09/12/2021

Satellite session

ECO Driving of E-bus

Slobodan Misanovic, PhD

Project manager,

City public transport company ''Belgrade''

AGENDA

- Polygon testing, Investigation of the influence of E-bus driving style on energy efficiency, comparise polygon test/simulation
- Real exploitation, Research of influencing factors on the electricity consumption of E-buses

POLYGON TESTING

The question

Why polygon testing ?

POLYGON TESTING

The answer: The best way to research

Controlled conditions:

- defined length of the test track
- defined driving cycle
- without influence from other vehicles, traffic light
- one test driver, different ways of accelerating and braking the E-bus
- repeatability of the test
- the same mass of vehicles
- Provided optimal operating voltage of supercapacitor, the maximum voltage drop was up to 10 % of the voltage value after charging (575 V), charger nearby,

Results from the polygon are the best way of verification of simulation results

POLYGON TESTING

Project: Research on the efect of driving style on energy efficiency of electric buses

Client of the project City Administration Belgrade-Secretariat for Public Transport

Project leader: Prof. Ivan Blagojevic*, PhD

Researchers:

Blagojevic I*, Stamenkovic D*, Ivankovic I*, Milicic B*, Maljkovic M*, Frlic N*, Zunjic M*, Mišanović S **, Ivanov S**

***Faculty of Mechanical Engineering in Belgrade**

**** JKP GSP Beograd**

POLYGON TESTING

Table 1 Characteristics of polygon sections

Section	Lenght [m]	Rise/fall [%]
P	295	0,00
M	310	-0,3
B	280	-0,7

Figure 1, Test section ''M''

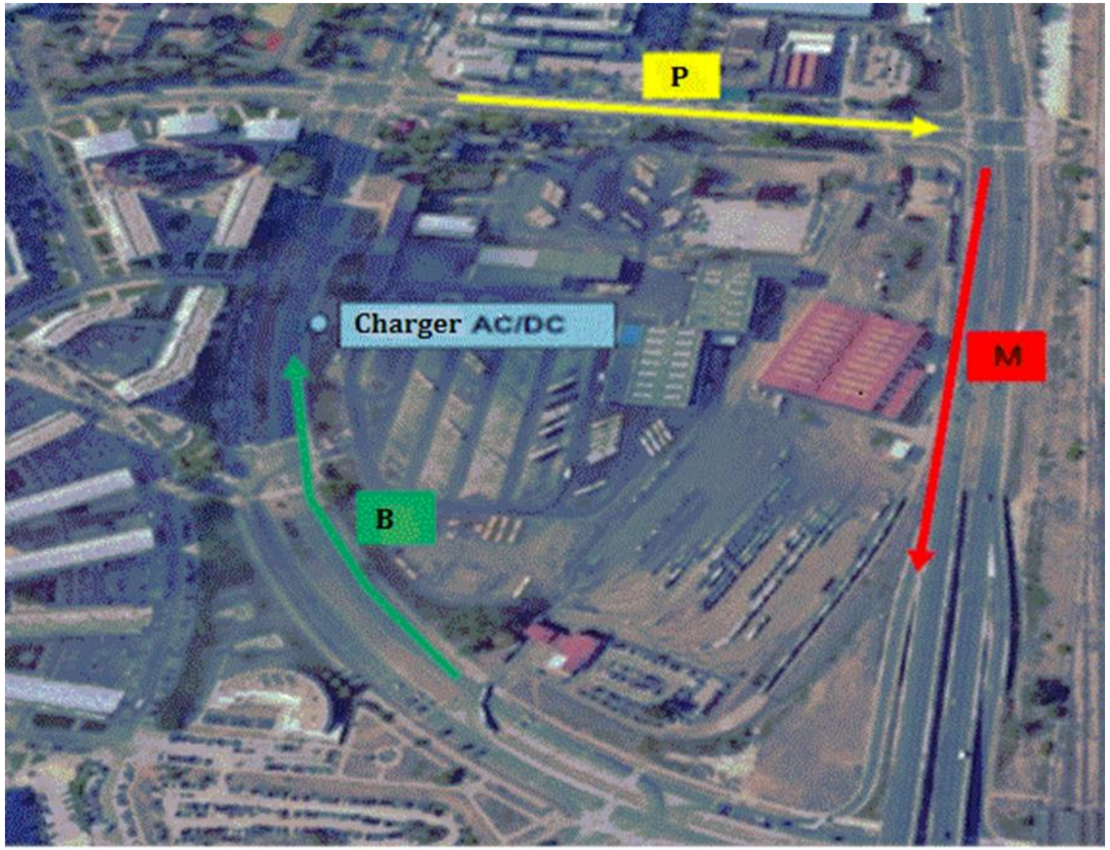


Figure 2 Polygon with test sections

POLYGON TESTING

E-bus, Higer KLQ6125GEV3 Ultracapacitor tehnology

Figure 3 Higer KLQ6125GEV3

Figure 4 Higer KLQ6125GEV3

Technical Data

Manufacturer .... Higer
Type .... Electric KLQ6125GEV3
Length / width / height .... 12000/2550/3680 mm
Curb weight...12540 kg
Passengers..82+1
Max.speed...70 km / h
Charging the terminus: 660 V DC or 380 V AC, 580 V DC output, 250 A
Charging time at the terminus ... . 5-8 minutes
Storage system .... super capacitors
Capacity .... 20 kWh
Manufacturer .... Aowei
Type .... U-CAP (37DT6-03210)
Traction motors 2
Manufacturer .... Siemens
Type 1PV5135
Power .... 2x90 kW (peak opt.)................ .... 2x67 kW (nom. Opt.)
Torque ....2x430 Nm
Inverter .... DC / AC
Manufacturer .... Zhonglian
Type .... IEVD 130-60ZO6GA
Working range .... 580 V DC / AC 500-650V
Convereter .... DC / DC
Manufacturer ....Zhonglian
Type DY074C
Working range ....12-24-48 V DC
Charging system:
Pantograph .... Aowei 37DT6-03212
Plug-in .... DUOSIDA 37XL2 -3709
Auxiliary systems:
Air conditioning .... Thermoking 81DT6
Pump control .... KVD HDZXB 1416
Compressor .... IEM ER 230
UC-Cooler .... Aowei 37DT6
Traction control .... Siemens 10DT6
External display .... Novatronic

POLYGON TESTING

Vehicle load

The vehicle is to be loaded with 50% of maximum payload, because at that time the load corresponds with SORT metodologys. The load can be achieved by evenly distributed sand bags of 40 kg each (total mass of 3060 kg), which corresponds with the mass of 45 passengers of 68 kg each (Figure 5). In each mode of testing and load, there are 3-7 examiners in the vehicle as well (total max.mass of 490 kg).

Figure 5 Vehicle load

POLYGON TESTING

Representative driving cycles

Based on the lengths of the test tracks (P, M, B), the basic driving cycle is defined, which includes the phases: acceleration, constant speed, deceleration. The maximum speed that was achieved was between 40 and 45 km / h.

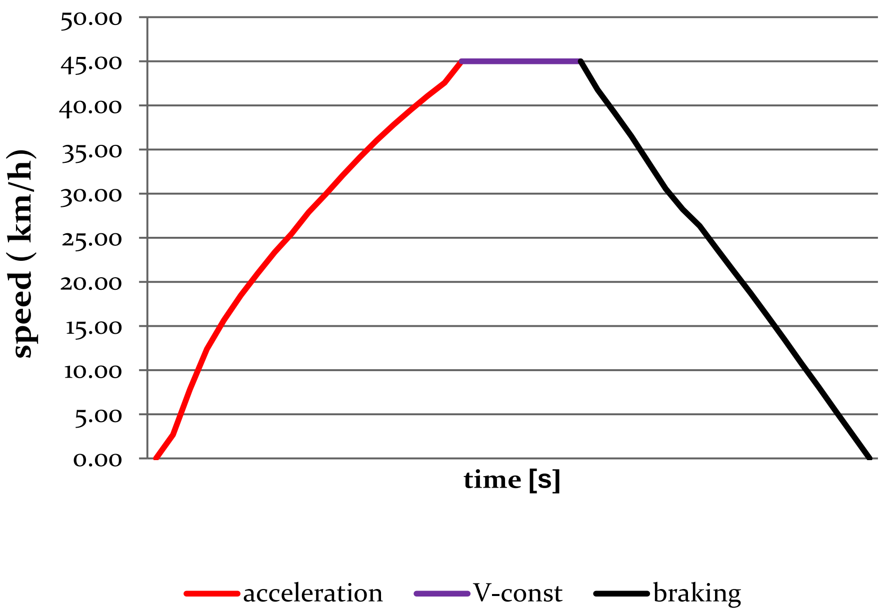


Figure 6 Basic driving cycle

POLYGON TESTING

Acceleration modes

Accelerator pedal position is the parameter according to which the driver inflicts the acceleration intensity. Therefore the testing of acceleration modes should cover constant accelerator pedal position, as well as variable accelerator pedal positions. To overcome the subjectivity problem, the way to inflict different accelerations that the driver is supposed to follow is implemented. According to Figure 7, several curves were established, each representing the change in speed during time spent to accomplish the same maximum value, defined by the equation:

$$v = v_0 + (v_f - v_0)\left(\frac{t - t_0}{t_f - t_0}\right)^{\beta}$$

where:

- *v, v_0, v_f – current, initial and final speed [m/s]*

Curves were obtained by adopting different values of coefficient β (β=0.7, 0.85, 1.4), where the coefficients less than 1 form convex curves, and coefficients greater than 1 form concave curves.

POLYGON TESTING

The driver can track speed via defined curves as shown on a tablet computer, so that the speed change over time dictates current position of acceleration pedal. During trial testing, it was observed that the curves defined by coefficient β < 0.7 were not reachable due to the limits of dynamic characteristic of the vehicle. Likewise, it was founded that when the coefficient is greater than 2, the vehicle needs a large amount of time to reach the desired speed, which is by no means energy efficient.

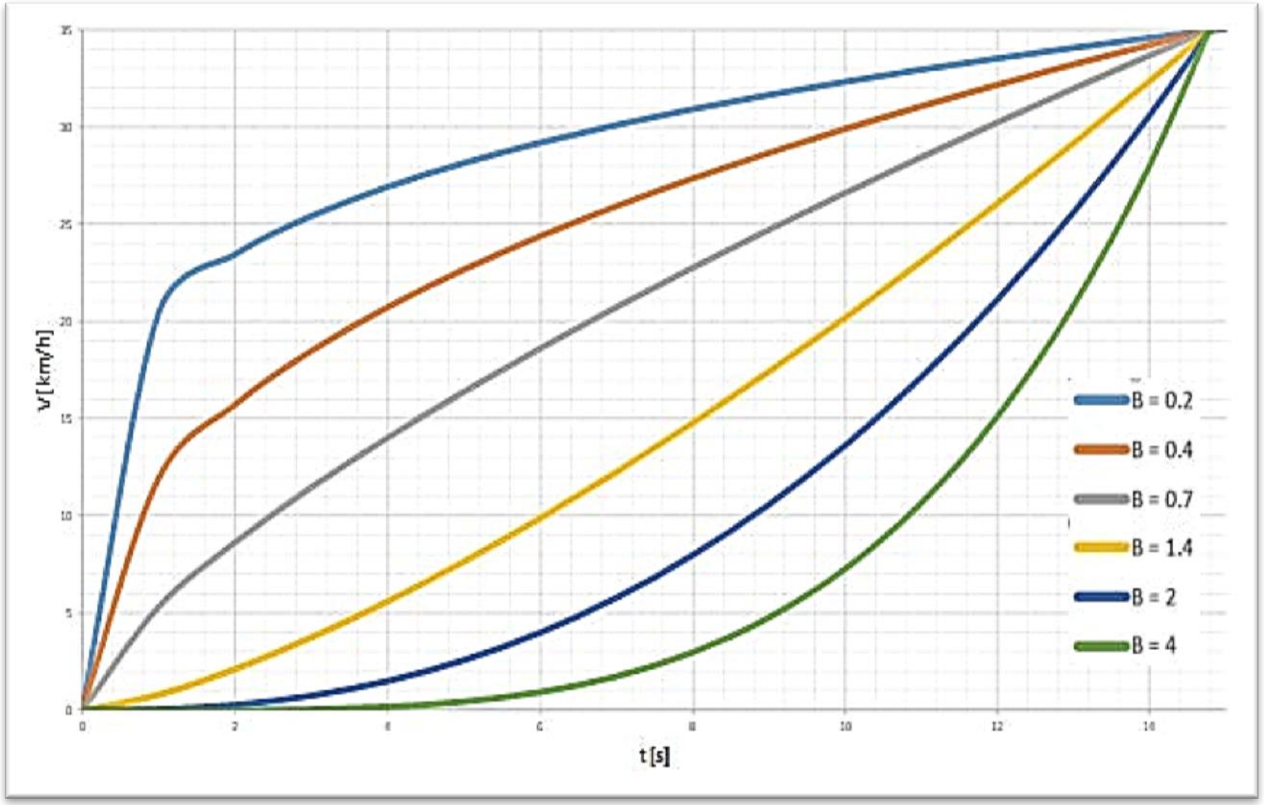


Figure 7 Curves (β=0.2,0,4,0,7,1,4, 2)

The driver can track speed via defined curves as shown on a tablet computer, so that the speed change over time dictates current position of acceleration pedal.

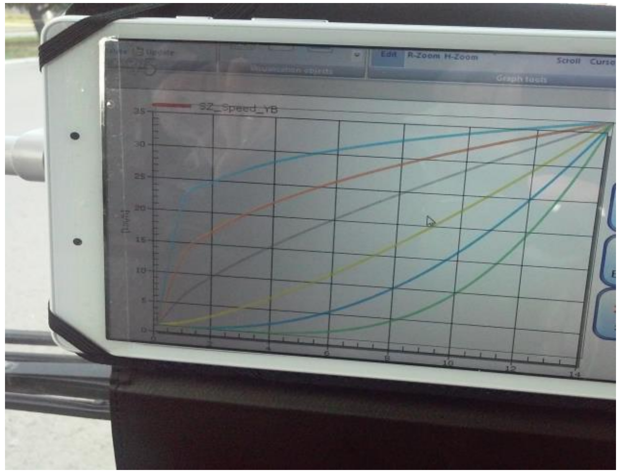


Figure 8 Tablet computer with curves

POLYGON TESTING

Constant speed modes

Testing is performed for different values of maximum speeds in the range from 40 to 45 km / h. Due to the limited length of the test track, the achieved speed was usually maintained between 2-4 seconds.

Deceleration modes

Low, medium, and high deceleration intensities, with the vehicle loaded and unladen, to determine the amount of energy recovered for the various accelerator pedal positions, load conditions, and speeds before and during the braking process

POLYGON TESTING

Measuring equipment

- HBM QuantumX MKS840A, measuring and acquisition device
- MTN / 7100 monitor, acceleration sensor
- Racelogic-Vbok, GPS speed sensor
- Fujitsu Lifebook E series, laptop
- Samsung Galaxy Tab A, Laptop (Figure 8)
- Catman AP V.3.5.1, data processing software package

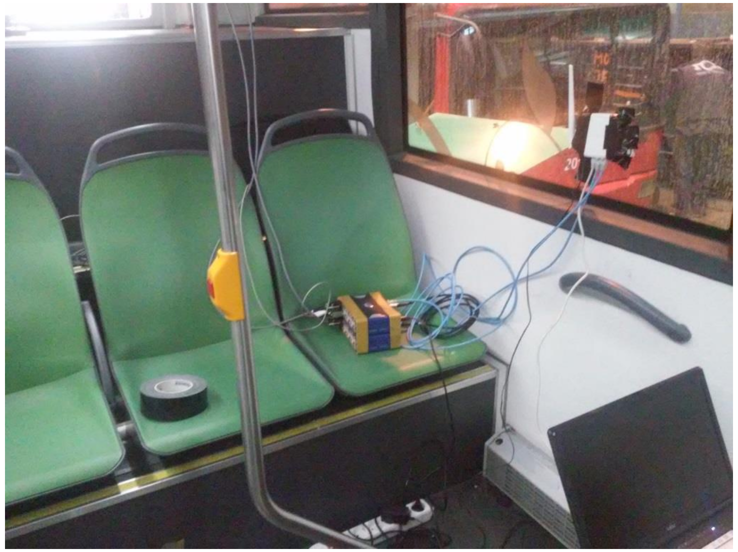


Figure 9 Measuring equipment

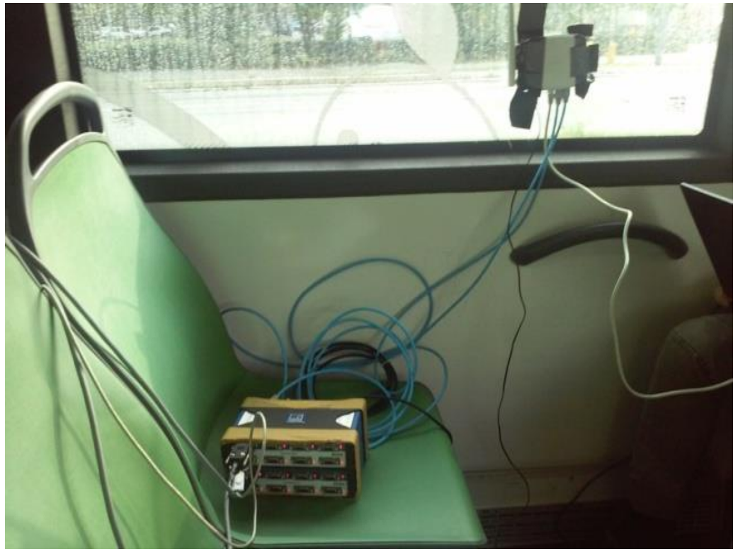


Figure 10 Measuring equipment

POLYGON TESTING

Bus parameters monitored during testing and the way of their quantifying and obtaining

Acquisition of desired parameters of electric bus is done by **V-CAN** and **S-CAN** output on CAN and selected analogue signals. Parameters monitored during testing:

- **Supercapacitor state of charge**: AW _SOC_ [%]
- **Motor torque**: Actual Drive Motor Torque [%]
- **Accelerator pedal position**: AP Position [%]
- **Brake pedal position**: Brake Pedal Position [%]
- **Motor speed**: Drive Motor Speed [rpm]

Several parameters are monitored over analogue signals in such manner that the cables are connected on data acquisition unit from adequate supercapacitor connection points:

- **Supercapacitor current**: I_uc [A]
- **Supercapacitor voltage**: U_uc [V]
- **Invertor current**: I_inv [A]
- **Longitudinal acceleration** over separate sensor: Monitran [g]

In order to check vehicle speed accuracy acquired over CAN, the speed sensor based on GPS and GLONASS signals is used. Data acquisition sampling rate was set to 50 Hz, except for vehicle speed measured via sensor, where it was set to 5 Hz.

POLYGON TESTING

Determination of consumed and recuperated energy

The consumed ($E_{p_{uc}}$) and recovery ($E_{r_{uc}}$) electricity from/in the supercapacitor [kWh] is calculated on the basis of analogously measured values of current ($I_{p_{uc}}$, $I_{r_{uc}}$) and voltage (U_{uc})in the observed time interval.
The energy consumed can be observed for any vehicle speed measured during the cycle. The regenerated energy is calculated for the braking period, which means from the moment the driver presses the brake pedal to the stop based on the current values of voltage and current flowing into the supercapacitor. The start and end of braking are determined based on the current position of the brake pedal. Recovery efficiency is expressed by the recovery efficiency coefficient (λ_{uc})as the ratio of electricity returned to the supercapacitor ($E_{r_{uc}}$) and electricity taken from the supercapacitor ($E_{p_{uc}}$) in the observed time period.

$$E_{p_{uc}} = \sum_{s=1}^{m} \frac{\int_{t_{ps}}^{t_{ks}} U_{uc} \cdot I_{p_{uc}} \cdot dt}{3600000}, \qquad \text{(kWh)}$$

$$E_{r_{uc}} = \sum_{s=1}^{p} \frac{\int_{t_{prs}}^{t_{krs}} U_{uc} \cdot I_{r_{uc}} \cdot dt}{3600000}, \qquad \text{(kWh)}$$

$$\lambda_{uc} = \frac{E_{r_{uc}}}{E_{p_{uc}}} \cdot 100, \qquad (\%)$$

POLYGON TESTING

Results analysis

- During Phase 1 of the project, there were three test days: November 15th, December 4th, and December 17th, 2019.
- Each cycle on a single section consists of a single planned acceleration mode for different values of coefficient β, after which follows the appropriate deceleration mode.
- Due to the nature of testing, it was necessary to repeat cycles on all sections ("P", "M", and "B").
- The effect of the state of charge of a supercapacitor is minimized with frequent charging, to exclude the effect of voltage change on the energy consumed.
- In all three aforementioned methods of proving ground testing, over 100 cycles were driven.
- Based on the described method of data analysis and calculation of consumed and recuperated energy during a cycle.

POLYGON TESTING

- **The table for 6 chosen characteristic cycles (out of a total of 27) on the with the loaded vehicle are made, with a maximum speed of 40 km/h.**

Section (max,min)	Cycle number/ section	Energy consumed until speed of 40 km/h [kWh]	Energy recuperated during braking [kWh]	Recovery efficiency λ_{uc} [%]	Supercapacitor voltage in the beginning (U_{UCp}) and in the end (U_{UCk}) of cycle [V]	Parameter of characteristics of acceleration [-]
B, max	27/B	Epuc40 = 0.367	Eruc = 0.139	37.8	Uucp, Uuck = 535, 516	β ≈ 0.7
B, min	9/B	Epuc40 = 0.389	Eruc = 0.094	24.1	Uucp, Uuck = 546, 526	β ≈ 0.85
P, max	16/P	Epuct40 = 0.384	Eruc = 0.125	32.5	Uucp, Uuck = 560, 540	β ≈ 1.4
P, min	13/P	Epuc40 = 0.410	Eruc = 0.093	22.6	Uucp, Uuck = 576, 560	-
M, max	14/M	Epuc40 = 0.386	Eruc = 0.121	31.3	Uucp, Uuck = 573, 553	β ≈ 1.4
M, min	8/M	Epuc40 = 0.399	Eruc = 0.095	23.8	Uucp, Uuck = 554, 533	β ≈ 0.85

Polygon test, Section ''B'' $\boldsymbol{\lambda_{uc-max} = 37.8\ \%}$, $\boldsymbol{\lambda_{uc-min} = 24.1\ \%}$

Value $\boldsymbol{\lambda_{uc}}$ (%), **the direct influence of the driving style**

Real operation: all influencing factors:

*line EKO1, direction ''A'' $\boldsymbol{\lambda_{uc-max} = 28.55\ \%}$, $\boldsymbol{\lambda_{uc-min} = 16.75\%}$, **average 22.9 %**

*line EKO1, direction ''B'' $\boldsymbol{\lambda_{uc-max} = 19.57\ \%}$, $\boldsymbol{\lambda_{uc-min} = 9.84\%}$, **average 13.9 %**

*Misanovic S.: Energy and environmental performance of E-bus in the passenger transport system, doctoral dissertation, Faculty of Engineering, University of Kragujevac, 2021

POLYGON TESTING

Cycle,27B max

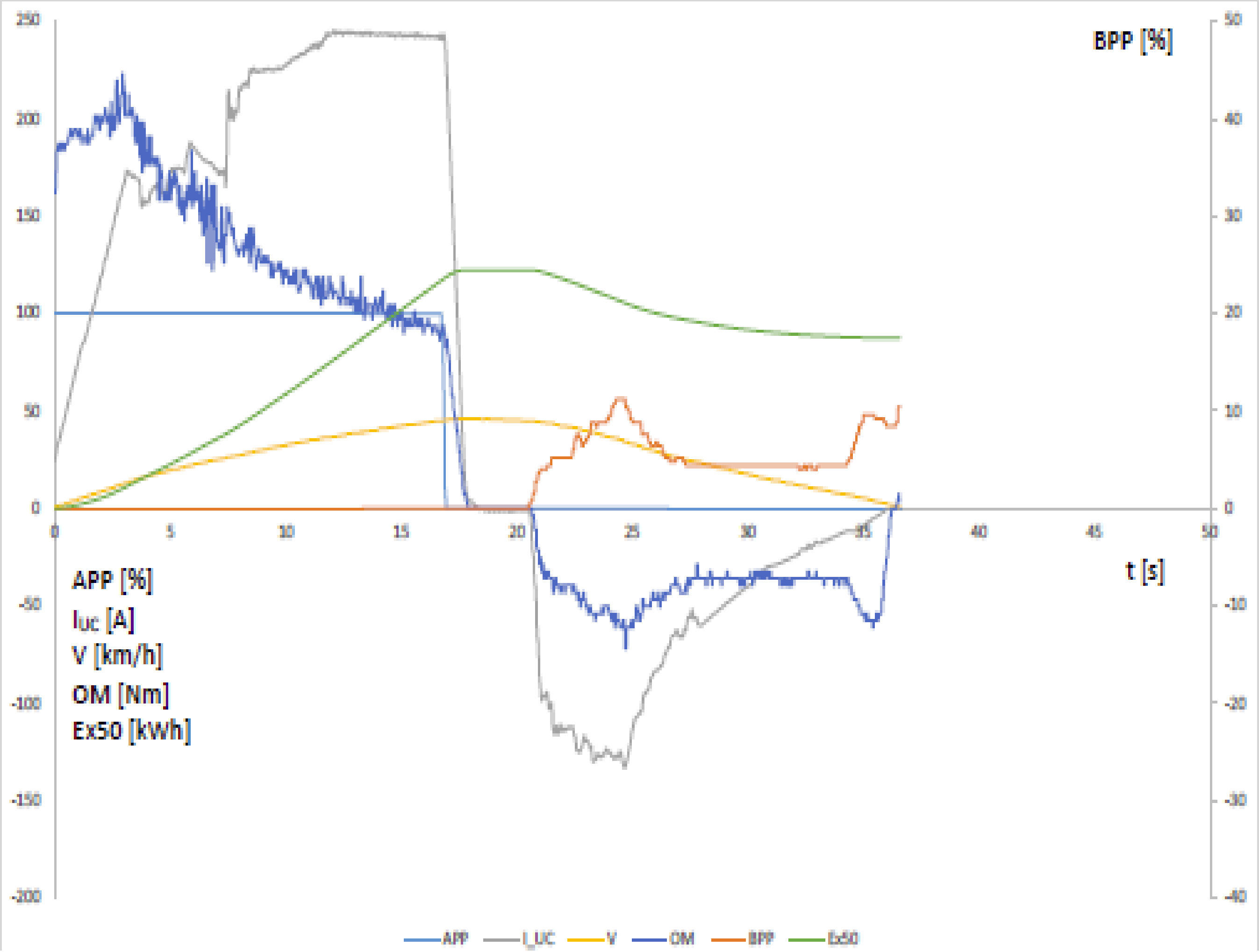


Figure 11 Measured values (Iuc, Torque, Vebus, APP, BPP)

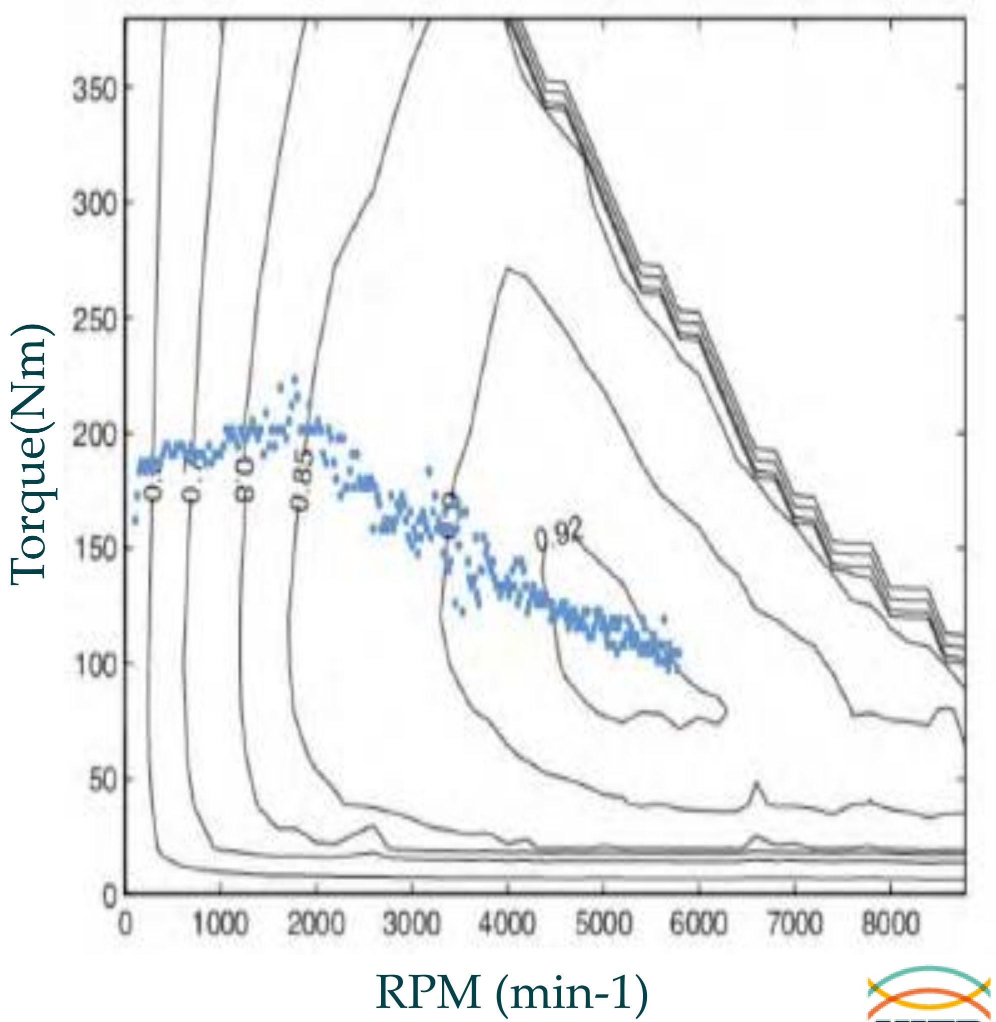


Figure 12
Energy efficiency map (electric motor / inverter)

POLYGON TESTING

Cycle 9B , min

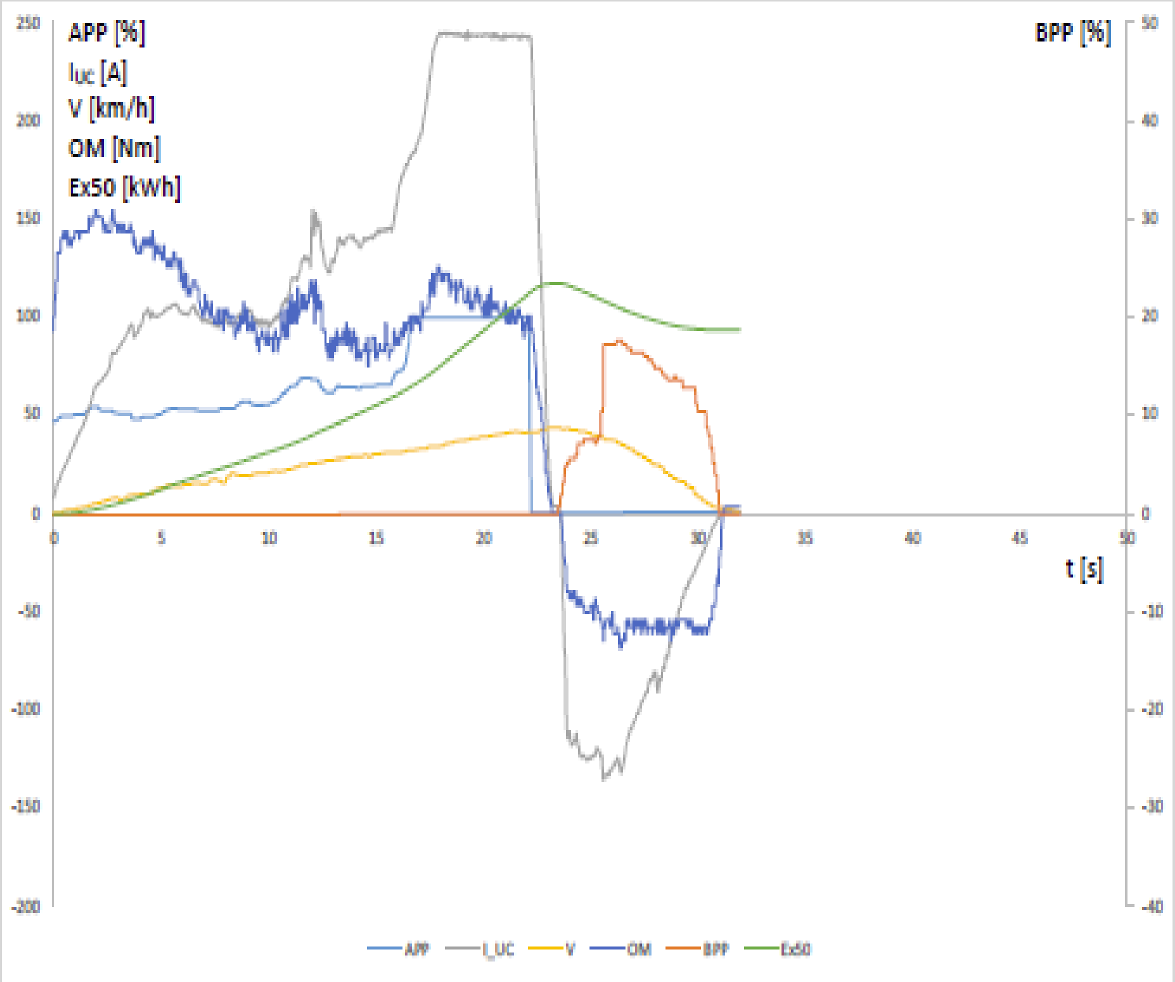


Figure 13 Measured values (Iuc, Torque, Vebus, APP, BPP)

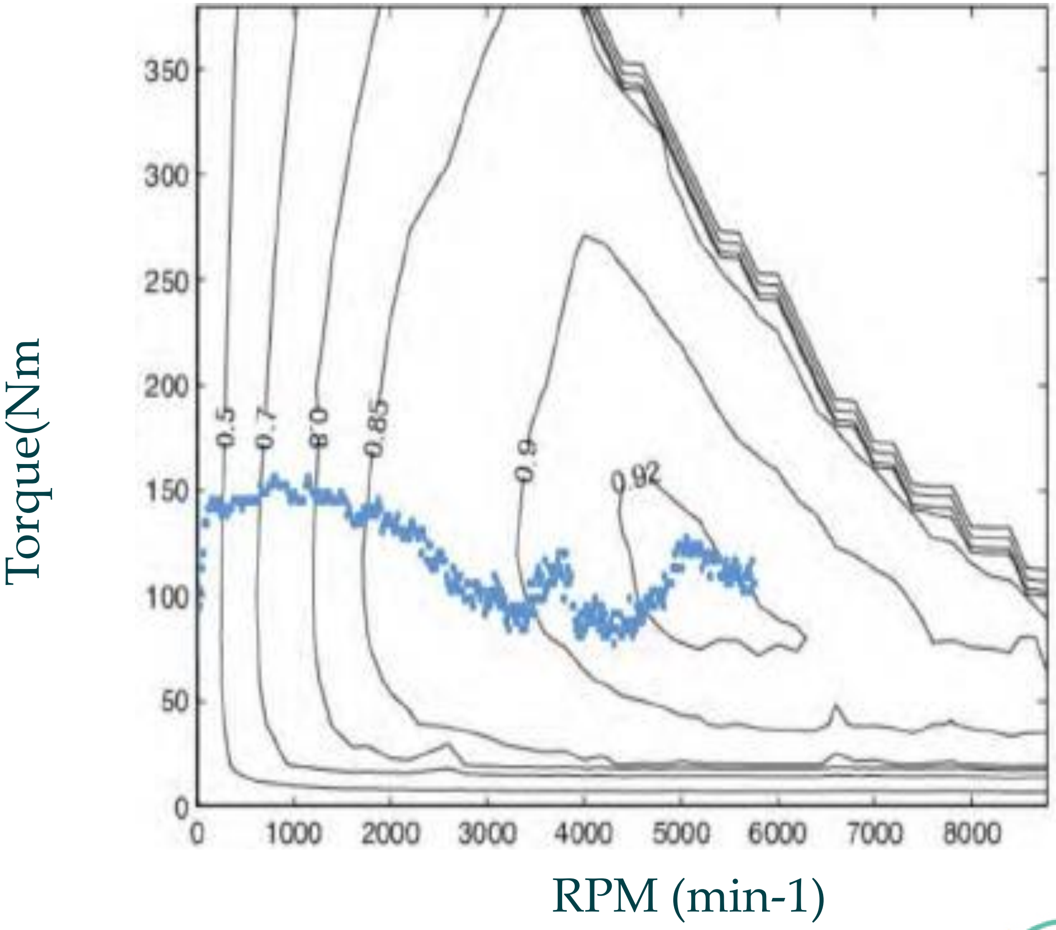


Figure 14

Energy efficiency map (electric motor / inverter)

POLYGON TESTING

• Recommendations

Based on the analysis of the results, the following recommendations were defined:

- In constant speed driving mode, the optimal value of speed is around 35 km/h. This was confirmed by the geometric place of points in the efficiency map.
- In acceleration modes, the accelerator pedal is to be pressed by a continual rate (positive or negative), and its position is not to oscillate. If the desired speed is reached by alternating the increase and decrease in the pedal position, the energy efficiency is far worse, as was confirmed by the tests and proven by geometric place of points in the efficiency map during the acceleration (more points are placed in lower efficiency region), as well as by the effect of rotating masses of drivetrain and transmission, and also the inertia of the whole vehicle. In case the driver accomplishes requested acceleration by continual position change of accelerator pedal, there are no aforementioned oscillations, so the seemingly inefficient cycle of maximum acceleration gives the best effect. Anyways, the stated effect would be even higher if the maximum deflection of the pedal is reached by its continual, and not abrupt change.
- Brake pedal, if the traffic allows, is to be kept in the interval from 0 to 28% of maximum position, which would permit only the regenerative braking in the range up to maximum brake torque of electric motor or generator.
- Energy is recuperated without braking, by means of vehicle inertia (regenerative torque is 34 Nm) in which case the time and length of travel where the energy recuperation occurs is extended.

POLYGON TESTING

- Based on the recommendations for E-bus the ideal cycle between two stops consists of a mode of continuous acceleration and deceleration by inertia and/or braking within the recommended limits.
- This cycle differs from the recommended cycle for a bus with an internal combustion engine, for the same distance traveled
- The recommended driving style implies that the section between the two stops must be approved in order for the cycle to be reported. This can be applied in special lanes (corridor) intended exclusively for buses with prior driver training

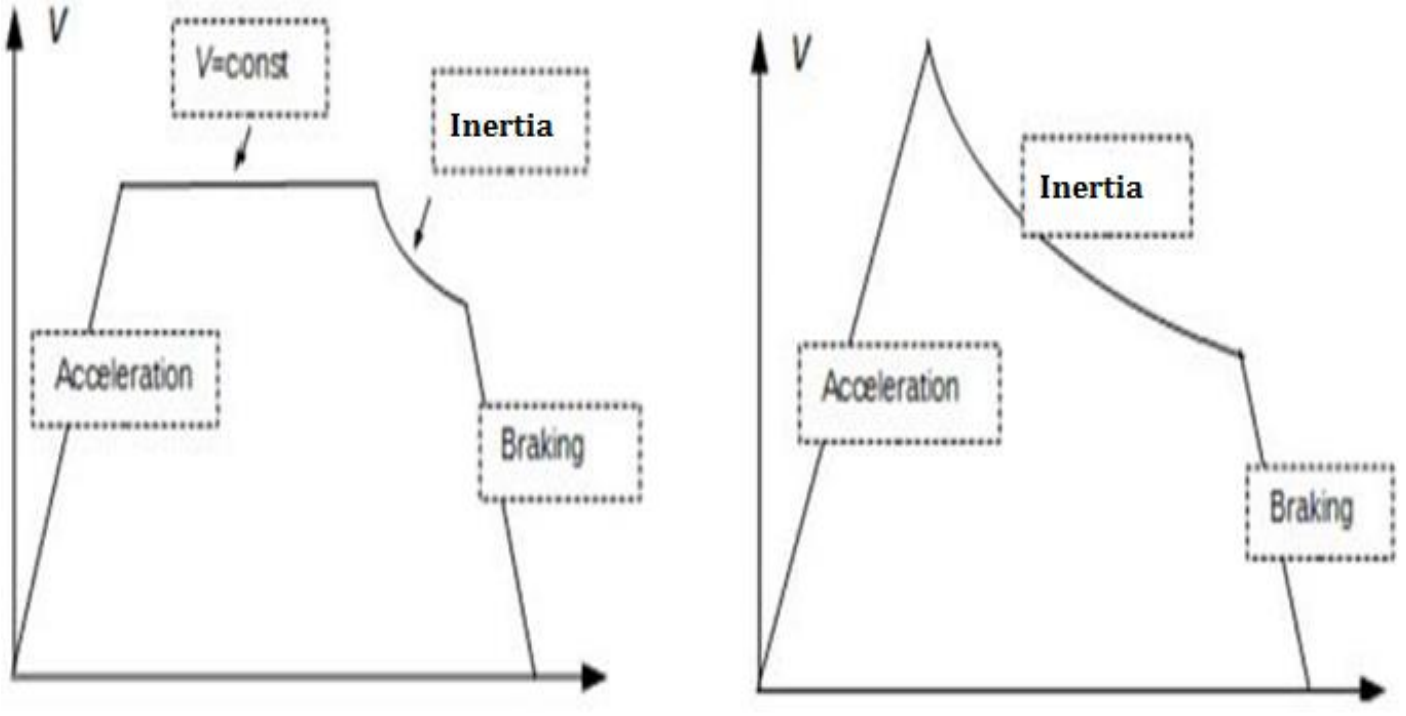


Figure 15 Recommended driving cycle based on speed between two stops for the case of electric bus (right) and internal combustion engine bus (left)

VERIFICATION OF SIMULATION RESULTS

Modelinig and Simulation

- Driving cycle modeling (acceleration, Vmax, V-const, deceleration)
- Technical characteristics E-bus, Higer KLQ6125GEV3
- Fundamentals of vehicle motion theory, Resistance, Power, Energy, calculation
- Specifics of the theory of regenerative braking of E-buses and electricity recovery (generator mode of electric motors)

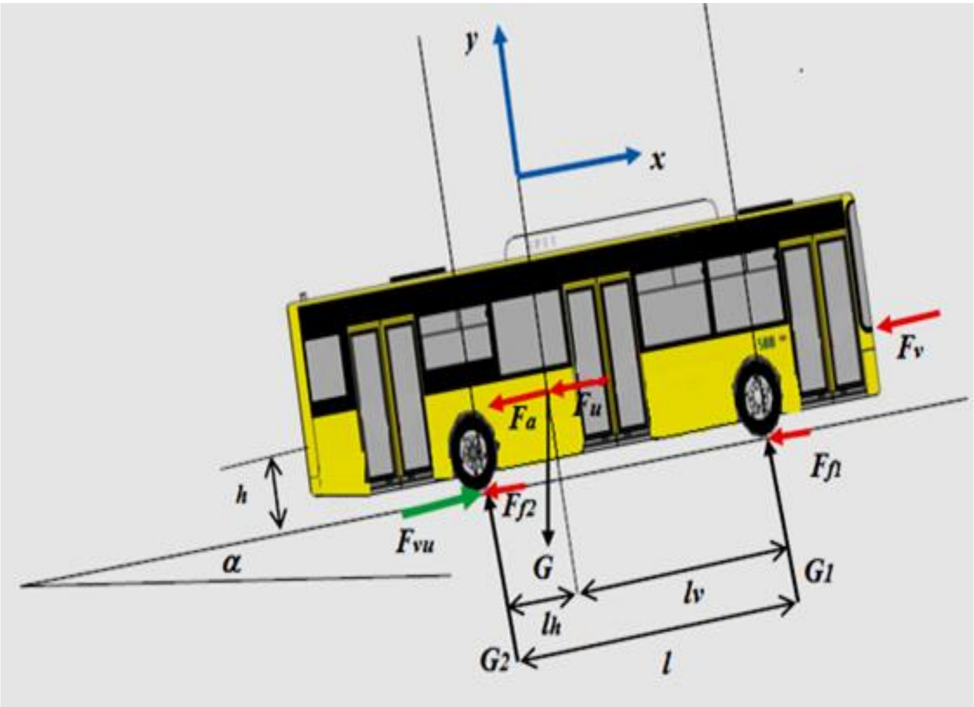


Figure 16 E-bus, Resistances

VERIFICATION OF SIMULATION RESULTS*

*Real driving cycle on poligon, section ''B''

	duration (s)	distance (m)
Acceleration	16.79	126.26
Constant speed, v_{const} =44 km·h^{-1}	3.68	44.94
Braking	15.81	100.69
Total	**36.28**	**271.89**

*Measurement results

v_{max}, km·h^{-1}	44
E_{puc}, kWh	0.4700
E_{ruc}, kWh	0.1390
λ_{uc}, %	29.57

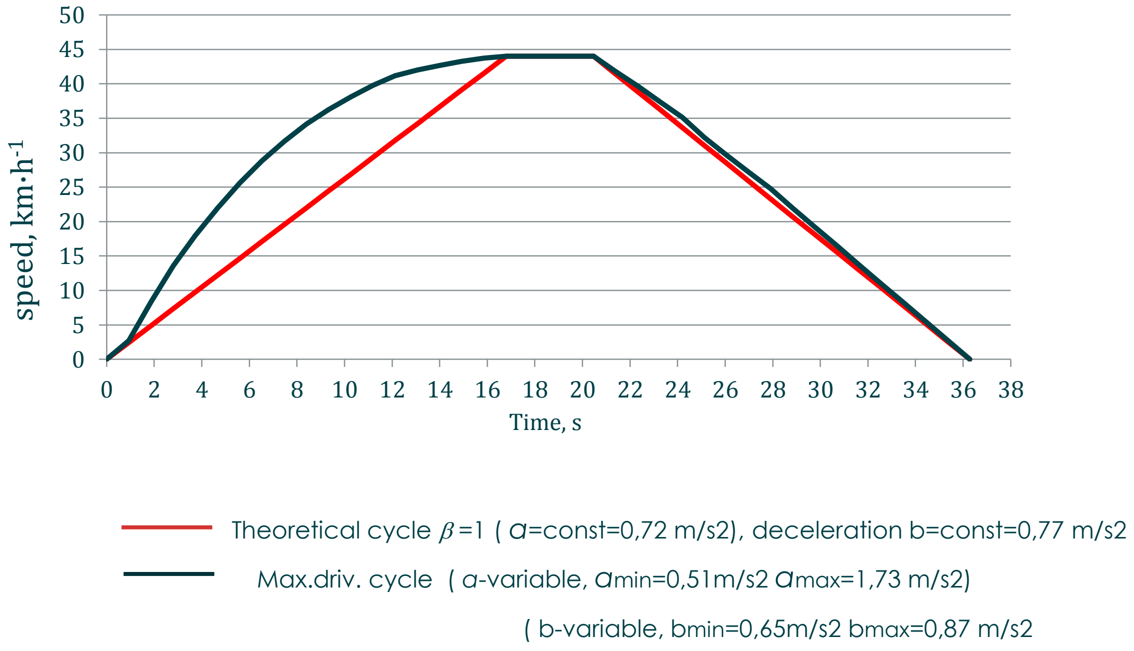


Figure 17

VERIFICATION OF SIMULATION RESULTS

Driving cycles, Simulation*

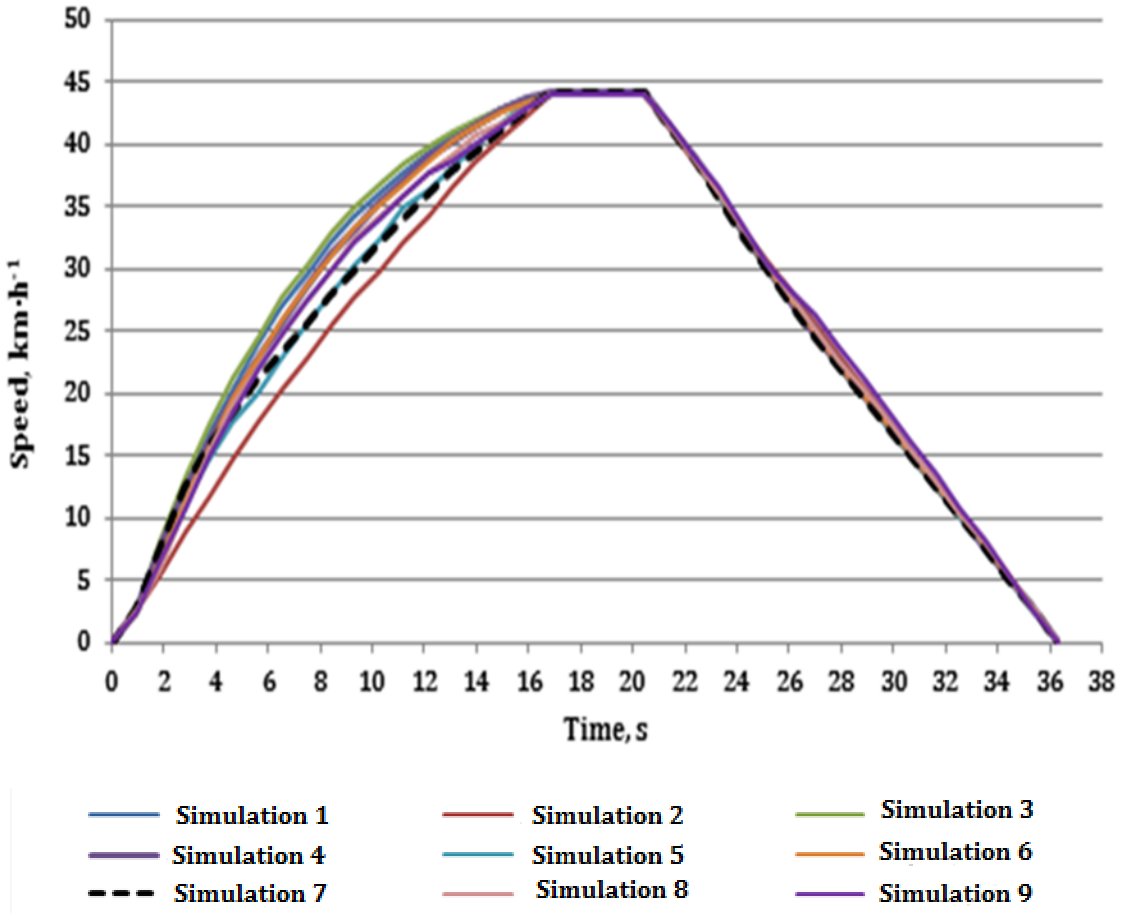


Figure 20 **Simulations***

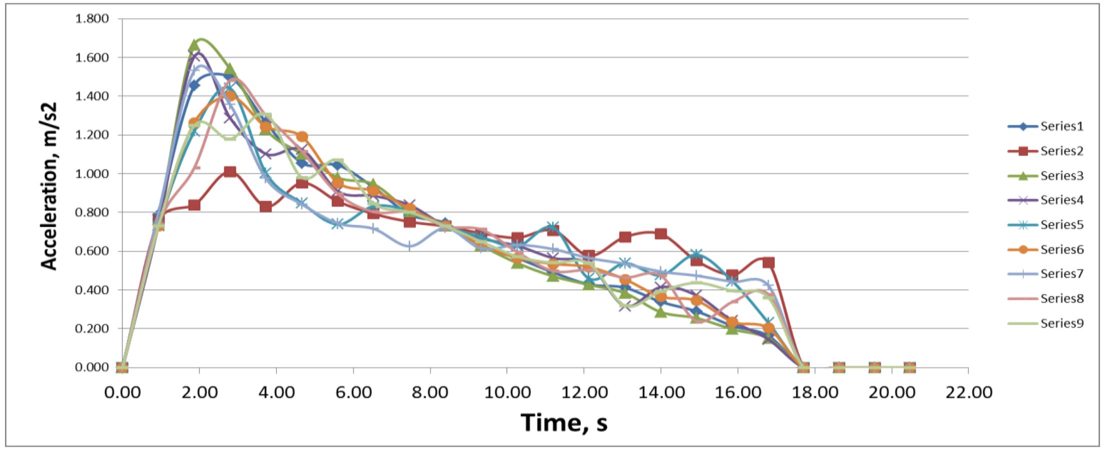


Figure 18 current acceleration, simulation

$$a'_{ebus} = \mathrm{RAND}()\cdot(a_{ebus\ max} - a_{ebus\ min}) + a_{ebus\ min}$$

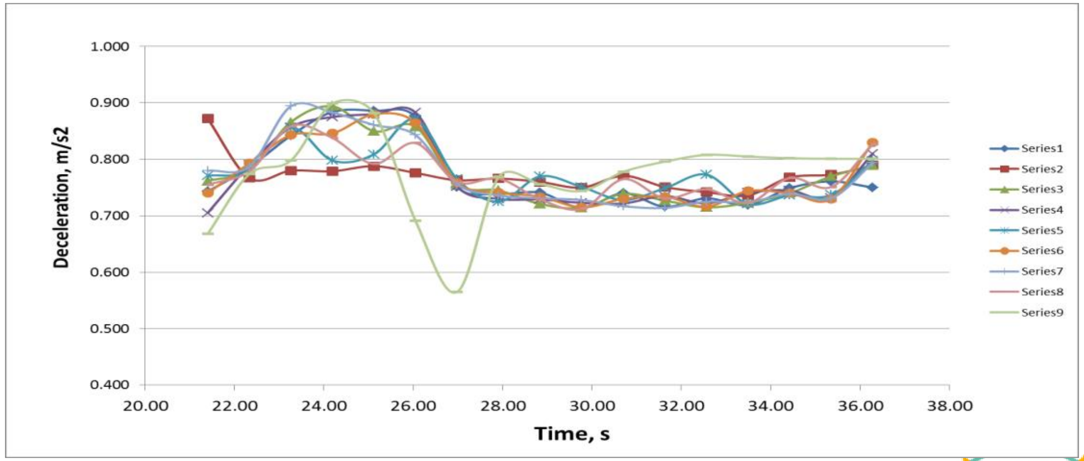


Figure 19 current deceleration, simulation

$$b'_{ebus} = \mathrm{RAND}()\cdot(b_{ebus\ max} - b_{ebus\ min}) + b_{ebus\ min},$$

VERIFICATION OF SIMULATION RESULTS

Results of Simulations*

v_{max}=44 km h^{-1}, υ=-0,7%	Distance m	$E_{p_{uc}}$ kWh	$E_{r_{uc}}$ kWh	λ_{uc} %
Teoretical driving cycle β=1	244,23	0,4608	0,1356	29,43
Max.driving cycle	283,7	0,4716	0,1321	28,01
Simulation 1	271,75	0,4692	0,1375	29,31
Simulation 2	252,83	0,4631	0,1364	29,45
Simulation 3	273,91	0,4699	0,1376	29,28
Simulation 4	269,61	0,4684	0,1371	29,27
Simulation 5	261,45	0,4654	0,1368	29,39
Simulation 6	268,72	0,4681	0,1371	29,29
Simulation 7	260,79	0,4649	0,1379	29,66
Simulation 8	266,11	0,4668	0,1367	29,28
Simulation 9	267,47	0,4665	0,1352	28,98

	Measurement	Simulation "7"
v_{max}, km·h^{-1}	44	44
$E_{p_{uc}}(v_{max})$, kWh	0.4700	0.4649
$E_{r_{uc}}$, kWh	0.1390	0.1379
λ_{uc}, %	29.57	29.66

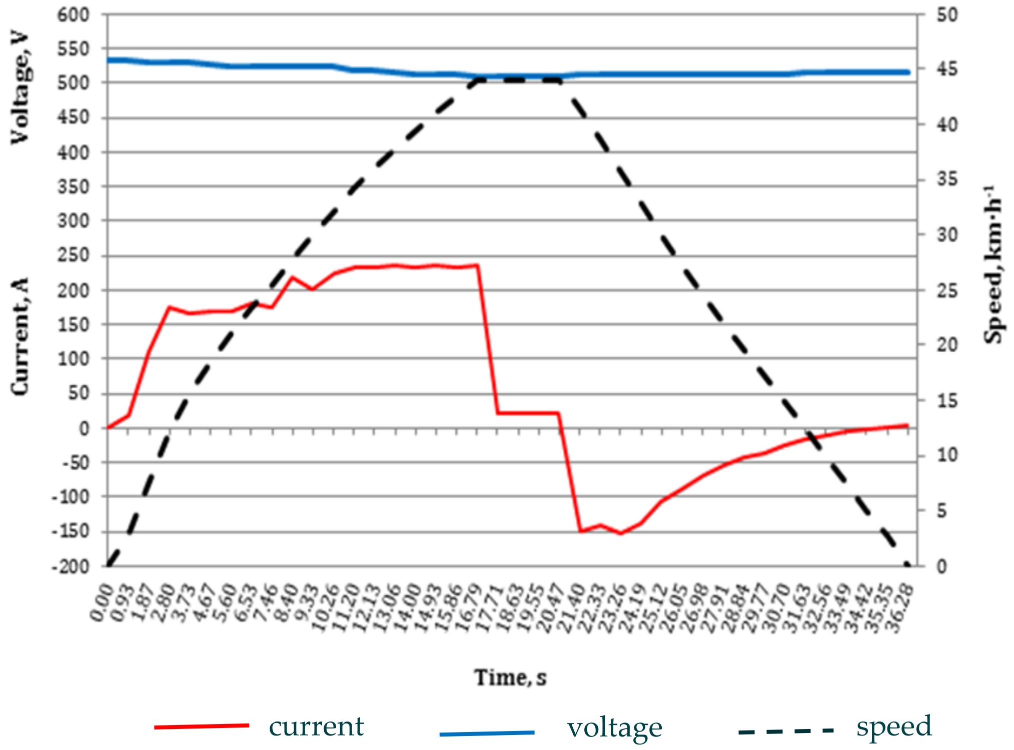


Figure 21 Simulations 7

*Misanovic S.: Energy and environmental performance of E-bus in the passenger transport system, doctoral dissertation, Faculty of Engineering, University of Kragujevac, 2021

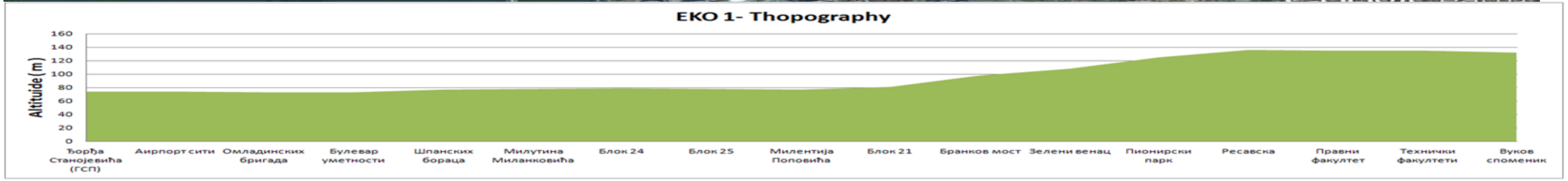
REAL EXPLOITATION

Research of influencing factors on the electricity consumption of E-buses

E-bus, consumers	Impact on consumption:
Electric drive motor	• Driving cycle: (acceleration, speed, number of stations, number of stops • Load (number of passengers in the vehicle) • Topography of the route • Driving style (eco style, moderate, aggressive) • E-bus performances (empty vehicle weight, aerodynamics) • Losses (electric motor, inverter, cables, battery, charger,
Auxiliary devices	• Compressor • Steering pump • Exterior and interior lighting, displays • Low voltage E-bus installation
E-bus heating system	• Seasonal-winter (outside temperature)
E-bus cooling system	• Seasonal-summer (outside temperature)

REAL EXPLOITATION

Line EKO 1 Belgrade



The mean length of the EKO 1 line is 7.98 km. (Direction ''A'' 7,47 km, Direction ''B'' 8.5 km)

The line with a flat configuration with a slight climb

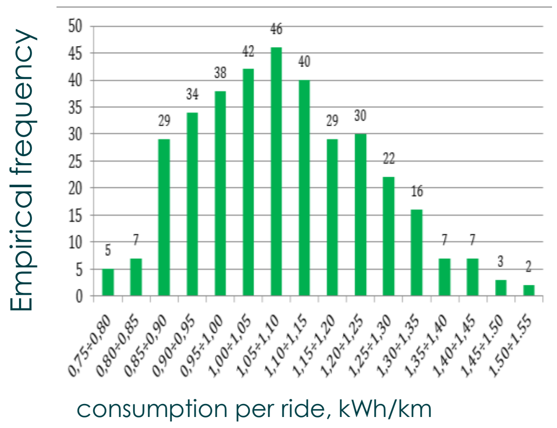
REAL EXPLOITATION

*Review of a sample of E-bus consumption, **

Period	Direction "A"	Direction "B"	Direction "A" + "B"
Spring-autumn	357	347	704
Summer	401	453	854
Winter	397	392	789
Total	**1155**	**1192**	**2347**

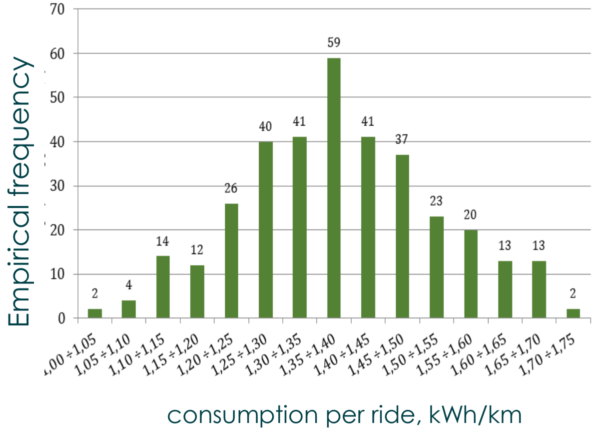
Gauss (normal) distribution

Direction "A"



$\chi^2 = 18{,}247 < \chi^{2(11)}_{0,05} = 19{,}657$

Direction "B"



$\chi^2 = 12{,}901 < \chi^{2(10)}_{0,05} = 18{,}307$

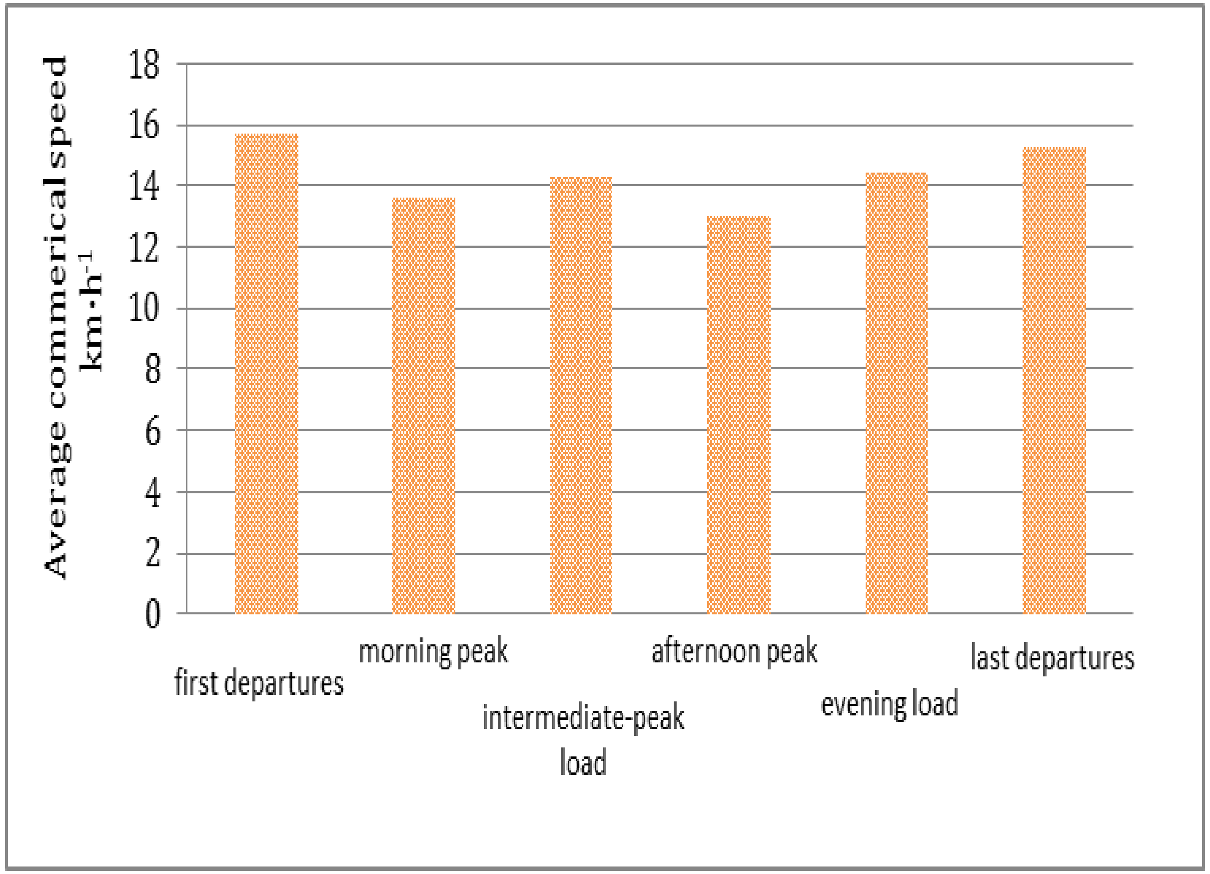
χ^2 – chi square test

*Misanovic S.: Energy and environmental performance of E-bus in the passenger transport system, doctoral dissertation, Faculty of Engineering, University of Kragujevac, 2021

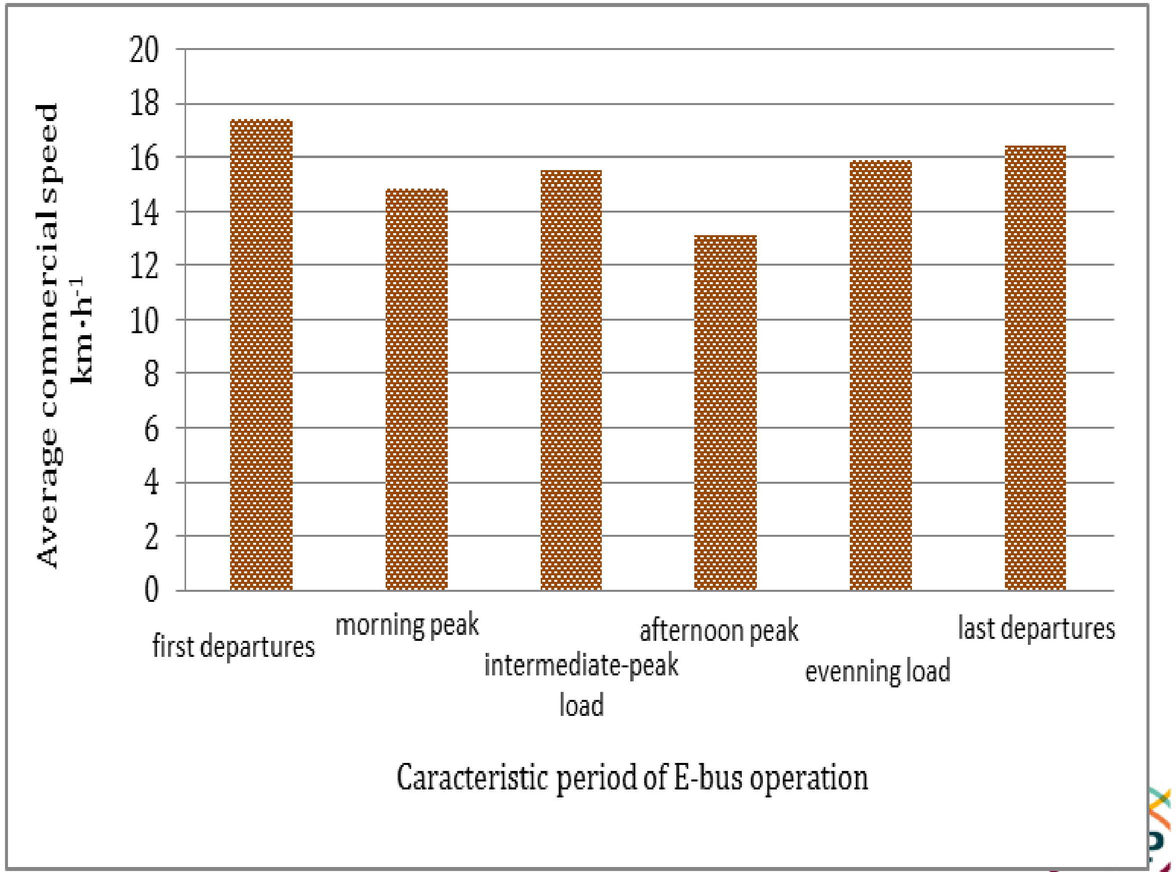
REAL EXPLOITATION

Analysis commercial speed

*Spring-autumn period, direction A, EKO 1 line

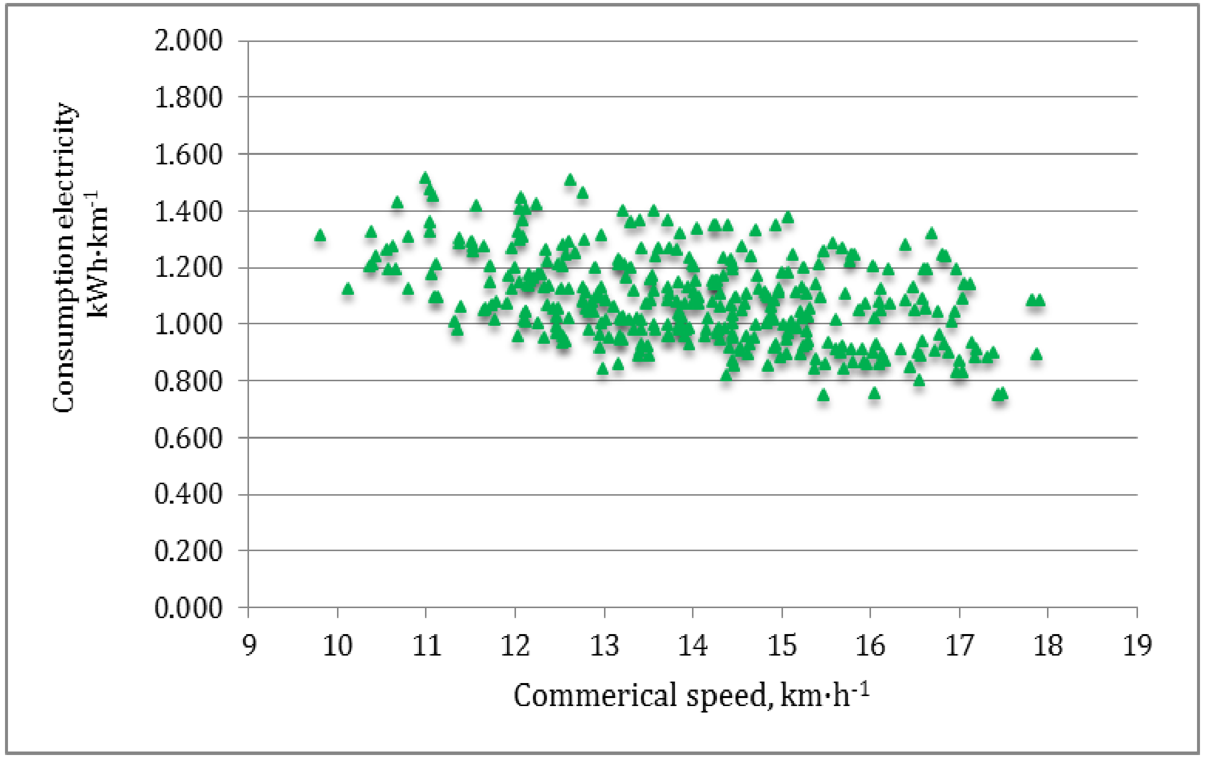


*Spring-autumn period, direction B, EKO 1 line

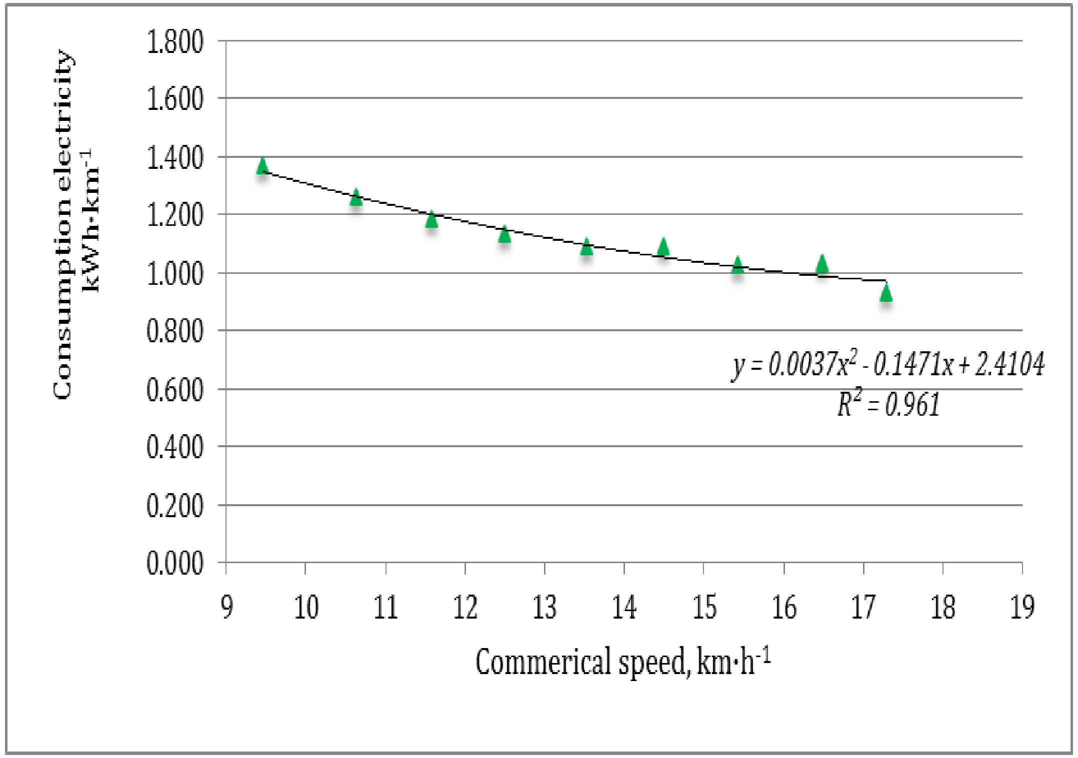


REAL EXPLOITATION

*Electricity consumption and commercial speed of e-bus, direction "A", spring-autumn period

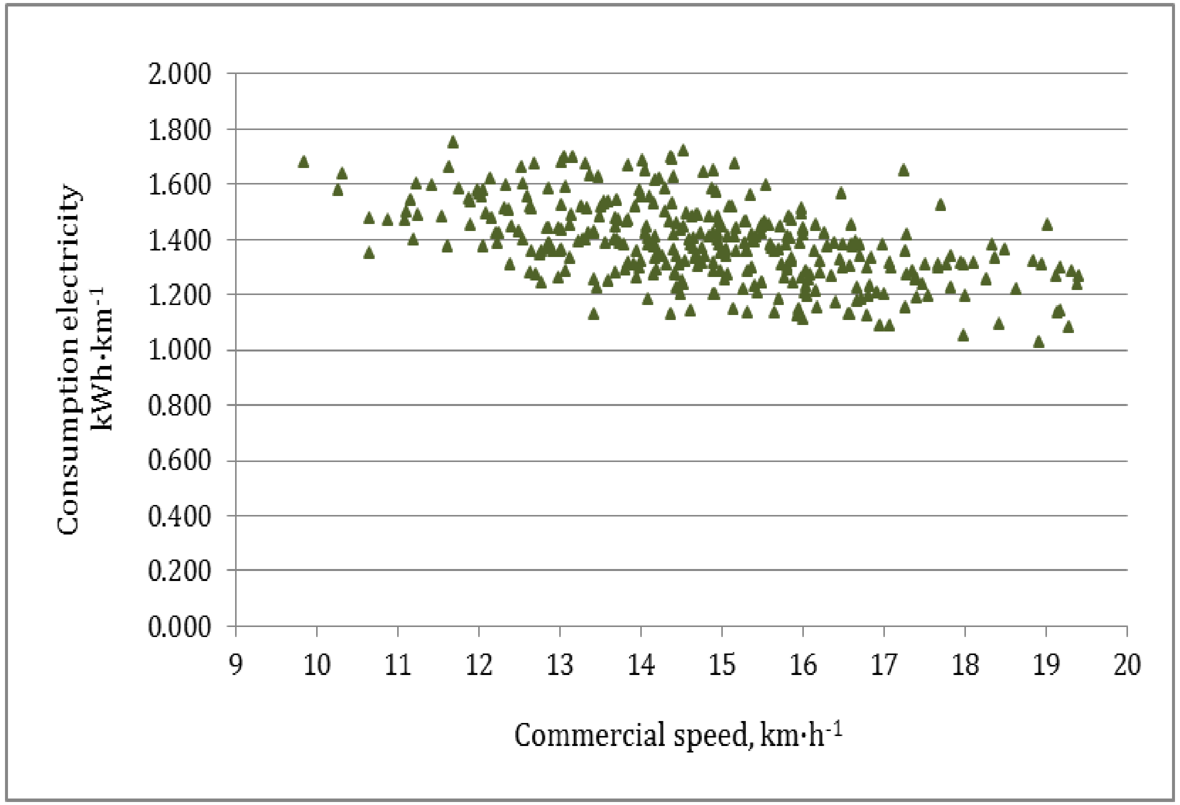


*Dependence of electricity consumption and commercial speed of E-bus, direction "A", spring-autumn period

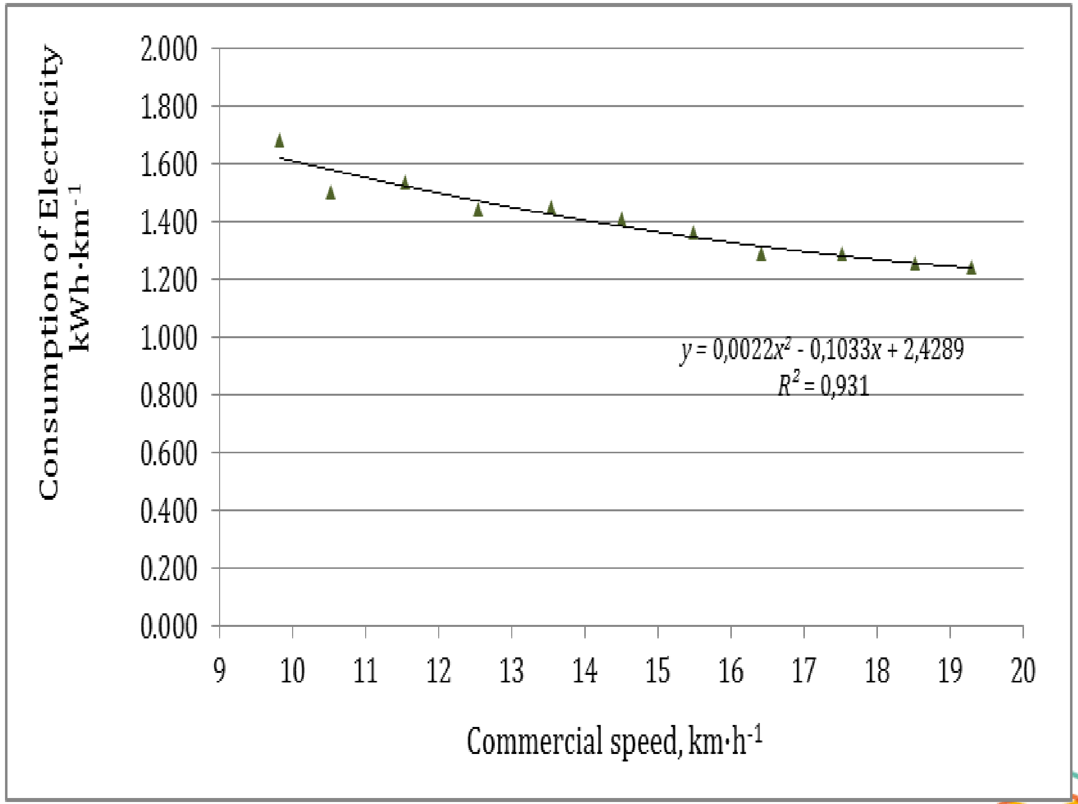


REAL EXPLOITATION

*Electricity consumption and commercial speed, direction „B", spring-autumn period



*Dependence of electricity consumption and commercial speed of E-bus, direction „B", spring-autumn period



UITP

REAL EXPLOITATION

***Average consumption electricity of E-bus, during daily operation, spring-autman period, line EKO 1, Impact (Load+speed+rise/fall) of the route**

Direction ''A''

Caracteristic period of E-bus operation	Sample	'Average consumption electricity of E-bus kWh · km^{-1}
First departures	24	0,943
Morning peak	64	1,112
Intermediate-peak load	81	1,043
Afternoon peak	91	1,209
Evenning load	71	1,049
Last departures	26	0,977
Total	**357**	**1,087**

Direction ''B''

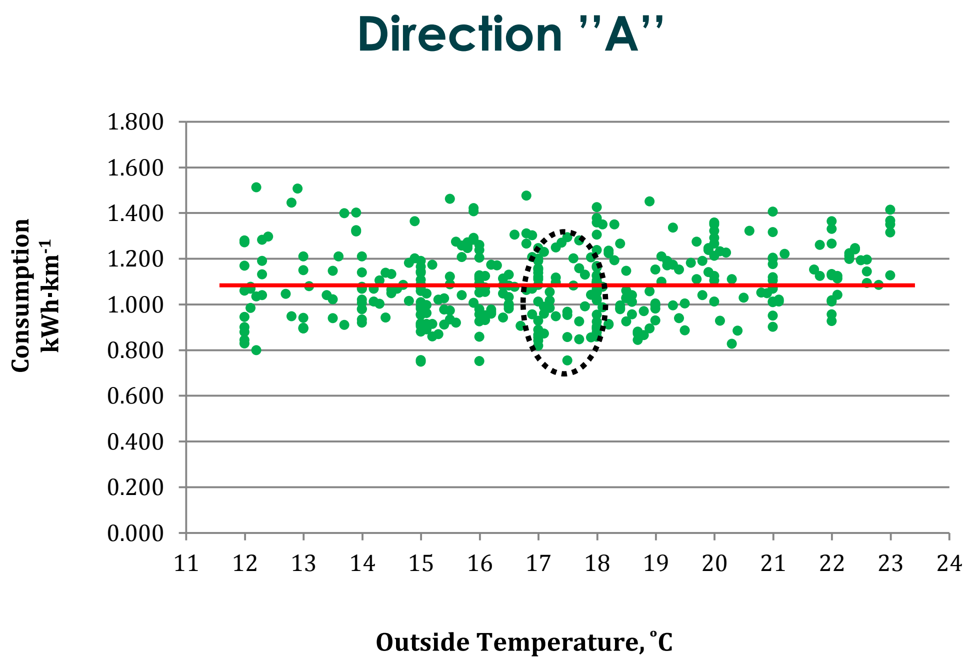
Caracteristic period of E-bus operation	Sample	'Average consumption electricity of E-bus kWh · km^{-1}
First departures	22	1,212
Morning peak	71	1,393
Intermediate-peak load	82	1,354
Afternoon peak	86	1,523
Evenning load	72	1,337
Last departures	14	1,223
Total	**347**	**1,386**

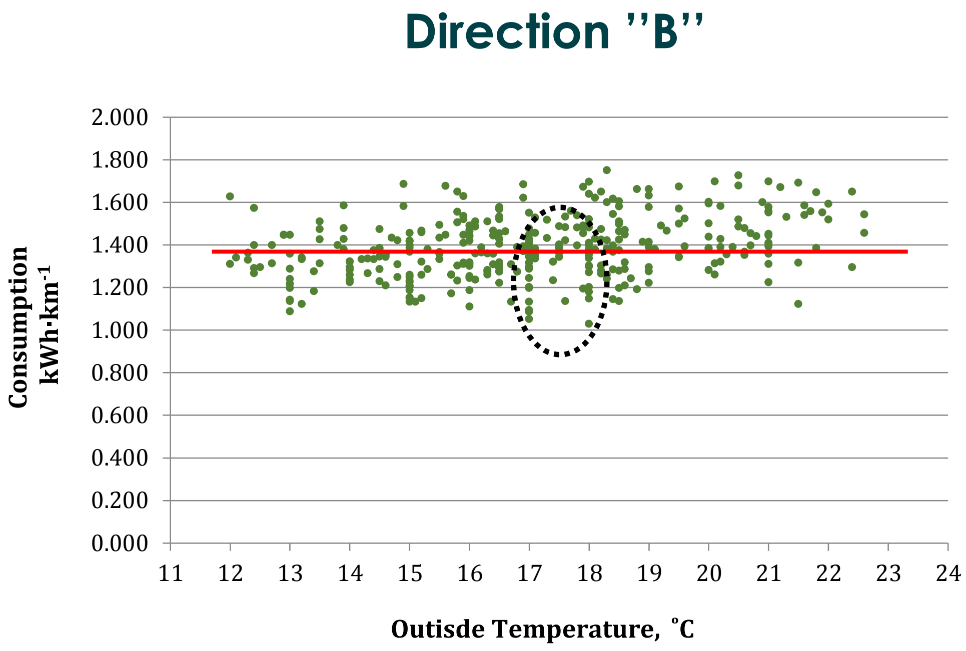
'Average consumption electricity of E-bus, losses in the charging phase are included

UITP

REAL EXPLOITATION

***Spring/autman period, outside temperature and consumption**



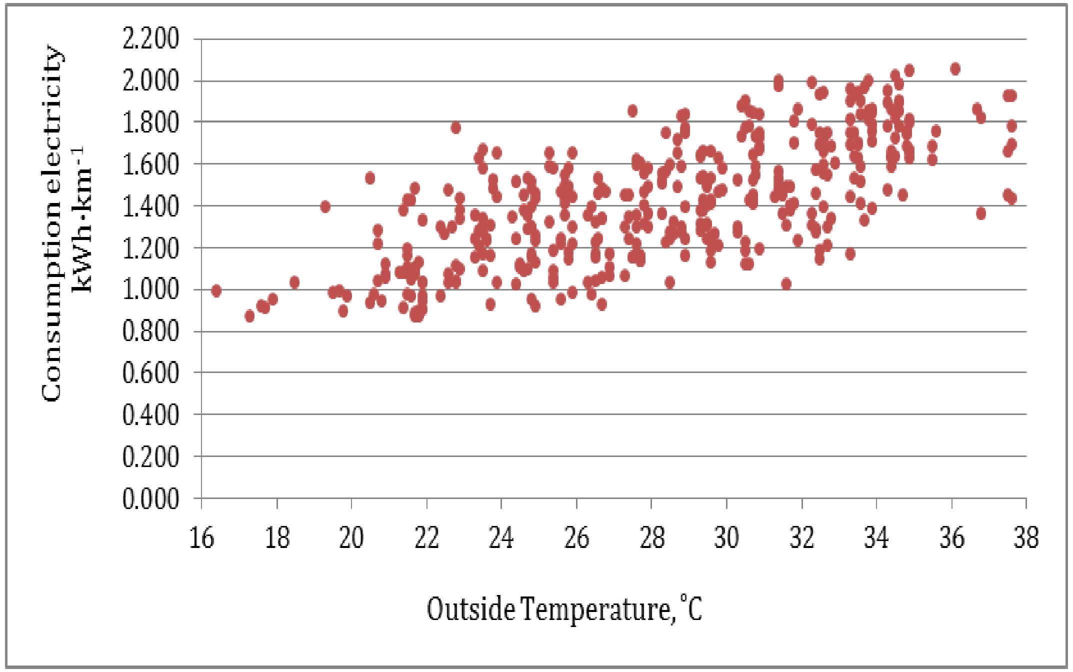


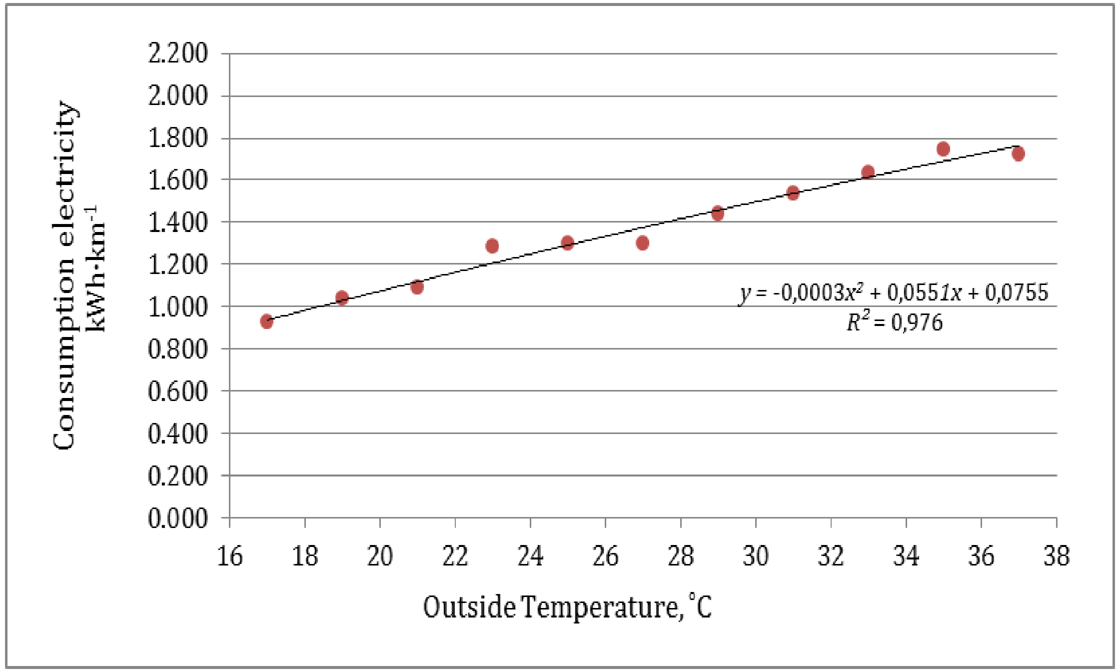
optimal consumption electricity of E-bus, depending on the outside temperature

REAL EXPLOITATION

*Summer period, outside temperatures 16÷38 °C and consumption

Direction ''A''

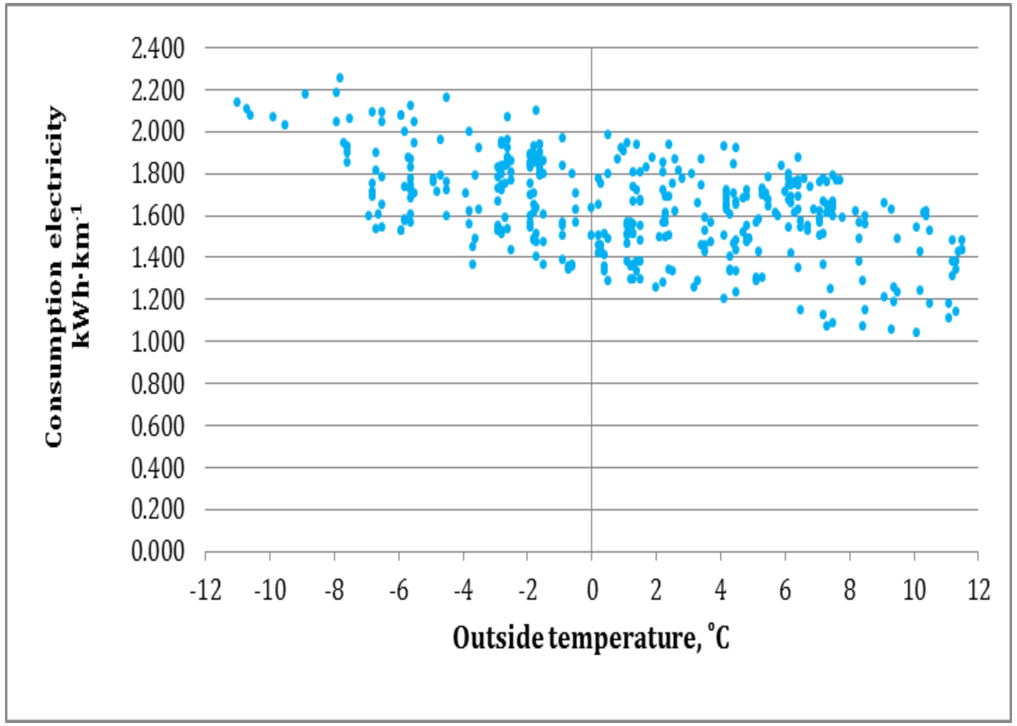


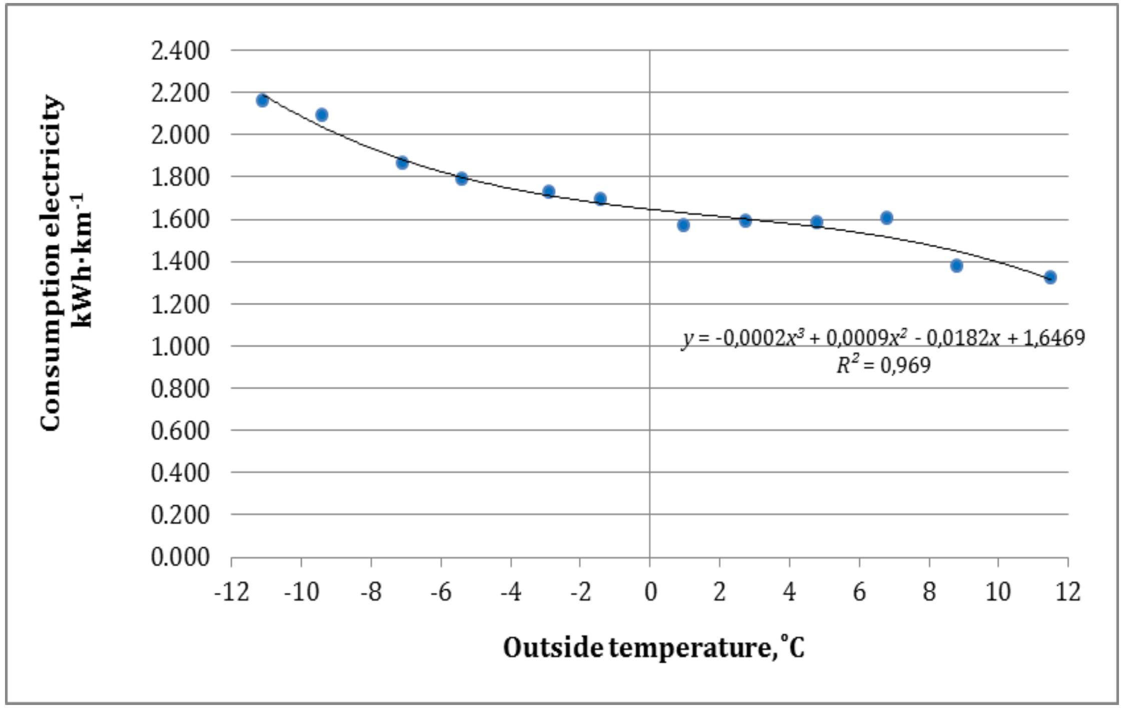


REAL EXPLOITATION

*Winter period, outside temperatures over -12 ÷ 12 °C and consumption

Direction ''A''





REAL EXPLOITATION

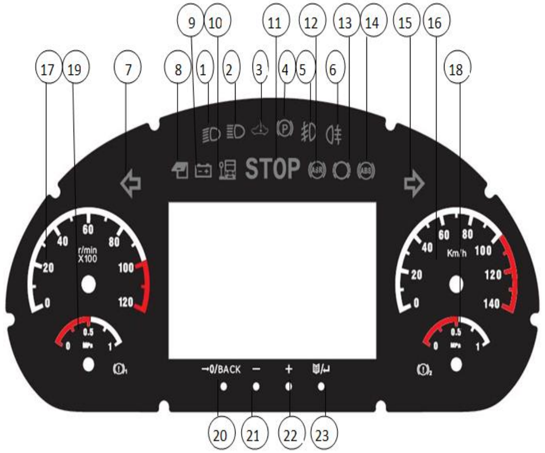
*Auxiliary devices

Electric motor to drive the air compressor

Auxiliary devices	Max.Power [kW]
DC / DC converter, instrument panel low voltage installation 24 V, lighting, signaling, displays	0.9
Air compressor	3.00
Steering hydro pumps	3.00
Total	6.9

Average (all auxiliary devices)	**3.1 – 3.9 kW**

Electric motor for drive steering drive hydro pumps



instrument panel

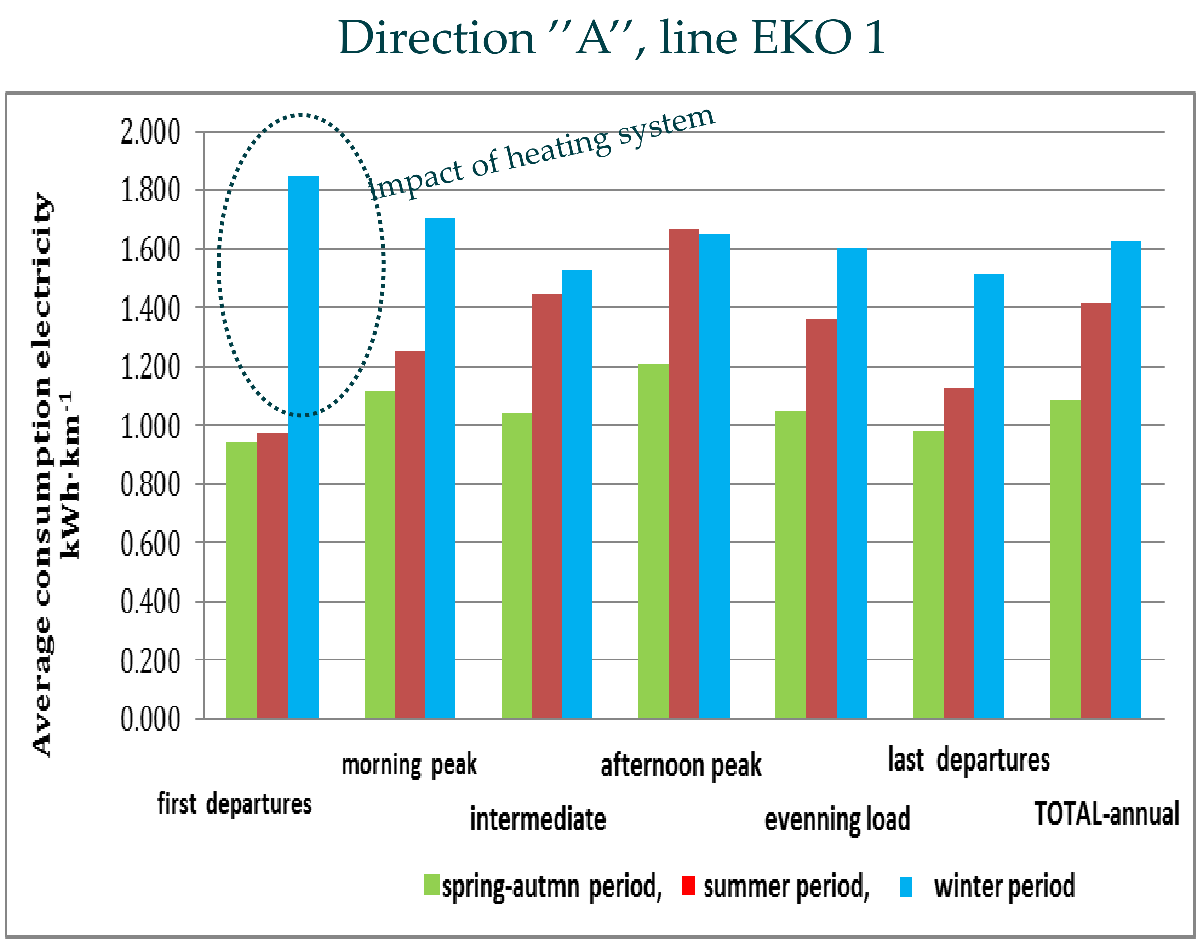
displays

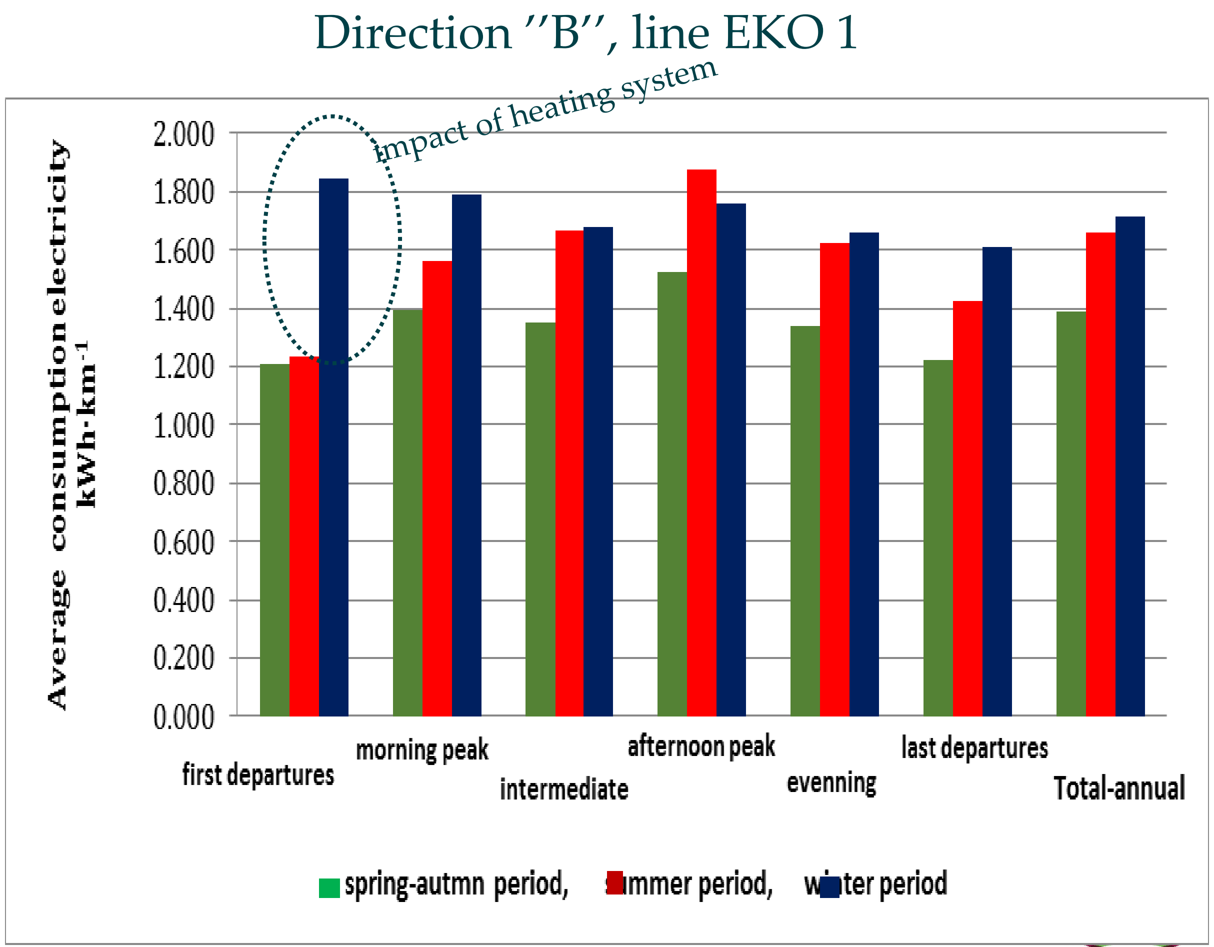
lighting, signaling

displays

REAL EXPLOITATION

*all factors: period of operation, speed, rise/fall, AC, heating...





QUESTIONS?

THANK YOU!