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RESEARCH ON THE EFFECT OF DRIVING STYLE ON ENERGY EFFICIENCY OF ELECTRIC BUSES

EXECUTIVE SUMMARY

UNIVERSITY OF BELGRADE
FACULTY OF MECHANICAL ENGINEERING

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„RESEARCH ON THE EFFECT OF DRIVING STYLE ON ENERGY EFFICIENCY OF ELECTRIC BUSES “

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Secretary, Ph.D. **Jovica Vasiljević,** MSc in Traffic Engineering

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9. Summary

Driving the motor vehicle represents one of the biggest challenges in reducing the harmful effect of the vehicle on the environment, as well as an increase of the energy efficiency of transport. The aforementioned problem does not except the vehicles with an electric drivetrain either. They do not pollute the environment by their exploitation, but, in case the electric energy used comes from non-ecological sources, the inefficient spending of the electric energy cannot be ignored. Apart from that, the energy efficiency of electric vehicles directly affects their range, which represents an important factor in exploitation. In that sense, the research on energy efficiency of electric buses used in public transport is of special importance.
The goal of the project is to determine the driving style by which the energy efficiency of the electric bus with a supercapacitor is improved and the quantity of recovered energy compared to spent energy is increased, as well as the range in real conditions of exploitation on determined public transport route.
The aforementioned goal implies the research on the effect of driving style on recovered energy gained during deceleration of the vehicle by converting kinetic energy to electric, as well as total electric energy spent while driving in different driving styles, both loaded and unloaded. In that sense, the research determines the method of following the operating parameters of the electric bus, and the precise determination of spent and recovered energy. There were over a hundred acceleration, deceleration and constant speed driving modes, for which the chosen driving and vehicle parameters were monitored and processed. Based on the testing carried out on road and proving ground, the recommended driving style was deduced, and it proved to be very efficient in terms of spent and recovered energy. The difference between energy spent in recommended (ecological) and aggressive driving style is between 23% and 30%, depending on route, while the portion of energy recovered while driving in a recommended mode is over 29%, which shows the improvement in energy efficiency. Also, the coasting and movement while braking contributes to the mentioned results. While driving as recommended, the driver achieved to drive over a half a route powered only by inertia of the vehicle.

10. Keywords:
ENERGY EFFIECIENCY, DRIVING STYLE, ELECTRIC BUSES, ENERGY RECOVERY, ENVIRONMENT PROTECTION, CITY OF BELGRADE

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1. About

Keeping in mind that a public transportation company *GSP "Beograd"* has five buses with electric drivetrain in its rolling stock, which commute on route EKO1 from *Vukov spomenik* to *Belville*, Secretariat for Public Transport of City Administration of the city of Belgrade (as a customer) issued an invitation to tender for the project "Research on the effect of driving style on energy efficiency of electric buses". Project implementation was assigned to the Faculty of Mechanical Engineering at the University of Belgrade (as a main contractor) in collaboration with Innovation Center of the Faculty of Mechanical Engineering in Belgrade, with the rights and responsibilities of customer and contractors defined by a signed contract, valid from October 8th, 2019. Activities defined in the contract the executant is obliged to complete are split into two phases, with the deadline of 50 and 35 days, respectively.

- Project staff:

  University of Belgrade, Faculty of Mechanical Engineering – main contractor:
  Ph.D. Ivan Blagojević, MSc in Mechanical Engineering, Project Leader
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  Persons employed by the main contractor on a contract:
  Slobodan Mišanović, MSc in Traffic Engineering
  Slobodan Ivanov, MSc in Electrical Engineering

- Project implementation plan:

The activities in phases 1 and 2 of the project are split between the Faculty of Mechanical Engineering and Innovation Center of the Faculty of Mechanical Engineering in 70:30 proportion in a way defined by a mutual contract. Activity plan for phase 1 (lasting 50 days) and phase 2 (lasting 35) days is shown in Table 1.1, whereas the time of project implementation is divided in weeks.

Table 1.1 Project implementation plan

PHASE 1	Week of implementation (09.11.2019. – 27.12.2019.: total of 50 days)						
Activity	11.11.-17.11.	18.11.-24.11.	25.11.-01.12.	02.12.-08.12.	09.12.-15.12.	16.12.-22.12.	23.12.-27.12.
Analysis of documentation concerning technical specification of E-Bus;	X	X					
Route EKO 1 description and energy efficiency indicators from 2016. to 2018.	X	X					
Definition of representative driving modes taking into account different values of acceleration, speed, deceleration, distance travelled and vehicle load;		X	X				
Definition of measuring method for comsumption and recuperation of electrical energy, as well as measuring acceleration and speed, with the description of measuring equipment to be used in testing;		X	X				
Definition of data analysis method;		X	X				
Testing a single electric bus on a proving ground according to acquired driving cycle with different values of acceleration and deceleration of the vehicle (low, medium and high) which will at that point be defined (with unloaded and loaded vehicle)				X	X		
Acquirement of data on consumed and recuperated energy based on a representative number of measurements for each defined mode				X	X		
After a statistical data evaluation, the proposition of recommended driving style will be done via optimal acceleration and deceleration range, which implies the maximum energy efficiency; Definition of driving styles for real conditions of exploitation to be used in Phase 2						X	X
PHASE 2	Week of implementation (28.12.2019. – 31.01.2020.: total 35 days)						
Activity	30.12.-05.01.	06.01.-12.01.	13.01.-19.01.	20.01.-26.01.	27.01.-31.01.		
Determination of criteria for efficiency control of the driver behavior based on driving style and expected effect on electric energy consumption of E-Bus based on the results from Phase 1	X	X					
Based on determined criteria (during testing of E-Bus on the testing ground), testing is conducted in real conditions of exploitation on the EKO 1 route (Vukov spomenik – Belville). The driver will drive in different styles (ecological, basic, aggressive) in order to verify the results from the proving ground in real conditions			X	X			
Training of drivers who drive the E-Bus with the purpose of using the vehicles more energy efficiently with the minimum electric energy consumption, but according to determined ecological driving style				X	X		
Presentation of results with an emphasis on promoting driving style most acceptable from the aspect of energy efficiency, traffic safety and comfort; After the training, the effects of the decrease in electrical energy consumption in all E-Buses will be tracked.					X		

2. Electric powered bus

There are five electric buses currently in Belgrade, manufactured by HIGER, that use supercapacitors as energy source, which makes up only 0.2% (16% including trolleybuses and trams) of total number of vehicles included in public city transport in Belgrade. Eighty new electric buses are planned to be purchased, which will in turn significantly decrease the air pollution.

Electric bus HIGER KLQ6125GEV3 is an electric vehicle that uses supercapacitor as an energy source and two electric motors SIEMENS 1PV5135-4WS28. Supercapacitor charging can be completed by connecting on a standard electric network as well as by a pantograph (mounted on the vehicle) while the vehicle is in a station or in a garage.

The diagram of energy efficiency versus torque and speed of electric motor is shown in Figure 2.2.

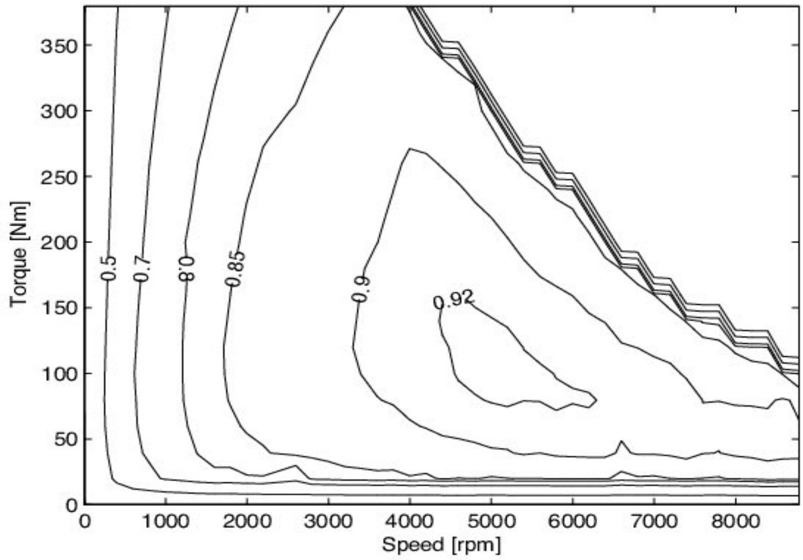

Figure 2.2 Diagram of energy efficiency related to torque and speed of electric motor SIEMENS 1PV5135-4WS28

3. Defining the test methods

3.1 Representative driving modes and loads

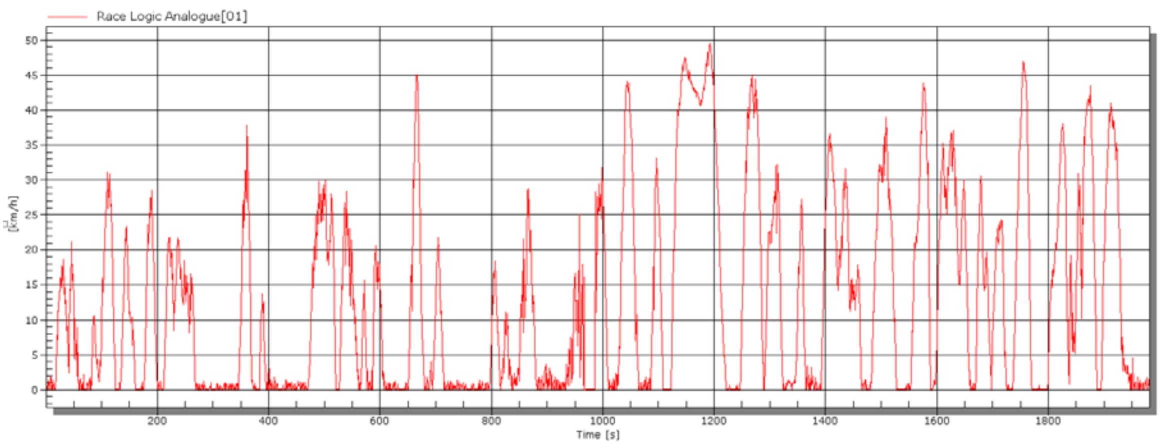

Figure 3.1 Speed of electric-powered bus in real conditions of exploitation with passengers on route EKO 1

Characteristic modes of electric bus testing on a proving ground should cover different accelerations, driving with different constant speed, as well as different decelerations. Before defining the testing modes, different values of speed in realistic driving conditions, with passengers on route EKO 1, were examined (Figure 3.1), where the speed of 40 km/h was rarely exceeded (only while crossing the *Brankov* bridge), based on what, during acceleration, speeds of 35 and 40 km/h may be assumed to be maximum achievable.

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 3.2, several curves were established, each representing the change in speed during time spent to accomplish the same maximum value, defined by equation:

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

where:

- *v,v0,vf – current, initial and final speed [m/s]*
- *t,t0,tf – current, initial and final acceleration time [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.

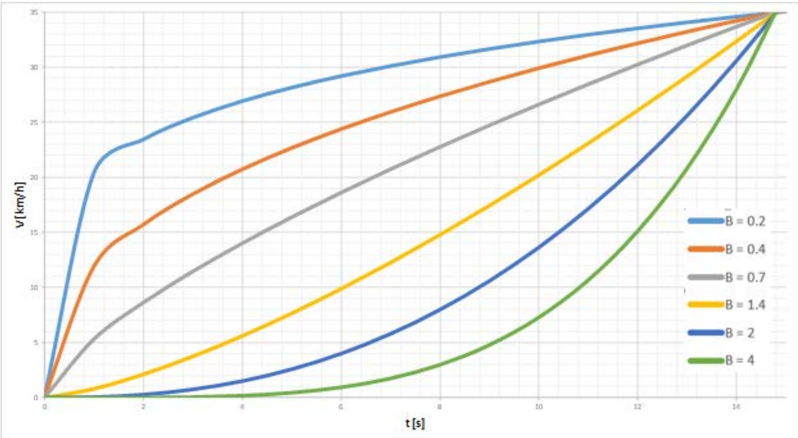

Figure 3.2 – Curves obtained by adopting different values of coefficient β

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.

Constant speed modes

Despite the constant speeds on route EKO 1 being rare, testing is done for different speed values ranging from 25 to 50 km/h, in order to determine constant speed at which the energy efficiency is highest.

Deceleration modes

Low, medium and high deceleration intensity are to be completed, with loaded and unloaded vehicle, in order to determine the amount of recuperated energy for different accelerator pedal positions, loading conditions and speeds before and during the braking process.

Vehicle load

Apart from data acquisition in actual vehicle exploitation, when the vehicle is loaded by passengers in everyday traffic and testing an empty vehicle, trial test is to be completed with a loaded vehicle as well.

The vehicle is to be loaded with 50% of maximum payload, because at that time the load corresponds with SORT cycles, used in determination of energy consumption of buses. 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 3.3). In each mode of testing and load, there are seven examiners in the vehicle as well (total mass of 490 kg).

Keeping in mind that the energy consumption for vehicle motion is to be tested, all other energy consumers need to be eliminated, primarily cooling and heating systems.

Figure 3.3 Simulated bus load during tests

3.2 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_Battery [%]
- Motor torque: ActualDriveMotorTorque [%]
- Accelerator pedal position: APPosition [%]
- Brake pedal position: BrakePedalPosition [%]
- Motor speed: DriveMotorSpeed [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: Ubrzanje 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.

3.3 Determination of consumed and recuperated energy

In order to determine the consumed and recuperated electric energy [kWh], primarily it is required to calculate the power of each electric motor in real time [kW], implying for each measured speed, based on analogously measured current and voltage. Afterwards, the area below the power curve is calculated, which provides the consumed/recuperated energy.

Consumed energy can be perceived for any of the vehicle speeds measured during the cycle. Recuperated energy is calculated for the braking period, which means from the moment the driver pushes the brake pedal up to stopping of any action on brake pedal, based on the difference in the energy consumed by the end of braking and the energy consumed at the start of braking. The start and the end of braking is determined based on the current brake pedal position.

4. Results analysis

During the Phase 1 of the Project, there were three test days: November 15th, December 4th, and December 17th 2019. Beforehand, trial test was enforced to determine the possibility of connecting the acquisition equipment with CAN and monitoring the adequate vehicle parameters, where the data acquisition in real conditions of exploitation on route EKO 1 (in both directions) takes place as well. The data acquisition on route EKO 1 is done in order to confirm the assumptions on choosing the characteristic parameters and perceive in which intervals their values change.

All three tests covered testing in real traffic conditions and proving ground tests according to planned driving cycles. Real traffic conditions testing implied the monitoring of characteristic parameters on the route from *GSP Dorćol* Depot to *GSP Novi Beograd* Depot, where in the reverse direction stopping on the bus stops was simulated. The first testing was done on an unloaded vehicle (only 6 examiners and the driver in the vehicle), while the other two were done with a payload (evenly distributed sand bags).

Tests on proving ground were done on sections “P”, “M”, “B” around *GSP Novi Beograd Depot* near Belville, because the traffic conditions were appropriate. Also, the fast-charge charger availability was crucial in order to repeat the driving cycles with the same state of charge of supercapacitor. Each of the aforementioned sections is specific. The “P” section is completely straight and horizontal (without elevation), “M” section is completely straight and horizontal in the first portion while the second portion is curved and elevated, and the “B” section forms a horizontal curve.

Figure 4.1 Test sections

Planned testing cycles were completed consecutively on each of the sections with several repetitions, implying different states of charge of supercapacitor, taking into account their effect on energy consumption during an adequate monitored cycle.

4.1 Driving with constant speed

One of the important conclusions established based on trial tests in real traffic conditions is that the speed rarely exceeds 35 km/h, and the speed of 40 km/h is reached in cases only while crossing the *Brankov* bridge when the traffic conditions allow. Also, it was concluded that constant speed mode of driving is relatively rare and brief, especially when the traffic is dense. Nevertheless, these modes have to be monitored in order to perceive the speed at which the energy efficiency is highest. The segments monitored closely are those at the constant speed of 30, 35, 40 and 50 km/h, and travelling at those speeds is shown as geometric place of points for which the energy efficiency can be perceived in a diagram versus torque and speed of electric motor (Figures 4.2 to 4.5, respectively). The optimal value of speed based on energy efficiency is 35 km/h, as deduced from the diagrams below.

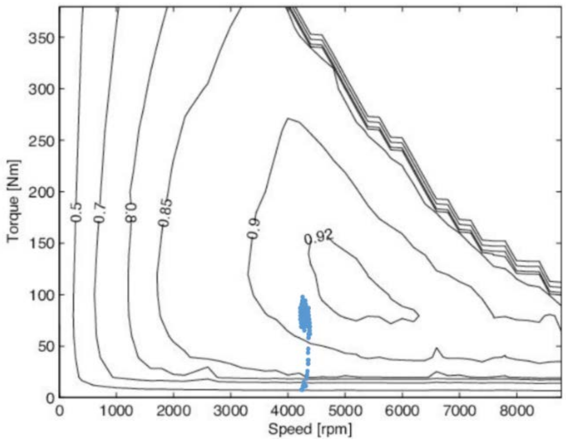

Figure 4.2 Geometrical place of points of energy consumption when V_{const} = 30 km/h

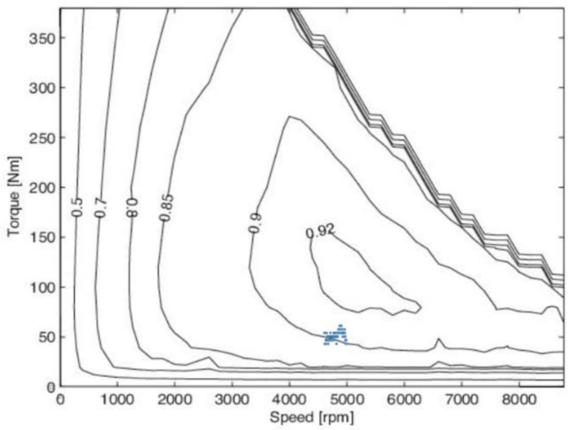

Figure 4.3 Geometrical place of points of energy consumption when V_{const} = 35 km/h

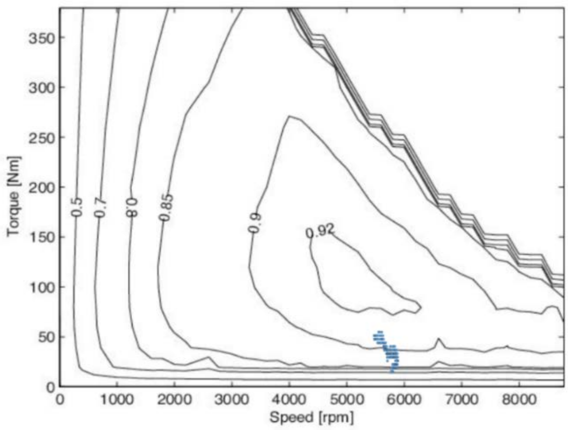

Figure 4.4 Geometrical place of points of energy consumption when V_{const} = 40 km/h

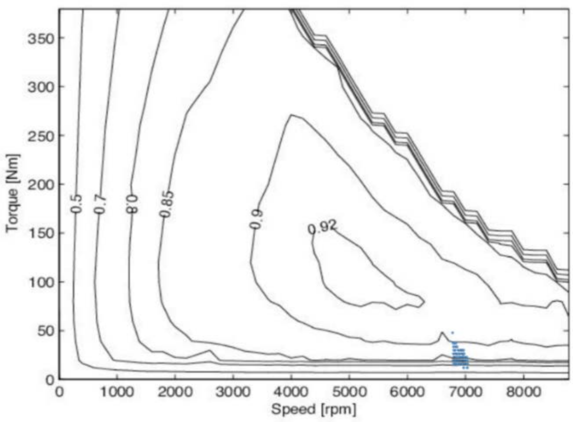

Figure 4.5 Geometrical place of points of energy consumption when V_{const} = 50 km/h

4.2 Cycles of acceleration and deceleration modes

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, with or without braking. 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 supercapacitor is minimized with frequent charging, to exclude the effect of voltage change on the energy consumed.

Based on the monitoring of possible speeds in real conditions of exploitation, as well on deduced conclusion on energy efficiency when travelling at constant speeds, it was recognized that the maximum speed to accelerate to is 40 km/h, so the analysis of acquired results was done both for mentioned speed and for the speed of 35 km/h, which proved to be the most efficient considering the energy consumption.

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, the diagrams for 6 chosen characteristic cycles (out of total of 27) on last testing with loaded vehicle are made, with maximum speed of 40 km/h. Each diagram is marked with a number from 1 to 27, section mark, total consumed energy until 35 km/h – E_{pot35} [kWh], total consumed energy to 40 km/h – E_{pot40} [kWh], total recuperated energy – E_{reg} [kWh], as well as value of voltage of supercapacitor at the start and at the end of a cycle – U_p, U_k [V]. Also, the value of β coefficient is given. For easier consideration, aforementioned information for chosen cycles are given in Table 4.1. Important parameters for the analysis are shown in diagrams: acceleration pedal position – *APP* [%], supercapacitor current - *I_UC* [A], vehicle speed - *V* [km/h], electric motor torque - *OM* [Nm], consumed and recuperated energy of each electric motor - *E/10* [kWh /10] and brake pedal position - *BPP* [%]. Acceleration modes with lowest and highest value of consumed energy are shown also using geometric place of points needed to perceive energy efficiency on a diagram of torque versus electric motor speed.

By considering different acceleration modes on the same section, it can be concluded that the biggest difference between minimum and maximum consumed energy when accelerating to 35 km/h is 14.7% (27/B : 9/B), which implies that different energy consumed can be achieved with different acceleration modes. Supercapacitor voltage decreased by the mean value of 18.45 V, but during testing, between the charging, its value fluctuated between 576 V (after charging) and 516 V, which means no more than 10%. This is important because starting value of supercapacitor voltage affects the value of energy consumed. The method of taking measurements is validated by the fact that for the acceleration modes that are mutually comparable using β coefficient (for values 0.7, 0.85 and 1.4), on section "B", there was always less energy consumption, whilst other two sections were quite similar in that way.

Table 4.1 Cycle overview

Cycle number/ section	Energy consumed until speed of 35 km/h [kWh]	Energy consumed until speed of 40 km/h [kWh]	Energy recuperated during braking [kWh]	Supercapacitor voltage in the beginning (U_{UCp}) and in the end (U_{UCk}) of cycle [V]	Parameter of characteristics of acceleration [-]
2/M	E_{pot35} = 0.298	E_{pot40} = 0.379	E_{reg} = 0.113	U_{UCp}, U_{UCk} = 569, 548	β ≈ 0.7
3/B	E_{pot35} = 0.283	E_{pot40} = 0.382	E_{reg} = 0.101	U_{UCp}, U_{UCk} = 561, 540	β ≈ 0.7
5/M	E_{pot35} = 0.311	E_{pot40} = 0.391	E_{reg} = 0.109	U_{UCp}, U_{UCk} = 570, 551	β ≈ 0.85
6/B	E_{pot35} = 0.293	E_{pot40} = 0.395	E_{reg} = 0.125	U_{UCp}, U_{UCk} = 563, 547	β ≈ 0.85
8/M	E_{pot35} = 0.313	E_{pot40} = 0.399	E_{reg} = 0.095	U_{UCp}, U_{UCk} = 554, 533	β ≈ 0.85
9/B	E_{pot35} = 0.309	E_{pot40} = 0.389	E_{reg} = 0.094	U_{UCp}, U_{UCk} = 546, 526	β ≈ 0.85
10/P	E_{pot35} = 0.306	E_{pot40} = 0.395	E_{reg} = 0.114	U_{UCp}, U_{UCk} = 575, 560	β ≈ 0.85
11/M	E_{pot35} = 0.306	E_{pot40} = 0.402	E_{reg} = 0.116	U_{UCp}, U_{UCk} = 571, 554	β ≈ 0.85
12/B	E_{pot35} = 0.299	E_{pot40} = 0.387	E_{reg} = 0.105	U_{UCp}, U_{UCk} = 565, 544	β ≈ 0.85
13/P	E_{pot35} = 0.310	E_{pot40} = 0.410	E_{reg} = 0.093	U_{UCp}, U_{UCk} = 576, 560	-
14/M	E_{pot35} = 0.299	E_{pot40} = 0.386	E_{reg} = 0.121	U_{UCp}, U_{UCk} = 573, 553	β ≈ 1.4
15/B	E_{pot35} = 0.280	E_{pot40} = 0.374	E_{reg} = 0.113	U_{UCp}, U_{UCk} = 567, 546	β ≈ 1.4
16/P	E_{pot35} = 0.297	E_{pot40} = 0.384	E_{reg} = 0.125	U_{UCp}, U_{UCk} = 560, 540	β ≈ 1.4
19/P	E_{pot35} = 0.302	E_{pot40} = 0.388	E_{reg} = 0.113	U_{UCp}, U_{UCk} = 576, 557	β ≈ 1.4
21/B	E_{pot35} = 0.282	E_{pot40} = 0.363	E_{reg} = 0.084	U_{UCp}, U_{UCk} = 567, 547	β ≈ 1.4
23/M	E_{pot35} = 0.301	E_{pot39} = 0.414	E_{reg} = 0.046	U_{UCp}, U_{UCk} = 558, 551	-
24/B	E_{pot35} = 0.294	E_{pot40} = 0.399	E_{reg} = 0.117	U_{UCp}, U_{UCk} = 551, 532	-
25/P	E_{pot35} = 0.291	E_{pot40} = 0.376	E_{reg} = 0.094	U_{UCp}, U_{UCk} = 545, 527	β ≈ 0.7
26/M	E_{pot35} = 0.290	E_{pot40} = 0.381	E_{reg} = 0.045	U_{UCp}, U_{UCk} = 542, 523	β ≈ 0.7
27/B	E_{pot35} = 0.270	E_{pot40} = 0.367	E_{reg} = 0.139	U_{UCp}, U_{UCk} = 535, 516	β ≈ 0.7

Comparation of the results shown in the Table 4.1 concerning consumed energy during acceleration on the basis of β coefficient, it can be concluded that the minimum energy is consumed with $\beta \approx 0.7$, which meets the maximum displacement of accelerator pedal. Based on energy consumption, cycles with $\beta \approx 1.4$ follow, which is the case where acceleration value gradually increases with time (concave speed curve), while the cycles with $\beta \approx 0.85$ were the least energy efficient. Also, when there is no gradual but oscillating increase/decrease in accelerator pedal displacement, energy consumption increases. This can be explained with the effect of inertia of rotating masses of drivetrain and transmission, but also the inertia of the vehicle as a whole. Oscillating displacement of accelerator pedal negatively affects the energy consumption. In such way the differences in consumption for different cycles with similar β value on the same section can be explained. In fact, in case the driver accomplishes requested acceleration by continual position change of accelerator pedal, the consumed energy would also decrease. However, if the requested speed is reached by alternating increase and decrease of accelerator pedal position, energy consumed is higher.

In case the driver keeps accelerator pedal position at maximum, there are no oscillations, so that seemingly energetically inefficient mode of maximum acceleration gives the best outcome.

In any case, that effect would be even higher if the maximum position of accelerator pedal is reached by its continual, and not abrupt alteration.

Graphs of change of adequate parameters over time, as well as geometric place of points of energy consumed when accelerating are given on following Figures 4.6, 4.7 and 4.8, respectively, in an energy efficiency map for most economical and non-economical cycle for each of the sections “P”, “M” and “B” of the proving ground. Acceleration modes are especially interesting to perceive in energy efficiency map, via geometric placing of points of dependence of torque and speed during acceleration, where the efficiency can be observed. Although with intense acceleration the point path does not obtain the shortest distance to the area of highest energy efficiency (0.92), the points will concentrate there more (e.g. 27/B), which means there will be no concentration of points in area of lower energy efficiency, as it can be seen in 8/M and 9/B. Also, aforementioned effects of oscillating displacement of accelerator pedal can be seen in the same map on the example of a cycle 13/P which was quite inefficient on the basis of consumed energy.

Concerning the energy recuperated by braking from 40 km/h until the stop (not taking into account the energy recuperated without braking – by means of inertia), its maximum value is 0.14 kWh (27/B), and minimum value is 0.045 kWh (26/M). Large differences can be explained with a large spectrum of applied means of braking in cycles, which can be differentiated on the diagrams: from very intensive braking (8/M), over controlled extended braking (27/B), to abrupt braking (26/M). Torque of electric motor or generator defining recuperated energy can be seen to increase with the change of displacement of brake pedal (%) just until the certain (maximum) value on more diagrams, so that with an intense braking (greater brake pedal displacement) there is a shorter stopping distance but not greater energy recuperation. In other words, extended braking with smaller deflection of brake pedal ensures greater energy recuperation, and in turn more efficient use of regenerative braking. The real evidence for that is already mentioned cycle 27/B. Brake pedal, if the traffic allows, should be kept in the interval from 0 to 9°, which means 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.

One cycle represents the section consisting of acceleration and deceleration modes. If one looks at it that way, cycle 27/B is the most energy efficient with the energy consumed for reaching the 40 km/h being 0.37 kWh and energy recuperated being 0.14 kWh, with 38% of recuperated energy. By combining the optimal (recommended) acceleration mode with an optimal (recommended) deceleration mode, one can get energy efficient cycle of travel between two stops.

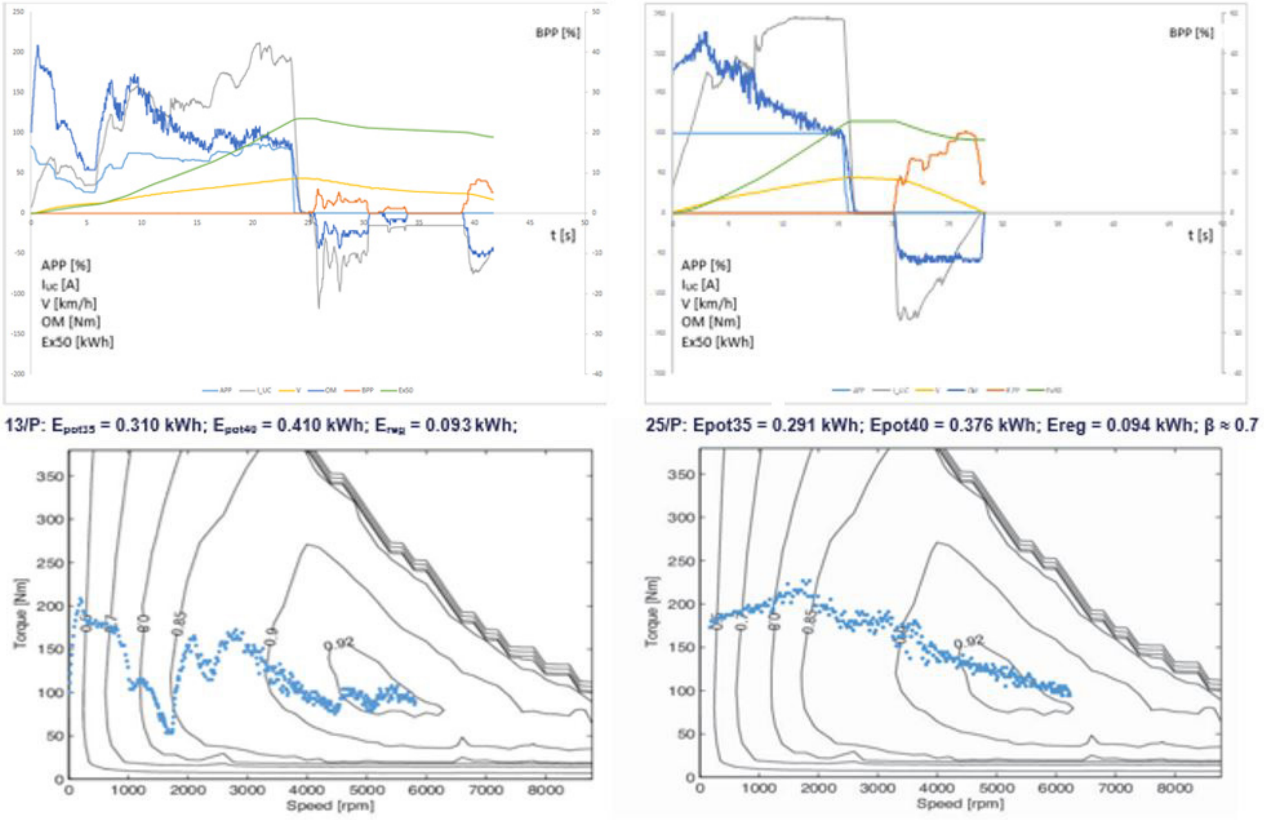

Figure 4.6 Graphs of least efficient (left) and most efficient (right) cycle for the section "P" of the proving ground

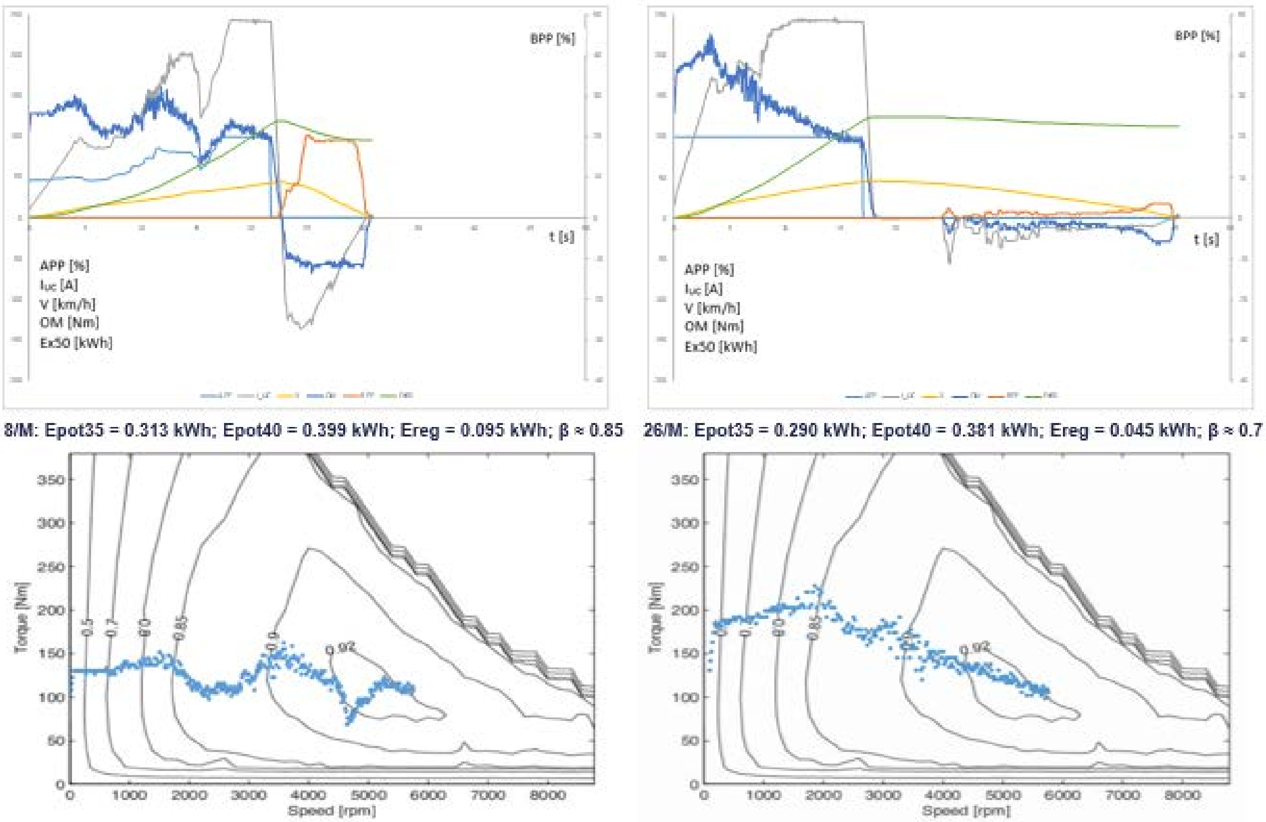

Figure 4.7 Graphs of least efficient (left) and most efficient (right) cycle for the section "M" of the proving ground

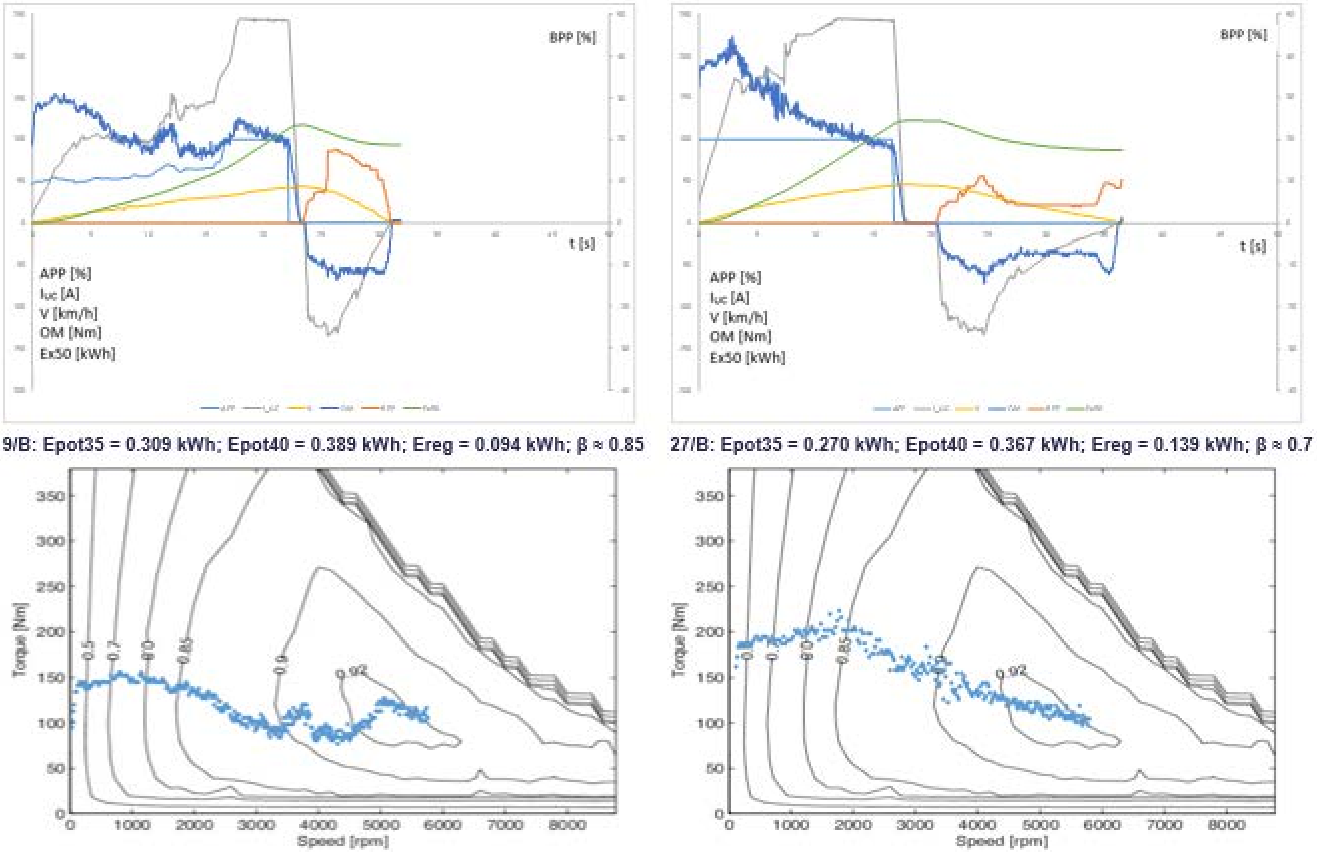

Figure 4.8 Graphs of least efficient (left) and most efficient (right) cycle for the section "B" of the proving ground

4.3 Recommendations

Based on the analysis of the results carried out and shown in the first phase of the project, 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 9°, which means 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, too, by means of vehicle inertia, in which case the time and length of travel where the energy recuperation occurs is extended.

Based on recommendations, the ideal cycle between two stops consists of continual acceleration mode and deceleration by inertia and/or braking in recommended limits (Figure 4.9 right). For small amount of

acceleration and maximum speed of 50 km/h, distance travelled is 500 m, also 350 m for maximum speed of 40 km/h. This cycle is different from recommended cycle for the bus with an internal combustion engine, for the same distance travelled (Figure 4.9 left).
Recommended driving style implies that on a section between two stops it has to be granted for the cycle to be possible to be carried out. In that way, observing the space in front of the vehicle and to the next stop is very important requirement for the driver. Thus the start of motion, especially on sections of privileged public transport traffic ("yellow lane"), can be deferred until sufficient space is freed.

The route EKO 1 has only one section (with no turns) between two stops that can be longer than 500 m if the traffic allows. That is the section on the *Brankov* Bridge. On such section, in the direction towards *Novi Beograd*, from the last stop before the bridge to the first traffic light after the bridge, the distance of 960 m can be covered based on the given recommendation. After accelerating to 50 km/h on the shorter part of the section with minor elevation, follows the longer part of the section with a downhill slope, which can be fully covered by coasting, and the energy can be recuperated the whole time. In other direction, larger part of the stated section is an uphill slope that needs to be covered by establishing the constant speed, recommended for that travelling mode.

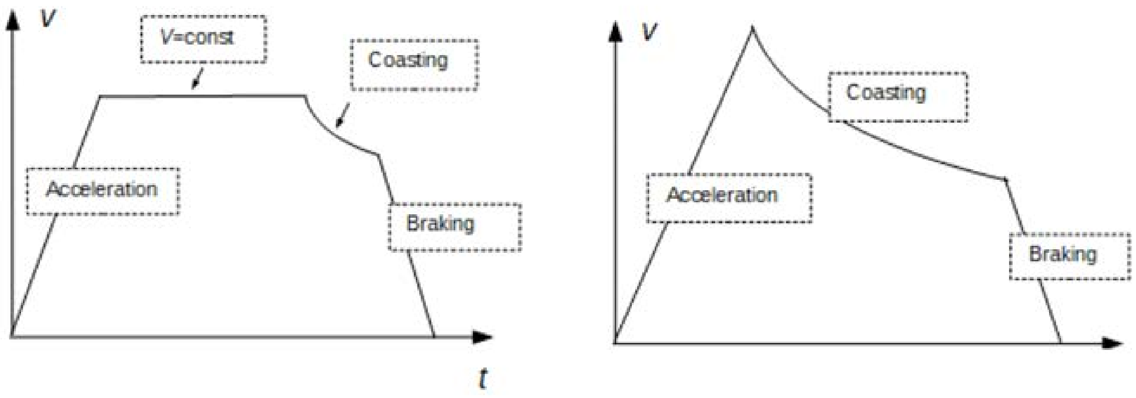

Figure 4.9 Recommended driving cycle based on speed between two stops for the case of electric bus (right) and internal combustion engine bus (left)

In order to perceive the effect of driving style, it is necessary to construct criteria needed to perceive the effect of driving style:

- Total consumed energy per route, which has to be observed with respect to duration of travel. The outliers, both positive and negative, have to be observed with the respect to the number of passengers on board during travel, which can be done by observing the video made during the travel in focus.
- Total recuperated energy per route, that has to be observed with the respect to duration of travel
- The ratio of recuperated and consumed energy as a relative indicator excluding the duration of travel
- The change of speed throughout the time, observed in a diagram of speed versus time for each of the acceleration modes
- Brake pedal position, observed in a diagram of the brake pedal position versus time for each of the acceleration modes

The share of time spent coasting versus total time of travel, meaning the ratio of time where accelerator pedal position and brake pedal position have the value of 0% while the vehicle is in motion (speed greater than zero) and the total time spent in motion (speed greater than zero).

4.4 Verification of the effects of recommendations

The effect of recommendations for energy efficient driving of electric buses on route EKO 1 is confirmed in the Phase 2 of the Project by testing in real conditions of exploitation. In first two cycles (from Vukov Spomenik to Belville and back) the driver drove according to recommendations and under supervision. Next two cycles (from Vukov Spomenik to Belville and back), the driver drove "aggressively" based on real (everyday) experience.

Table 4.2 Results obtained on route Vukov Spomenik to Belville with economical and aggressive driving style

Vukov Spomenik to Belville	**E_consumed total [kWh]**	**E_recuperated total [kWh]**	**E_recuperated [%]**	**Time [min]**
Economically	9.559	2.789	29.182	30.377
Aggressively	11.766	2.890	24.566	27.511
Difference	23%			

Table 4.3 Results obtained on route Belville to Vukov Spomenik with economical and aggressive driving style

Belville To Vukov Spomenik	**E_consumed total [kWh]**	**E_recuperated total [kWh]**	**E_recuperated [%]**	**Time [min]**
Economically	12.944	2.258	17.443	34.331
Aggressively	16.907	2.453	14.509	35.804
Difference	30%			

The data acquired on the route *Vukov Spomenik – Belville* and *Belville – Vukov Spomenik* for both driving styles (recommended and aggressive) is shown in tables 4.2 and 4.3: consumed energy, recuperated energy, and the share of consumed and recuperated energy. Also, the duration of both travels is given. The route *Belville– Vukov Spomenik* is longer which resulted in longer time it took to complete it. The difference between consumed energy while driving economically and aggressively is 23% and 30%, respectively. On route *Vukov Spomenik – Belville*, the portion of recuperated energy is over 29%, whilst in the case of aggressive driving it decreases to 24.6%. In opposite direction (in both cases) less energy was recuperated due to a portion of route being elevated, but there is still an advantage in economical driving style's favour (17.4% : 14.5%). Given differences in consumption and portion of recuperated energy are significant and represent a possibility of savings, and energy reserve in reaching the desired autonomy when the consumption due to heating and cooling is significant.

It is interesting to observe the change of speed during characteristic cycle consisting of the acceleration and deceleration for both driving styles. Two cycles were isolated on the same route, lasting 52 s between two stops, whereat in Figure 4.10, the speed versus time for driving economically is shown, while same relation for the aggressive driving style is shown in Figure 4.11. Even though the duration was equal, and there is longer travelled distance in the first case, the two cycles differ in consumed energy.

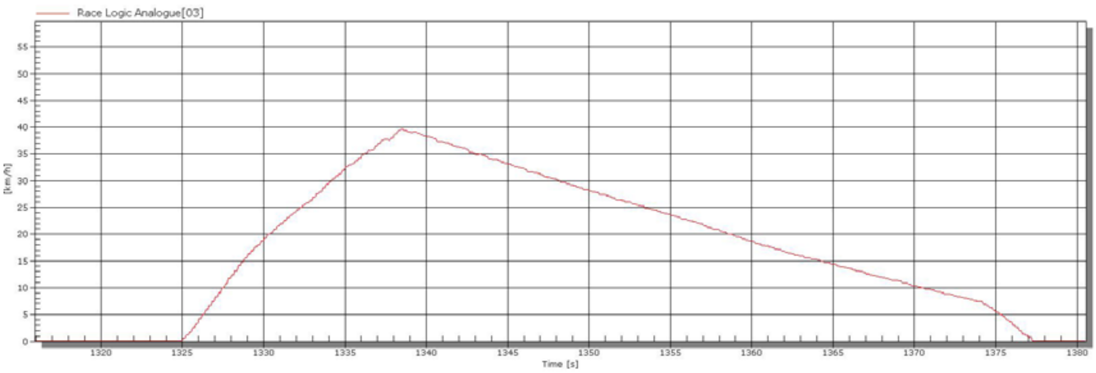

Figure 4.10. Cycle between two stops lasting 52 s while driving economically in real conditions of exploitation

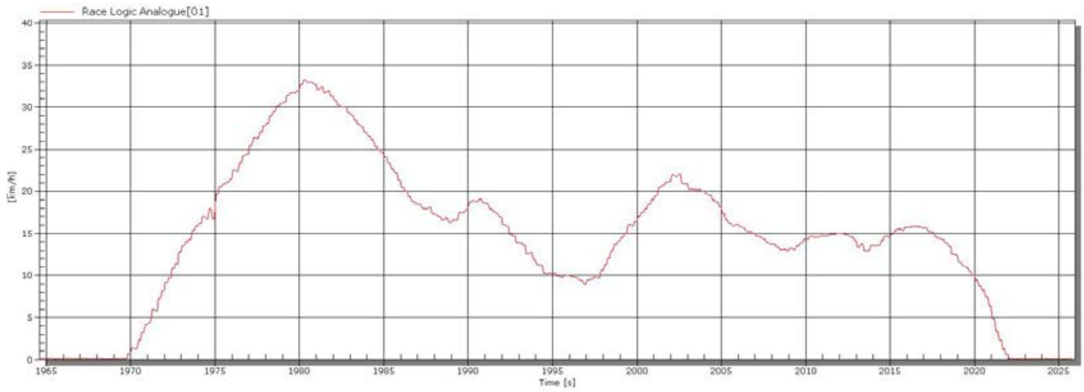

Figure 4.11. Cycle between two stops lasting 52 s while driving aggressively in real conditions of exploitation

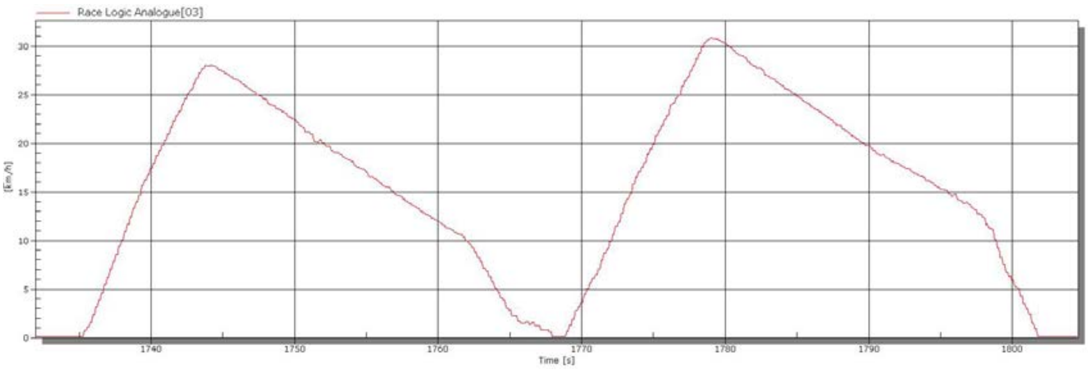

Figure 4.12. Two consecutive cycles between stops lasting 33 s each when driving economically in real conditions of exploitation

Figure 4.12 depicts the speed versus time for two consecutive cycles of the same duration of 33 s. This shows that the recommended driving cycle is possible to be carried out in real conditions of exploitation, due to stopping between two cycles in this case not being conditioned by stopping on the station or at traffic lights, but with short stopping due to the traffic density (duration of stopping 1 s).

The differences between recommended economical and aggressive styles of driving can be perceived by observing the usage of the brake pedal, as well as using inertia for motion. Tables 4.4 and 4.5 show the stated differences.

Table 4.4. Mean value of speed, share of braking and coasting on route Vukov spomenik – Belville on recommended economical and aggressive driving style

Vukov Spomenik to Belville	**Mean value of speed** [km/h]	**Share of braking in total amount of time spent in motion** [%]	**Mean value of brake pedal position** [%]	**Share of coasting in total amount of time spent in motion** [%]	**Share of coasting in total distance of travel** [%]	**Total duration of motion** [min]	**Total duration of travel** [min]
Economically	20.67	11.43	6.63	27.38	49.67	20.17	30.377
Aggressively	24.17	17.43	6.94	12.43	21.54	17.37	27.511

Table 4.5. Mean value of speed, share of braking and coasting on route Belville – Vukov spomenik on recommended economical and aggressive driving style

Belville to Vukov Spomenik	**Mean value of speed** [km/h]	**Share of braking in total amount of time spent in motion** [%]	**Mean value of brake pedal position** [%]	**Share of coasting in total amount of time spent in motion** [%]	**Share of coasting in total distance of travel** [%]	**Total duration of motion** [min]	**Total duration of travel** [min]
Economically	19.96	6.30	5.48	32.23	50.04	24.87	34.33
Aggressively	24.41	13.48	6.97	9.28	17.90	20.37	35.80

5. Conclusion

All scheduled activities were completed up to the deadline. Based on implied road and proving ground tests for several acceleration, deceleration and constant speed modes, the recommended driving style, that is confirmed to be very efficient in the matter of consumption and energy recuperation, can be deduced. Also, the method of monitoring the vehicle parameters of the electric bus has been deduced, as well as a precise determination of consumed and recuperated energy.

Nevertheless, driving style and the effects of the training of each driver have to be constantly quantified and monitored. The indicator of the driving style for each driver is to be analyzed. In case of good results the driver is to be stimulated, and the bad results are to be pointed at. One of the means of long-term energy savings is for the recommendations for energy efficient driving and its indicators to be available to the driver in real time.

It is crucial to imply unique research which would as a result allow recommendations concerning specific sections between two stops (bus-stops, traffic lights), taking into account the section length and the travel duration based on current traffic conditions. In that way, the driver would have recommendations for each section for maximum speed and the way of acceleration to reach it, the point at which to start the motion by inertia or when and how much to brake.

Also, it is needed to perceive the energy consumed by auxiliary consumers, especially heating and cooling systems, because there the significant savings can be made.