many studies which are devoted to public bus energy consumption are available. One study [6] indicates that the average annual energy consumption, including fuel used for heating in autumn – winter period and for air conditioning in summer, in the urban cycle for diesel buses (Euro VI standard) is 4.13 kWh per kilometer (forecast for 2030 is 3.89 kWh·km^{-1}), for buses using compressed natural gas – 5.21 kWh·km^{-1} (forecast for 2030 is 5 kWh·km^{-1}), for electric buses using additional charging during short stops – 1 8 kWh·km^{-1} (forecast for 2030 is 1.58 kWh·km^{-1}), and for electric buses using slow charging at route destinations – 1.91 kWh·km^{-1} (forecast for 2030 is 1.68 kWh·km^{-1}). The results of another research show that diesel buses energy consumption is in the range between 3.583 and 4.944 kWh·km^{-1}, and natural gas-powered buses energy consumption is in the range between 4.9 and 6.833 kWh·km^{-1}, compared to the electric buses with trolley connection consumption showing 2.2 kWh·km^{-1} [7].

Spanish scientists, in turn, have figured out that the energy consumption of standard city bus depends on the number of passengers – in low load periods the energy consumption is in average 3.61 kWh·km^{-1}, but in high load periods the consumption increases to 4.59 kWh·km^{-1} [8] . German scientists study concluded that the bus energy consumption is strongly seasonal - during summer it is around 2.1 kWh·km^{-1}, but during winter it rises to 4.1 kWh·km^{-1}, 1.7 kWh·km^{-1} of which is being used for passenger comfort and other functions that are not directly related to the bus movement [9].

Information analysis shows substantial difference in energy consumption, which varies from country to country, thus the research results cannot be used directly for Latvia, and it was decided to research public bus energy consumption trends in the city cycle in Latvia, and to evaluate the possibility to use semi-dynamic charging for electric buses in Latvia environment.

Materials and methods

Diesel bus Ambassador 200 produced under license agreement in Jelgava, Latvia was used as a trial object. The bus is equipped with the Cummins 6.7-liter, 225 HP diesel engine and Voith 4-gear automatic transmission. The bus was used for public passengers' transportation in Jelgava, Latvia (city with around 62 thousand inhabitants).

Data collection was organized on weekly basis; the research period was from January 01, 2014 till March 31, 2014 – winter-spring season with theoretically the highest energy consumption. The data were collected at the end of each week, using the Cummins built-in diagnostic system, which is connected also to the automatic transmission control system.

Preliminary data collection showed that only selected data can be obtained directly. The remaining data necessary for energy consumption analysis and for the evaluation of the possibility to transfer this bus type to electric drive with possible semi-dynamic charging on short stops will be calculated during the analysis.

Results and discussion

The sample data set collected at the end of the first week and statistically processed values for full research period are presented in Table 1. The lines in the table marked using * were calculated using the obtained data. Data analysis revealed that the average bus speed is rather low – only 20.50 ± 1.45 km·h^{-1}. Specific fuel consumption - 28.75 ± 1.83 83 l·100^{-1}·km^{-1}, mean power and mean engine load are rather low (46.58 ± 1.93 HP, which comprises 37.13 ± 1.63 % from the engine nominal power). The reason for so low results could be extensive driving in urban mode. Further studies should be carried out to evaluate conformity assessment of the engine used.

Data correlation analysis showed various trends associated with the bus usage for passenger transportation in the urban cycle. It was found that the inertial movement has significant negative correlation (determination coefficient R^2 = -0.34) with the fuel consumption – the higher the distance covered using inertial movement, the smaller the fuel consumption. Bus driver training oriented towards using inertial driving could substantially reduce the energy consumption.

Very strong positive correlation (R^2 = 0.92) was revealed between the fuel consumption and mileage - most of the fuel was spent for moving the bus and passengers. At the same time, thefuel consumption dependence on driving on particular gear had substantial variations – for driving on the first gear R^2 = 0.95, on the 2nd and 3rd gear R^2 = 0.65, and on top (4th) gear – R^2 = 0.48. This may indicate either that drivers use a more aggressive driving style on higher gears, or automatic gearbox control system operation mistuning – inability to adequately respond to the driver's operation of the accelerator.

The currently used gearbox has only 4 gears, but other producers of city buses use automatic transmissions with 6.8 gears – this also could improve fuel consumption. Correlation between the average movement speed and total fuel consumption is very strong and negative (R^2 = -0.88). This indicates that driving on low gears and high engine rotation speeds took place, as well as that the bus had to stop for passenger upload and unload with the engine running. Too slow driving also could create fuel consumption increase.

Table 1

Data from Cummins diagnostic system, week 1 – January 01, 2014 to January 07, 2014, and statistically processed data for full research period

Measurements	**Week 1, 01. - 07.01.2014**	**Processed data**	
		Mean	SD
Total fuel consumption, $l \cdot 100^{-1}$ km	27.78	28.75	1.83
Driving distance, km	1040	1080.20	180.74
Inertial movement, km	97	87.32	14.19
Driving distance, first gear, km	345.50	426.50	93.47
Driving distance, top (4th) gear, km	336	362.68	79.10
Fuel consumption, driving, l	249.10	270.68	49.19
Fuel consumption, driving on the first gear, l	73.10	86.78	19.80
Fuel consumption, driving on the top (4th) gear, l	74.40	56.78	13.97
Specific fuel consumption, inertial movement, $l \cdot 100^{-1}$ km	9.09	9.80	0.68
Specific fuel consumption, driving on the first gear, $l \cdot 100^{-1}$ km	21.16	20.33	0.89
Specific fuel consumption, driving on the top (4th) gear, $l \cdot 100^{-1}$ km	22.14	15.81	3.03
Average driving speed, $km \cdot h^{-1}$	22	20.50	1.45
Engine mean rotation frequency, min^{-1}	1100	1095.00	6.02
Mean load, when driving, %	39	37.13	1.63
Mean power, when driving, HP	48	46.58	1.93
Max speed, $km \cdot h^{-1}$	75	82.42	5.43
*Fuel consumption, inertial movement, l	8.82*	8.51*	1.14*
*Driving distance, 2nd and 3rd gear together, km	261.5*	203.70*	61.18*
*Fuel consumption, driving on the 2nd and 3rd gear together, l	132.59*	159.14*	33.83*
*Specific fuel consumption, driving on the 2nd and 3rd gear, $l \cdot 100^{-1}$ km	25.35*	41.15*	11.55*

*Calculated data

The analysis results of the driving distance covered on different gears are presented in Fig.1. a). The longest distance was driven using the first gear– 39 %. This explains low average driving speed in the urban cycle. At the same time 34 % of the distance was covered by driving on the top gear – this is either the specifics of the particular gearbox, or drivers managed to accelerate to the top gear speed even in the urban cycle.

The fuel consumption analysis results when running on different gears are presented in Fig.1. b). Driving on the 2nd and 3rd gear showed the largest fuel consumption – 32 % of total fuel consumption for both of them. It seems that the bus designers should re-evaluate the automatic gearbox operation efficiency and control unit operation quality for buses used in the urban cycle.

The calculated average specific energy consumption for Ambassador 200 used for public passenger transportation in Jelgava city during the observation period was 2.86 $kWh \cdot km^{-1}$ ± ± 0.036 $kWh \cdot km^{-1}$ – lower than the public bus average energy consumption results obtained by other researchers. This result proves that the mechanical design of a particular bus is appropriate for transforming the bus from diesel drive to electric drive, and introduction of the breaking energy recuperation system. As the bus power consumption is only 2.86 $kWh \cdot km^{-1}$ in the diesel mode, the requirements for bus electrical power unit may be minimal.

The following assumptions and principles obtained from the research were used for specific energy consumption calculation, when transforming the Ambassador 200 bus to the electric drive.

- Fuel (total energy consumed) was used for bus movement only (special separately fuelled heater was used for bus saloon heating);

- Inertial movement in the diesel mode still consumes fuel (engine is running), but does not consume energy in the electric driving mode.
- Breaking energy recuperation system is installed in the electric drive system. Since there is a lack of information regarding the efficiency of recuperation systems for public buses operating on the urban cycle, it is assumed that the one established on Ambassador 200 works with average efficiency 50 %, i.e. at least 50 % of the movement energy can be recovered (the most modern serial hybrid recuperation systems reach 66.76 % efficiency [10]).

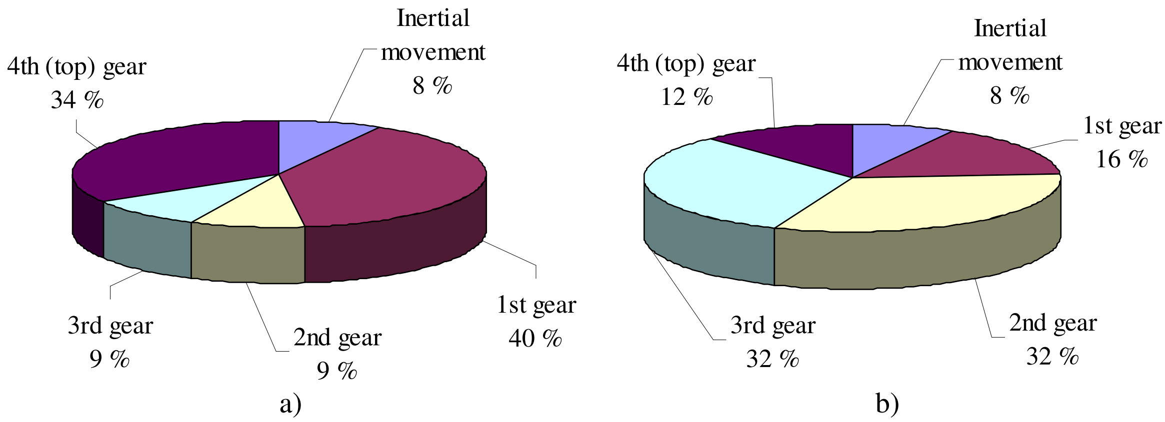

Fig. 1. **Driving distance (a) and specific fuel consumption (b) distribution on different gears**

Taking into account the mentioned assumptions, formula (1) was created, allowing to calculate the bus theoretical specific energy consumption at different recovery modes and driving patterns (accrued experience):

$$E_{sum}^{el} = \left(FC - FC_i - FC_1 \cdot R_1 - FC_{2,3} \cdot R_{2,3} - FC_4 \cdot R_4\right) \cdot E_{fuel} / FC_{100} \,, \quad (1)$$

where E_{sum}^{el} –specific summary electric energy consumption, kWh·km^{-1};
FC – total fuel consumption, l;
FC_i – fuel consumption in inertial movement, l;
FC_4 – fuel consumption, driving on the top (4th) gear, l;
FC_1 – fuel consumption, driving on the first gear, l;
$FC_{2,3}$ – fuel consumption, driving on the 2nd and 3rd gear, l;
R_1 – recuperation efficiency, driving on the first gear, %;
$R_{2,3}$ – recuperation efficiency, driving on the 2nd and 3rd gear, %;
R_4 – recuperation efficiency, driving on the top (4th) gear, %;
E_{fuel} – specific energy of particular fuel, kWh·l^{-1}, for diesel fuel E_{fuel} = 9.961 kWh·l^{-1}.
FC_{100} – mean specific fuel consumption, l·100km^{-1}.

Three models were created with different recuperation principles and efficiencies used.

The first model was conservative – with the lowest recuperation efficiency equal for each gears – $R_1 = R_2 = R_3 = R_4$= 50 %. The second model had equal recuperation efficiency, but it was increased to the 65 %. The third model had different recuperation efficiencies for different gears – R_1 = 50 %, $R_2 = R_3$ = 75 %, and R_4= 95 %.

The simulation results of the electric energy specific consumption for the three models were the following: for the first model E_{sum}^{el} = 0.99 ± 0.054 kWh·km^{-1}, for the second model E_{sum}^{el} = 0.57 ± ± 0.029 kWh·km^{-1}, and for the third model E_{sum}^{el} = 0.42 ± 0.012 kWh·km^{-1}.

Power requirements for the semi-dynamic charging system are defined by three main parameters - the bus power consumption, the distance between the charging points, as well as the bus stay time in the charging zone. The impact of the first two parameters on the required power is directly proportional – the larger the bus energy consumption, and longer the distance between the charging points, the larger the charging power. At the same time, the longer the stop time in the charging zone, the less powerful the charger must be. Taking into account the 0.4 kV three-phase electrical power network restrictions, 30 kW power is a limiting factor for semi-dynamic chargers, as this power does not require extra connection fees.

Using the simulation results of the specific electric energy consumption for three models, and taking into account the power limitations, it can be calculated that the bus operating under the 1st model must be charged for at least 20 seconds, and the distance between the stops (charging points) should not exceed 200 m. At the same time, the bus operating under the 2nd model and charged for 20 seconds can cover 300 meters between the charging points. The bus operating under the 3rd model and charged for the same 20 seconds can have next charging after 400 meters, but when charged for 10 seconds, can drive for 200 m to the next charging point.

Conclusions

1. Energy consumption for the bus Ambassador 200 used for passenger transportation in the city cycle in Jelgava, Latvia during winter-spring was 2.86 $kWh \cdot km^{-1}$.
2. Correlation analysis showed also that there is potential for the bus efficiency increase and energy consumption decrease. The main sources of efficiency increase – drivers training on efficient driving skills and appropriate choice of automatic transmission elements, and engine power level for bus driving in the city cycle only.
3. Simulation of bus transition to electric drive and breaking recuperation introduction revealed that the energy consumption decreases to 0.42-0.99 $kWh \cdot km^{-1}$ depending on the recuperation strategy introduced.
4. Using the ordinary 0.4 kV electric net as semi-dynamic charging supply (power limit 30 kW), a bus with energy consumption 1.02 $kWh \cdot km^{-1}$ should be charged for at least 20 seconds in order to drive 200 meters to the next charging point. If the energy consumption is 0.60 $kWh \cdot km^{-1}$, the driving distance increases to 300 m, and with energy consumption 0.42 $kWh \cdot km^{-1}$ – over 400 m.

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