PLATON –

Planning Process and Tool for Step-by-Step Conversion of the Conventional or Mixed Bus Fleet to a 100% Electric Bus Fleet

Deliverable 5.4:	**User's manual**
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Contents

1 Introduction

The deliverable presents the results of the project work carried out by consortium partners in the WP 5.8: User’s manual. It sets out system requirements, objectives, inputs and outputs as well as the cores of the PLATON toolkit’s components. The content of this report is written from the viewpoint of the user. The scientific methodology of the components and its IT implementation has been discussed in the previous deliverables.

The PLATON Toolkit consists of a range of components. There are two planning levels distinguished: *strategic corporate planning level* and the *transport operation planning level.* The architecture of the PLATON toolkit is presented in Figure 1 and was already discussed from the viewpoint of IT implementation in the previous deliverables. A user will see a set of components to and will be able to choose the one is the most needed.

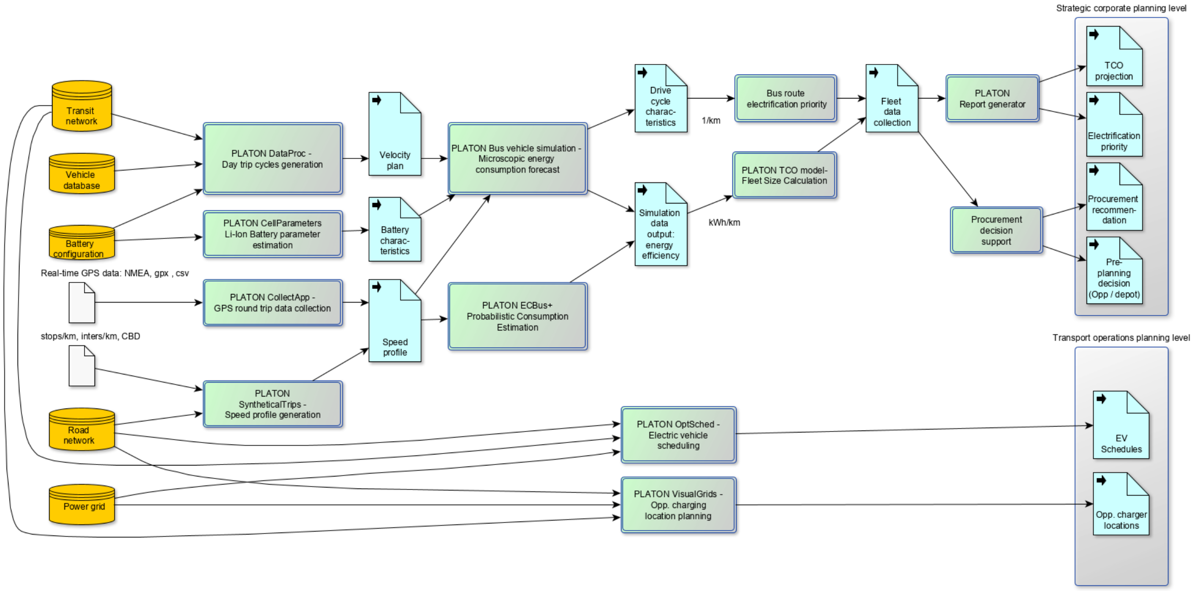


Figure 1 Technology Architecture of the PLATON Toolkit

In the following subsections the PLATON toolkit’s components are described in details.

2 Component DataProc

The component *DataProc* is used to generate trip cycles of electric bus operation in form of a velocity plan for a bus route in a transit network. It uses input information from a transit network, vehicle data and battery configuration data that must be provided in form of comma separated text files.

2.1 System requirements of the DataProc

DataProc is a script program in the syntax of Matlab. It can be executed in the open source environment of Octave on a typical equipped PC without special hardware requirements on Windows or Linux.

2.2 Objective of the DataProc

The objective of *DataProc* is to generate a velocity plan for a given bus route in order to incorporate bus movements and maneuvers at terminals, stops and intersections that resemble the acceleration and deceleration behavior of a real bus vehicle operating in revenue service in the road network that is represented by a digital georeferenced map. The generated velocity plan is used as input for the microscopic *BusVehicleSimulation* component.

2.3 Input data for the DataProc

The input data for *DataProc* is provided in form of the comma separated files named `shelev.csv` and `stops.csv`.

The file structure of `shelev.csv` consists of 4 comma separated columns in the following order: latitude (float), longitude (float), elevation (float), number (integer), see the following listing fragment.

- `shelev.csv`:

```
52.140712,11.656466,44.310000,0
52.140705,11.656498,44.550000,1
52.140690,11.656536,44.640000,2
52.140673,11.656574,44.720000,3
52.140654,11.656620,44.230000,4
52.140637,11.656651,43.650000,5
52.140618,11.656678,44.310000,6
52.140605,11.656704,44.550000,7
52.140598,11.656737,44.230000,8
```

The file `shelev.csv` contains consecutive numbered geographical points of the bus route in WGS84 coordinates including elevation in meters above sea level.

The file structure of `stops.csv` consists of 4 comma separated columns in the following order: stop id (integer), latitude (float), longitude (float), number (integer), see the following listing fragment.

- `stops.csv`:

```
100,52.140720,11.656421,0
100,52.140299,11.646473,1
100,52.133614,11.643478,2
100,52.135131,11.640996,3
100,52.136277,11.639479,4
100,52.139463,11.633731,5
100,52.140964,11.623860,6
100,52.140000,11.617786,7
```

The file `stops.csv`: contains consecutive numbered geographical points of the bus stops in WGS84 coordinates including the id of the bus stop of the referring bus route described in `shelev.csv`.

Both input data files must reside in the same directory of the *DataProc* script program.

2.4 The core of the DataProc

The core functionality of the *DataProc* component includes the following processes. The bus route tracking data and stop locations are loaded into the program. All distances between points are calculated. Trip shapes are formed for each adjacent track point. For each of the stops it is determined at which bus route track point it is located by closest distance. The distance between stops are calculated by adding all trip shape distances. Trip segments are formed between bus stop locations. The grades between stops are calculated and assigned to the trip segment. A desired speed is calculated for each bus track point based on the distance to the next shape point. The desired speed takes into account cases when the stop distance is lower than acceleration and deceleration distance together. Speed reductions at intersections are taken into account based on the distances between track points. A second-by-second driving velocity for the trip is calculated and written to the output file.

2.5 The outputs of the DataProc

The output data for *DataProc* is provided in form of a Matlab/Octave matrix File `vplan.mat` and `gplan.mat` for further processing by the *BusVehicleSimulation* component. Both are human readable and contain the velocity plan and the inclination values of elevation changes for the planned trip.

3 Component CellParameters

In order to build battery models for the simulation of energy storage system on BEBs (Battery Electric Buses), the first step is to estimate parameters of specific battery cells.

An estimation algorithm is implemented in the component CellParameters, aiming to fit parameters of the third-order equivalent circuit model to the original measurement data of a real battery cell based on triple-exponential curve-fitting method.

By means of the light-weighted estimation algorithm, CellParameters can generate lookup tables for circuit elements with high accuracy, without dependencies on high required device.

3.1 System requirements of the CellParameters

The premise for parameter estimation is the acquisition of the terminal voltage of a battery cell. A Li-ion battery cell from A123 Systems® with a capacity of 2500 mAh was selected, whose terminal voltage was measured by the instrument of c't-Lab®. This device can also communicate with computer side via a COM port. The charging or discharging process was controlled by the software of LabVIEW®, in order to discharge the cell from 100% to 0% with 10 times.

The software to implement CellParameters is called SIMBA# [1], which is a kind of simulation tool programmed in C# and can be operated under Windows 7, 8 and 10. The demo version without license can run the estimation algorithm and check related results sufficiently. However, if users want to edit the algorithms packaged in the modules in SIMBA#, a license must be required.

3.2 Objective of the CellParameters

The objective of CellParameters is to generate lookup tables to determine the values of circuit elements in the battery model at specific SOC (State of Charge), as shown in Figure 2. Furthermore, the determined values of these elements, such as capacitances and resistances, can be installed to construct an accurate battery model, which could simulate the energy consumption in cooperation with the bus driving model in a system.

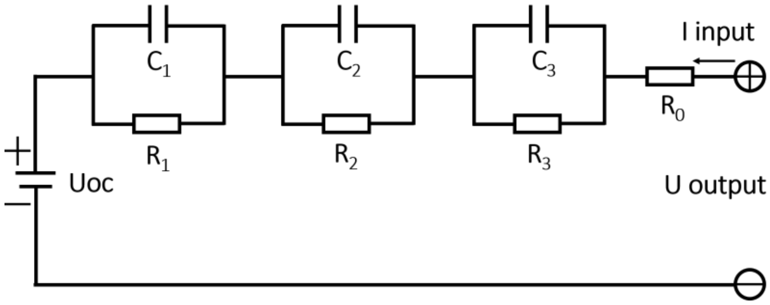


Figure 2 Third-order equivalent circuit.

3.3 Input data for the CellParameters

After the measurement of terminal voltage, data can be stored in an Excel file with the extension of xlsx. A series of sample data points are listed in Table 1 for an example. As is presented, the first column marked as “x” is the time in seconds, and the second column represents the corresponding measured voltages. A further process is required to calculate the slopes of every two neighboring data points, which are listed in the column “Slope”. The columns of “Delta(Y)” and “Delta(X)” are the differences between two neighboring points of “y” and “x” to make it more convenient to obtain the slopes. After the experiment, there are 289,880 data points in total sampled to be further processed as the input to the CellParameters.

Table 1 Sample input data for CellParameters

x	y	Delta(Y)	Delta(X)	Slope
0	3.369989	0	0	0
0.156	3.369989	0	0.156	0
0.297	3.369993	4E-06	0.141	2.8369E-05
0.437	3.369993	0	0.14	0
0.578	3.370011	1.8E-05	0.141	0.00012766
0.734	3.369948	-6.3E-05	0.156	-0.0004038
0.89	3.370005	5.7E-05	0.156	0.00036538
1.031	3.369993	-1.2E-05	0.141	-8.511E-05
1.172	3.369993	0	0.141	0

3.4 The core of the CellParameters

1. Start

Use SIMBA# to open the project file, named Parameter_Estimation_LiFePO4(A123)Roundcell.simu. The graphical interface is presented in Figure 3.

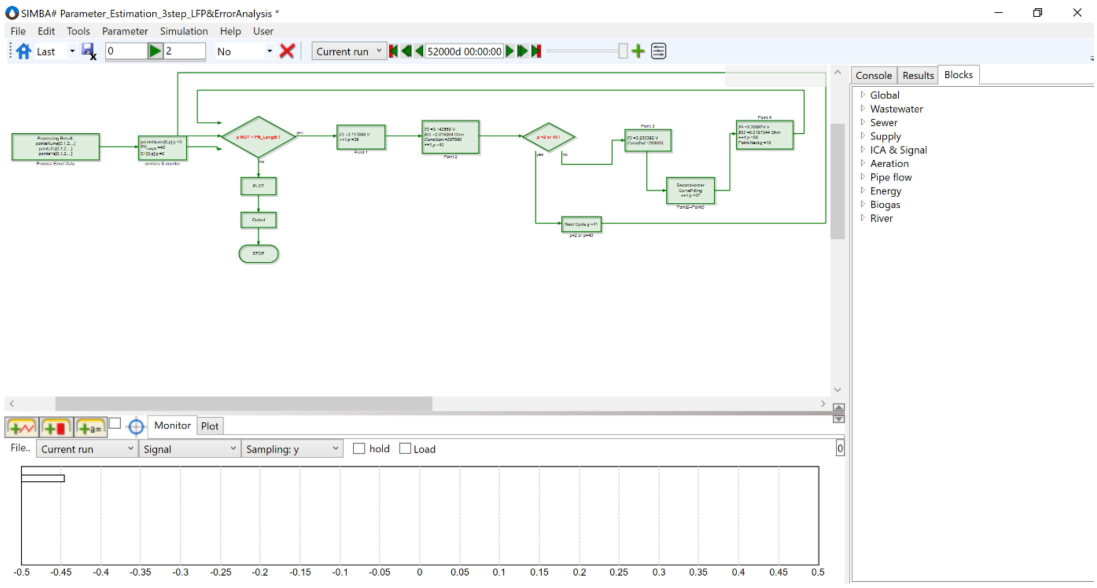


Figure 3 Graphical interface of CellParameters.

2. Initialize

Right click on the second module, which is named "pointers & counter", to select the function of "Edit script" to reset some variables for simulation, as shown in Figure 4.

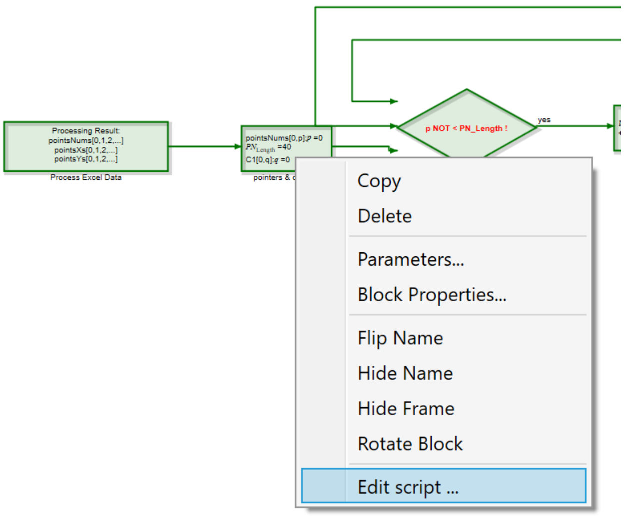


Figure 4 Functions of modules.

Firstly, please find p and q from global variables, which are the counters for key points existing in the voltage curve. As shown in Figure 5, the default values of p and q should be initialize to be 0. The variable of “I” represents the discharging current, for the case in PLATON, the discharging current for the LFP (Lithium iron phosphate) cell is set to be -1.25A.

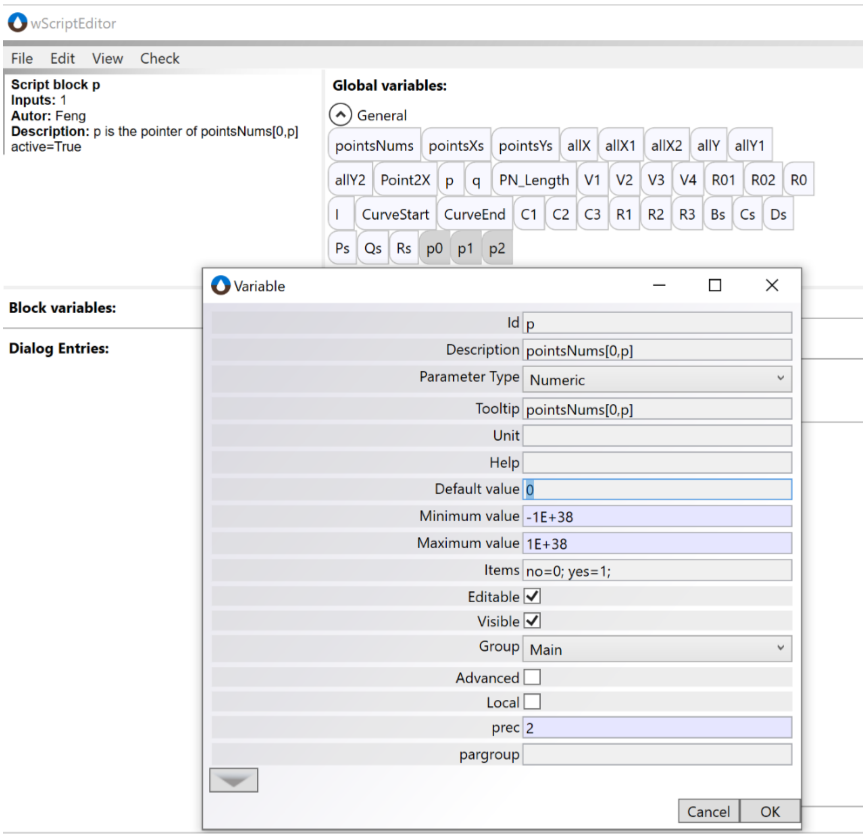


Figure 5 Editing global variables.

In addition, if users want to estimate parameters based on their own measurement data, please right click on the first module, called “Process Excel Data”, to edit script. As presented in Figure 6, users should replace the measurement file in the code area. Please make sure that the voltage file exists in the same path with the project file.

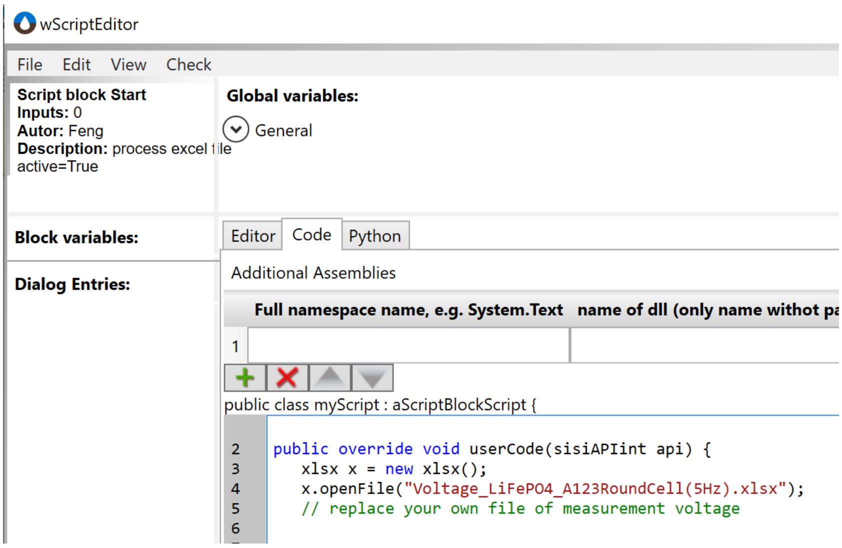


Figure 6 Replacement of the file of measurement voltage.

3. Run Simulation

Double click on the first module, then select the "Run" function in Figure 7, which is marked by the red box. If users want to run the estimation process step by step, the "OK/Next" button should be clicked. Then users need only to wait all blocks to be executed to get the final results.

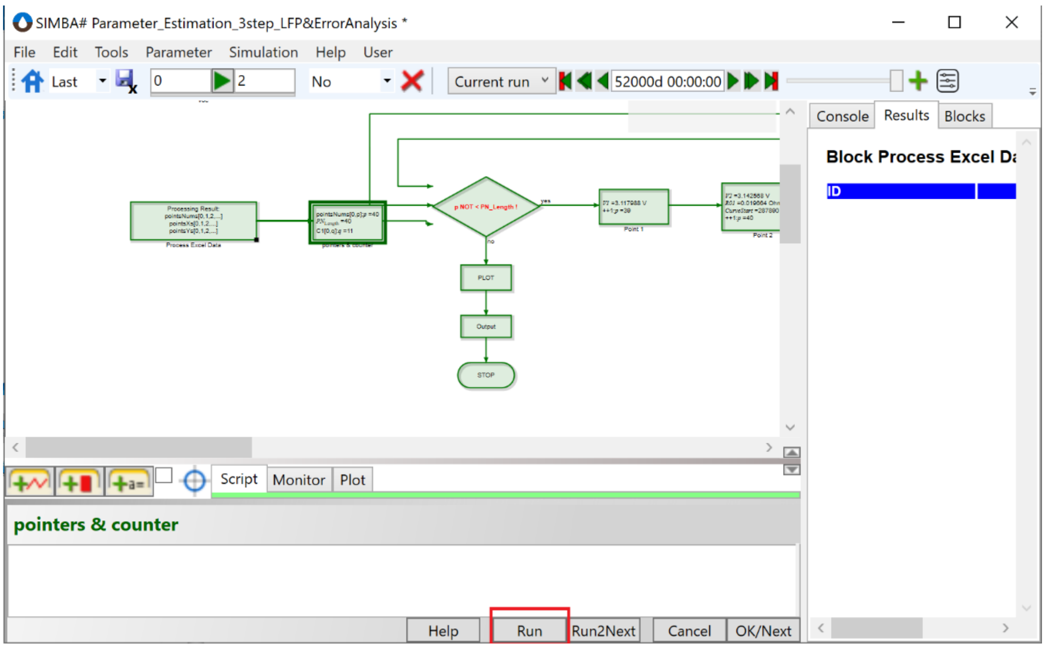


Figure 7 Activation of estimation.

3.5 The outputs of the CellParameters

After the accomplishment of execution of the last block, final results will be presented in the form of graphical windows and arrays (see Figure 8).

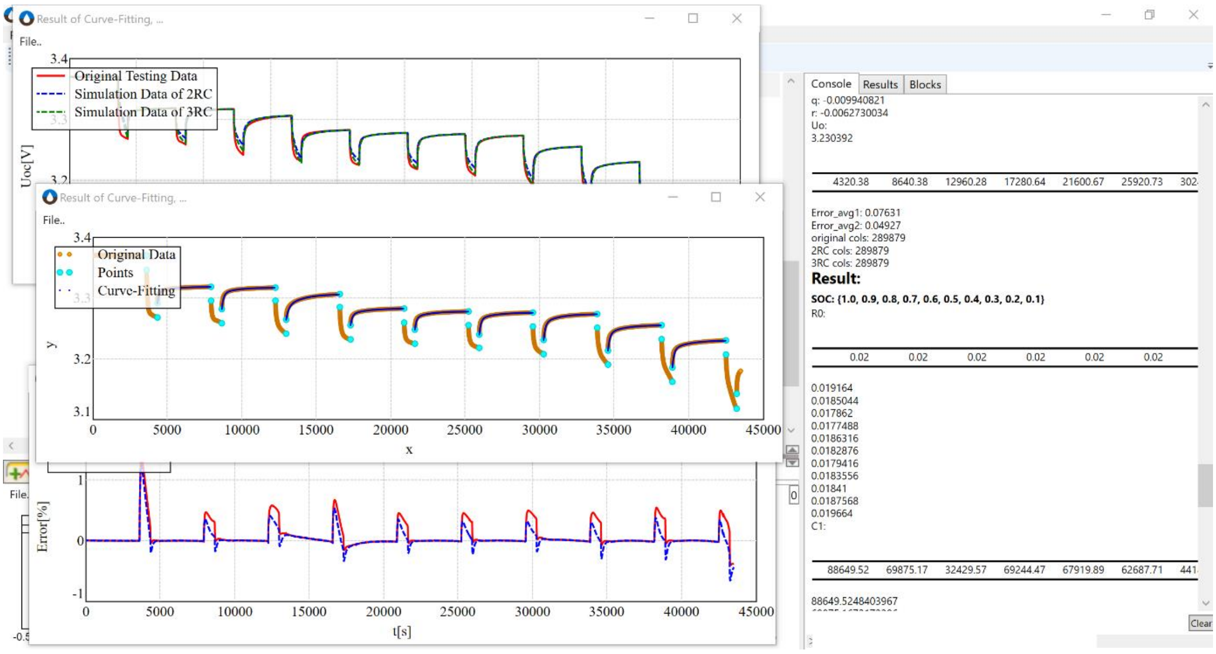


Figure 8 Window of final results.

3.5.1 Curve-fitting Results

Curve-fitting result is presented in Figure 9, where the red solid line represents the testing data of terminal voltage, the blue dashed line is the simulation data of battery model with 2RC branches, while the green dashed line is the simulation result of 3RC branches. After comparison, 3RC battery model have better fitting results especially during the discharging intervals, since an additional RC branch is used to calibrate the data of 2RC model.

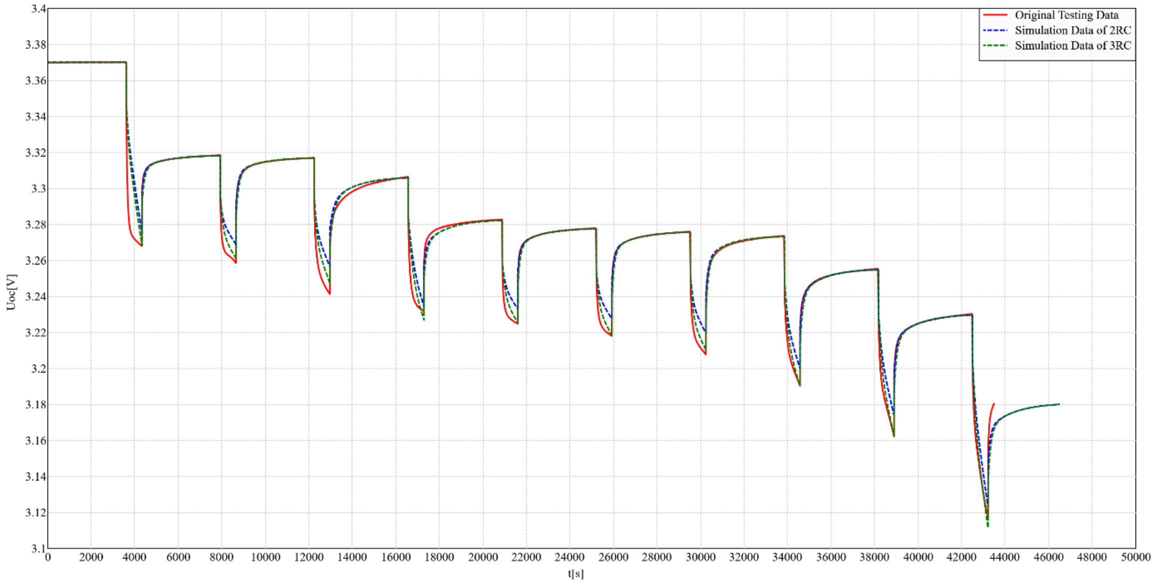


Figure 9 Curve-fitting results of 2RC and 3RC branches.

3.5.2 Parameter Estimation

The procedure of estimation process is clearly shown in Figure 10. Cyan points are defined as the key points to locate the instants when discharging starts and ends. Then the recovery periods at each SOC level are captured for curve fitting. After parameter estimation, the simulation data are presented by blue dots.

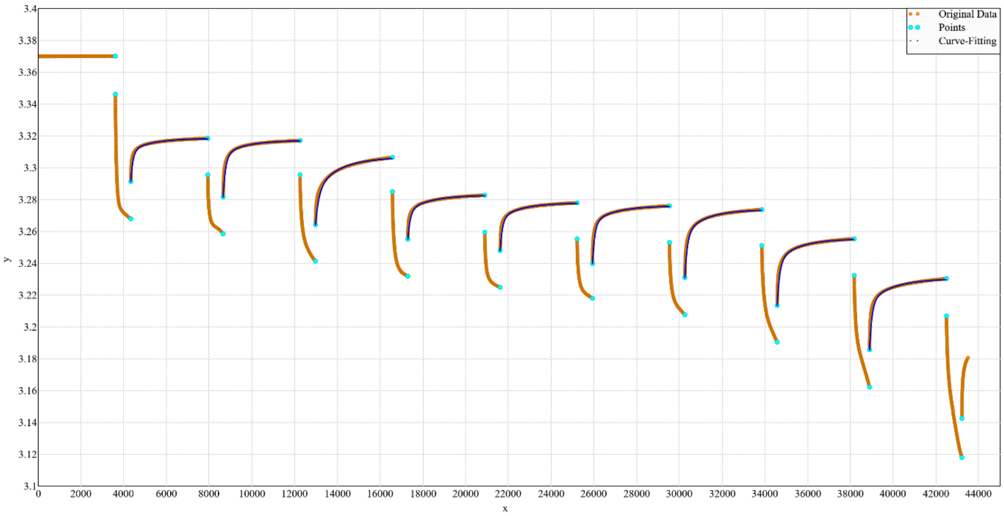


Figure 10 Procedure of parameter estimation for 3RC branches.

As shown in Figure 11, by means of the mouse wheel, the figure could be zoomed in to observe the more detailed situation.

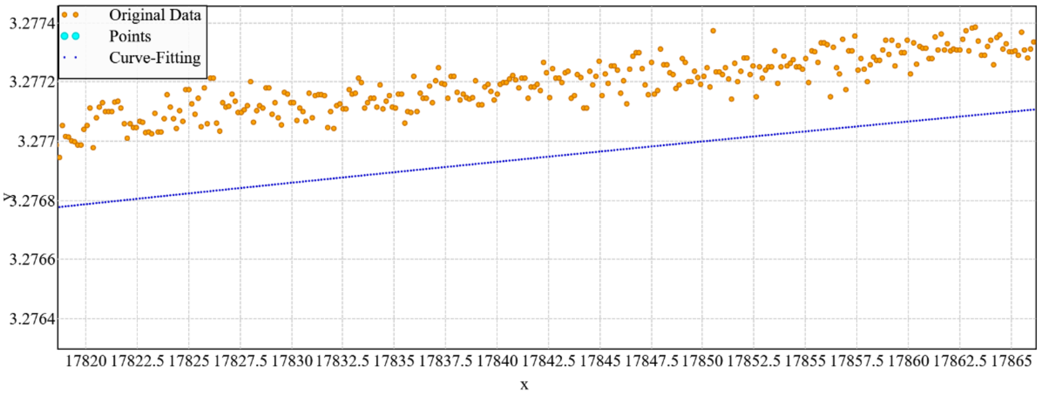


Figure 11 Detailed view of fitting result.

3.5.3 Error Analysis

In order to compare the errors of 2RC and 3RC models more directly, the errors are calculated and further put into the excel file for process. Then the data are plotted to be shown in the form of a graphical window (see Figure 12).

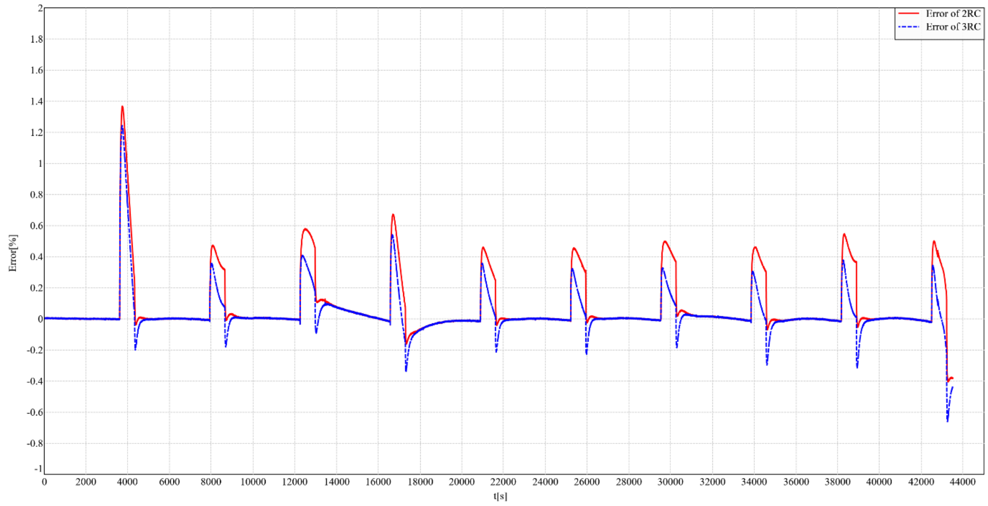


Figure 12 Errors of 2RC and 3RC models.

3.5.4 Lookup Tables

Besides the graphical windows to present the results, estimated parameters for circuit elements are written in the form of lookup tables, which is shown in "Console" window in the right part of Figure 8. For better understanding, the related parameters of the circuit model in Figure 2 are listed in the following tables. Because CellParameters only estimates the values at stable SOC levels, lookup tables for RC branches have only values from SOC=90% to SOC=10%.

Table 2 Lookup tables of Uoc

SOC	1.0	0.9	0.8	0.7	0.6	
U_{oc} [V]	3.370138	3.318478	3.317131	3.306537	3.282775	
SOC	0.5	0.4	0.3	0.2	0.1	0.0
U_{oc} [V]	3.277943	3.276075	3.273696	3.255334	3.230392	3.204631

Table 3 Lookup tables of R0

SOC	1.0	0.9	0.8	0.7	0.6	
R0 [Ω]	0.019164	0.0185044	0.017862	0.0177488	0.0186316	
SOC	0.5	0.4	0.3	0.2	0.1	0.0
R0 [Ω]	0.0182876	0.0179416	0.0183556	0.01841	0.0187568	0.019664

Table 4 Lookup tables of C1

SOC	0.9	0.8	0.7	0.6	0.5
C1 [F]	88649.52	69875.16	32429.57	69244.46	67919.88
SOC	0.4	0.3	0.2	0.1	
C1 [F]	62687.70	44183.53	47530.39	47807.36	

Table 5 Lookup tables of R1

SOC	0.9	0.8	0.7	0.6	0.5
R1 [Ω]	0.0119985923	0.0143648425	0.0341167589	0.0154274873	0.0151123609
SOC	0.4	0.3	0.2	0.1	
R1 [Ω]	0.0168209511	0.0228762165	0.021541318	0.0242167009	

Table 6 Lookup tables of C2

SOC	0.9	0.8	0.7	0.6	0.5
C2 [F]	9031.449	7339.79	15561.19	11595.07	9338.03
SOC	0.4	0.3	0.2	0.1	
C2 [F]	7415.13	7248.93	7657.28	6535.35	

Table 7 Lookup tables of R2

SOC	0.9	0.8	0.7	0.6	0.5
R2 [Ω]	0.0101044481	0.0145924171	0.0101093361	0.0089427779	0.0101215302
SOC	0.4	0.3	0.2	0.1	
R2 [Ω]	0.0131461809	0.0152655866	0.0143370065	0.0153924806	

Table 8 Lookup tables of C3

SOC	0.9	0.8	0.7	0.6	0.5
C3 [F]	25830.19	23884.97	25076.28	27951.54	23017.49
SOC	0.4	0.3	0.2	0.1	
C3 [F]	18322.70	21120.84	18200.30	17236.21	

Table 9 Lookup tables of R_3

SOC	0.9	0.8	0.7	0.6	0.5
R3 [Ω]	0.00574142	0.0064794475	0.0077033425	0.0056000223	0.0062681505
SOC	0.4	0.3	0.2	0.1	
R3 [Ω]	0.0075267555	0.0072819393	0.0083221051	0.0092487384	

3.5.5 References to the CellParameters

[1] ifak (2018). Simba# 3.0. ifak e.V. Magdeburg. URL https://simba.ifak.eu.

4 Component CollectApp

The component *CollectApp* is used to collect and process real-time GPS tracking data of bus operation for use in the *BusVehicleSimulation* component. The tracking data is collected by both a smartphone app for Android devices in low resolution and for a Linux makeshift device in high resolution.

4.1 System requirements of the CollectApp

For the smartphone based version of *CollectApp* an Android device such as a tablet or phone is required. Any Android version newer than of 2017 will suffice. For the high resolution version, a Linux makeshift device is assembled using a configurable GNSS-receiver producing NMEA sentences with update rates of 200 milliseconds (or a frequency of 5 Hz), a Raspberry Pi Linux computer for data acquisition, processing and storage, and a mobile battery pack for power supply as shown in the picture below.

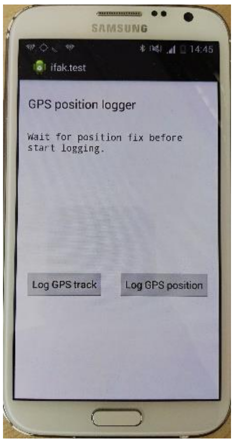


Figure 13 CollectApp implementation in smartphone (left) and Raspberry Pi Logger device (right).

4.2 Objective of the CollectApp

The objective of *CollectApp* is to collect real-time data for a given bus route in order to track bus movements and maneuvers during the route service, at stops and intersections. The collected data is used to generate speed profiles similar to the velocity plan that is created out of mapping data. The collected speed profiled can also be used in both microscopic simulation component *BusVehicleSimulation* and in *ECBus+* for the probabilistic energy consumption estimation.

4.3 Input data for the CollectApp

For this data producing component (data feed) no input data is required.

4.4 The core of the CollectApp

The core functionality of the *CollectApp* component includes the following steps. In order to commence the data collection process, the user of the *CollectApp* component has to make sure that sufficient reception conditions exist in the vehicle for which the data is to be collected.

The Android device must therefore firmly be held in a sitting position near to a window. The arm holding the device should rest on the leg to avoid distorting acceleration movements. After start of the app the user must wait for a position fix that is displayed on the screen. To start the continuous logging process, the button [Log GPS track] is pressed. Additional waypoints, such as bus stop locations are logged by pressing the button [Log GPS position]. To end the logging process, the user closes the app.

The RaspBerry Pi Logger is started by connecting the USB power supply of the battery pack to the Raspberry USB power inlet. The GNSS-receiver must be switched on before the boot process of RaspBerry Linux is finished. The first satellite positioning fix may be received after one minute, depending on line of sight to satellite constellations. Therefore, an early start of the device is advisable before the vehicle is moving. The logging process starts automatically. The makeshift device should be hold firmly in the lap of the user during data collection. In order to avoid unnecessary fears amongst the passengers the blinking electronic device should be concealed by a cloth while fumbling the wires into the socket. To end the logging activity the user should press a small button next to the GNSS receiver USB outlet to initiate a regular shutdown process of the Linux system and to maintain file integrity.

4.5 The outputs of the CollectApp

The output file structures of the *CollectApp* component from both hardware platforms are identical. On the Android device the files `GPSlog.txt` and `BusStoplog.txt` are saved into the directory `/storage/emulated/0`.

Both files can be retrieved by connecting the Android device to a desktop PC over the regular USB connection.

The output data on Raspberry Pi are named according the date and time of data collection according to the scheme `YYYY-MM-DD-hhmmss.txt`. The files are saved to the folder `/home/pi` and can be retrieved either by using `scp (secure copy)` command on the Raspberry to a remote Linux node while the Raspberry is connected in a local area network. Easier is to remove the SD-card from the Raspberry Pi and insert it in a

Linux desktop PC with SD-card reader. The SD-card cannot be read from a Windows PC as its file system `ext3/ext4` is not compatible with Windows.

The file structure of `GPSlog.txt` consists of 9 comma separated columns in the following order: timestamp (datetime), latitude (float), longitude (float), distance in meters (float), timestep in milliseconds (float), velocity in m/s (float), acceleration in m/s² (float), barometric pressure in mBar (float), calculated elevation difference in meters (float). For an example, see the following listing fragment:

```
"Fri Nov 09 14:12:11 MEZ 2018",52.1407125,11.656466,1.79,1000,1.79,1.63,1009.81,-3.69
"Fri Nov 09 14:12:12 MEZ 2018",52.1407051,11.6564979,2.34,1000,2.34,1.21,1009.74,-3.45
"Fri Nov 09 14:12:13 MEZ 2018",52.1406903,11.6565356,3.06,1000,3.06,1.53,1009.83,-3.36
"Fri Nov 09 14:12:14 MEZ 2018",52.1406731,11.6565739,3.25,1000,3.25,1.57,1009.83,-3.28
"Fri Nov 09 14:12:15 MEZ 2018",52.1406539,11.6566197,3.8,1000,3.8,1.87,1009.92,-3.77
"Fri Nov 09 14:12:16 MEZ 2018",52.1406371,11.6566509,2.83,1001,2.83,1.5,1009.78,-4.35
"Fri Nov 09 14:12:17 MEZ 2018",52.1406181,11.6566776,2.8,1000,2.8,1.44,1009.87,-3.69
"Fri Nov 09 14:12:18 MEZ 2018",52.1406045,11.6567044,2.38,1000,2.38,1.35,1009.82,-3.45
"Fri Nov 09 14:12:19 MEZ 2018",52.1405978,11.6567366,2.32,1000,2.32,1.36,1009.87,-3.77
```

The file structure of `BusStoplog.txt` consists of 5 comma separated columns in the following order: timestamp (datetime), latitude (float), longitude (float), barometric pressure in mBar (float), calculated elevation difference in meters (float). For an example, see the following listing fragment:

```
"Fri Nov 09 14:35:03 MEZ 2018",52.1358902,11.6071774,1008.26,9.61
"Fri Nov 09 14:48:54 MEZ 2018",52.1362432,11.6078855,1008.23,0
"Fri Nov 09 14:49:39 MEZ 2018",52.1364022,11.6100514,1008.22,-0.74
"Fri Nov 09 14:50:30 MEZ 2018",52.1389132,11.6099136,1008.11,0.9
"Fri Nov 09 14:52:01 MEZ 2018",52.1400081,11.6170485,1007.97,0.82
"Fri Nov 09 14:53:14 MEZ 2018",52.1404317,11.6214067,1008.21,-0.33
"Fri Nov 09 14:55:34 MEZ 2018",52.1395583,11.6327621,1008.66,-4.44
"Fri Nov 09 15:02:09 MEZ 2018",52.1363693,11.6393296,1008.19,0
```

The file structure of `YYYY-MM-DD-hhmmss.txt` consists of 5 comma separated columns in the following order: day (date), time (time), latitude (float), longitude (float), velocity in km/h (float). For an example, see the following listing fragment:

```
2020-03-12,07:43:27.50,52.0943393,11.5628223,32.02
2020-03-12,07:43:27.60,52.0943377,11.5628387,32.14
2020-03-12,07:43:27.70,52.0943360,11.5628587,32.28
2020-03-12,07:43:27.80,52.0943343,11.5628758,32.21
2020-03-12,07:43:27.90,52.0943323,11.5628907,32.18
2020-03-12,07:43:28.00,52.0943308,11.5629095,32.49
2020-03-12,07:43:28.10,52.0943295,11.5629285,32.39
2020-03-12,07:43:28.20,52.0943283,11.5629475,32.26
2020-03-12,07:43:28.30,52.0943270,11.5629660,32.55
```

5 Component SyntheticalTrips

The component *SyntheticalTrips* is used to generate speed profiles of electric bus operation in form of a velocity plan for a hypothetical bus route of a transit network. It uses input information from a road network, and generic information on the number of stops per kilometer and intersections per kilometer of urban city districts to generate stochastic speed profiles.

5.1 System requirements of the SyntheticalTrips

SyntheticalTrips is a script program in the syntax of Matlab. It can be executed in the open source environment of Octave on a typical equipped PC without special hardware requirements on Windows or Linux.

5.2 Objective of the SyntheticalTrips

The *SyntheticalTrips* component comprises a simulation model for the automatic generation of typical dynamic motion sequences of bus vehicles in urban public transport. Typical motion sequences include traffic-related starting and braking processes in connection with the traffic flow, turning processes at unsignalled and signalled junctions and the operation of bus stops for passenger exchange. The speed profiles represent the most realistic vehicle behaviour possible and are to be used for estimating energy consumption with an existing vehicle model for an electric bus and with the processing program provided by *ECBus+* component.

5.3 Input data for the SyntheticalTrips

For the generation of the speed profiles, input data such as the maximum acceleration and braking acceleration, the permissible maximum speed, the traffic density, the density of intersections in the traffic network and the density of stops are used as variables. The input data must be provided in the json-file `SynthTrips-inpdata.json` as shown in Table 10. Discrete probability density functions (PDF) are given as vectorial data with parameters. The vectorial data values describe the frequencies of the histogram. The parameters of the PDF are the histogram bucket width (i.e. histogram interval width) and the start value of the minimum bucket. The number of buckets is equal to the number of vector elements. With these parameters the PDF are fully described. For example, the stop density function in Table 10 has 5 vector elements: [5 6 20 40 20], a bucket width of 50, the minimum stop density is 250 m. Hence, the 5 buckets at 50 m width are holding the frequency of stop distances in the ranges [250-300] → 5 | [301-350] → 6 | [351-400] → 20 | [401-450] → 40 | [451-500] → 20 meters.

Table 10 Example of input file `SynthTrips-inpdata.json`

```
{
 "triplength_m":5500,
 "maxspeed_kmph":50,
 "traffdens_vecpkm":[[10 20 30 40 60 80 60 40 20 10]],
 "trafdens_bucketwidth":10,
 "trafdens_min":0,
 "intsecdens_m":[[1 2 5 10 50 60 70 20 10 10]],
 "intsecdens_bucketwidth":50,
 "intsecdens_min":20,
 "stopdens_m":[[5 6 20 40 20]],
 "stopdens_bucketwidth":50,
 "stopdens_min":250
}
```

The json-file `SynthTrips-inpdata.json` must reside in the same directory as the *SyntheticalTrip* script file.

5.4 The core of the SyntheticalTrips

The core functionality of the *SyntheticalTrips* component includes the following processes. The input data set is loaded into the program. The probability density functions are used to generate random numbers according to the PDF distributions. For the input trip length, a speed profile is simulated that takes into account stop distances, intersections distances and possible impacts of traffic density.

5.5 The outputs of the SyntheticalTrips

The output file of *SyntheticalTrip* is structured as comma separated file with two columns for the time in seconds and the velocity in kilometers per hour. The file can be used as input to the component *ECBus+.*

6 Component BusVehicleSimulation

The component *BusVehicleSimulation* is used to simulate the physical movements of an electric bus vehicle driving a given route of a normal revenue service over a full day of operation. The sub-microscopic vehicle model enables to calculate the energy demand of the powertrain during motion and the recharging operations taken en-route and overnight.

6.1 System requirements of the BusVehicleSimulation

BusVehicleSimulation is a script program in the syntax of Matlab. It can be executed in the open source environment of Octave on a typical equipped PC without special hardware requirements on Windows or Linux.

6.2 Objective of the BusVehicleSimulation

The objective of *BusVehicleSimulation* is to support the transport operations planner to calculate the energy efficiency for a given bus vehicle on real service route in order to assess the feasibility of equipped vehicle battery sizes for the given daily vehicle transport cycle. The simulation determined energy efficiency can be used as input to TCO projection and fleet size calculation. The *BusVehicleSimulation* component can also be used to determine drive cycle characteristics such the Kinetic Intensity which is essential to compare bus routes for its electrification priority.

6.3 Input data for the BusVehicleSimulation

The input data for *BusVehicleSimulation* is provided by the components *DataProc*, *CellParameters* and *CollectApp*. In addition, vehicle specific parameters are provided from the vehicle database table. The data set for the expert tool component is divided into the following groups: common parameters such as air density, and gravity constant, road conditions such as rolling resistance, vehicle parameters such as frontal area, wheel radius, and total mass, motor parameters such as loss constants, final drive ratio, maximum rotational speed and torque. Battery parameters are partially provided by *CellParameters*. General parameters are capacity, open circuit voltage and internal resistance. These parameters are adjusted directly in the script file of *BusVehicleSimulation*.

The drive plan includes velocities and grades as provided by *DataProc* output matrix files `vplan.mat` and `gplan.mat` which are loaded automatically from the same directory of the *BusVehicleSimulation* component.

The full-day trip plan for the bus vehicle is adjusted in the script file as follows. The variable `trip_plan` holds a matrix of the trip legs in the dimension (2,m). The first column holds the control variable of trip leg direction (1=towards, -1=backwards, 2=pull out, -2= pull in), the second column holds the charge time in seconds after each of the m trip leg, as shown in the following example:

```
% trip plan 1=towards  -1=backwards 300=charge time in seconds
%            2=pull out -2=pull in
trip_plan=[2 0;     % pull out
           1 0;     %1
          -1 300;   %
           1 0;     %2
…          ];
```

6.4 The core of the BusVehicleSimulation

The vehicle driving cycle is simulated by means of a closed-loop discrete system of the vehicle model and a controller in a feedback loop. A proportional integral (PI)-controller is used to simulate the acceleration and deceleration actions of the driver. The output of the simulation is shown in the figure below. The velocity profile is used as the timevariant reference variable that is obtained either from the acquired output of the *CollectApp* tool component or from the generated speed profile output of the *ECBus+* tool component.

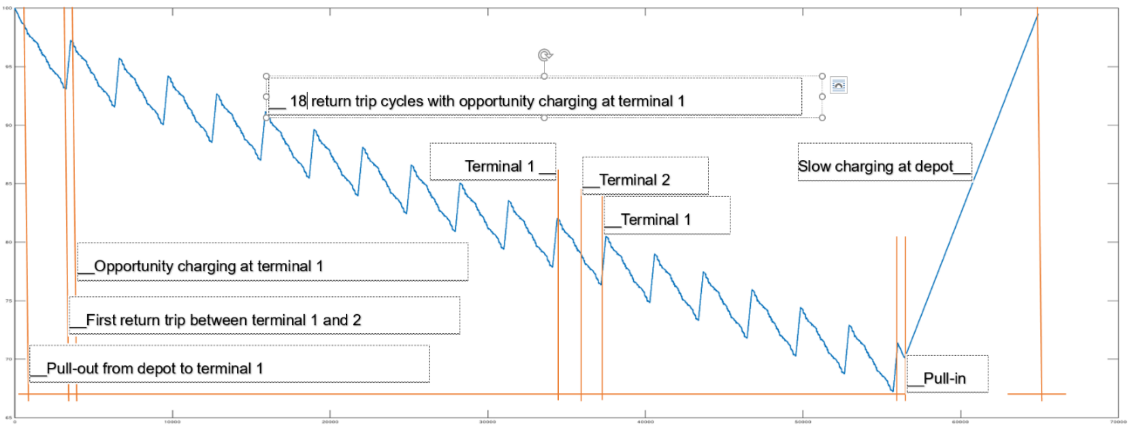


Figure 14 State of Charge over full day trip cycles from output of *BusVehicleSimulation*.

6.5 The outputs of the BusVehicleSimulation

The output of *BusVehicleSimulation* is presented by graphical charts of the simulation run for the following variables: simulated velocity in m/s, torque in Nm, rotational speed in radians, motor current in A, state of battery charge in percent of capacity. Figure 15 presents the results of a one way trip between two terminal stops for a real bus route.

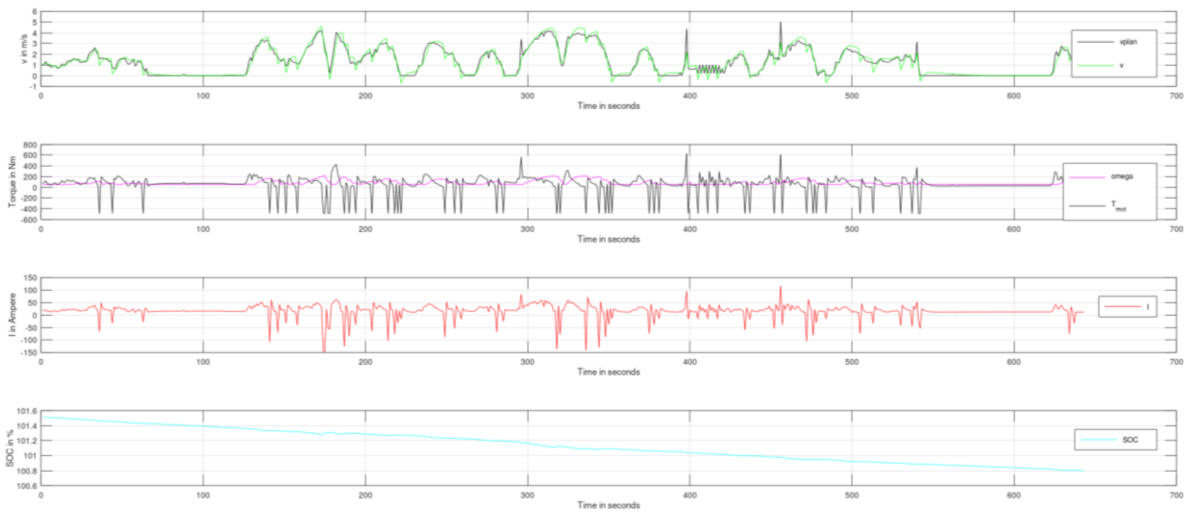


Figure 15 Output variables of *BusVehicleSimulation*.

Beside graphical representation any variables are saved into comma separated text file for further analysis of simulation results. Further, the Octave simulation environment allows to monitor any existing internal interesting variable. So, the user with simulation expertise and consulting experience is enabled to draw important conclusions in result of the output information analysis of the following kind:

- "The selected battery configuration allows for sufficient spare capacity that would allow deploying the bus/battery configuration for routes with trip lengths exceeding the considered one. "
- "The full day duty cycle is accomplished in 18 hours at a slow charging time in the depot of 2.4 hours, which leaves enough time for slow charging of more buses in the depot."
- "The return trip travel time of 46 minutes including average dwell times in 10 trip stops of each 20 seconds allows for sufficient time for opportunity charging in one of the terminal stops."
- "Consequently, an installation of an opportunity charging facility in one of the terminals is sufficient for the given route."
- "The selected bus route appears well suited for electrification as the typical urban acceleration scenario allows for battery recuperation during deceleration maneuvers that relates to a higher Kinetic intensity."

7 Component ECBus+

The complete *ECBus+* tool component includes: (1) software "*ECBus v 4.0*"; (2) procedure *EC-Compare* and (3) procedure *ECPro.*

- *ECBus v 4.0* and the *EC-Compare* allow you to determine the electric bus energy consumption for specific conditions.
- ECBus v 4.0 is also used to estimate energy and fuel consumption as well as pollutant emissions of a diesel bus.
- Using the *ECPro*, an interested party can choose a calculated (design, rated) value, which corresponds to a certain probability for a variety of values set under various conditions*.*

Due to this fact, particular elements of the user's manual will be written separately for each of the abovementioned.

7.1 Software ECBus

The software ECBus v 4.0 is designed to calculate the energy consumption of electric and diesel buses on the route.

Even if the user does not specify the corresponding data for the electric or diesel bus, the calculation is performed with the data specified in the program by default.

ECBus v 4.0 can be used to evaluate the following parameters:

1. Energy consumption of the electric and diesel bus on the route *for electric buses*
2. Electric energy costs per day, month, year
3. Bus battery capacity for a specific set of routes
4. Distance that a bus with a known battery capacity can travel by a given route after charging (to determine the location for the next charger) *for diesel buses*
5. Fuel consumption
6. Pollutant emissions

Note. In the European Union, emissions of nitrogen oxides (NO_x), total hydrocarbon (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM) are regulated for most vehicle types, including cars, trucks (lorries), locomotives, tractors and similar machinery, barges, but excluding seagoing ships and airplanes. For each vehicle type, different standards apply. Emissions data for heavy-duty diesel engines of lorries and buses are presented in Table 11. This table is used to estimate emissions depending on the energy consumption of a bus diesel engine on a route.

Table 11 Emission standards for heavy-duty diesel engines of lorries and buses, g/kWh (based on European emission standards: https://en.wikipedia.org/wiki/European_emission_standards)

Standard	*Carbon monoxide (CO)*	*Hydrocarbons (HC)*	*Nitrogen oxides (NO_x)*	*Particulate matter (PM)*
Euro I	4.5	1.1	8.0	0.36
Euro II	4.0	1.1	7.0	0.15
Euro III	2.1	0.66	5.0	0.1
Euro IV	1.5	0.46	3.5	0.02
Euro V	1.5	0.46	2.0	0.02
Euro VI	1.5	0.13	0.4	0.01

Approach peculiarities. The ECBus v 4.0 program has the following features in calculating energy consumption during bus movement [1].

1. The speed profile is described with horizontal and inclined lines (sections). The bus movement is considered as a set of elementary modes with constant accelerations during time interval (t_i, t_{i+1}) for each section.

   When moving with constant acceleration / deceleration, the work of the air resistance forces can be determined using the equivalent resistance force for the considered section of the speed profile. So, all the forces are simple to calculate and determine the traction force F_E. In this case, the energy for each section of the velocity profile is calculated as: *Energy=Work=Force • Distance.*

2. When using any numerical methods, the calculation is reduced to the consideration of time periods for which it is assumed that the accelerations for them are constant. In this case, a situation may arise when at the boundary points of the time interval t_i and t_{i+1} the values of the traction force F_E have different signs. This situation is especially relevant when the speed profile is schematized by sufficiently long sections of traffic with constant acceleration. What is why, the program includes a special procedure that control the sign of traction force.

3. In addition, a simple calculation of the traction force and the determination of its sign allow you to set the type of mode: traction or recuperative. This is important for properly accounting for the recovered energy.

7.1.1 System requirements of the ECBus

The program components of *ECBus+* are developed in the integrated environment of Microsoft Visual Studio 2012 based on NET.Framework 4.5, the programming language is C #, the application type is Windows Application.

Input files must be created in Microsoft Excel, and have the extension “*.xls”.

7.1.2 Objective of the ECBus

Objective of ECBus v 4.0 is calculate the energy consumption for a bus on a route when a speed profile, bus data and road data are given. Some additional results are provided: graphs of energy consumption and traction over time, as well as distribution of bus speeds and accelerations.

7.1.3 Input data for the software ECBus

The input to the program are:

– Calculation identifier;

– Route description (Infrastructure):

- Identifier of the route in question;
- Route length, m;
- Number N of route segments;
- Segments lengths, m (Segment numbers and Segment lengths);
- Altitudes at the stopping points, m (Stopping points and Altitudes at the stopping points);

– Bus data:

- Identifier of the bus in question;
- Bus weight without passengers, kg;
- Max number of passengers;
- One passenger weight, kg (default is 70 kg);
- Cross section area, m2 (default is 6.6 m2);
- Coefficient of air resistance, Ns2/m4 (default is 0.4 Ns2/m4);
- Rotation inertia factor (default is 1.05);
- Rolling resistance (for planned types of bus tires and road surfaces) (default is 0.008 in summer);
- Maximum electrical power of auxiliary system or its subsystems with battery energy consumption, kW;
- Average efficiency of the invertor (default is 0.98);
- Average efficiency of the motor (default is 0.95);
- Average efficiency of the transmission (default is 0.95);
- Regeneration (recuperation) factor (default is 0.6);

- Effective efficiency of the diesel (default is 0.33);
- Transmission efficiency (default is 0.90);
- Coefficient taking into account the diesel power consumption for equipment drive (by default 1.05);
- Calorific value of diesel fuel, MJ/l (default is 43.12 MJ/l);
- Diesel emission standard, EURO;

– Trip data:
    - Identifier of the trip in question;
    - Passenger loads by segments (Segment numbers and % of passenger load per segment);

– Fuel consumption and Ecology;
– Profile speed.

7.1.4 The core of the ECBus

Start

After starting the program ECBus v 4.0, the tab "Source information" opens (Figure 16

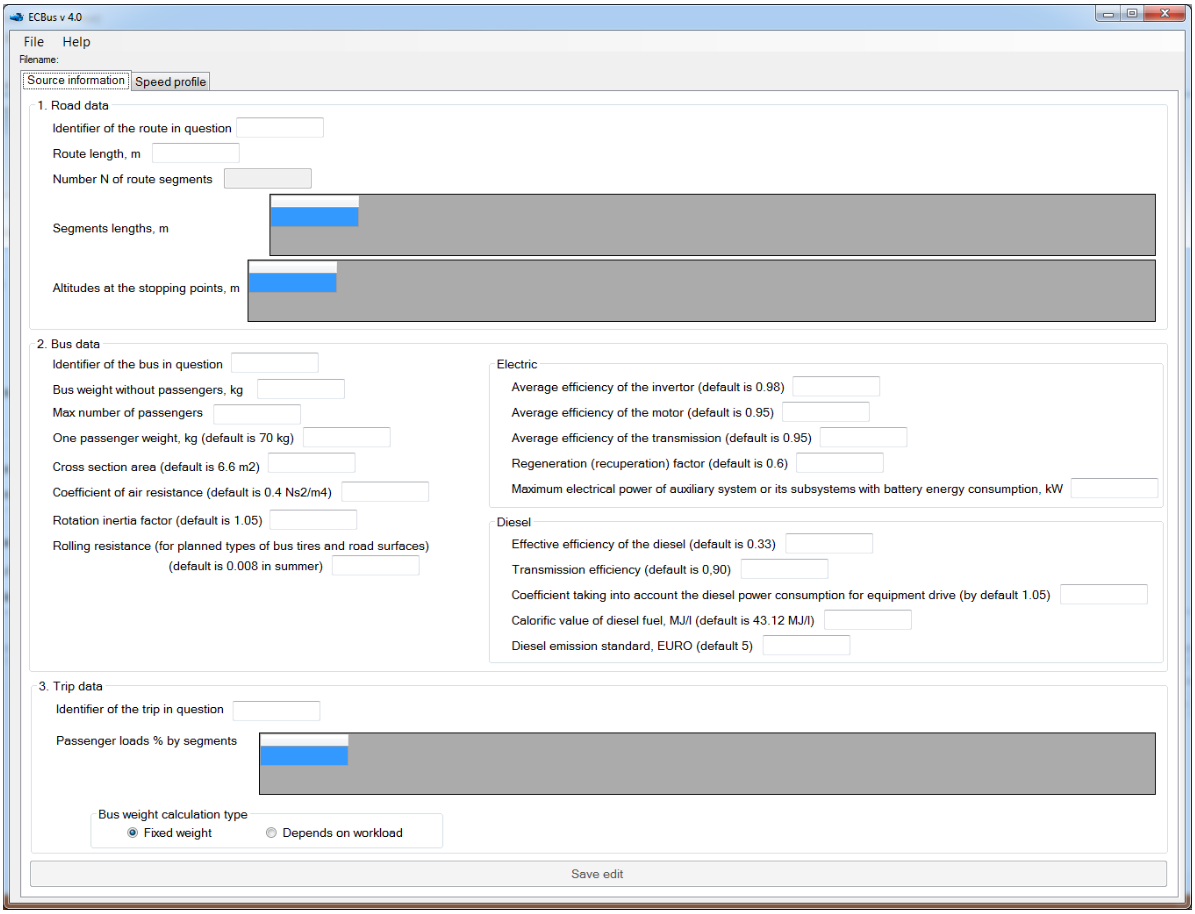


Figure 16 Window after starting the program

Download data on the road, bus and route

To download the data on the road, bus and route it is necessary to press “File” -> “Open” (Figure 17). In the window that appears, select the file and press “Open” (Figure 18).

Downloadable Excel-file with the extension *.xls, must be filled in according to the template, an example of which is shown in Figure 19 - Figure 22.

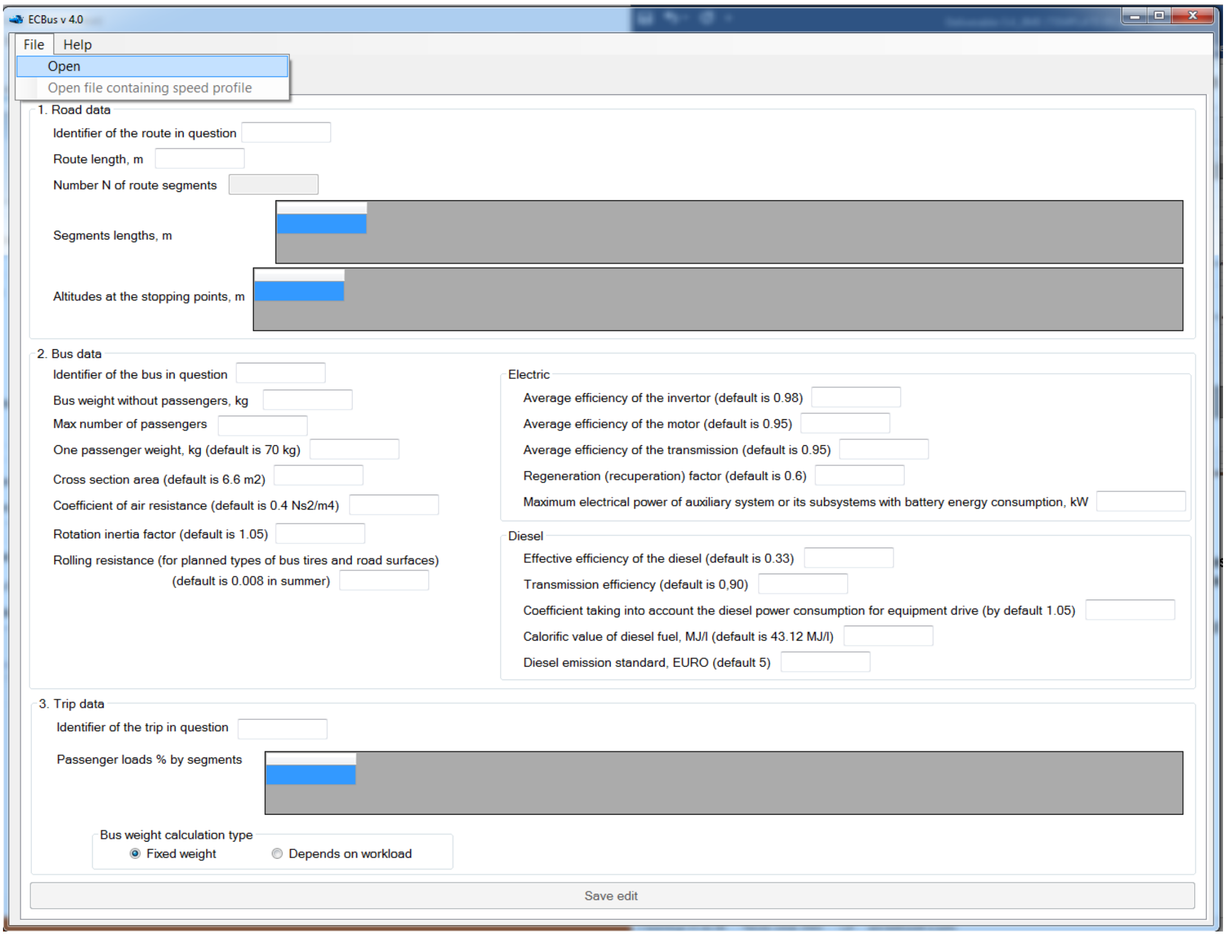


Figure 17 Opening the program file

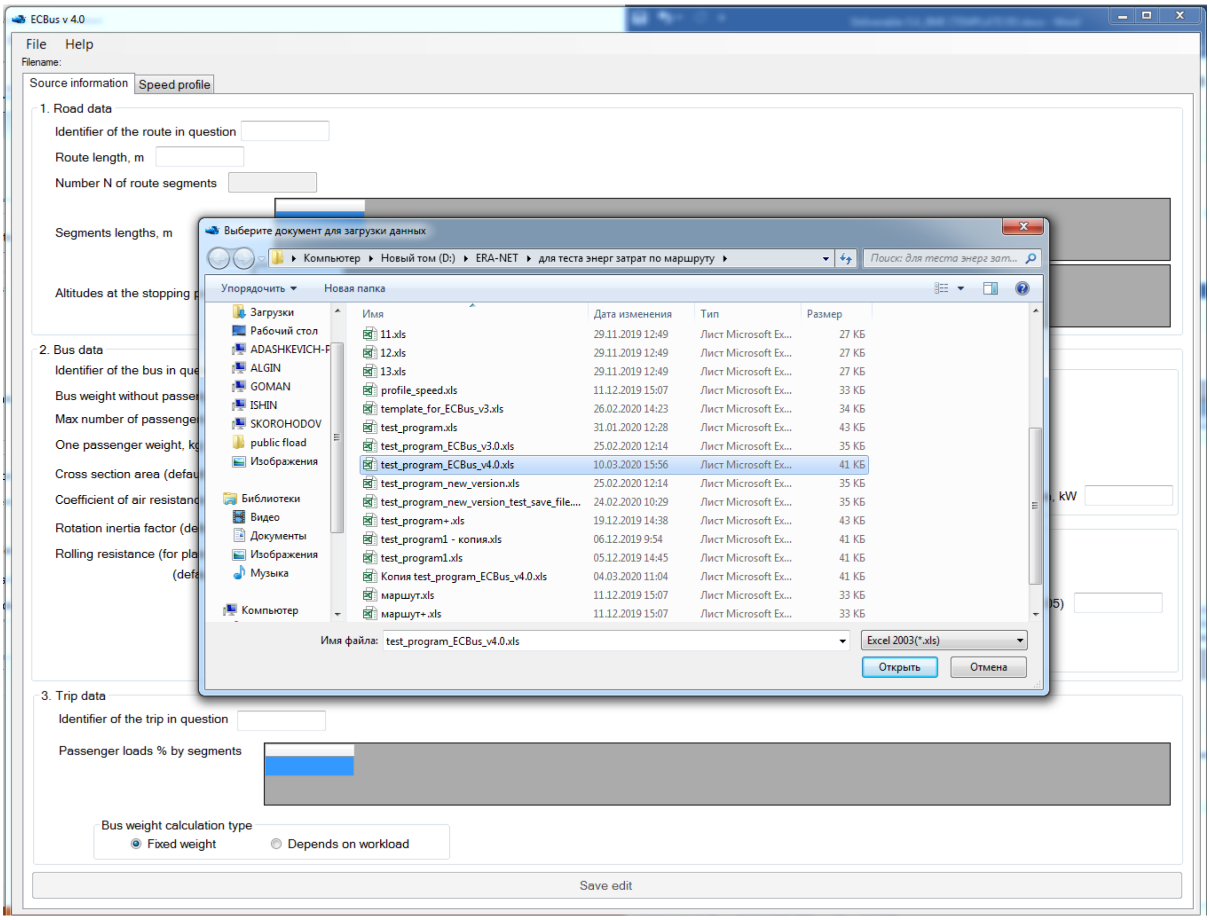


Figure 18 Selecting an openable file with a description of the road, bus and route

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Calculation identifier	1													
2															
3	1. Route description (Infrastructure)														
4	Road data														
5	Identifier of the route in question	1													
6	Route length, m	8232,5													
7	Number N of route segments	13													
8	Segments lengths														
9	Segment numbers 1, 2, …, N	1	2	3	4	5	6	7	8	9	10	11	12	13	
10	Segment lengths s(1), s(2),…,s(N), m	1095,8	515,5	1034,7	667,7	522,8	483,2	129,6	356,1	561,5	434,2	866,7	608,3	956,4	
11	Altitudes at the stopping points														
12	Stopping points 1, 2, …, N+1	1	2	3	4	5	6	7	8	9	10	11	12	13	14
13	Altitudes at the stopping points h(1), h(2),…,h(N+1), m	224	223	222	212	210	198	194	193	199	206	211	211	222	224
14															

Figure 19 An example of filling out the “Route description” template

	A	B
15	2. Bus data	
16	Identifier of the bus in question	1
17	Bus weight without passengers, kg	15000
18	Max number of passengers	80
19	One passenger weight, kg (default is 70 kg)	70
20	Cross section area (default is 6.6 m^2)	6,6
21	Coefficient of air resistance (default is 0.4 Ns^2/m^4)	0,4
22	Rotation inertia factor (default is 1.05)	1,05
23	Rolling resistance (for planned types of bus tires and road surfaces) (default is 0.008 in summer)	0,008
24	Electric	
25	Maximum electrical power of auxiliary system or its subsystems with battery energy consumption, kW	0
26	Average efficiency of the invertor (default is 0.98)	0,98
27	Average efficiency of the motor (default is 0.95)	0,95
28	Average efficiency of the transmission (default is 0.95)	0,95
29	Regeneration (recuperation) factor (default is 0.6)	0,6
30	Diesel	
31	Effective efficiency of the diesel (default is 0,33)	0,33
32	Transmission efficiency (default is 0,90)	0,9
33	Coefficient taking into account the diesel power consumption for equipment drive (by default 1.05)	1,05
34	Calorific value of diesel fuel, MJ/l (default is 43.12 MJ/l)	43,12
35	Diesel emission standard, EURO	4

Figure 20 An example of filling out the “Bus data” template

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
37	3. Trip data													
38	Identifier of the trip in question	1												
39	Passenger loads by segments													
40	Segment numbers 1, 2, … N	1	2	3	4	5	6	7	8	9	10	11	12	13
41	% of passenger load per segment	100	50	25	40	30	80	20	40	90	75	60	30	100

Figure 21 An example of filling out the “Trip data” template

	A	B	C	D	E
43	4. Fuel consumption and Ecology				
44	Standard	Carbon monoxide (CO)	Hydrocarbons (HC)	Nitrogen oxides (NO_x)	Particulate matter (PM)
45	Euro I	4,5	1,1	8	0,36
46	Euro II	4	1,1	7	0,15
47	Euro III	2,1	0,66	5	0,1
48	Euro IV	1,5	0,46	3,5	0,02
49	Euro V	1,5	0,46	2	0,02
50	Euro VI	1,5	0,13	0,4	0,01

Figure 22 An example of filling out the “Fuel consumption and Ecology” template

The first section “Trip data” must be filled in the downloaded file, other values can be accepted by default.

Figure 23 shows the result of loading data from the file.

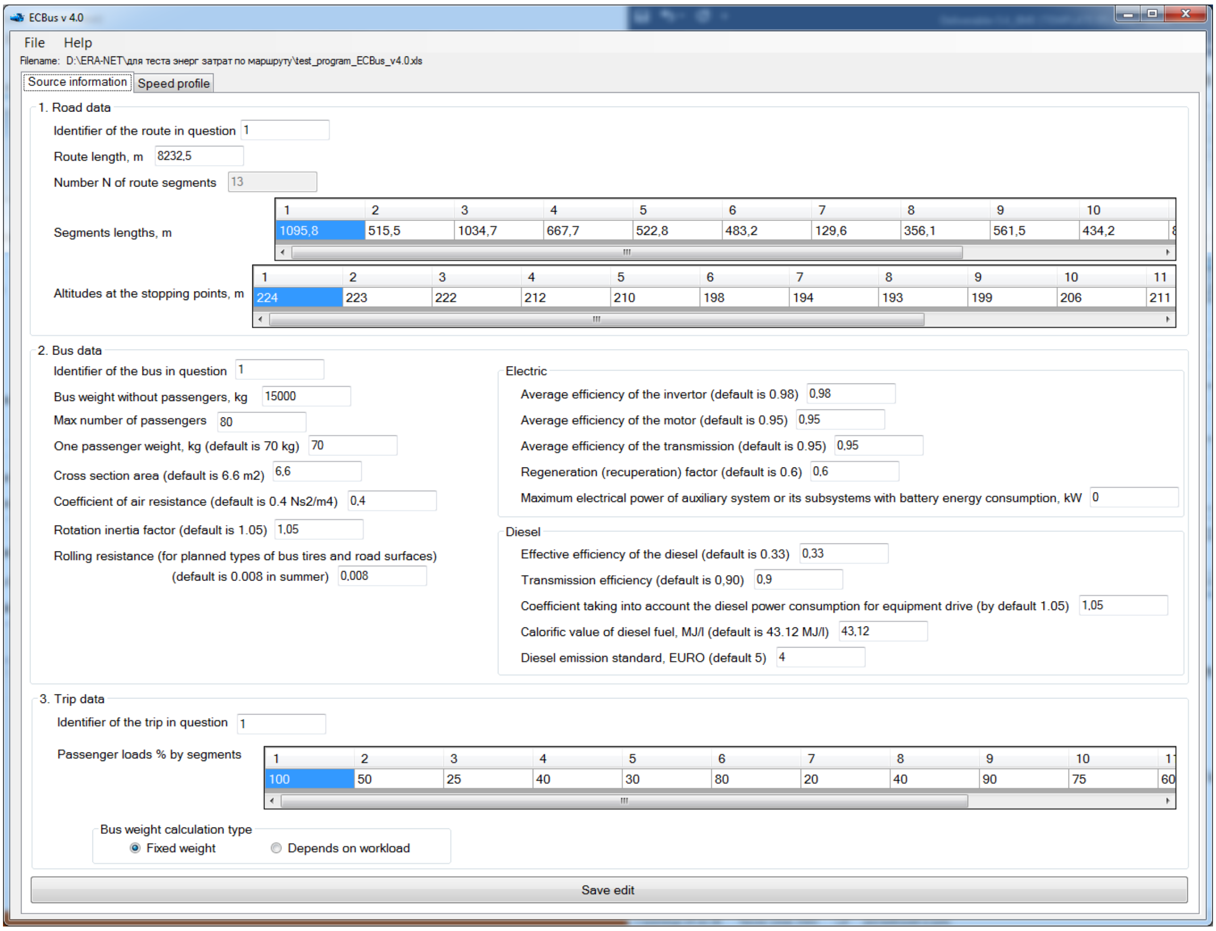


Figure 23 Downloaded data

If there is a need to make changes to the data displayed in Figure 23, you must perform the following steps:

1) edit the necessary data;

2) click the “Save edit” button.

After that, updated data will be used for calculation, which will also be saved in the file.

Downloading a file containing a speed profile

To download a file containing a speed profile, click “File” -> “Open file containing speed profile” (Figure 24), then select the required file and click “Open” (Figure 25).

A file containing data describing the speed profile must be created in Excel and have the extension *.xls. Figure 26 shows an example of filling a file with a speed profile: values of time (s), and speeds (km per hour), corresponding to time values.

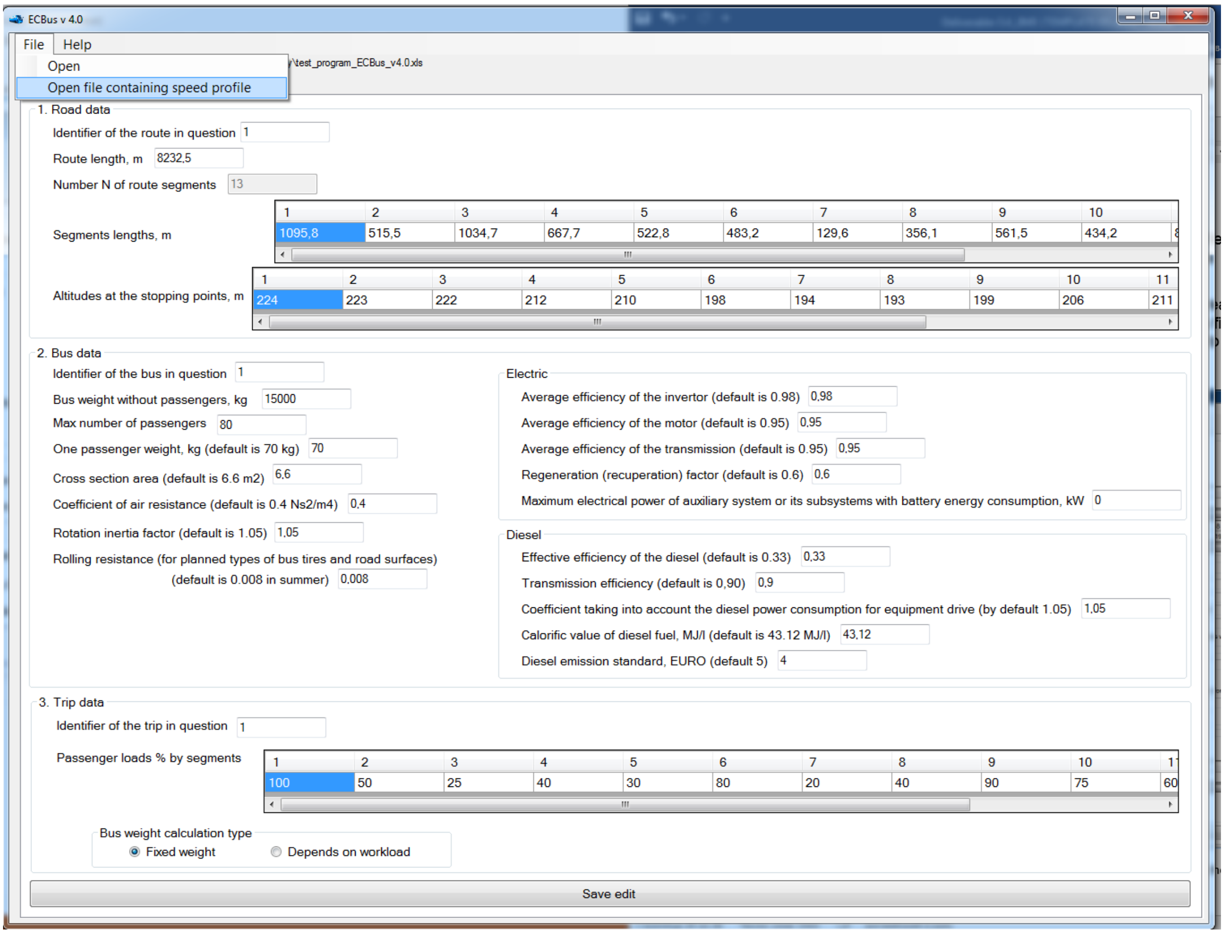


Figure 24 Opening the file with the speed profile using the menu

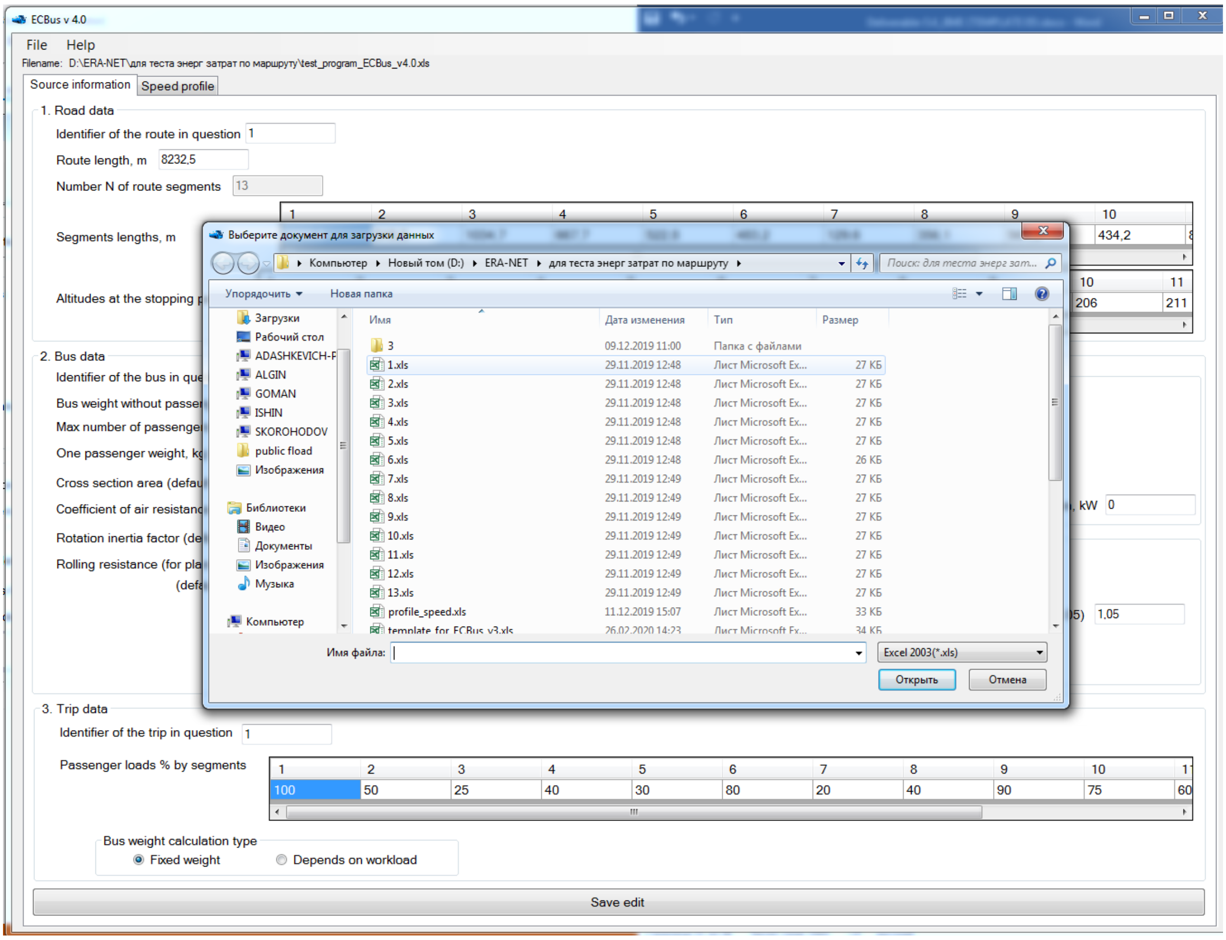
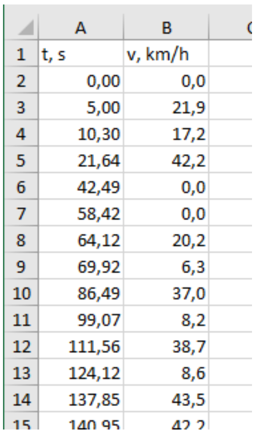
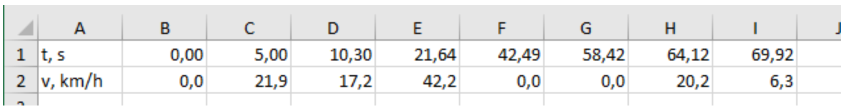


Figure 25 Selecting a file containing a speed profile



	A	B
1	t, s	v, km/h
2	0,00	0,0
3	5,00	21,9
4	10,30	17,2
5	21,64	42,2
6	42,49	0,0
7	58,42	0,0
8	64,12	20,2
9	69,92	6,3
10	86,49	37,0
11	99,07	8,2
12	111,56	38,7
13	124,12	8,6
14	137,85	43,5
15	140,95	42,2



	A	B	C	D	E	F	G	H	I
1	t, s	0,00	5,00	10,30	21,64	42,49	58,42	64,12	69,92
2	v, km/h	0,0	21,9	17,2	42,2	0,0	0,0	20,2	6,3

Figure 26 Views of Excel-files with speed profiles: vertical or horizontal tables

Switching the user to the tab “Speed profile”

After loading the speed profile and switching the user to the tab “Speed profile”, the contents of the open file are displayed. A graphical representation of the speed profile is shown in the tab “Chart speed profile” (Figure 27).

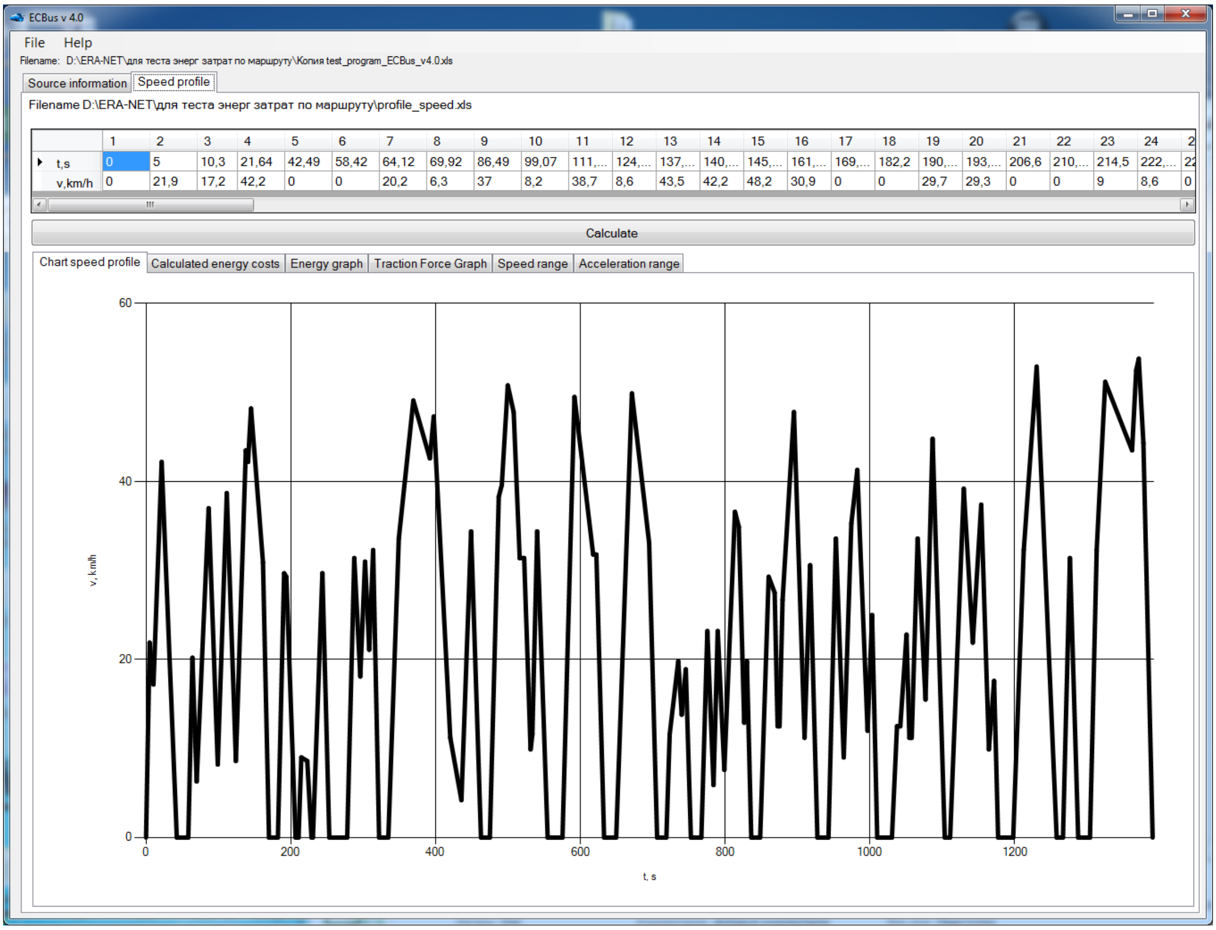


Figure 27 Speed profile and its graphical representation

Calculating

Before clicking on the “Calculate” button, it is necessary to select the method of weight accounting: fixed weight or changing weight on each segment depending on the passenger load (%). A button for the choice of weight is located on the tab “Source information”.

To calculate energy costs when driving a bus on the route, you must click “Calculate”.

7.1.5 The outputs of the ECBus

After calculating and switching to the tab “Calculated energy costs”, the following data are displayed: path length, calculated according to the speed profile, energy expended for movement, recuperated energy, total energy consumption for movement, specific consumption, energy consumption for heating / cooling the bus compartment and driver’s cabin, energy costs for heating / cooling and movement, the total energy taking into account heating / cooling as well as the specific energy consumption in this case, diesel energy consumption (kWh), fuel consumption (liters per route), fuel consumption (liters per 100 km), pollutant emission (g) for the route: CO, HC, NO_x, PM. The results of the calculations of these parameters are presented in Figure 28.

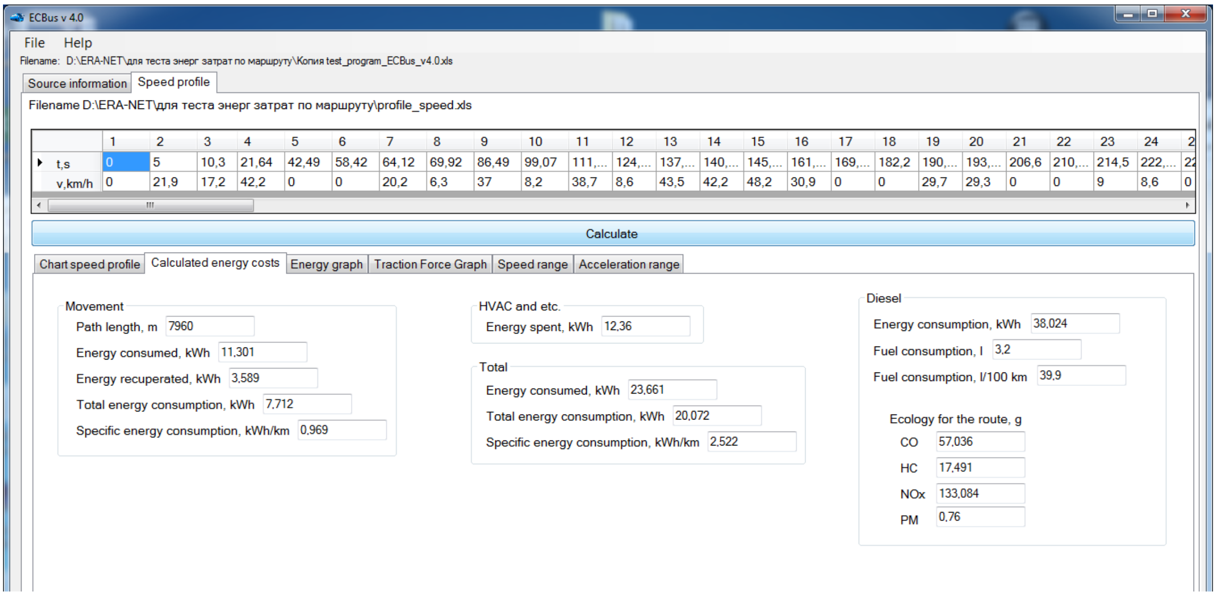


Figure 28 Results of energy calculations

Energy graphs

After switching to the tab “Energy graph”, the graphs of changes in the consumed, recovered, total (resulting) energies for electric and diesel energy consumption are displayed (Figure 29).

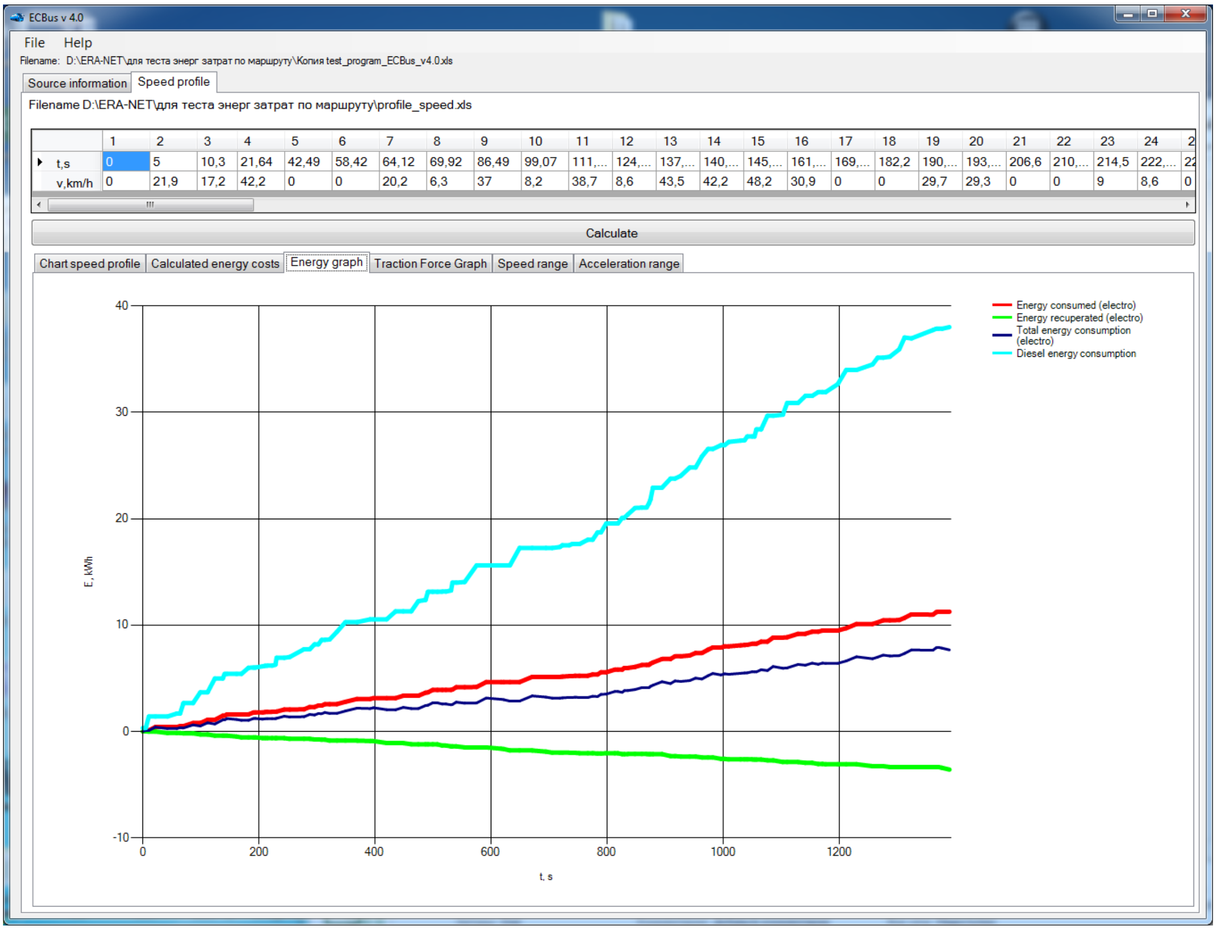


Figure 29 Graphs of energy changes

Traction force graph

To view the graph of change in the traction force, you must go to the tab “Traction Force Graph” (Figure 30).

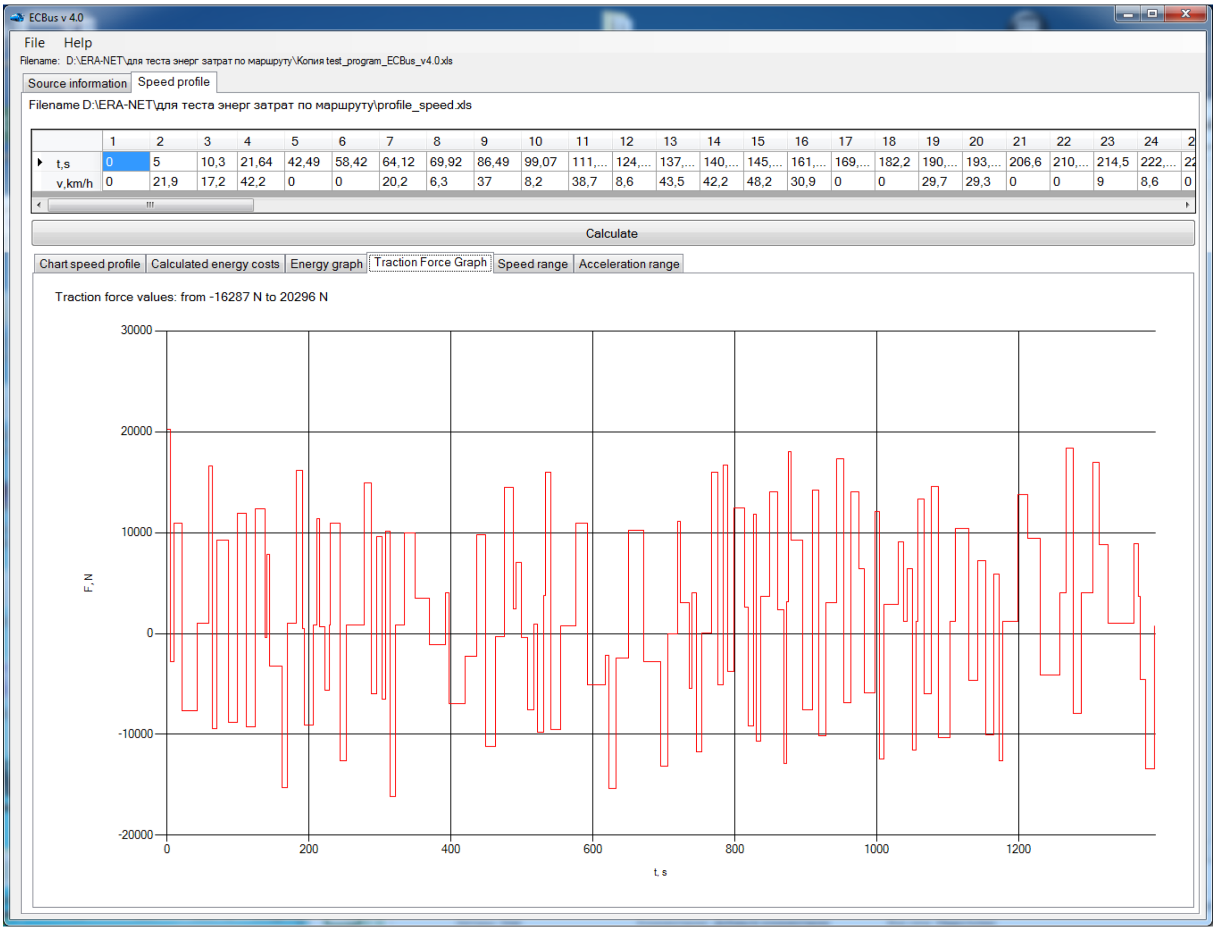


Figure 30 Graph of change in traction force

Histogram of the speed distribution

A histogram of the speed distribution is displayed after the switching to the tab «Speed range» (Figure 31).

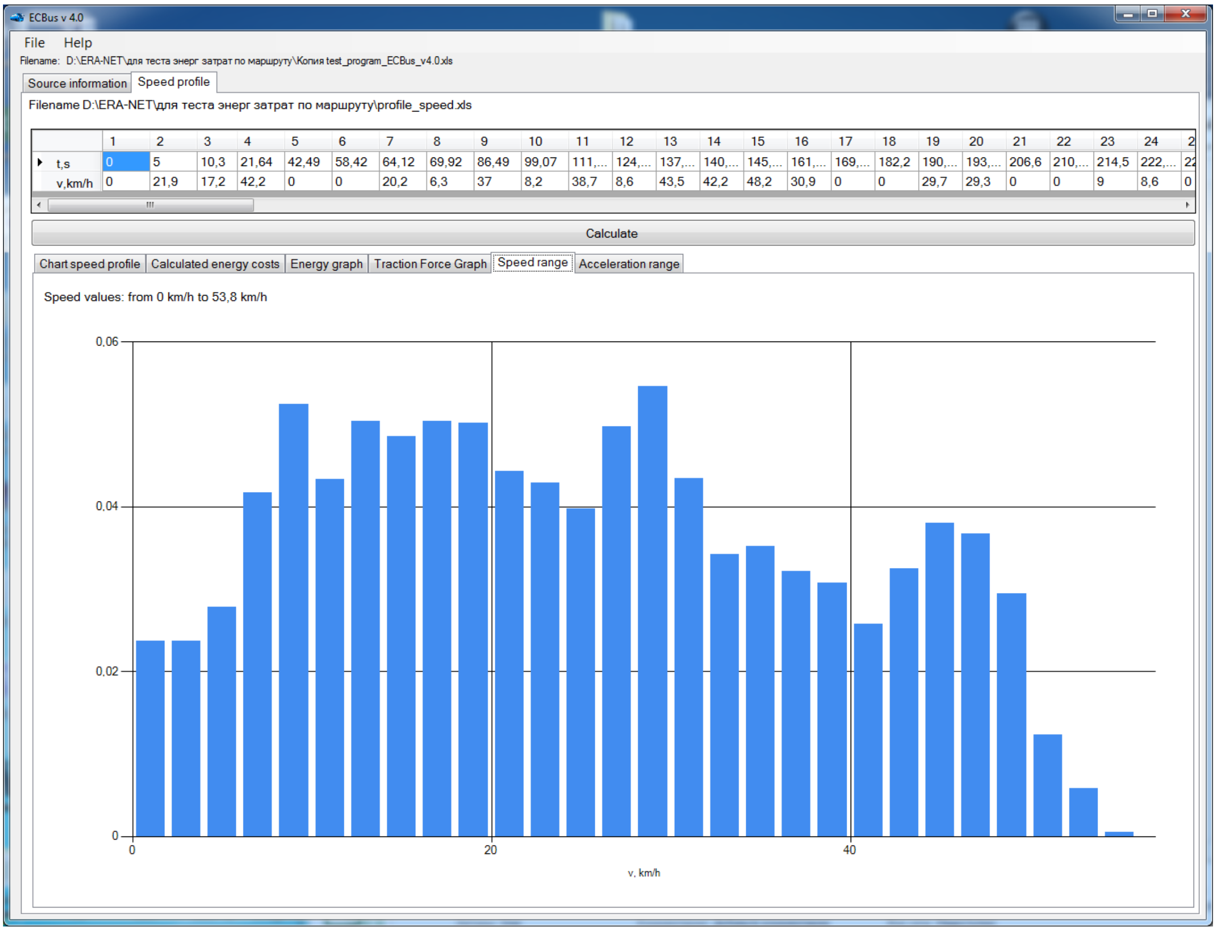


Figure 31 Histogram of the speed distribution

\

Accelerations distribution

After switching to the tab “Acceleration range”, a histogram of the distribution of accelerations is displayed (Figure 32).

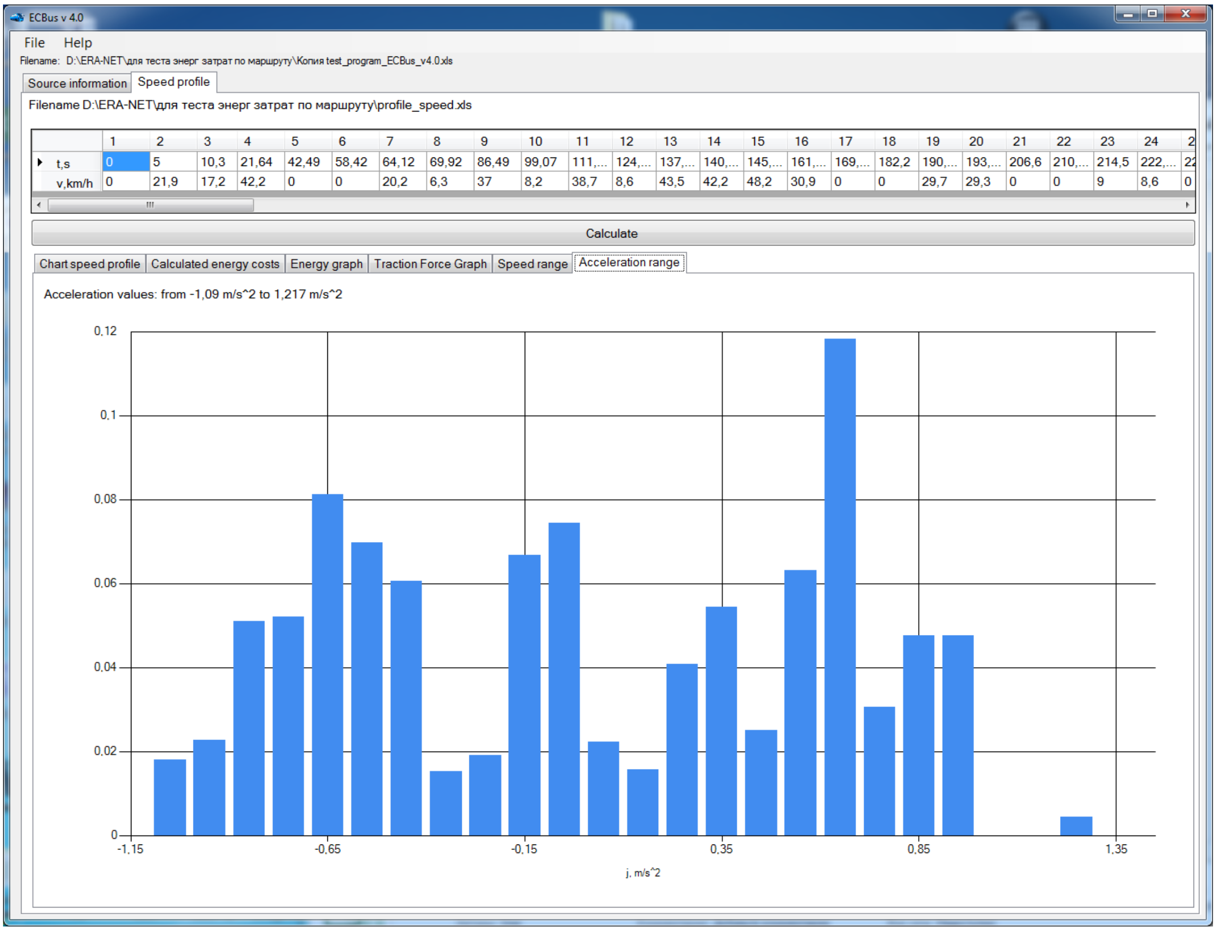


Figure 32 Histogram of the accelerations distribution

Information about the organization-developer

After switching “Help” -> “About”, information about the organization-developer of the program will be displayed (Figure 33).

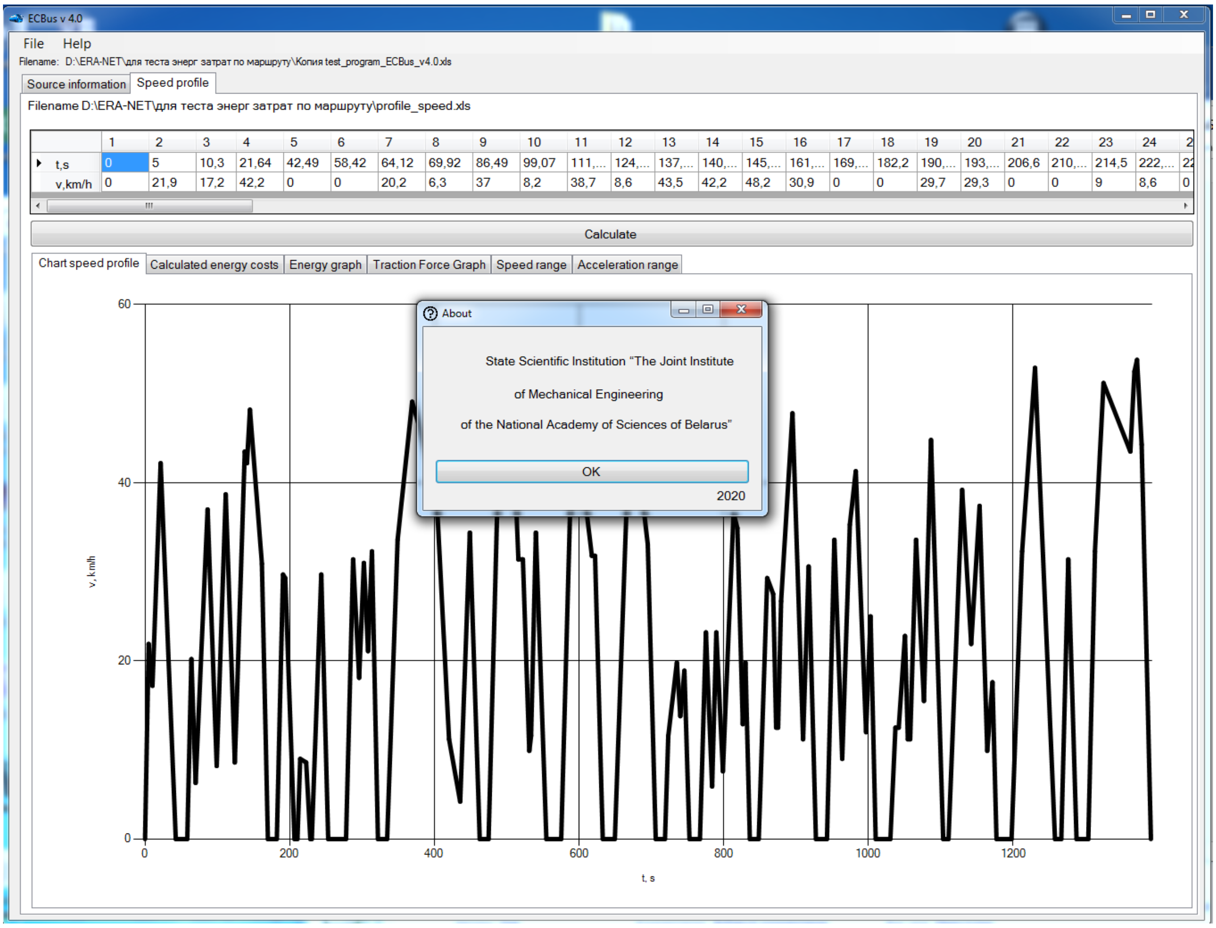


Figure 33 Organization-developer

7.2 Procedure EC-Compare

Procedure EC-Compare is designed to calculate the energy consumption of an electric bus on the route taking into account the fuel consumption of the similar diesel bus. The result is energy consumption by the electric bus under the same conditions as a diesel-analog [2].

7.2.1 System requirements of the EC-Compare

To realize the procedure EC-Compare, the personal computer with OS Windows and Excel application is used.

7.2.2 Objective of the EC-Compare

Objective of EC-Compare is to calculate the energy consumption for an electric bus using data on energy consumption of a diesel bus on the same route and take into their different Tank-to-Wheels (TTW) losses and the ability to recover the energy of an electric bus.

7.2.3 Input data for the EC-Compare

Input data are presented in Figure 34.

	A	B	C
1	**EC-Compare**		
2			
3	**Input data**		
4	1) Road data		
5	Route length, m	7960	
6	Total driving time, including stops, s	1390	
7			
8	2) Bus data		
9	(Remark. Diesel and electric buses should be about the same weight!)		
10	2.1 Diesel bus		
11	Effective efficiency of the diesel (default is 0,23)	0.23	
12	Transmission efficiency (default is 0,90)	0.92	
13	Coefficient taking into account the diesel power consumption for equipment drive (by default 1.05)	1.05	
14	Calorific value of diesel fuel (default is 43.12 MJ/l)	43.12	
15	Diesel bus fuel consumption (default is 37.40 l/100 km)	37.40	
16	2.2 Electric bus		
17	Maximum electrical power of auxiliary system or its subsystems with battery energy consumption, kW	6.00	
18	Average efficiency of the invertor (default is 0.98)	0.98	
19	Average efficiency of the motor (default is 0.95)	0.95	
20	Average efficiency of the transmission (default is 0.95)	0.95	
21	The degree of energy recuperation on the route (default is 10%)	0.10	
22			

Figure 34 Input data for EC-Compare

7.2.4 The core of the EC-Compare

The Excel file of the EC-Compare provides the intermediate calculations presented in Figure 35.

22		
23	Intermediate calculations	
24	TTW1 (diesel)	0.212
25	The energy expenditure of a diesel bus per km of the route, MJ/km	16.127
26	Energy for movement, MJ/km	3.250
27		
28	TTW2 (electric bus)	0.884
29	Energy consumption of the electric bus for movement	
30	MJ/km	3.307
31	kWh/km	0.919
32	Energy consumption for the entire auxiliary system of the electric bus	
33	kWh/km	0.291
34		

Figure 35 Intermediate calculation

7.2.5 The outputs of the EC-Compare

The final result of the EC-Compare is the total energy consumption of the electric bus (for movement and entire auxiliary system), kWh/km (see Figure 36).

34		
35	Final result	
36	Total energy consumption of the E-bus (for movement and entire auxiliary system), kWh/km	1.210

Figure 36 final result of the EC-Compare

7.3 Procedure ECPro

Procedure ECPro is designed to help the user in choosing the calculated (design, rated) value on a probabilistic representation of possible cases for an object operation under various factors.

Procedure ECPro realizes an approach to assessing energy consumption by electric buses, based on a probabilistic representation of space for numerous cases caused by the inevitable variation of operating factors on a given bus route [2].

The main idea of probabilistic approach that is realized in ECPro procedure is as follows. Any particular solution (for example, determining energy consumption of an electric bus for individual case/route or set of routes) is not base for decision making. It is necessary to consider numerous possible situations and on this basis to justify the calculated (rated) case.

This procedure may be applied to different objects and situations. In context of Platon project, ECPro is used to select the calculated energy consumption of the buses. Factors that lead to changes in energy consumption are: passenger load, temperature, driving style, road conditions, etc.

It is assumed, firstly, that the user has data that corresponds to the average value or the modal (most likely) value of energy consumption for the conditions under consideration.

Secondly, the user must evaluate the degree of possible data scattering, and what probability distribution is suitable for his case: narrow (weak) scattering or wide (strong) data scattering. The ECPro procedure implements two characteristic cases. The first case is described by the distribution of LN03 with a coefficient of variation of 0.11, and the second is described by the distribution of LN03 with a coefficient of variation of 0.2. Both distributions LN05 and LN03 are lognormal.

The LN03 is designed for cases when several factors are known and taken into account (season, snow appearance, action of HVAC) and at the same time other factors vary (driving style, passenger load, road congestion).

The LN05 is designed for cases with wide variation all factors (all seasons and operation conditions): driving style, passenger load, action of HVAC and others auxiliaries, snowfall, route congestion.

The third key problem is the choice of the probability with which the user wants to determine the calculated (rated) value of energy consumption, taking into account the possible excess in real operation of the average or modal value obtained by him. It is recommended to take the probability F_C for the calculated value within F_C = 0.8 ... 0.9, which corresponds to the actual practice of decision-making in reliability theory and other areas of engineering.

Having made decisions on these issues, the user receives a reasonable value of energy consumption E_C, which corresponds to the probability of F_C.

7.3.1 System requirements of the ECPro

To realize the procedure ECPro, the personal computer with OS Windows and Excel application is used.

7.3.2 Objective of the ECPro

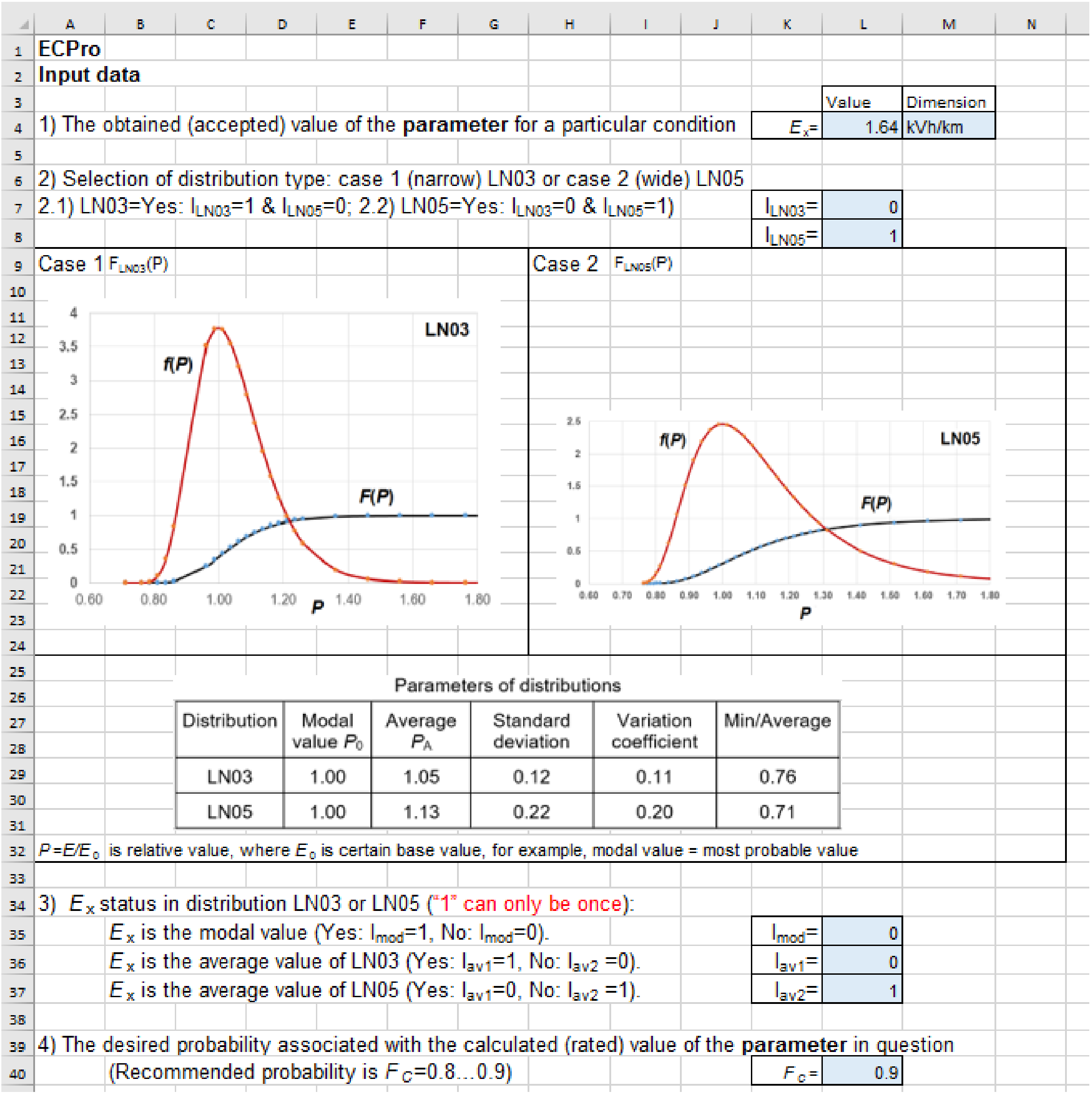
Objective of ECPro is to help the user to responsibly select the calculated value of energy consumption, based on probabilistic distribution of energy consumption for various situation and given that the calculated value refers to the probability accepted by the user.

As result, the user receives the calculated value of bus energy consumption E_C that relates to the accepted probability F_C.

7.3.3 Input data for the ECPro

Procedure ECPro is implemented in Excel.

Input data are presented in Figure 37. The user should fill in the value E_x. He may indicate any dimension of this quantity. The calculated energy consumption E_c will be displayed with the specified dimension.



ECPro

Input data

1) The obtained (accepted) value of the **parameter** for a particular condition — E_x= 1.64 (Value), kVh/km (Dimension)

2) Selection of distribution type: case 1 (narrow) LN03 or case 2 (wide) LN05

2.1) LN03=Yes: I_{LN03}=1 & I_{LN05}=0; 2.2) LN05=Yes: I_{LN03}=0 & I_{LN05}=1) — I_{LN03}= 0; I_{LN05}= 1

Case 1 $F_{LN03}(P)$ — Case 2 $F_{LN05}(P)$

Parameters of distributions

Distribution	Modal value P_0	Average P_A	Standard deviation	Variation coefficient	Min/Average
LN03	1.00	1.05	0.12	0.11	0.76
LN05	1.00	1.13	0.22	0.20	0.71

$P=E/E_0$ is relative value, where E_0 is certain base value, for example, modal value = most probable value

3) E_x status in distribution LN03 or LN05 ("1" can only be once):

E_x is the modal value (Yes: I_{mod}=1, No: I_{mod}=0). — I_{mod}= 0

E_x is the average value of LN03 (Yes: I_{av1}=1, No: I_{av2} =0). — I_{av1}= 0

E_x is the average value of LN05 (Yes: I_{av1}=0, No: I_{av2} =1). — I_{av2}= 1

4) The desired probability associated with the calculated (rated) value of the **parameter** in question

(Recommended probability is F_C=0.8…0.9) — F_C= 0.9

Figure 37 Input data for ECPro

7.3.4 The core of the ECPro

The Excel file for realization of ECPro contains the auxiliary data to describe the distributions LN03 and LNO5 by digital data (see Figure 38).

41													
42	**Auxiliary data: Tables describing distributions**												
43													
44	Table 1	Case 1											
45	$F_{LN03}(P)$	0.021	0.248	0.340	0.434	**0.525**	**0.610**	**0.685**	**0.749**	**0.803**	**0.847**	**0.882**	**0.910**
46	P	0.86	0.96	0.99	1.01	1.04	1.06	1.09	1.11	1.14	1.16	1.19	1.21
47													
48	Table 2	Case 2											
49	$F_{LN05}(P)$	0.280	0.342	0.402	0.460	**0.515**	**0.566**	**0.614**	**0.657**	**0.695**	**0.730**	**0.762**	**0.789**
50	P	0.99	1.01	1.04	1.06	1.09	1.11	1.14	1.16	1.19	1.21	1.24	1.26
51													

Figure 38 Data to describe the distributions

During the calculation, the user generates Table 3 in an open Excel file based on the data from Table 1 or 2. As an intermediate result, the calculated value of energy consumption in relative (dimensionless) form is determined (see Figure 39).

51									
52	**Calculation**								
53									
54	**1) Form Table 3 of values F1(P1) and F2(P2) closest to selected probability for the selected case**								
55	Example:	F_C = 0.8	Case 1			Table 3			
56	F1=	**0.749**	F2=	**0.803**		F1=	**0.836**	F2=	**0.901**
57	P1=	1.11	P2=	1.14		P1=	1.31	P2=	1.41
58									
59	**2) Read the relative calculated value**					P_C=	1.41		
60									

Figure 39 Forming Table 3 and determination of calculated energy consumption in relative unit

7.3.5 The outputs of the ECPro

The results are presented in final Table that is presented in Figure 40.

60						
61	**Results**					
62	I_{LN03}= 0	I_{LN05}= 1	E_x= 1.64		For F_C= 0.9	
63	Parameters	Relative values		Absolute values		Dimension
64	Modal value	P_0=	1.00	E_0=	1.45	kVh/km
65	Average value	P_A=	1.13	E_A=	1.64	kVh/km
66	Accepted (given) value	P_x=	1.13	E_x=	1.64	kVh/km
67	**Calculated value**	P_C=	**1.41**	E_C=	**2.04**	kVh/km
68						

Figure 40 Final table containing input and main results including the calculated energy consumption EC

7.4 References to the ECBus+ Component

1. Algin V., Goman A., Skorokhodov A. (2019) *Main Operational Factors Determining the Energy Consumption of the Urban Electric Bus: Schematization and Modelling*. In: Topical issues of mechanical engineering: Collection of scientific papers, Minsk, iss. 8, pp. 185-194. DOI: 10.13140/RG.2.2.32154.80328, 2019.
2. Algin V. (2019) *Calculated Modes for Assessing Operation Properties and Dependability of Vehicles*. In: Uhl T. (eds) Advances in Mechanism and Machine Science. IFToMM WC 2019. Mechanisms and Machine Science, vol 73. Springer, Cham, pp. 3749-3758, doi: 10.1007/978-3-030-20131-9_370

8 Component TCOModel

The TCOModel component aims to calculate the total cost of ownership for the electric bus operation. The component is divided into *Static* and *Socially-oriented dynamic TCO model*. In the static TCO model the following assumptions were made regarding the calculation and analysis of the bus fleet conversion process:

a) One-time purchase of the necessary number of buses immediately and construction of the infrastructure in an amount ensuring full service of the bus battery charging needs,

b) Different financing models for the purchase of buses and battery charging infrastructure:

- Self-financing,
- Self-financing and subsidy,
- Loan for own funds,

c) fixed values of all characteristics/variables in subsequent years of the analysis period, including annual bus operation, prices of electricity and its supply, bus prices and infrastructure construction costs,

d) Cost allocation for only one stakeholder/beneficiary of the investment

The scheme of the static model is presented in the picture below (Figure 41).

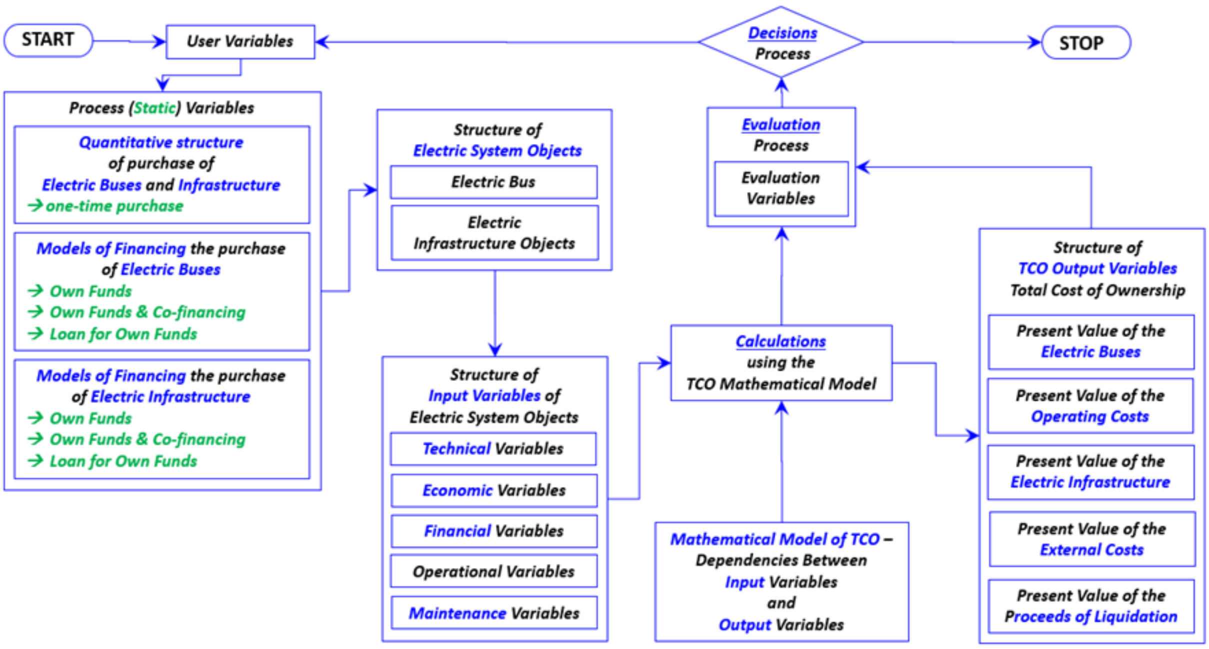


Figure 41 General algorithm of socially-oriented model of TCO (static approach)

Socially-oriented dynamic TCO model is presented in Figure 42. The dynamics of the TCO model is primarily to take into account the following phenomena overtime associated with the period of calculations and analyses of bus fleet conversion processes:

a) Purchase of the necessary number of buses immediately,

b) Purchase of buses in tranches from time to time,

c) Construction of infrastructure in an amount to provide full service to the needs of bus battery charging,

d) Expansion of infrastructure as the growing needs arising from the purchase of buses in tranches from time to time,

e) Different financing models for the purchase of buses for each of options a) and b):

- Self-financing,
- Self-financing and subsidy,
- Loan for own funds,
- Leasing,

f) Different financing models for bus battery charging infrastructure for each of options c) and d):

- Self-financing,
- Self-financing and subsidy,
- Loan for own funds,
- Leasing,

g) Change in the values of the following characteristics/variables in subsequent years of the analysis period:

- Annual bus operation,
- The price of electricity and the price of the supply of this energy,
- Bus price in subsequent tranches,
- Price of infrastructure in subsequent tranches,

h) Different cost-sharing structure for individual stakeholders/investment beneficiaries:

- Operator,
- Transport organizer,
- Public transport authority / local government.

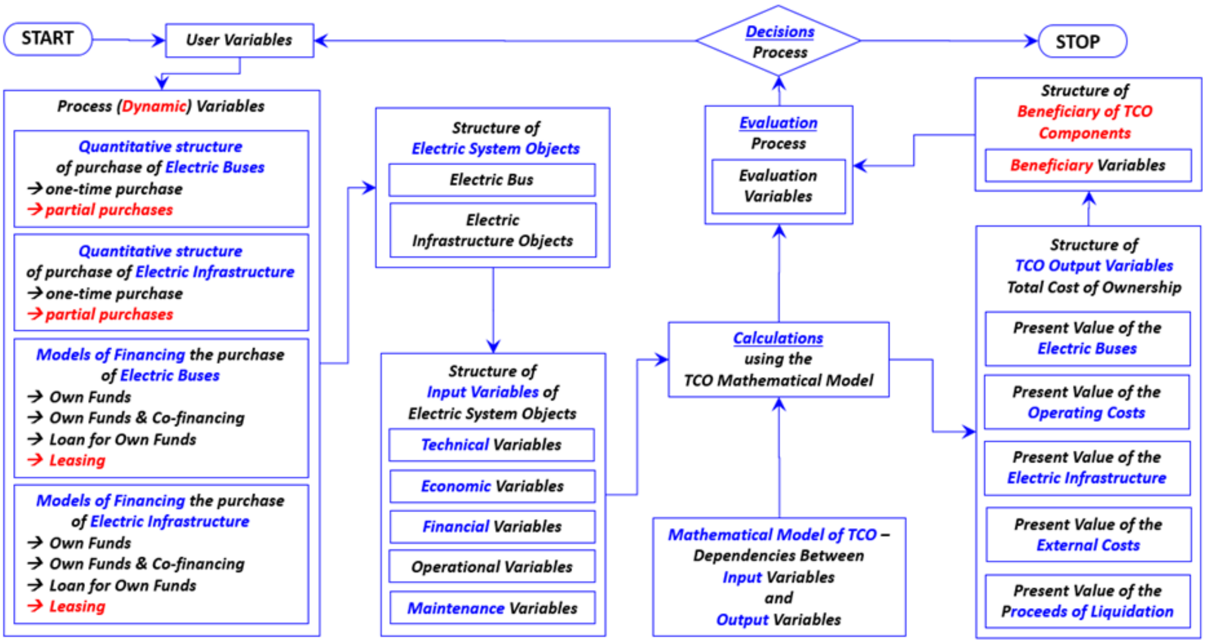


Figure 42 General algorithm of socially-oriented model of TCO (dynamic approach)

The differences between the dynamic and static approach to the TCOModel component are the following:

I) The purchase of the required number of buses in the static model was carried out in full, i.e. without tranches. Whereas in the dynamic model, variants a) and b) were additionally included**,**

II) The purchase and construction of the needed bus battery charging infrastructure in the static model were carried out in its entirety, i.e. without tranches. Whereas in the dynamic model, variants c) and d) were additionally included,

III) In the dynamic model, combinations of variants for the purchase of buses and variants for the construction of the infrastructure are additionally possible, e.g.:

i. a) & c);

ii. a) & d), however, there may be limited possibilities of bus coverage due to the phased construction of the infrastructure (in tranches),

iii. b) & c), however, it is recommended to adapt the needs of servicing a specific number of buses in subsequent tranches to the resources of the battery charging infrastructure - to optimally use the resources of the battery charging infrastructure to the changing needs of bus service related to their number in subsequent tranches,

iv. b) & d), however, it is recommended to adapt the required amount of infrastructure in subsequent tranches to the assumed number of buses in subsequent tranches

- to optimally use the resources of the battery charging infrastructure for the needs of bus service,

IV) In the dynamic model, combinations of variants for financing bus purchase models are additionally possible e) with models for financing bus battery charging infrastructure f) for specific combinations of variants regarding bus purchase and infrastructure construction - point III.

V) In the dynamic model, additional values of specific characteristics/variables can be changed in subsequent years of the analysis period, including:

i. The annual work operating the bus,

ii. The price of electricity and the price of the supply of this energy,

iii. The price of the bus in subsequent tranches,

iv. Price of infrastructure in subsequent tranches,

VI) In the dynamic model, additional variants of the distribution of TCO costs into various stakeholders/beneficiaries of the investment related to the purchase of buses and the infrastructure of electric battery charging are possible.

VII) In the dynamic model, in addition to the static model, all of the above-mentioned data change possibilities are possible at any time during the analysis - the variables are time-dependent.

8.1 System requirements of the TCOModel

TCOModel is a web-based tool and only internet access and an up-to-date internet browser (eg. Firefox, Chrome) is required. We recommend using Microsoft Office's Excel to read and edit .csv files, however, the latter is not necessary – one may use freeware tools too.

8.2 Objective of the TCOModel

The main objective of the developed TCO model is to investigate all, true costs of ownership of electric buses fleet throughout the entire life cycle of this investment. From the company's viewpoint (that is a public transport operator), the most important objective of the TCO model is to identify costs of investment (acquisition and operation) in the long period. From the economic point of view, the main objective of TCO model is to identify all, true and usually hidden costs of investment, so including external costs in the entire life cycle. Knowing these costs is necessary from the point of view of the efficiency of decision making.

8.3 Input data for the TCOModel

The input data for the TCOModel may be typed in using two different ways:

- With the use of dedicated .csv file
- With the use of the form on the website of the tool

The .csv form is quite a long file which includes a set of input parameters (Table 12). The .csv input file will be able to be downloaded from the dedicated website. One may edit it in Excel (what we recommend), however other .csv editors like Notepad++ are possible to be used. All the parameters are discussed in the third separated value (column 3 in Table 12). Only first two columns are machine-readable, so moving them is not permissible (this may result in crashing the file).

Table 12 Parameters of input data file for TCO calculation

Parameter name	*Unit*	*Short description*	*Broad description*
Bat_{life}	[years]	durability (lifetime) of the bus battery	Assumed durability (lifespan) of a battery, defined by the manufacturer. Estimated usage time - the period during which the capacity decrease will not be greater than a certain percentage of the nominal capacity of the battery.
Bat_{cap}	[kWh]	battery capacity	Battery capacity according to the catalogue data provided by th manufacturer
Bus_{life}	[years]	bus durability (lifetime)	Certain assumed durability (lifespan) of a bus/infrastructure. Estimated usage time. The time during which the product retains the utility functions and features that are important to the user and the period during which the operating and maintenance costs do not increase significantly.
i_{bat}	[%]	discount rate for bat1	The discount rate is the interest rate used to determine the present value of future future cash flows, so all kinds of costs and revenues. Cash flows are discounted with a discount rate adequate for the year in which such cash flows take place. Assumed discount rate is 5% as recommended by the European Commission for the programming period 2014-2020. https://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf
i_{bat2}	[%]	discount rate for bat2	The discount rate is the interest rate used to determine the present value of future cash flows, so all kinds of costs and revenues. Cash flows are discounted with a discount rate adequate for the year in which such cash flows take place. Assumed discount rate is 5% as recommended by the European Commission for the programming period 2014-2020. https://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf

Parameter name	*Unit*	*Short description*	*Broad description*
i_{bus}	[%]	discount rate (buses)	The discount rate is the interest rate used to determine the present value of future future cash flows, so all kinds of costs and revenues. Cash flows are discounted with a discount rate adequate for the year in which such cash flows take place. Assumed discount rate is 5% as recommended by the European Commission for the programming period 2014-2020. https://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf
i_{infra}	[%]	discount rate (infrastructure)	The discount rate is the interest rate used to determine the present value of future future cash flows, so all kinds of costs and revenues. Cash flows are discounted with a discount rate adequate for the year in which such cash flows take place. Assumed discount rate is 5% as recommended by the European Commission for the programming period 2014-2020. https://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf
$EPoll_{cost\_er}$	[EUR/vkm]	rate of air pollutant and GHG emission per vehicle-km	Negative effects of provided services transferred to third parties who did not to incur that cost. They primarily affect the quality of environment and human health. Externalties are valued according to a strictly defined methodology. Unit values were adopted in accordance with the guidelines of European Commission: https://ec.europa.eu/transport/sites/transport/files/studies/internalisation-handbook-isbn-978-92-79-96917-1.pdf
$Noise_{cost\_r}$	[EUR/vkm]	cost rate of noise emission per 1 vehicle-km	Negative effects of provided services transferred to third parties who did not to incur that cost. They primarily affect the quality of environment and human health. Externalties are valued according to a strictly defined methodology. Unit values were adopted in accordance with the guidelines of European Commission: https://ec.europa.eu/transport/sites/transport/files/studies/internalisation-handbook-isbn-978-92-79-96917-1.pdf For electric buses, it is assumed to be about 50% of the value assumed for Diesel buses.

Parameter name	Unit	Short description	Broad description
$HPoll_{cost\_er}$	[EUR/vkm]	cost rate of pollutant emission per 1 vkm (bus heating with oil)	Negative effects of provided services transferred to third parties who did not to incur that cost. They primarily affect the quality of environment and human health. Externalties are valued according to a strictly defined methodology. Unit values were adopted in accordance with the guidelines of European Commission: https://ec.europa.eu/transport/sites/transport/files/studies/internalisation-handbook-isbn-978-92-79-96917-1.pdf Heating a vehicle with diesel oil is associated with the emission of pollutant emission.
pl_r	[%]	residual value rate of the bus	The residual value is the estimated value of an asset that is expected to obtain when the asset is dispositioned at the end of its useful life.
$AC_{bat2\_self}\ (t = Bat_{life})$	[EUR]	acquisition costs of spare battery [EUR] after period t equal lifetime of the bus battery bat_life,	Nominal acquisition costs of an additional, spare battery after specified period t, which is equal to the durability period of the first battery.
$Bat_{unit_{Cost}}$	EUR/kWh	Cost of battery unit capacity	Unit costs of 1 kWh battery capacity.
$BatD_i\ (t = Bat_{life})$	[EUR]	costs of battery disposal for i-th bus [EUR] after period t equal lifetime of the bus battery bat_life	Nominal costs of battery disposal for i-th specific bus after some period t , which is equal to the lifetime period of the battery and will no longer will no longer be used.
$AC_{bus\_nom_i}$	[EUR]	Nominal acquisition costs of bus	Nominal acquisition costs of bus, including the costs of battery and the cost of a bus without batteries. Bus purchase can be financed from own resources, leasing or co-financed by a subsidy as well.
Bus_{self_i}	[EUR]	costs of bus acquisition (self-financing)	Nominal costs of bus acquisition form the company's own funds.
Bus_{sub_i}	[EUR]	subsidies for bus	Nominal value of subsidies obtained for the purchase of buses.
Bus_{cost}	[EUR]	bus costs	Nominal cost of a bus without batteries.
$Vbus\_init_i$	[EUR]	value of the leased bus without initial fees	Nominal value of the leased bus without initial fees.
$Vbus\_pur_i$	[EUR]	value of the leased bus purchase	Nominal purchase value of the leased asset with the ownership right, paid after the end of the leased contract. Usually 0.1%-1% of initial value of the leased asset.
$i_{bus_{leas}}$	[%]	Leasing interest rate	A percentage indicator reflecting the charge for the use of an asset that is leased (per annum).

Parameter name	*Unit*	*Short description*	*Broad description*
$AC_{bus\_cred_i}$	[EUR]	amount of credit for the bus purchase	Nominal value of bank credit for the bus purchase. Two types of bank credit are possible: bank credit with equal instalments (annuities) or bank credit with decreasing instalments (instalments with fixed capital part).
s_{bus}	[%]	credit interest rate (bus)	Bank cedit interest rate per annum for bus purchase.
$OC_{bus\ fl}$	[EUR]	annual operating costs of the bus fleet	Nominal annual operating costs of the bus fleet including energy costs, maintenance costs, insurance, energy supply costs etc.
OC_{ener}	[EUR]	annual energy costs	Annual energy costs used for service.
OC_{maint}	[EUR]	annual maintenance costs	Annual maintenance costs of electric bus fleet.
OC_{insur}	[EUR]	annual insurance cost	Annual insurance costs for electric bus fleet.
OC_{ener_supp}	[EUR]	annual costs of daily energy supply	Annual costs of daily energy supply.
$\mathrm{OC_{other}}$	[EUR]	other annual costs (for example vehicle tax)	Other annual costs associated with electric bus fleet (for example vehicle tax).
$Ener_{supp\_cost\_r}$	[EUR/vkm]	energy supply cost rate	Energy supply cost rate per 1 vkm.
$Staff_{cost\_r}$	[EUR/staff-service-hours]	staff service cost rate	Staff service cost rate (technical service)
$Ener_{cost\_LV}$	[EUR/kWh]	cost rate of energy (low-voltage energy grid)	The cost of the low-voltage energy according to the price list (offer) of the energy supplier
$Ener_{cost\_MV}$	[EUR/kWh]	cost rate of energy (medium-voltage energy grid)	The cost of the medium-voltage energy according to the price list (offer) of the energy supplier
Tax_{relief_LV}	[EUR/kWh]	tax relief (low-voltage energy grid)	Value of tax relief for low-voltage energy cost rate
Tax_{relief_MV}	[EUR/kWh]	tax relief (medium-voltage energy grid)	Value of tax relief for medium-voltage energy cost rate
$PkWh$	[kWh]	annual energy consumption for charging vehicles	-
$PkWh\_MV$	[kWh]	annual energy consumption for charging vehicles (medium-voltage energy grid)	-

Parameter name	*Unit*	*Short description*	*Broad description*
$PkWh\_LV$	[kWh]	annual energy consumption for charging vehicles (low-voltage energy grid)	-
AC_{infra_self}	[EUR]	costs of infrastructure acquisition (self-financing)	Nominal costs of infrastructure acquisition form the company's own funds.
$Infra_{sub}$	[EUR]	subsidies for infrastructure	Nominal value of subsidies obtained for the purchase of charging infrastructure.
AC_{infra_nom}	[EUR]	infrastructure nominal acquisition costs	Nominal acquisition costs of infrastructure, which can be financed from own resources, leasing or co-financed by a subsidy as well.
AC_{infra_dep}	[EUR]	acquisition costs of depot conductive plug-in charging	Nominal acquisition costs of depot conductive plug-in charging.
AC_{infra_swap}	[EUR]	acquisition costs of battery swapping-charging	Nominal acquisition costs of battery swapping-charging
AC_{infra_panto}	[EUR]	acquisition costs of pantograph charging	Nominal acquisition costs of pantograph charging
AC_{infra_stop}	[EUR]	acquisition costs of on bus-stop charging	Nominal acquisition costs of on bus-stop charging
AC_{infra_induct}	[EUR]	acquisition costs of in-motion inductive charging	Nominalne acquisition costs of in-motion inductive charging.
AC_{infra_lease}	[EUR]	nominal value of annual leas instalment (infrastructure)	-
i_{infra_lease}	[%]	lease interest rate	A percentage indicator reflecting the charge for the use of an asset that is leased (per annum).
V_{infra_init}	[EUR]	value of the leased infrastructure without initial fees	Nominal value of the leased infrastructure without initial fees.
V_{infra_purch}	[EUR]	value of the leased infrastructure purchase	Nominal purchase value of the leased asset (infrastructure) with the ownership right, paid after the end of the leased contract. Usually 0.1%-1% of initial value of the leased asset.
AC_{infra_cred}	[EUR]	acquisition costs of infrastructure with credit	Nominal value of bank credit for the infrastructure acquisition. Two types of bank credit are possible: bank credit with equal instalments (annuities) or bank credit with decreasing instalments (instalments with fixed capital part).
s_{infra}	[%]	credit interest rate (infrastructure)	Bank cedit interest rate per annum for infrastructure acquisition).

Parameter name	Unit	Short description	Broad description
MC_{infra_dep}	[EUR]	annual maintenance costs of depot conductive plug-in charging	-
MC_{infra_swap}	[EUR]	annual maintenance costs of battery swapping-charging	--
MC_{infra_stop}	[EUR]	annual maintenance costs of on bus-stop charging	-
MC_{infra_induct}	[EUR]	annual maintenance costs of in-motion inductive charging	-
$\mathrm{MC_{infra\_panto}}$	[EUR]	annual maintenance costs of pantograph charging	-
MC_{other}	[EUR]	other annual costs (for example insurance, taxes)	-
$Work_{staff\_service}$	[staff-service-hours/bus]	staff service hours per year per bus	-
Bus_{oper_ann}	[vkm/year]	annual transport work	Number of vehicles x mileage in a given year
$Bus_{oper\_ann\_h}$	[vkm/year]	annual transport work of bus fleet with oil heating	-
$Ener_{cons}$	[kWh/vkm]	energy consumption	-
$\mathrm{Infra_{life}}$	[years]	infrastructure life	Certain assumed durability of a bus/infrastructure. Estimated usage time. The time during which the product retains the utility functions and features that are important to the user and the period during which the operating and maintenance costs do not increase significantly.

Recommended default values of the variables presented in Table 12, are presented in Table 13. The following values are just recommendations; one may type in other values, according to the situation.

Table 13 Recommended default values

Variable	Unit	Default
Bat_{life}	[years]	7
Bat_{cap}	[kWh]	240
Bus_{life}	[years]	20

Variable	Unit	Default
i_{bat}	[%]	4,5
i_{bat2}	[%]	4,5
i_{bus}	[%]	4,5
i_{infra}	[%]	4,5
$EPoll_{cost\_er}$	[EUR/vkm]	0,32
$Noise_{cost\_r}$	[EUR/vkm]	0,067
$HPoll_{cost\_er}$	[EUR/vkm]	0,16
pl_r	[%]	5
$AC_{bat2_{self}}$ $(t = Bat_{life})$	[EUR]	-
$Bat_{unit_{Cost}}$	EUR/kWh	1000
$BatD_i$ $(t = Bat_{life})$	[EUR]	500
$AC_{bus\_nom_i}$	[EUR]	400 000
Bus_{self_i}	[EUR]	-
Bus_{sub_i}	[EUR]	0
Bus_{cost}	[EUR]	400 000
$Vbus\_init_i$	[EUR]	400 000
$Vbus\_pur_i$	[EUR]	2 000
$i_{bus_{leas}}$	[%]	4
$AC_{bus\_cred_i}$	[EUR]	-
s_{bus}	[%]	14
OC_{bus}	[EUR]	67 000
$OC_{bus\ fl}$	[EUR]	-
OC_{ener}	[EUR]	25 000
OC_{maint}	[EUR]	10 000
OC_{insur}	[EUR]	10 000
OC_{ener_supp}	[EUR]	22 000
$\mathrm{OC}_{\mathrm{other}}$	[EUR]	-
$Ener_{supp\_cost\_r}$	[EUR/vkm]	0,2
$Staff_{cost\_r}$	[EUR/staff-service-hours]	5,0
$Ener_{cost\_LV}$	[EUR/kWh]	0,1
$Ener_{cost\_MV}$	[EUR/kWh]	0,2
Tax_{relief_LV}	[EUR/kWh]	0
Tax_{relief_MV}	[EUR/kWh]	0
$PkWh$	[kWh]	-
$PkWh\_MV$	[kWh]	-

Variable	*Unit*	*Default*
$PkWh\_LV$	[kWh]	-
AC_{infra_self}	[EUR]	-
$Infra_{sub}$	[EUR]	0
AC_{infra_nom}	[EUR]	100 000
AC_{infra_dep}	[EUR]	30 000
AC_{infra_swap}	[EUR]	30 000
AC_{infra_panto}	[EUR]	30 000
AC_{infra_stop}	[EUR]	150 000
AC_{infra_induct}	[EUR]	75 000
AC_{infra_lease}	[EUR]	-
i_{infra_lease}	[%]	4
V_{infra_init}	[EUR]	100 000
V_{infra_purch}	[EUR]	500
AC_{infra_cred}	[EUR]	120 000
s_{infra}	[%]	14
MC_{infra_dep}	[EUR]	10 000
MC_{infra_swap}	[EUR]	800
$\mathrm{MC_{infra\_panto}}$	[EUR]	1200
MC_{infra_stop}	[EUR]	1200
MC_{infra_induct}	[EUR]	2500
MC_{other}	[EUR]	-
$Work_{staff\_service}$	[staff-service-hours/bus]	2200
Bus_{oper_ann}	[vkm/year]	85 000
$Bus_{oper\_ann\_h}$	[vkm/year]	80 000
$Ener_{cons}$	[kWh/vkm]	1,2 per 12m bus; 1,8 per 18m bus
$\mathrm{Infra_{life}}$	[years]	20

The file should be uploaded using the screen in the Figure 43.

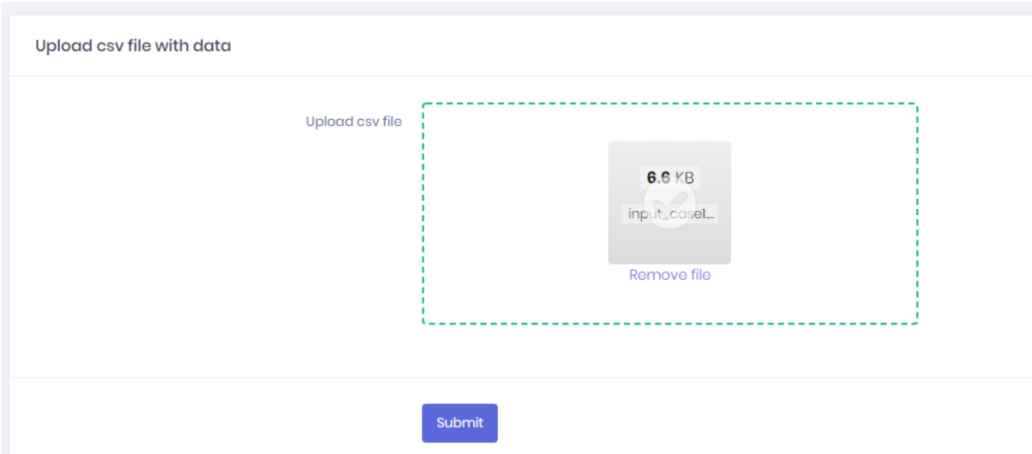


Figure 43 Submitting of .csv file

To fill in the input data one may also use the form available on the website directly. Using this method, one may see the recommended default values as shown in Figure 44.

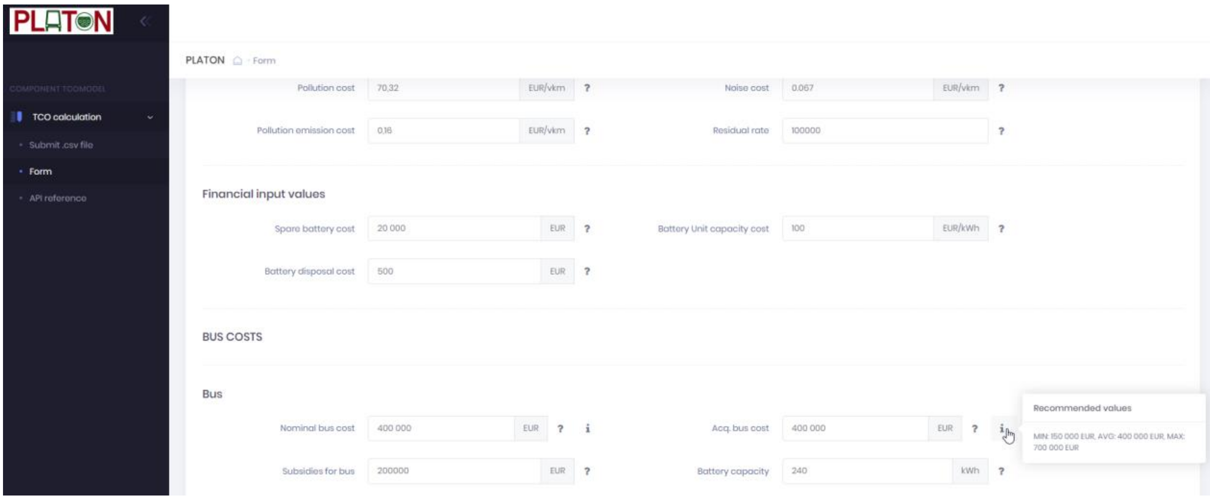


Figure 44 Recommended default values

Another way of using the TCOModel component is the PHP interface.

8.4 The core of the TCOModel

All the calculations takes place in background. The Total Cost of Ownership is calculated using the following formula:

$$(1) \qquad TCO = (PV_{bus} - PVL_{liq\_bus}) + PVOC_{bus} + PV_{infr} + PVE_{exter}$$

where:

TCO – total cost of ownership [PLN, EUR],

$\mathrm{PV_{bus}}$ – present value of the acquisition costs of electric buses [PLN, EUR],

$\mathrm{PVOC_{bus}}$ – present value of buses operating costs [PLN, EUR],

$\mathrm{PV_{infr}}$ – present value of the infrastructure [PLN, EUR],

$\mathrm{PVE_{exter}}$ – present value of the external costs [PLN, EUR],

$\mathrm{PVL_{liq\_bus}}$ – present value of the proceeds of liquidation [PLN, EUR]

Electric Buses Acquisition Costs

Present value of the acquisition costs of electric buses is a sum of discounted nominal acquisition costs of each purchased bus:

$$(2) \qquad \boldsymbol{PV_{bus} = \sum_{i=1}^{n} DAC_{bus\_nom_i}}$$

Where:

$\mathrm{DAC_{bus\_nom_i}}$ – discounted nominal acquisition costs of i-th bus [EUR]

i – number of consecutive bus (i-th bus number)

n – number of purchased buses

Discounted nominal acquisition costs of i-th bus is carried out by the formula:

$$(3) \qquad \boldsymbol{DAC_{bus\_nom_i} = \sum_{m_{ac}}^{M_{ac}} \left(AC_{bus\_nom_i} \cdot \frac{1}{(1+i_{bus})^{m_{ac}}} \right)}$$

Where:

$\mathrm{AC_{bus\_nom_i}}$ – nominal acquisition costs of bus [EUR]

$\mathrm{i_{bus}}$ – discount rate (buses) [%],

$\mathrm{M_{ac}}$ – investment term [years],

i – number of consecutive bus (i-th bus number)

$\mathrm{m_{ac}}$ – time with bus acquisition

Nominal Acquisition costs of bus are calculated as sum of battery nominal costs and bus costs:

$$(4) \qquad \boldsymbol{AC_{bus\_nom_i}} = \left(\boldsymbol{Bat_{cap}} \cdot \boldsymbol{Bat_{unit_{Cost}}}\right) + \boldsymbol{Bus_{cost}}$$

where:

$\mathrm{AC_{bus\_nom_i}}$ – nominal acquisition costs of bus [EUR]

$\mathrm{Bat_{cap}}$ – battery capacity [kWh]

$\mathrm{Bat_{unit_{Cost}}}$ – cost of battery unit capacity [EUR/kWh]

$\mathrm{Bus_{cost}}$ – bus costs [EUR]

The economic, dynamic model of TCO provides several options of financing of investment, taking into account different possibilities of combining own resources (self-financing), bank credit, subsidies and leasing:

$$(5) \qquad \boldsymbol{AC_{bus\_nom_i}} = \boldsymbol{AC_{bus\_cred\_i}} + \boldsymbol{Bus_{self_i}} + \boldsymbol{Bus_{sub_i}} + \boldsymbol{Vbus\_init_i}$$

where:

$\boldsymbol{AC_{bus\_nom_i}}$ – nominal acquisition costs of bus [EUR]

$\boldsymbol{AC_{bus\_cred_i}}$ – amount of credit for the bus purchase [EUR]

$\boldsymbol{Bus_{self_i}}$ – costs of bus acquisition (self-financing) [EUR]

$\boldsymbol{Bus_{sub_i}}$ – subsidies for bus [EUR]

$\boldsymbol{Vbus\_init_i}$ – value of the leased bus without initial fees

Thus, various combinations of purchase financing sources are possible. In addition, according to the developed model different batches of purchased buses can be financed in different ways. In addition, the model takes into account that cash flows resulting from the purchase of a bus fleet can take place in different time periods, i.e. that the fleet is purchased in batches in subsequent years / periods (which is not a rare situation taking into account the specific procedures for this type of investment resulting from public procurement law). The subsidy can also take place in different time periods and can be paid in tranches (which happens quite often, especially for projects financed from European Union funds, when the payment is delayed after presentation of relevant accounting documents, etc.).

Each of these cash flows (CF) is discounted in time with a discount rate adequate to the period in which a given cash flow occurs, and Present Value is the sum of these discounted flows in time.

Taking into consideration diversified funding structure of bus fleet acquisition in time the present value of the acquisition costs of electric buses is carried out using the following formula:

$$(6) \quad \boldsymbol{PV_{bus}} = \sum_{i=1}^{n} (\boldsymbol{DAC_{bus\_cred_i}} + \boldsymbol{DAC_{bus\_self_i}} - \boldsymbol{DBus_{sub_i}} + \boldsymbol{DBus_{leas_i}} + \boldsymbol{DAC_{bat2_i}} + \boldsymbol{DBatD_i})$$

where:

DAC_{bus_cred} – discounted annual instalments for bus acquisition with credit [EUR]

$DAC_{bus\_self_i}$– discounted costs of bus acquisition (self-financing) [EUR]

$DBus_{sub_i}$ – discounted annual subsidies for bus acquisition [EUR]

$DBus_{leas_i}$ – discounted annual bus lease instalments [EUR]

DAC_{bat2_i} – discounted costs of spare battery for i-th bus[EUR]

$DBatD_i$ – discounted costs of battery disposal for i-th bus [EUR]

i – number of consecutive bus (i-th bus number)

n – number of purchased buses

The developed model of TCO includes two types of bank credit:

- Credit with equal instalments (annuities),
- Credit with decreasing instalments (instalments with fixed capital part).

Credit with equal instalments (annuities)

The structure of instalments is not the same for each period. In the initial periods, the share of interest is larger than the share of capital. Over time, the share of interest decreases and the share of capital increases. The calculation of nominal value of annual annuity is carried out by the formula:

$$(7) \quad \boldsymbol{AC_{bus\_cred\_ann_i}} = \boldsymbol{AC_{bus\_cred}} \cdot \frac{s_{bus} \cdot (1+s_{bus})^{n_{bus}}}{(1+s_{bus})^{n_{bus}} - 1}$$

where:

$\boldsymbol{AC_{bus\_cred_i}}$ – amount of credit for the bus purchase [EUR]

$\boldsymbol{n_{bus}}$ – number of payments/annuities,

$\boldsymbol{s_{bus}}$ – credit interest rate (bus) [-],

Credit with decreasing instalments (instalments with fixed capital part)

In case of credit with decreasing instalments each instalment is with fixed capital part. Nominal value of annual credit instalment for the instalment number $\mathrm{n_{inst}}$ can be calculated using the following formula:

$$(8) \qquad \boldsymbol{AC_{bus_{cred_{inst\,i}}}(n_{inst}) = \frac{AC_{bus\_cred_i}}{n_{bus}}\left[1 + (n_{bus} - n_{inst} + 1)s_{bus}\right]}$$

where:

$\boldsymbol{AC_{bus_{cred_{inst\,i}}}}$ – amount of credit for the bus purchase [EUR]

$\boldsymbol{n_{bus}}$ – number of payments/annuities,

$\boldsymbol{s_{bus}}$ – credit interest rate (bus) [-],

$\boldsymbol{n_{inst}}$- number of credit instalment

TCO analysis is carried out annually, so if instalments payments are monthly, then in order to receive the nominal annual value, the monthly instalments of a given year should be added together.

There is need to decide for which type of instalments the analysis will be carried out. Usually bank credit with decreasing instalments is cheaper than the credit with decreasing instalments. In the next step to calculate the PV, instalments are discounted with a discount rate adequate for the year in which such cash flows take place (credit repayments) and then Present Value is the sum of these discounted flows in time:

$$(9) \qquad \boldsymbol{DAC_{bus_{cred_i}} = \sum_{m_{bus}}^{M_{bus}}\left(AC_{bus\_cred\_ann\_i} \cdot \frac{1}{(1+i_{bus})^{m_{bus}}}\right)}$$

or

$$(10) \qquad \boldsymbol{DAC_{bus_{cred_i}} = \sum_{m_{bus}}^{M_{bus}}\left(AC_{bus\_cred\_inst\_i} \cdot \frac{1}{(1+i_{bus})^{m_{bus}}}\right)}$$

where:

DAC_{bus_cred} – discounted annual annuities for bus acquisition with credit [EUR]

$AC_{bus\_cred\_ann\_i}$ – nominal value of annual credit instalment (annuity) [EUR]

$AC_{bus\_cred\_inst_i}$- nominal value of annual credit instalment for the rate number n_{inst}

i_{bus} – discount rate (buses) [%],

M_{bus} – repayment term [years],

i – number of consecutive bus (i-th bus number)

m_{bus} – time with credit instalment for bus acquisition

The investment can be financed from own resources, leasing or co-financed by a subsidy as well. In such case each cash flow are discounted with a discount rate adequate for the year in which such cash flows take place:

$$(11) \qquad \boldsymbol{DAC_{bus\_self_i} = \sum_{m_{self}}^{M_{self}} \left(Bus_{self_i} \cdot \frac{1}{(1+i_{bus})^{m_{self}}} \right)}$$

where:

$DAC_{bus\_self_i}$– discounted costs of bus acquisition (self-financing) [EUR]

Bus_{self_i} – costs of bus acquisition (self-financing) [EUR]

m_{self} – time with payment (self-financing)

M_{self} – investment term (self-financing)

$$(12) \qquad \boldsymbol{DBus_{sub_i} = \sum_{m_{sub}}^{M_{sub}} \left(Bus_{sub_i} \cdot \frac{1}{(1+i_{bus})^{m_{sub}}} \right)}$$

where:

$DBus_{sub_i}$ – discounted subsidies for bus acquisition [EUR]

m_{sub} – time with subsidy

M_{sub} – subsidised investment term

Bus_{sub_i} – subsidies for bus [EUR]

$$(13) \qquad DBus_{leas_i} = \sum_{m_{leas}}^{M_{leas}} \left(AC_{bus_{leas_i}} \cdot \frac{1}{(1+i_{bus})^{m_{leas}}} \right)$$

where:

$DBus_{leas_i}$– discounted annual annuities for bus acquisition with credit [EUR]

$AC_{bus\_leas\_i}$ – nominal value of annual leas instalment [EUR]

i_{bus} – discount rate (buses) [-],

M_{leas} – bus leasing term [years],

i – number of consecutive bus (i-th bus number)

m_{leas} – time with bus lease instalments

The nominal value of annual leas instalment ($\mathrm{AC_{bus\_leas\_i}}$) may be the value entered by the user for example on the basis of offers received or calculated on the basis of the formula for an equal lease instalment:

$$(14) \quad AC_{bus\_leas\_i} = \frac{Vbus\_init_i \, i_{bus_{leas}} \left(1+ i_{bus_{leas}}\right)^{n_{lease}} - Vbus\_pur_i \, i_{bus_{leas}}}{\left(1+ i_{bus_{leas}}\right)^{n_{lease}} - 1}$$

where:

$AC_{bus\_leas\_i}$ – nominal value of annual leas instalment [EUR]

$i_{bus_{leas}}$ – lease interest rate [%],

n_{lease} – number of lease instalments,

$Vbus\_init_i$ – value of the leased bus without initial fees

$Vbus\_pur_i$ – value of the leased bus purchase

TCO analysis considers also costs of spare battery and costs of used battery disposal. Such costs are discounted with a discount rate adequate for the year in which such cash flows take place as follows:

$$(15) \quad \boldsymbol{DAC_{bat2_i}} = AC_{bat2_{self}}(t = Bat_{life}) \cdot \frac{1}{(1+i_{bat2})^{Bat_{life}}}$$

where:

DAC_{bat2} – discounted costs of spare battery [EUR]

AC_{bat2_self} $(t = Bat_{life})$ – acquisition costs of spare battery [EUR] after period *t* equal lifetime of the bus battery *bat_life,*

i_{bat2} – discount rate for bat2 [%],

Bat_{life} – lifetime of the bus battery [years],

(16) $$\boldsymbol{DBatD_i} = BatD_i(t = Bat_{life}) \cdot \frac{1}{(1+i_{bat})^{Bat_{life}}}$$

where:

$\boldsymbol{DBatD_i}$ – discounted costs of the battery disposal for i-th bus [EUR]

$BatD_i\ (t = Bat_{life})$ – costs of battery disposal for i-th bus [EUR] after period *t* equal lifetime of the bus battery *bat_life,*

i_{bat} – discount rate for bat1 [%],

Bat_{life} – lifetime of the bus battery [years],

Operating Costs

The analysis of operating costs is conducted globally, i.e. for the entire fleet operating in a given year. This model takes into account not only the costs of future maintenance of buses planned to be bought. As part of the cash flow in the year "0" – so the year of conducting analysis and making decisions, it is possible to include operating costs of the fleet that the investor already has and forecast the value of these costs in the future as future cash flows, so discounting them with a discount rate appropriate for a given year using the following formula:

(17) $$PVOC_{bus} = \sum_{\boldsymbol{m_{OC}}}^{\boldsymbol{Bus_{life}}} \left(OC_{bus} \cdot \frac{1}{(1+i_{bus})^{m_{OC}}} \right)$$

where:

OC_{bus}– annual buses operating costs [EUR],

i_{bus} – discount rate (buses) [%],

m_{OC} – time with operating costs

Bus_{life} – bus lifetime [years],

Nominal value of annual operating costs of electric buses is calculated as a sum of annual energy costs, maintenance costs, insurance, costs, costs of daily energy supply and other costs:

$$(18) \qquad \boldsymbol{OC_{bus} = OC_{ener} + OC_{maint} + OC_{insur} + OC_{ener\_supp} + OC_{other}}$$

where:

OC_{bus} – annual operating costs of the bus fleet [EUR],

OC_{ener} – annual energy costs [EUR],

OC_{maint} – annual maintenance costs [EUR],

OC_{insur} – annual insurance cost [EUR],

OC_{ener_supp} – annual costs of daily energy supply [EUR],

OC_{other}- other annual costs (for example vehicle tax) [EUR]

Annual costs of the daily energy supply are calculated using the following formula:

$$(19) \qquad \boldsymbol{OC_{ener\_supp} = Bus_{oper\_ann} \cdot Ener_{supp\_cost\_r}}$$

where:

OC_{ener_supp} – annual costs of the daily energy supply [EUR],

Bus_{oper_ann} – annual transport work [vkm/year],

$Ener_{supp\_cost\_r}$– energy supply cost rate [EUR/vkm],

The calculation of annual energy costs is carried out by the formula:

$$\boldsymbol{OC_{ener} = Bus_{oper\_ann} \cdot [Ener_{cons} \cdot \frac{\left(\left(Ener_{cost_{LV}} - Tax_{relief_{LV}}\right) \cdot PkWh_{LV} + \left(Ener_{cost_{MV}} - Tax_{relief_{MV}}\right) \cdot PkWh\_MV\right)}{PkWh}]}$$

where:

OC_{ener} – annual energy costs [EUR],

Bus_{oper_ann} – annual transport work [vkm/year],

$Ener_{cons}$ – energy consumption [kWh/vkm],

$Ener_{cost\_LV}$ – cost rate of energy (low-voltage energy grid) [EUR/kWh],

$\mathrm{Tax}_{\mathrm{relief\_LV}}$ – tax relief (low-voltage energy grid) [EUR/kWh],

$\mathrm{Ener}_{\mathrm{cost\_MV}}$ – cost rate of energy (medium-voltage energy grid) [EUR/kWh],

$\mathrm{Tax}_{\mathrm{relief\_MV}}$ – tax relief (medium-voltage energy grid) [EUR/kWh],

PkWh - annual energy consumption for charging vehicles [kWh]

PkWh_MV - annual energy consumption for charging vehicles (medium-voltage energy grid) [kWh]

PkWh_LV - annual energy consumption for charging vehicles (low-voltage energy grid) [kWh]

Based on business practice there are some cases, that cost rates for energy consumption from low-voltage energy grids differ from cost rates for energy consumption from medium-voltage energy grids, as included in the model. The final cost rate is therefore the weighted average of both rates.

Annual maintenance costs depend on the number of staff service hours and staff service cost rate as follows:

$$OC_{maint} = Work_{staff\_service} \cdot Staff_{cost\_r} \quad (20)$$

Where:

OC_{maint} – annual maintenance costs [EUR],

$Work_{staff\_service}$ – staff service hours [staff-service-hours/bus],

$Staff_{cost\_r}$– staff service cost rate [EUR/staff-service-hours],

Other annual costs and annual insurance costs are user input values entered in years such cash flows take place.

Infrastructure costs

Infrastructure nominal acquisition costs in a given year include all types of charging infrastructure and are calculated using the following formula:

(21) $$\boldsymbol{AC_{infra\_nom_y}} = \boldsymbol{AC_{infra\_dep}} + \boldsymbol{AC_{infra\_swap}} + \boldsymbol{AC_{infra\_panto}} + \boldsymbol{AC_{infra\_stop}} + \boldsymbol{AC_{infra\_induct}}$$

where

AC_{infra_nom} – infrastructure nominal acquisition costs [EUR]

AC_{infra_dep} – acquisition costs of depot conductive plug-in charging [EUR]

AC_{infra_swap} – acquisition costs of battery swapping-charging [EUR]

AC_{infra_panto} – acquisition costs of pantograph charging [EUR]

AC_{infra_stop} – acquisition costs of on bus-stop charging [EUR]

AC_{infra_induct} – acquisition costs of in-motion inductive charging [EUR]

The calculation of present value of infrastructure is carried out the same way as in previous cases, so as a sum of discounted nominal infrastructure acquisition costs by the formula:

(22) $$\boldsymbol{PV_{infra}} = \sum_{\boldsymbol{m_{infra\_ac}}}^{\boldsymbol{M_{infra\_ac}}} \left(\boldsymbol{AC_{infra\_nom_y}} \cdot \frac{\boldsymbol{1}}{(\boldsymbol{1}+\boldsymbol{i_{infra}})^{\boldsymbol{m_{infra\text{-}ac}}}}\right)$$

where

$AC_{infra\_nom_y}$- infrastructure nominal acquisition costs (in a given year)

i_{infra} – discount rate of infrastructure [%],

M_{infra_ac} – repayment term of infrastructure [years],

m_{infra_ac}- time with infrastructure acquisition

Furthermore, the structure of financing the purchase or construction of an appropriate infrastructure may be analogous to that for a bus fleet, i.e. various combinations of own funds, credit, subsidies and leasing as follows:

(23) $$\boldsymbol{AC_{infra\_nom_y}} = AC_{infra\_cred} + AC_{infra\_self} + Infra_{sub} + V_{infra\_init}$$

where

$AC_{infra\_nom_y}$ – infrastructure nominal acquisition costs (in a given year)

AC_{infra_cred} – acquisition costs of infrastructure with credit [EUR]

AC_{infra_self}- costs of infrastructure acquisition (self-financing) [EUR]

$Infra_{sub}$ –subsidies for infrastructure [EUR]

V_{infra_init} – value of the leased infrastructure without initial fees [EUR]

Including diversified investment funding structure and annual maintenance costs of infrastructure the present value of infrastructure is calculated using the following formula:

(24) $$PV_{infra} = DAC_{infra\_cred} + DAC_{infra\_self} - DAC_{infra\_sub} + DAC_{infra\_lease} + DMC_{infra}$$

where:

DAC_{infra_cred} – discounted annual instalments for infrastructure acquisition with credit [EUR]

DAC_{infra_self} – discounted acquisition costs of infrastructure (self-financing) [EUR]

DMC_{infra} – discounted annual Maintenance Costs of infrastructure [EUR]

DAC_{infra_sub} – discounted annual subsidies for infrastructure acquisition [EUR]

DAC_{infra_lease}- discounted annual infrastructure lease instalments

Including investment funding from bank credit there is need to decide for which type of instalments the analysis will be carried out (annuities or decreasing instalments) as follows:

Credit with equal instalments (annuities)

(25) $$\boldsymbol{AC_{infra\_cred\_ann} = AC_{infra\_cred} \cdot \frac{s_{infra} \cdot (1+s_{infra})^{n_{infra}}}{(1+s_{infra})^{n_{infra}}-1}}$$

where

$AC_{infra\_cred\_ann}$ – annual annuity acquisition costs of infrastructure with credit [EUR]

AC_{infra_cred} – acquisition costs of infrastructure with credit [EUR]

n_{infra} – number of payments/annuities [-],

s_{infra} –credit interest rate (infrastructure) [%],

Credit with decreasing instalments (instalments with fixed capital part)

$$(26) \qquad \boldsymbol{AC_{infra_{cred}(n_{inst})}} = \frac{\boldsymbol{AC_{infra\_cred}}}{\boldsymbol{n_{infra}}} \left[\mathbf{1} + (\boldsymbol{n_{infra}} - \boldsymbol{n_{inst}} + \mathbf{1})\boldsymbol{s_{infra}}\right]$$

where

AC_{infra_cred} – acquisition costs of infrastructure with credit [EUR]

n_{infra} – number of payments/annuities [-],

s_{infra} –credit interest rate (infrastructure) [%],

$\boldsymbol{n_{inst}}$- number of credit instalment

In the next step to calculate the PV, instalments are discounted with a discount rate adequate for the year in which such cash flows take place (credit repayments) and then Present Value is the sum of these discounted flows in time:

$$(27) \qquad \boldsymbol{DAC_{infra\_cred}} = \sum_{\boldsymbol{m_{infra}}}^{\boldsymbol{M_{infra}}} \left(\boldsymbol{AC_{infra\_cred\_ann}} \cdot \frac{\mathbf{1}}{(\mathbf{1}+\boldsymbol{i_{infra}})^{\boldsymbol{m_{infra}}}}\right)$$

or

$$(28) \qquad \boldsymbol{DAC_{infra\_cred}} = \sum_{\boldsymbol{m_{infra}}}^{\boldsymbol{M_{infra}}} \left(\boldsymbol{AC_{infra\_cred(n_{inst})}} \cdot \frac{\mathbf{1}}{(\mathbf{1}+\boldsymbol{i_{infra}})^{\boldsymbol{m_{infra}}}}\right)$$

where

$AC_{infra\_cred\_ann}$ – nominal value of annual credit instalments [EUR]

i_{infra} – discount rate of infrastructure [%],

M_{infra} – repayment term of infrastructure [years],

m_{infra}- time with annuity for infrastructure acquisition

Infrastructure acquisition can be financed from own resources, leasing or co-financed by a subsidy as well. In such case each cash flow are discounted with a discount rate adequate for the year in which such cash flows take place:

$$(29) \qquad \boldsymbol{DAC_{infra\_self}} = \sum_{m_{infra_{self}}}^{M_{infra\_self}} \left(\boldsymbol{AC_{infra\_self}} \cdot \frac{1}{(1+i_{infra})^{m_{infra\_self}}} \right)$$

Where:

i_{infra} – discount rate of infrastructure [%],

M_{infra_self} – investment term (self-financing) [years],

m_{infra_self} - time with payment from own resources (infrastructure)

AC_{infra_self}- costs of infrastructure acquisition (self-financing) [EUR]

$$(30) \qquad \boldsymbol{DAC_{infra\_sub}} = \sum_{m_{infra\_sub}}^{M_{infra\_sub}} \left(\boldsymbol{Infra_{sub}} \cdot \frac{1}{(1+i_{infra})^{m_{infra\_sub}}} \right)$$

Where:

$Infra_{sub}$ –subsidies for infrastructure [EUR]

i_{infra} – discount rate of infrastructure [%],

M_{infra_sub} – subsidised investment term (infrastructure) [years],

m_{infra_sub} – time with subsidy

$$(31) \qquad \mathbf{DAC_{infra\_lease}} = \sum_{m_{leas}}^{M_{leas}} \left(\boldsymbol{AC_{infra\_lease}} \cdot \frac{1}{(1+i_{infra})^{m_{leas}}} \right)$$

Where:

AC_{infra_lease} – nominal value of annual leas instalment (infrastructure) [EUR]

i_{infra} – discount rate of infrastructure [%],

M_{leas} – infrastructure lease term [years],

m_{leas} – time with infrastructure lease instalments

The nominal value of annual leas instalment (AC_{infra_lease}) may be the value entered by the user for example on the basis of offers received or calculated on the basis of the formula for an equal lease instalment:

(32) $$\boldsymbol{AC_{infra\_lease}} = \frac{V_{infra\_init}\, i_{infra\_leas}(1+ i_{infra\_leas})^{n_{lease}} - V_{infra\_purch}\, i_{infra\_leas}}{(1+i_{infra\_leas})^{n_{lease}} - 1}$$

Where:

i_{infra_lease}– lease interest rate [%],

n_{lease} – number of lease instalments,

V_{infra_init} – value of the leased infrastructure without initial fees

V_{infra_purch}– value of the leased infrastructure purchase

Furthermore, annual maintenance costs of infrastructure are discounted with a discount rate adequate for the year in which such cash flows take place (credit repayments) and then Present Value is the sum of these discounted flows in time:

(33) $$\boldsymbol{DMC_{infra} = \sum_{m_{infra_{life}}}^{Infra_{life}} ((MC_{infra\_dep} + MC_{infra\_swap} + MC_{infra\_panto} + MC_{infra\_stop} + MC_{infra\_induct} + MC_{other}) \cdot \frac{1}{(1+i_{infra})^{m_{infra}}})}$$

where:

DMC_{infra} – discounted annual Maintenance Costs of infrastructure [EUR]

MC_{infra_dep} – annual maintenance costs of depot conductive plug-in charging [EUR]

MC_{infra_swap} – annual maintenance costs of battery swapping-charging [EUR]

MC_{infra_panto} – annual maintenance costs of pantograph charging [EUR]

MC_{infra_stop} – annual maintenance costs of on bus-stop charging [EUR]

MC_{infra_induct} – annual maintenance costs of in-motion inductive charging [EUR]

MC_{other}- other annual costs (for example insurance, taxes) [EUR]

i_{infra} – discount rate of infrastructure [%],

m_{infra_life} – time with maintenance costs of infrastructure

$Infra_{life}$ – infrastructure life [years],

External costs

TCO analysis includes external costs as well. The calculation of annual external costs is calculated using the following formula:

$$(34) \quad \boldsymbol{EC_{exter}} = \boldsymbol{Bus_{oper\_ann}} \cdot (\boldsymbol{Noise_{cost\_r}} + \boldsymbol{EPoll_{cost\_r}}) + \boldsymbol{Bus_{oper\_ann\_h}} \cdot \boldsymbol{HPoll_{cost\_er}}$$

Where:

EC_{exter} – annual external costs of the bus fleet [EUR],

Bus_{oper_ann} – annual transport work [vkm/year],

$Bus_{oper\_ann\_h}$- annual transport work of bus fleet with oil heating [vkm/year],

$Ener_{cons}$ – energy consumption [kWh/vkm],

$EPoll_{cost\_er}$ – cost rate of air pollutant and GHG emission per vehicle-km [EUR/vkm],

$Noise_{cost\_r}$ – cost rate of noise emission per 1 vehicle-km [EUR/vkm],

$HPoll_{cost\_er}$ – cost rate of pollutant emission per 1 vkm (bus heating with oil) [EUR/vkm],

Cost rate for air pollutant emission includes marginal air pollution costs and marginal well-to-tank costs.

In the next step annual external costs are discounted with a discount rate adequate for the year in which such cash flows take place and then Present Value is the sum of these discounted flows in time:

$$(35) \quad \boldsymbol{PVE_{exter}} = \sum_{\boldsymbol{m_{EX}}}^{\boldsymbol{Bus_{life}}} (\boldsymbol{EC_{exter}} \cdot \frac{\boldsymbol{1}}{(\boldsymbol{1}+\boldsymbol{i_{bus}})^{\boldsymbol{m_{ex}}}})$$

Where:

PVE_{exter} – present value of the external costs [EUR],

EC_{exter} – annual external costs of the bus fleet [EUR],

i_{bus} – discount rate (buses) [%],

Bus_{life} – bus lifetime [years],

m_{EX} – time with external costs

Liquidation value

Liquidation value of a bus is discounted with a discount rate adequate for the year in which such cash flows take place. The calculation of discounted proceeds of bus liquidation is carried out by the formula:

$$(36) \qquad \boldsymbol{DPL_{liq\_bus_i}} = \sum_{m_{liq}}^{Bus_{life}} \left(\left(\boldsymbol{AC_{bus\_nom_i}} \cdot \boldsymbol{pl_r} \right) \cdot \frac{1}{(1+i_{bus})^{m_{liq}}} \right)$$

where:

Bus_{life} – bus life [years],

m_{liq} – time with proceeds of bus liquidation

AC_{bus_nom} – nominal acquisition costs of bus [EUR]

pl_r – residual value rate of the bus [-],

i_{bus} – discount rate (buses) [%],

The PV of proceeds of liquidation for e-bus fleet is calculated as sum of discounted cash flows in a given period for n buses as follows:

$$(37) \qquad \boldsymbol{PVL_{liq\_bus}} = \sum_{i=1}^{n} \boldsymbol{DPL_{liq\_bus_i}}$$

where:

DPL_{liq_bus} – discounted proceeds of i-th bus liquidation [EUR]

i – number of consecutive bus (i-th bus number)

n – number of purchased buses

8.5 The outputs of the TCOModel

The output of the TCOModel is presented in the form of charts and tables on the website. One will have an option to download the data in a few formats like .csv. The results will also be available in .json file.

9 Component OptimSched

The tool component OptimSched is intended for solving optimization problems related to planning the process of conversion of conventional or mixed bus fleet to an electric bus (e-bus) fleet (e-fleet). It uses input data file interface prepared either au-tomatically within PLATON Toolkit or manually by transportation engineering ex-perts.

The tool component OptimSched is comprised of three optimization modules: Opt, DepOpt and OptSched. The module Opt is intended to determine a fleet of e-buses with fast-charging batteries and a respective charging infrastructure such that the required passenger flow is provided, cost constraints are satisfied and the total passenger demand satisfied by electric buses is maximized. The module DepOpt allows to determine the required electric power supplied to the depot by the city power grid, the type and the number of charging stations of this type in the depot, types of slow-charging e-bus batteries and charging times of each e-bus while it is in the depot such that the total daily cost of the equipment and the consumed energy is minimized, provided that the arrival and departure times of e-buses to/from the depot, the dynamic upper bound on the supplied power and functions of charge and discharge of the batteries are addressed. The third module OptSched is capable to determine a balanced route timetable providing the same average traffic interval of all public vehicles of the same route in the most representative time period.

9.1 System requirements of the OptimSched

The modules Opt, DepOpt and OptSched are implemented in C++ in two ways: as dynamic load libraries moboptdll.dll, chargedll.dll and scheddll.dll, respectively, and standalone executable files mobopt.exe, charge.exe and schedule.exe, respectively, for 32-bit Windows. The executable files can also be run on 64-bit Windows. The module DepOpt uses Open Source mathematical programming solver LPSolve. All modules can be used on a PC of a standard configuration.

9.2 Objective of the OptimSched

The module Opt determines a e-fleet of e-buses with fast-charging batteries, places for charging stations and transformers, assignment of charging stations to the selected places, assignment of charging stations to the transformers and assignment of charging stations to the routes such that all e-buses can feasibly drive, the re-quired traffic interval is maintained, and the output power of any transformer is not exceeded. The objective is to maximize the total value (positive ecological and social effect expressed quantitatively), provided that the total capital cost and the total op-erating, depreciation and energy cost do not exceed their upper bounds. It is as-sumed that Opt will be used repeatedly for several successive planning periods (years). Decisions made in the past periods will be used as a part of the input for the future period.

The module DepOpt is intended to determine the cost-effective slow charging infra-structure of a depot and options of batteries for a given set of battery e-buses serving assigned to them day-to-day trips over the city routes according to given timetable. The depot charging infrastructure is defined by the rated maximum electric power sup-plied to the depot by the city power grid, the type and the number of charging stations of this type in the depot to be determined. When solving the problem DepOpt options of e-bus batteries are selected from the given sets for each of e-buses, charging dura-tions for each of e-buses are determined in periods while e-buses are located in the depot such that the total daily cost of charging equipment of the depot, of e-bus bat-teries and the consumed energy is minimized, provided that the arrival and departure times of e-buses to/from the depot, the dynamic upper bound on the supplied power are satisfied for given functions of charge and dis-charge of the batteries.

The module OptSched determines a route timetable such that the same average traf-fic interval of all public vehicles of the same route is maintained and departures of public vehicles of the same type assigned to the same route are distributed as smoothly as possible over departures of all public vehicles in the most representa-tive time pe-riod.

9.3 Input data for the OptimSched

Two formats of the input files are implemented. One of them is the JSON format, see

http://www.json.org/index.html for the description, and the other is a simple text for-mat. Input data in the JSON format can be prepared in two ways:

i) single file;

ii) set of separate files.

For the module Opt these files are:

i) problem.json;

ii) probl.json, stations.json, buses.json, cbuses.json, nodes_st.json, graph.json, transf.json, nodes_nm.json, nodes_ch_time.json, croutes.json, tdepots.json, bus-es1.json and buses2.json.

For the module DepOpt these files are:

i) charge.json;

ii) stations.json, batteries.json, fbatteries.json, fcbatteries.json, buses.json, routes.json, trips.json, fleet.json, febuses.json, fpower.json.

For the module OptSched only one file schedin.json should be prepared.

For the module Opt, file probl.json includes values of the following parameters: number of links of any location with a new charging station with the transformer nodes, upper bound on the total capital cost, upper bound on the total operating, depreciation and energy cost, and duration of the decisive time period.

File stations.json describes the set of charging stations and their parameters.

File buses.json describes the set of e-bus types and their parameters.

File cbuses.json describes the set of the conventional vehicle types and their pa-rameters.

File nodes_st.json describes the set of locations of charging stations and their parameters.

File graph.json describes the set of stops of the transportation network and their parameters.

File transf.json describes the set of potential locations for transformers and their parameters.

File routes.json describes the set of routes of the transportation network and their parameters.

File nodes_ch_time.json describes charging times for the set of charging stations.

File croutes.json should be prepared if there are routes that are already served by e-buses. It describes charging station types associated with nodes of each route served by old e-buses.

File tdepots.json describes the set of depot nodes and their parameters.

File nodes_nm.json describes sets of “obligatory” nodes for location of charging station and their parameters.

File buses1.json describes the set of e-buses with batteries which have enough capacity to drive with a single charge at the corresponding depot during the day.

File buses2.json describes the set of e-buses with one charge at the corresponding depot and one charge at a non-depot node during the day.

File problem.json contains files probl.json, stations.json, buses.json, cbuses.json, nodes_st.json, graph.json, transf.json, nodes_nm.json, nodes_ch_time.json, croutes.json, tdepots.json, buses1.json and buses2.json as its sections.

If the input data are prepared in the text format, then the input files are probl.txt, stations.txt, buses.txt, cbuses.txt, nodes_st.txt, graph.txt, transf.txt, routes.txt, nodes_ch_time.txt, tdepots.txt, croutes.txt, nodes_nm.txt, buses1.txt and buses2.txt, and they include the same content as the corresponding JSON files. For a more detailed description of the files see Deliverable 4.4.

For the module DepOpt, the content of input files is the following.

File stations.json describes the set of charging stations types and their parameters.

File batteries.json describes the set of batteries options and their parameters.

File fbatteries.json describes the functions of charging e-bus batteries at each feasible type of charging station.

File fcbatteries.json describes the functions of maximal number of charge/discharge cycles of batteries in their lifetime, depending of their average discharge level.

File buses.json describes the set of e-buses types and their parameters.

File routes.json describes the set of routes and their parameters.

File trips.json describes the set of trips and their parameters.

File fleet.json describes the e-bus fleet including assigned trips, feasible battery options and annual number of charge/discharge cycles.

File febuses.json describes functions of resulting SOC level of the battery after completing the assigned trip depending on the battery option, trip and initial SOC level.

File fpower.json includes description of functions of upper limit of supplied to the depot electric power, electric power rates and annual cost of the additional depot charging infrastructure.

File charge.json contains files stations.json, batteries.json, fbatteries.json, fcbatteries.json, buses.json, routes.json, trips.json, fleet.json, febuses.json and fpower.json as its sections.

If the input data are prepared in the text format, then the input files are stations.txt, batteries.txt, fbatteries.txt, fcbatteries.txt, buses.txt, routes.txt, trips.txt, fleet.txt, febuses.txt and fpower.txt. For a more detailed description of the input files see Deliverable 4.4.

For the module OptSched, the file schedin.json describes types of vehicles (e-buses and conventional vehicles) and numbers of vehicles of each type. If the input data are prepared in the text format, then the file schedin.txt is used. For a more detailed description, see Deliverable 4.4.

9.4 The core of the OptimSched

If the executable files are used, then parameters of the command line are:

full name of the directory with the input data;

full name of the directory with the configuration file (probl.ini for Opt, charge.ini for DepOpt and sched.ini for OptSched).

Parameters of the configuration are represented as follows: parameter name=value. Parameters of the file probl.ini are described in Table 14.

Table 14 Parameters of configuration file for Opt

Parameter name	Value
json	format of the input data 0 text 1 separate json files 2 single json files Default: 0
nit	maximum number of iterations (related to solution quality) Default: 10000
max time	maximum calculation time in seconds (related to solution quality) Default: 600
m	number of links of any charging station location with transformers Default: 1
nit non	maximum number of iterations without improving the objective function value (related to solution quality) Default: 200
route	name of the route selected for conversion
e-bus	name of the e-bus type selected for conversion
routes	list of route names selected for conversion
e-buses	list of e-bus types selected for conversion
meth	type of execution 0 optimization for all routes and e-buses 6 optimization for one route specified by the parameter “route” 7 optimization for one route and one e-bus type specified by the parameters “route” and “e-bus” 24 optimization for the set of routes specified by the parameter “routes” 25 optimization for the set of routes and the set of e-bus types specified by the parameters “routes” and “e-buses” 50 transformation of the input text files to the separate json files 51 transformation of the input text files to a single json file Default: 0

Parameters of the file charge.ini are described in Table 15. Abbreviation PSO specifies the used Particle Swarm Optimization technique.

Table 15 Parameters of configuration file for DepOpt

Parameter name	Value
json	format of the input data 0 text 1 separate json files 2 single json files Default: 0
hour	format of departure and arrival times of trips 0 times are given in format “hour.min” 1 times are given in format “hour” Default: 0
n_max_var	maximum number of feasible variants of batteries options for a fixed upper bound of the supplied to the depot power and the same type of the charging station Default: 10000
nit	maximum number of iterations of PSO (related to solution quality) Default: 1000
nit_non	maximum number of iterations of PSO without improving the objective function value (related to solution quality) Default: 100
npt	number of particles of PSO (related to solution quality) Default: 100
batteries	list of batteries selected for installation on e-buses
typ_pr	type of execution 1 optimization for all options of batteries 3 transformation of the input text files to the separate json files 4 transformation of the input text files to a single json file 5 optimization for selected options of batteries specified by parameter “batteries” Default: 1

The file sched.ini sets the only parameter json (format of the input data).

9.5 The outputs of the OptimSched

Two formats of the output file for the modules Opt, DepOpt, OptSched are implemented. One of them is the JSON format (solution.json for Opt and DepOpt, sched.json for OptSched), and the second is a simple text format (solution.out for Opt and DepOpt, sched.out for OptSched).

For the module Opt, all the obtained solutions are placed into a single file. The out-put for each solution includes: the total value, the total capital cost and the total op-erating, depreciation and energy cost, the selected routes for conversion, places for new charg-ing stations and transformers, power requirement of each transformer. For each se-lected route, the output is: the sequence of stops, the selected e-bus types, the number of new e-buses of each type, the total passenger capacity of new e-buses, the capital cost of new e-buses, the operating and energy cost of new e-buses, the conventional vehicle types remained in operation and their numbers, the average length of the traffic interval for all vehicles serving the route, the locations of new charging stations, the recommended departure order of all the vehicles. For a more detailed description of the files solution.json and solution.out see Deliverable 4.4.

For the module DepOpt, the output includes: the optimal value of the power supplied to the depot, the optimal type of the identical charging stations and their number, the unused charging time resource for each period, the total used daily charging time re-source, the share of the used daily charging time resource, as well as the total cost and its components. For each e-bus, the output is: the selected battery option, the total charging time, the charging durations and periods of charging. For a more de-tailed description of files solution.json and solution.out see Deliverable 4.4.

For the module OptSched, the output represents the departure order of e-buses and conventional vehicles of different types. For a more detailed description of files sched.json and sched.out see Deliverable 4.4.

10 Component VisualGrids

VisualGrids is a kind of web-tool designed based on OSM (OpenStreetMap), requiring open source data via Overpass API. It can search and edit a specific bus route in a city. After request of VisualGrids, a layer with power substations can be shown on the map in the visual range. And a distance measurement tool is implemented to help power suppliers measure possible paths of cables connecting the power substations and bus stops, and decide the optimal location to implement a charging station.

10.1 System requirements of the VisualGrids

Since *VisualGrids* is a web-based tool, users can access it by means of general browsers, such as Chrome, Firefox, Safari, IE and so on.

10.2 Objective of the VisualGrids

The component of *VisualGrids* aims to provide a web-tool for bus-fleets operators to search and edit the existing bus routes for electrification. Furthermore, it can show locations of power substations. By means of the measurement tool, VisualGrids will help power suppliers and operators to find appropriate locations for charging stations. To sum up, *VisualGrids* will help accelerate the electrification of public transportation.

10.3 Input data for the VisualGrids

Generally, users only need to input the required number of bus route, which should be in the visual range of the map. Then *VisualGrids* will send Http request to obtain corresponding data via Overpass API. A sample request format for bus route of 73 is shown in Table 16.

Table 16 API of OSM parameters for queries

```
 [out:json][timeout:25];
// gather results
(
// query part for: “ref=73”
node["ref"="73"]({{bbox}});
way["ref"="73"]({{bbox}});
relation["ref"="73"]({{bbox}});
);
// print results
out body;
>;
out skel qt;
```

10.4 The core of the VisualGrids

10.4.1 Start

The start interface of VisualGrids is presented in Figure 45, when users visit the URL: http://service.ifak.eu/PLATON-Tool/

via a browser (Chrome is used in this manual for an example).

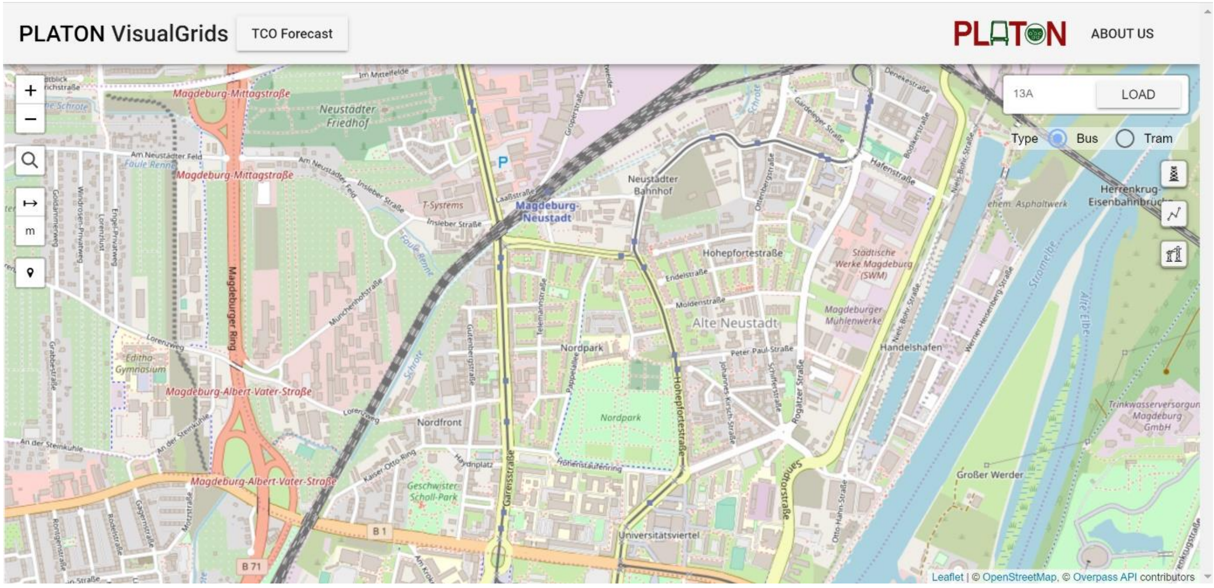


Figure 45 Start interface of VisualGrids.

10.4.2 Request Bus Routes

Users can search bus or tram routes in the search box on the top right corner of the interface. Please make sure that the routes must exist in the visual range of the map. The result of bus route 73 is shown in Figure 46 for an example. By clicking on the routes or icons of stations, further information will be shown in the form of tags like Table 17. It includes the relations number in OSM, starting and terminal stations, bus number and so on.

Table 17 Tags info of bus route

```
Relation 2061374
from=Wissenschaftshafen
name=Bus 73: Wissenschaftshafen => Ol-
venstedter Platz
public_transport:version=2
ref=73
route=bus
to=Olvenstedter Platz
type=route
```

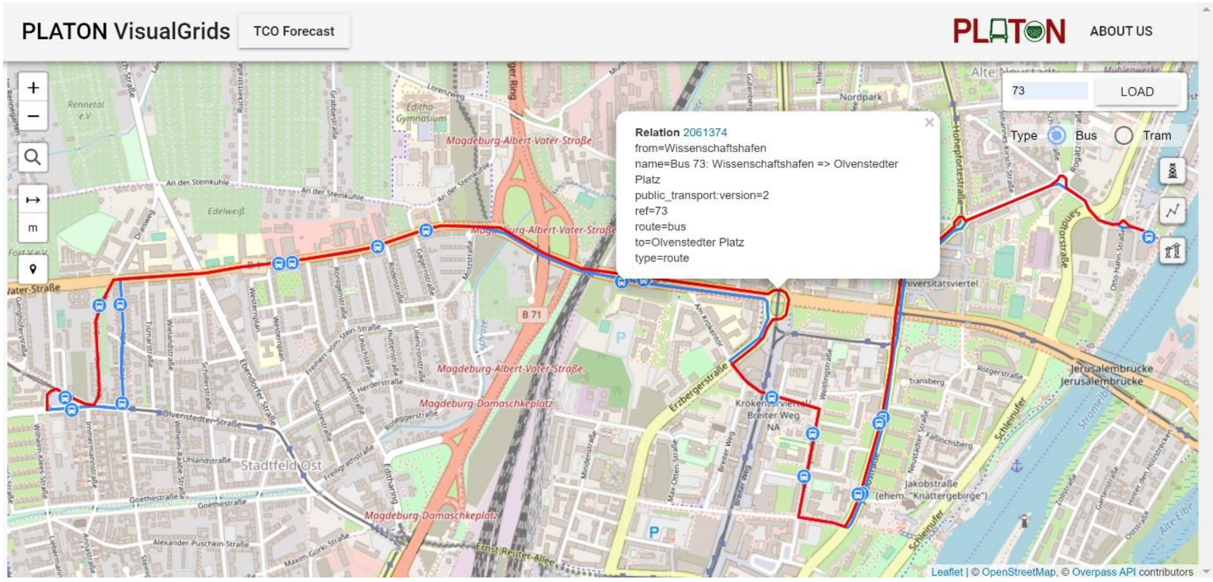


Figure 46 Bus route of No. 73.

If the provided bus routes do not meet requirements of users, they can be further edited by the function of the second square button on the right side, with the tooltip of “Show editable points”. As shown in Figure 47, the shape of the route can be changed by clicking and dragging the editable points. The editable points can be deleted by a right click. After editing, the function should be deactivated by click on the button again with the tooltip of “Hide editable points”.

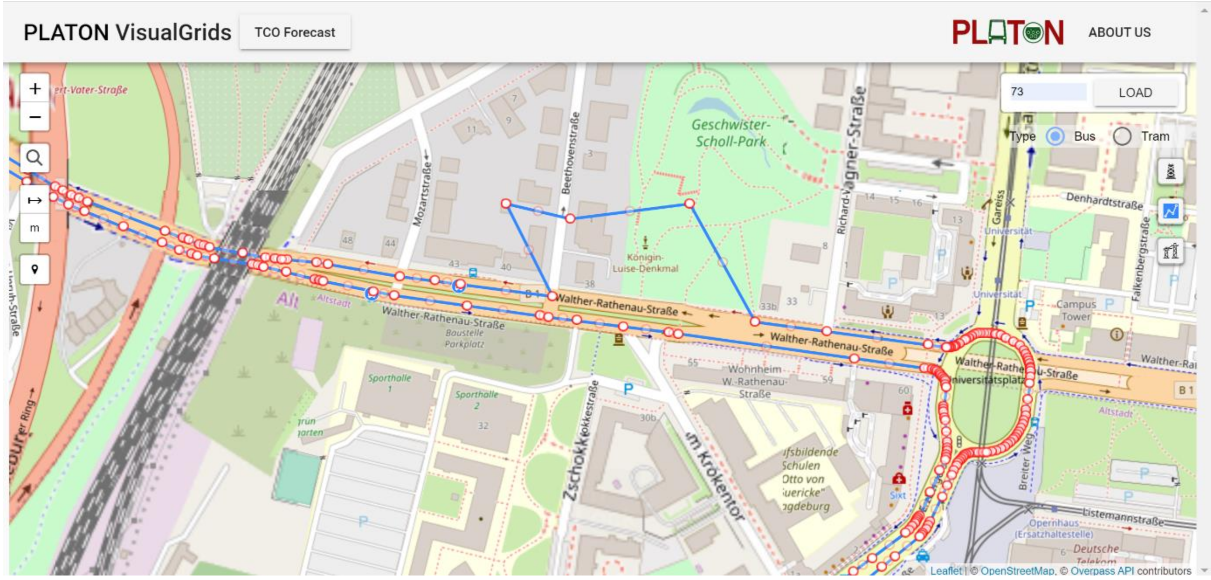


Figure 47 Editable points on bus routes.

10.4.3 Request Power Substations

A click on the first square button on the right side of the interface can show the layer of power substations in the visible range on the map. As presented in Figure 48, locations of power substations are marked by orange icons with basic info.

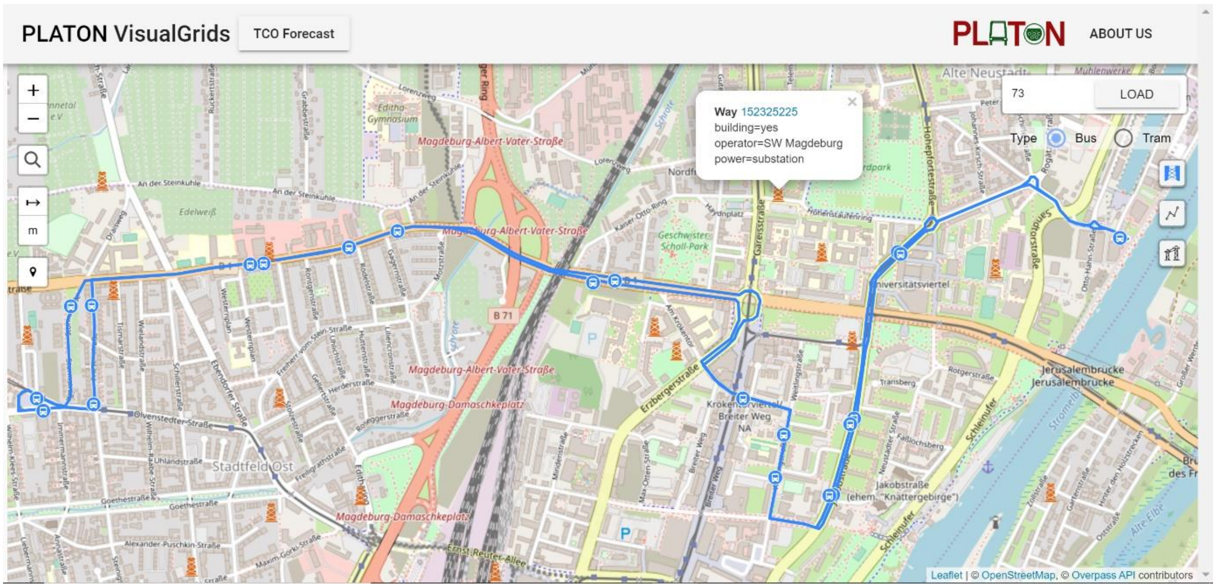


Figure 48 Layer of power substations.

10.4.4 Distance Measurement

The function of distance measurement can be activated by clicking on the left square button with the icon of an arrow. A possible path of 235m for cables connecting a bus station and power substation is drawn in Figure 49. After activation, the icon of mouse will become into a cross. Then click on the map with the cross to start measurement. The path could be easily drawn by click and adding points. The path is adjustable when the point is clicked and dragged. Press SHIFT-key and click will delete the point. More points on the path can be added by pressing Ctrl-key and click. When the measurement ends, just click on the terminal point.

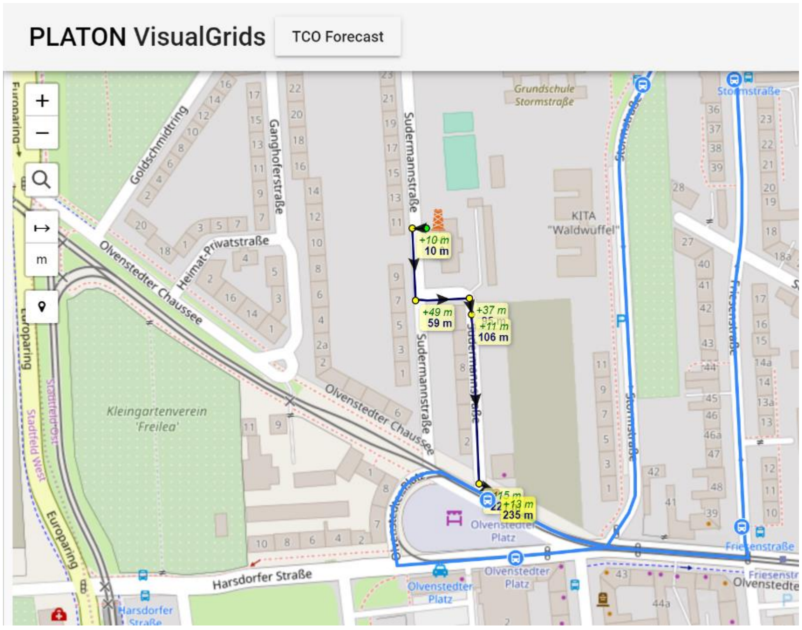


Figure 49 Layer of power substations

.

In addition, the button below, with marker of “m”, can switch the unit of distance to meters, land miles and nautical miles.

10.5 The outputs of the VisualGrids

With operations mentioned above, distances of possible paths connecting stations and power substations are obtained. Then the output results could be collected for further process. Power supplies could evaluate the costs for implementation of a charging station. And operators could determine appropriate locations to charge a BEB (Battery Electric Bus) as well as adjust schedules to meet charging plans. These results can also be the inputs to the component of *TCOModel* to calculate and optimize the total cost for public transportation electrification.

11 Components Report generator and Procurement decision support

The *ReportGenerator* component of the PLATON Toolkit System is an important output element of the decision support to be provided for the strategic planning level of a transit agency in function of its management board. Therefore, the required elements to be included in the generated report are determined by the kinds of decision problems to be supported by the PLATON Toolkit System.

11.1 System requirements of the Report generator and Procurement decision support

ReportGenerator is a script program in the syntax of Matlab. It can be executed in the open source environment of Octave on a typical equipped PC without special hardware requirements on Windows or Linux.

11.2 Objective of the Report generator and Procurement decision support

For the practical realization of the economical, technical and operational decision support a concise reporting document is generated to contain the basic results of total cost of ownership projection for the mid-term financial planning horizon, further a proposal for electrification priority of bus routes based on calculated kinetic intensity, a procurement recommendation based on the bus vehicle market research and battery configuration with opportunity or slow depot charging option.

11.3 Input data for the Report generator and Procurement decision support

Input data elements for the ReportGenerator are summarized for the tasks of Total Cost of Ownership projection, electrification priority, and procurement recommendation as follows.

- Vehicle and charger data,
- Simulated, calculated or manufacturer specified energy efficiencies,
- Energy and maintenance costs,
- Fleet related data such as routes, peak headway, return trip lengths, average speed,
- Simulated kinetic intensity
- Bus vehicle parameters

All input data elements are provided in json-files as described in the Deliverable 5.2 Report Generator. The following example is extracted from D5.2 to demonstrate the principle of input data provision.

- Vehicle / charger data:

  Data on bus capital cost for a 12m and 18m bus, charger capital cost, charger installation cost, midlife cost that must be given in the json-file `veh-ch-inp-data.json` as follows.

Table 18 Example of input file veh-ch-inp-data.json

```
{
  "buscapcost12":625000,
  "buscapcost18":900000,
  "chargercost":45000,
  "chargerinst":49100,
  "midlifecost":67000
}
```

The json-file `veh-ch-inp-data.json` must reside in the same directory as the report generator component.

11.4 The core of the Report generator and Procurement decision support

The concise reporting document is expected to provide an easy-to follow decision support by collection of output data from different tool components of the Technology architecture. Similar to the report generator the Procurement decision support component serves to summarize the configurations of vehicle and charging infrastructure that have been analyzed be the toolkit for the given deployment case under consideration of the respectively existing markets for buses, batteries and charging facilities. The tool component is provided to facilitate the tendering process by definition of operational and technical specifications that meet the requirements of each considered deployment case.

11.5 The outputs of the Report generator and Procurement decision support

The presentation of results from the ReportGenerator component is deliberately designed as a concise and clearly structured document, to support the decision body as effectively as possible. All resulting data and information is summarized in the report document. An example of the report document is shown below.

```
Total cost of ownership analysis
Transit agency: Magdeburger Verkehrsbetriebe GmbH & Co. KG

INPUT DATA

Capital cost of 12m bus      (EUR)   = 625000
Capital cost of 18m bus      (EUR)   = 900000
Capital cost charger equip   (EUR)   = 45000
Capital cost charger equip   (EUR)   = 45000
Install cost charger equip   (EUR)   = 49100
Midlife cost                 (EUR)   = 67000
Efficiency of 12m bus     (kWh/km)   = 1.5
Efficiency of 18m bus     (kWh/km)   = 1.7
Average fuel cost         (EUR/kWh)  = 0.15
Average maintenance cost  (EUR/km)   = 0.67

Bus routes    Peak headway (mins)    Departures (per h)   Return trip length (km)   Avg speed
(km/h)
   51.00   20.00    3.00   12.80   32.00
   52.00   20.00    3.00   22.80   20.10
   53.00   20.00    3.00   11.80   22.10
   54.00   20.00    3.00   25.80   24.20
   55.00   20.00    3.00    9.20   19.20
   56.00   60.00    1.00   22.40   26.90
   57.00   20.00    3.00   11.60   23.20
   58.00   20.00    3.00   22.40   24.90
   59.00   60.00    1.00    9.60   18.00
   61.00   60.00    1.00   10.20   19.10
   69.00   20.00    3.00   15.20   19.00
   71.00   60.00    1.00   13.20   18.80
   72.00   20.00    3.00   14.80   18.50
   73.00   10.00    6.00   11.00   19.40

RESULTS

Bus routes    Yearly TCO (EUR)    Energy consumption (kWh)   km travelled
        51.00     259053.27     252288.00     168192.00
        52.00     966229.11    1018612.80     599184.00
        53.00     238814.74     232578.00     155052.00
        54.00    1093364.52    1152640.80     678024.00
        55.00     186194.54     181332.00     120888.00
        56.00     226671.61     220752.00     147168.00
        57.00     234767.03     228636.00     152424.00
        58.00     680014.84     662256.00     441504.00
        59.00      97144.98      94608.00      63072.00
        61.00     103216.54     100521.00      67014.00
        69.00     483114.56     509306.40     299592.00
        71.00     139848.95     147430.80      86724.00
        72.00     449295.52     437562.00     291708.00
        73.00     466163.17     491436.00     289080.00

Annual  TCO of 12m bus      (EUR)   = 145598.4161
Monthly TCO of 12m bus      (EUR)   = 12133.2013
Annual  TCO of 18m bus      (EUR)   = 196795.0198
Monthly TCO of 18m bus      (EUR)   = 16399.585
Annual  EUR/km of 12m bus           = 1.5402
Annual  EUR/km of 18m bus           = 1.6126
```

12 How-To Line Electrification Selection

12.1 Input data for the Report generator and Procurement decision support

The on-line macroscopic network simulation needs three data files. One XML file contains GPS WGS84 data of the bus lines in GML format, but also length of the routes/lines and in the best case also distances in line segments between stops, the other two files are VDV452 compliant text exports, using the csv ending instead. (REC_FRT and SEL_FZT_FELD). The names of the CSV files are constructed from the name of the GML file where the word Linien is replaced automatically by the postfix of the VDV exports. So the names are xy_Linien.xml xy_rec_frt.csv and xy_sel_fzt_feld.csv. Reading the XML-file takes quite a long period of time on the server, so for subsequent calculations extracted data is stored in a file named erg_cx_Linien.txt, which is serialized data. The calculation then needs no input, but uses default values, which you might alter. If the times for the departure from the stops are given in minutes this would induce errors when calculating the average velocities between stops. It would be beneficial using recorded real time data with higher precision or NeTEx CEN T 16441 using seconds for driving times (ServiceLinkInJourneyPattern). NeTEx also knows intermediate points (PointOnLink) which might be used increasing granularity. The ServiceLink structure, including position data, would render the GML file obsolete. If you have such data please contact the author to get a variant using the NeTEx format.

The input forms of the current implementation Version 0.2 have three sections:

1. Parameters controlling the calculation
2. Input for economic calculation
3. Altering Euro-Class and bus type per bus line

The first group is the most important. A capping value for the yearly expenditure is given, and the amount of differing rechargeable battery sizes. A checkbox allows using the raw GML data, this is useful if the GML file was changed (or the program reading it). During the test, it appeared that the server ran out of memory for large GML files. The checkbox for the sensitivity analysis allows varying the input data by +/- 10%. This results in outputting result tables for selected lines for every variant, omitting the output for the whole tables with results for lines.

The input for the economic analysis uses fixed investment data per kW and kWh. The cost for repair and maintenance is calculated as fraction (not percent) of the investment cost. The cost for the electricity includes fixed cost for power access and metering. All cost should not include VAT. The max. DoD defines how much energy from the rechargeable battery is used in one cycle. The cycle starts and ends at one terminal stop. So far, no positions of substations are inputted, so the distance from the center is used to decide which terminal station should be selected for charging. The yearly operation is assumed to be uniform, the day type having the most tours is chosen for the calculation. While the median of the head times is used to calculate the number of buses, for calculating the immission, the real amount of bus tours per day is taken. If you click on the "Send" button below the input for the lines, this data is stored, and recalled if the page is called for the first time (in a new browser window)..

12.2 The outputs of the Report generator and Procurement decision support

The first image shows the routes modelled as taken from the GML-file. For the coordinates of the xy chart the GPS values are taken without projection.

For each bus line, it is possible selecting the EURO class and the type of busses (standard, articulated) mostly used. Mixed operation is not supported yet, since the exported VDV data does not reveal the busses used.

The immission map - using a 100x100 raster - depicts the bus lines with a color representing the estimated local immision. The brighter, the more bus emissions were summarized at the spot. For the environmental benefit, this value is multiplied for each of the locations by the bus emission of the line, also taking into consideration the emission at the given average velocity for the given Bus size and Euro class. Exponential curves are used for the approximation of the emission of EURO 3 to 5, linear interpolation for the low values of Euro 6. Of course, calculation of the energy demand also uses the bus size and average velocity as input.

As for the output tables, the first one shows the input data for the upcoming line selection process. For every bus line, the cost and the benefit are calculated.

Finally, the list of bus lines is sorted according to the (environmental) benefit to TCO ratio. In the second table and figure only bus lines are shown which totaling cause cost below the investment cap. These bus line do have the best benefit to cost ratio. The last figure shows the average velocity per line for further analysis. Efficiency of the system may be improved asking for traffic light pre-emption and separate bus lanes. If there is a very special situation, it makes sense using the microscopic simulation tool to secure that operation is possible with the calculated rechargeable battery size. In order to receive support for acquiring the NMEA data by GPS, the user is supposed to contact the indicated web address.

13 NMEA-record based microscopic simulation tool

13.1 Introduction

This is a web app which was implemented by effiziente.st, demonstrating a back-looking simulation of buses on the basis of GNSS-logs (NMEA files) for the longitudinal movement. When acquiring data from inside the bus, data shall be recorded using two GPS mice at the opposite positions of the bus with an update rate of 5Hz. Using two mice, more satellite visibility is achieved. Anyhow without having a DGPS setting, altitude cannot be used. For the measurements USB mice were used according to Figure 50.

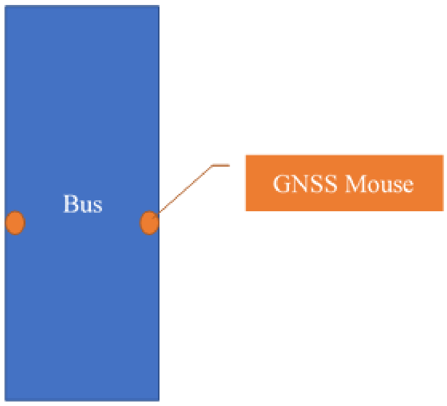


Figure 50 Position for GNSS acquisition devices in the bus

Bluetooth is possible if you manage to get the data stream over to the data collecting unit. Since the timestamp stems from the GPS, delay is no problem.

Of course, roof mounted antennas would be better suited, but regulations have to be met if the bus drives under tram catenaries partly.

Using a one-dimensional vehicle and accumulator (rechargeable battery) model, the calculation allows testing different charging strategies. By stapling tours, a longer simulation is possible, even covering a whole shift if the bus serves only one route. You may select depot charging, opportunity charging and in motion charging. Some iteration allows determining rechargeable battery size. Figure 51 shows the approach which is explained in greater detail in the following figure.

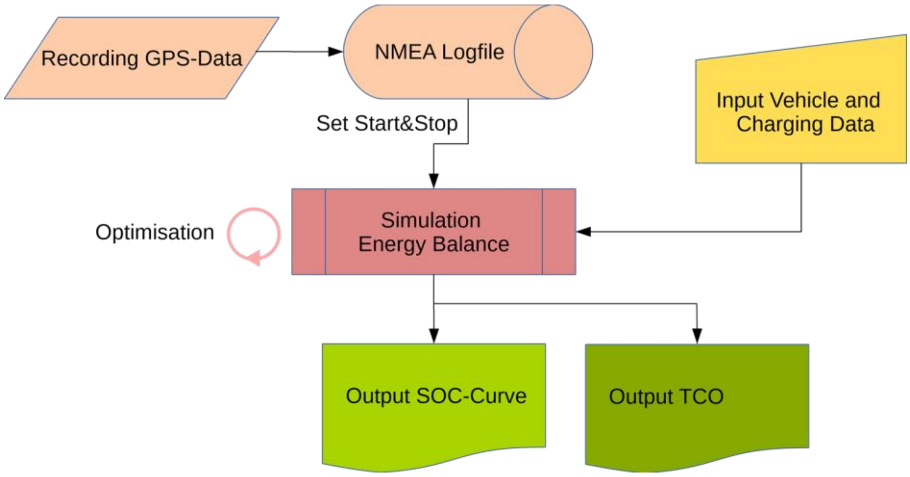


Figure 51 Position for GNSS acquisition devices in the bus

The principal assumption is that battery electric buses will have similar longitudinal movements, this might not be true for vehicles with hand gear shifting.

13.2 How-To

13.2.1 Basic steps using the tool

In the following, the steps to be performed for running the on-line simulation are described. Those include:

1. select the NMEA logfile
2. enter a cut off time (example "02/14/18 12:10:08") if necessary, to strip of recorded data
3. set power of charging in the pauses (zero if the stop is due to congestion)
4. click on calculate
5. you might enter one additional charging pause by clicking in the map (timestamp should be before cut-off time)

The NMEA logfile is plain text, so it can be sanitized before uploading. All incomplete GPS fixes may be removed. If the bus circulates in tunnels, odometry shall be used to get the translational data.

13.2.2 Additional functionality

The number of tours may be given, to see if battery electric operation with depot charging is feasible. More in detail with opportunity charging the duration of the charging may be varying over the day.

The value for opportunity charging may be now set with one click for all stations.

The program allows for an automatic variation of energy storage size and charging power to satisfy SOC-requirements. What-If-scenarios are to be applied manually, e.g. increasing number and length of the charging stop.

Alternative static cost calculation without using effective energy turnover as cost driver is possible, so the depreciation is only depending on the time and not on the energy turnover.

13.3 Simulation details

13.3.1 Rechargeable battery cell model

The rechargeable battery model is a black box electrical model not considering chemical processes in the rechargeable battery, nor influences of the temperature or aging. The model is

- solving for current and voltage using internal resistance of the cell pack
- using no separate model for EDLC

The costs of degrading the rechargeable battery is including a dependency of the usable cycles from the DoD.

13.3.2 Charging agnostic energy balance

The energy balance is calculated for all operational models

- depot or overnight charging
- opportunity charging, determining stops automatically
- en-route charging, defining charging stretches manually

The time to connect and to disconnect is considered in the simulation. Charging losses calculated using the charging efficiency. Ancillary consumers may be calculated on the basis of bus length, number of axles and doors using a pop-up window. Cost for catenary stretches used in both directions are discounted. When surpassing 100% SOC, the charging losses are set to the given input value – representing the standby loss. The standby losses of the chargers are added to the losses during the operation for the given number of rounds. The SOC is calculated dynamically taking into consideration resistive losses.

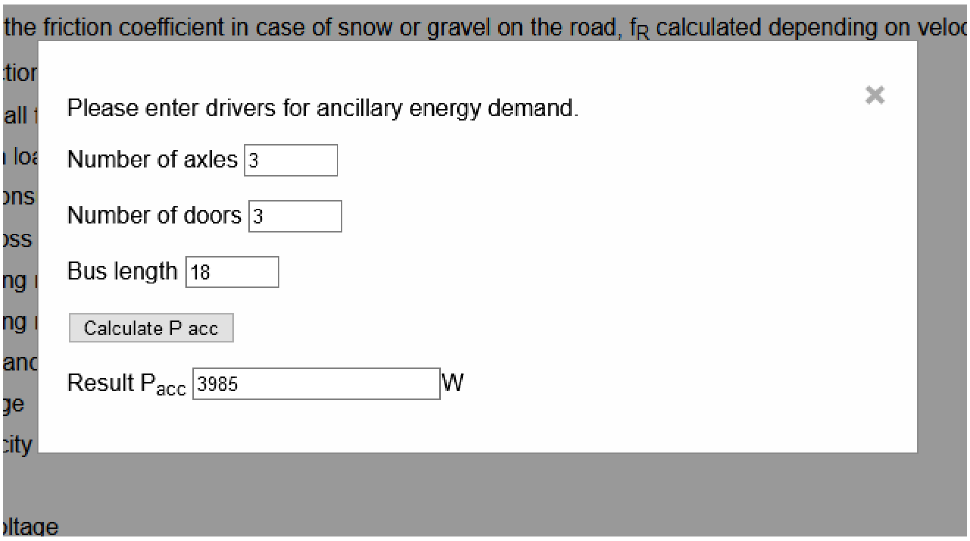


Figure 52 Pop-up window with javascript as side calculation of the ancillary energy demand

13.3.3 Vehicle translation

The one-dimensional model should work independent of the data acquisition rate. It filters the velocity readings, with a sample size depending on the variance (useful for 5 Hz)

There are fixed assumptions for rotational masses. The user may choose the vehicle type from a library or enter specific data. A dimensionless efficiency map is used for motor and generator, the max. power and efficiency when exceeding max. power was assumed.

13.3.4 Heat demand

The calculation for the heat demand is sophisticated. The ambient temperature is read from the form. A minimum convective heat loss is assumed, velocity depending convective losses are added. The heat loss is including heat loss through open doors for the period of stand still. This is certainly overdoing this type of losses, on the other hand losses through bringing in cold coats are not taken into consideration. An empiric curve is used for open door heat losses and the time with open door might be limited. The doors are assumed to be open 2 seconds after start of standstill and before departure. For the use of waste heat a utilisation rate of 1/3 was assumed.

No heating/cooling energy for the rechargeable battery pack is assumed.

13.4 Data Input

We now walk through the input forms explaining wherever necessary.

The inputted data may be stored locally. Data is stored by your currently used Internet Browser (and only this one installation) persistently. This means if you clear all, or change the browser you are not able working with that data.

The following form allows inserting a timespan for charging

You may click on one Point in the map (with still stand) or manually enter one additional charging time insert. This will elongate the tour.

Timestamp for insert	0	related to the GPS-point
Duration of the new charging point	0	sec.
Charging Power	0	kW

Figure 53 Inserting charging pauses

The following form allows to enter charging at the identified stops. It also is possible to assume a catenary section for the route to the next stop. The first input allows filling all the input fields with the same charging power. The charging power is defined as the power transmitted over the conductive connection.

Input data for opportunity charging

Fill all fields with 240 kW

Potential charging pauses/stretches	Input	Catenary
0: at 15.445867666667 47.0448235 max. **280 sec.** from 2/6/18 08:10:37.2 until 2/6/18 08:15:17.8	0 kW	☐
after 15.445867666667 47.0448235 from 2/6/18 08:15:17.8	same as stretch 0	☐
Calculate n-times	1	
Maximum tolerated velocity stillstand	1	m/s

Figure 54 Inserting charging pauses

The following form allows cutting the recorded timespan to get rid of NMEA parts you need to board or leave the bus when recording.

Variable	Input	Explanation
delayed start time		timestamp, original time domain without insert
Cut-off time		timestamp, original time domain without insert

Figure 55 Reduction of used data

Some NMEA files were uploaded, you might use them. If you opt for uploading your own, it will not be offered to others, but stored on the server, so you have to give consent to that.

Select another NMEA data file

NMEA_Test.txt (398.2 kB)
NMEA__logfile_2018-02-14_12h40.txt (5824.3 kB)
NMEA__logfile_2018-02-14_12h40_short.txt (3423.4 kB)

Filename new NMEA file upload: I agree to store the data on the server ☐

Figure 56 NMEA input

The next pop-up form allows to calculate the rolling friction coefficient, depending on the axle load and the energy label of the tyre.

Axle	Load on Axle	Energy Label
Axle 1		
Axle 2		
Axle 3		

Figure 57 Input for calculating rolling friction

The following option allows to enable the solver. It determines the charging power a rechargeable battery size necessary not to drop below the minimum SOC.

Solve for charging power and accumulator size ☑

Figure 58 Program control

The following checkbox enables using altitude information from the NMEA-log file, this is not recommended due to steps/inaccuracies in the NMEA values.

Use altitude information from NMEA log ☑

Figure 59 Selection of altitude usage

The following checkbox enables the mouse over responsiveness. You may click on a point of the route and enter a charging pause, see Figure 60.

Implement mouse over action ☑ (for retrieving insert locations)

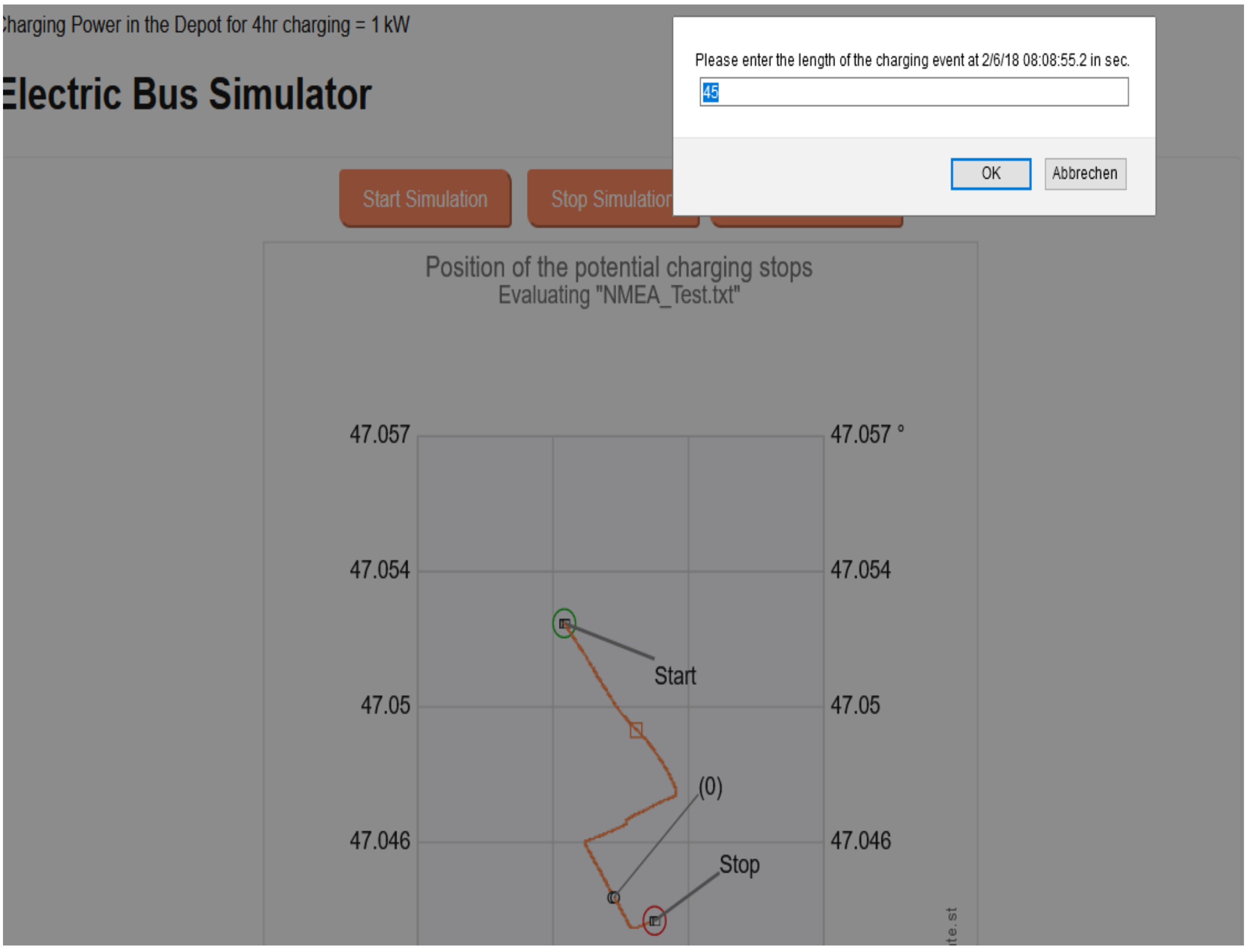


Figure 60 Entering additional charging pauses

The following form allows entering data for calculating the heat loss (red), the boundary conditions for the accumulator data and other electrical characteristics (blue), some vehicle date influencing drag (green). The friction coefficient is calculated depending on the velocity.

Vehicle data for extreme operational conditions (winter)

You may select preset values

Variable	Input	Explanation
max. duration with open doors	20 sec.	
Number doors	3	Number double doors
Doors width	2 m	Total width double door
Doors height	2.2 m	
Bus length	12 m	
Insulation thickness	15 mm	
u-value windows	2 W/m²K	
Share of glazing	50 %	for side walls
Air exchange rate	5 per hour	
Coefficient of performance Heat Pump	3.5 -	maximum COP
Percentage of recyclable waste heat	20 %	
Heat release per person	80 %	
Ambient temperature	-15 °C	for calculation of heat loss and SOC
Size of accumulator	55 kWh	usable energy capability
Initial SOC accumulator	80 %	determining charge at the start of the trip
Factor tyre friction	150 %	factor for the friction coefficient in case of snow or gravel on the road, f_R calculated depending on velocity
Air resistance A*c_w air drag	6 m²	cross-sectional area * drag coefficient
Mass of the vehicle:	1800(kg	including all fluids and the driver
Max. passenger load:	6000 kg	maximum load, theoretically the bus may recover energy if passengers board on a hill
Other electric consumers:	2.5 kW	electric consumers for steering, doors, passenger information, light...
Wind speed:	0.1 m/s	for heat loss with open doors
max. vehicle speed:	80 km/h	determining relative RPM of the electric machine when calculating efficiency

Figure 61 Form for entering vehicle characteristics

In the following table the data for the TCO calculation are entered.

Economic data bus and charging facilities

Variable	Input	Explanation
Investment cost vehicle without energy storage:	40000 €	procurement costs vehicle without accumulator but including electronics
Investment cost energy storage:	250 €/kWh	procurement costs energy storage (accumulator including BMS)
Operation hours vehicle:	28800 hrs	productive operation hours in the total lifespan
Service and maintenance cost vehicle:	5 %/a	service and maintenance costs vehicle without accumulator but including electronics
Specific total cost vehicle accumulator :	0.15 €/kWh	round trip storage cost including depreciation and maintenance.
Driver cost:	30 €/hr	including overheads and costs for unproductive time
Specific investment cost stationary charging infrastructure:	1388 €/kW	procurement costs charging infrastructure
Lifespan charging infrastructure:	20 yrs	maximum years in operation
Specific service and maintenance cost charging infrastructure:	2 %/a	service and maintenance costs charging infrastructure
Specific investment cost en-route charging infrastructure:	3000 €/m	procurement costs catenary en-route charging infrastructure
Lifespan en-route charging infrastructure:	15 yrs	maximum years in operation
Specific service and maintenance cost en-route charging infrastructure:	3.5 %/a	service and maintenance costs charging infrastructure
Energy procurement cost:	0.15 €/kWh	electricity for charging
Number of tours per day:	10	average round trips

Figure 62 Form for entering data for economic calculation

In the following fields you may enter information to save that data and to comment on the tool:

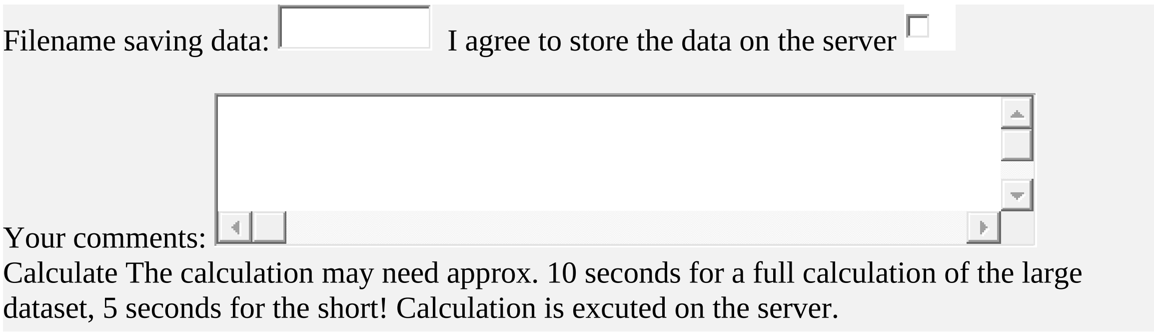


Figure 63 Final data to be entered optionally

13.5 Results

The following output allows to see some intermediate calculation steps.

The total mass amounts to 24000 kg

With 221 parallel and 29 serial cells the ESR evaluates to 0.48 Ohms.

Tries reading from NMEA_Test.txt

Checks whether charging points match in the List having 1 entries.

In Motion Charging is not active

Heat loss open doors=80259 W

Heat pump actual COP=2.28

Total Losses: frict=11053 drag=563 accel=104 pot=0 Total=11721

Total power charging stations: 0 kW

Variant Depot Charging

Start: SOC = 80 %

Distance simulated=0.7 km average velocity 6 km/hr

Runs the tour 1-times

1 calculations not performed from 2128 in total.

Round = 1: min SOC = 76.5 %

Depth of Discharge = 35 %

Total time for all 1 rounds = 0.25 hrs

Total Energy needed for 1 rounds = 1.53 kWh

Charging Power in the Depot for 4hr charging = 1 kW

Figure 64 Some data showing calculation progress

13.5.1 Energy balance

The following output gives results from the calculation of the energy balance. In the figure data is visualized. The pie diagram gives the share of the losses, the Sankey diagram the energy flow. In the diagram showing the cumulative SOC the average energy demand may be seen.

Results Energy Balance

spec. Energy demand operation=2.07 kWh/km

Total charging duration=0 min.

Heat demand air exchange 4 kW

Charging excl. standby loss charger =0 MJ, while off duty for 22.8 hrs loss = 3.3 MJ

Energy demand per Passenger:

- Propulsion: 0.035 MJ
- Heating: 0.015 MJ
- Other: 0.012 MJ
- Charging Losses : 0.036 MJ

Figure 65 Data and results from the calculation of the energy balance

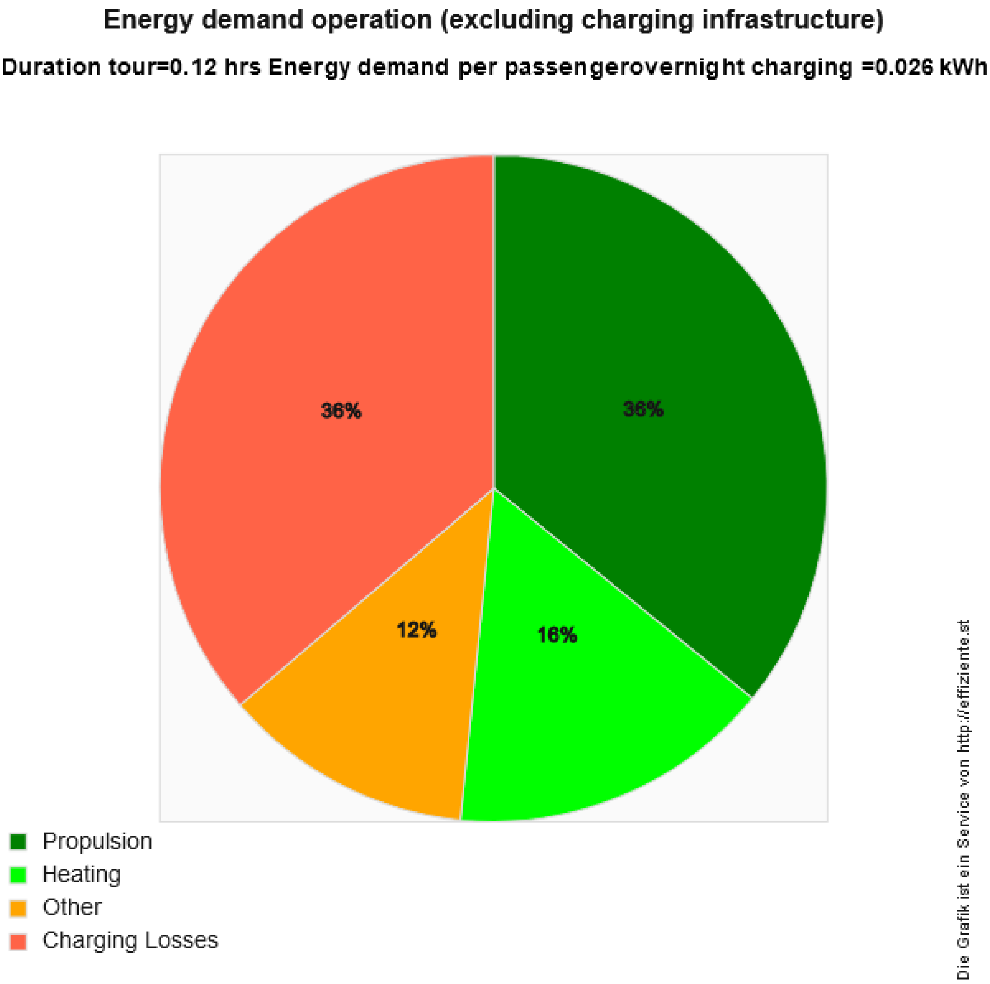


Figure 66 Pie diagram of energy demand

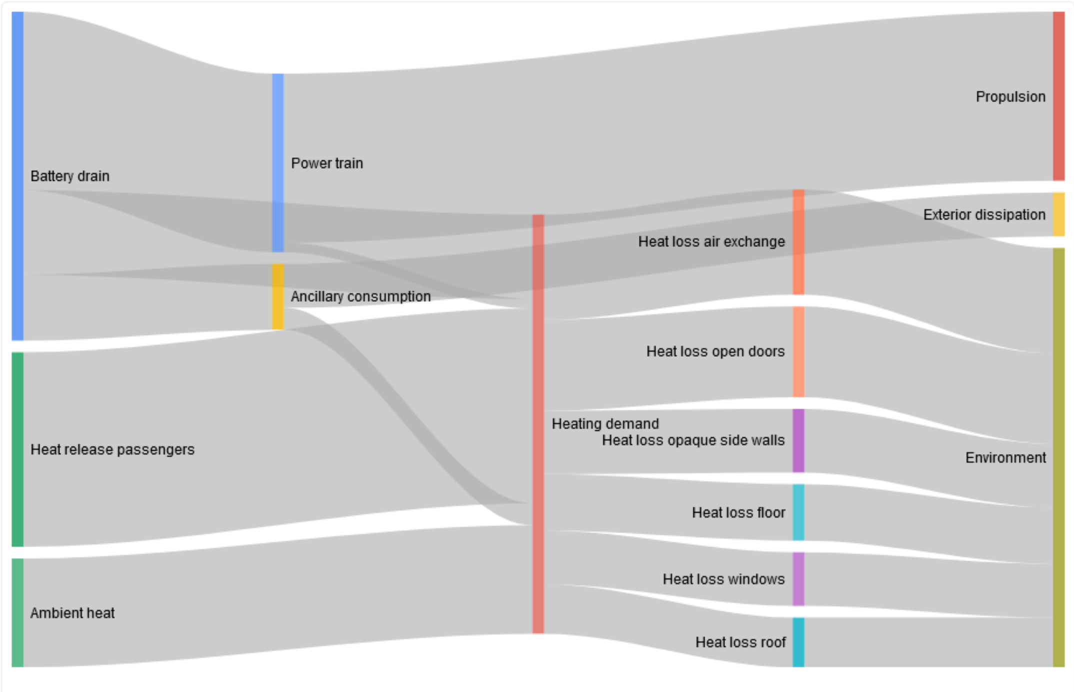


Figure 67 Sankey chart of energy flow

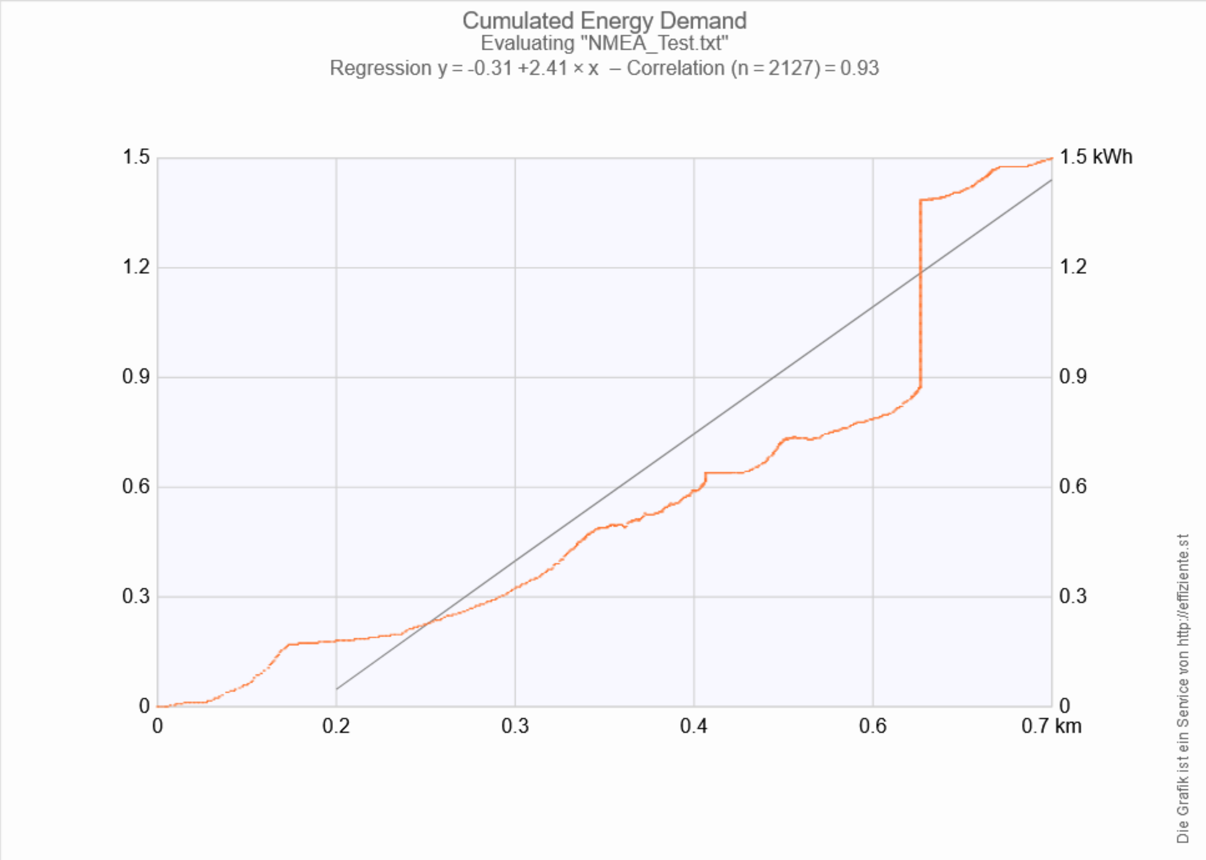


Figure 68 Cumulative SOC over the route

The vertical line stands for a charging event. The correlation only makes sense for depot charging.

13.5.2 Economic results

The last part of the output shows economic results. In Figure 70 the results from both TCO calculations are shown if the respective box is ticked. At the left side the formulas are shown for calculating the TCO.

Cost Calculation Scheme

$IC_{charging\ (per\ kW\ and\ tour)} = IC_{charging\ (per\ kW)} / (number_{tours\ per\ day} \times 360 \times lifespan_{charging\ infrastructure})$

$TCO_{vehicle} = IC_{vehicle} / hours_{\ in\ operation\ total} \times hours_{tour} * (1 + maintenance\ cost\ fraction_{vehicle\ per\ year})$

$TCO_{driver} = cost_{driver} * hours_{tour}$

$TCO_{charger} = IC_{spec.\ charging\ (per\ kW\ and\ tour)} \times Total\ kW_{charging\ stations} \times (1 + maintenance\ cost\ fraction_{charger\ per\ year}$

$TCO_{energy} = Energy_{Charging} \times (\ spec.\ cost_{energy\ (per\ kWh)}(0) + cost_{Accumulator}\ per\ kWh\ turn\ around\ )$

overnight charging: Total 1 kW IC/(kW tour)=0.019 €/kW 10 tours per day

DoD=0.35 TCO Bat. =0.0659 €/KWhr

IC discounted for 28800 hours of operation

Figure 69 Formulas for TCO calculation

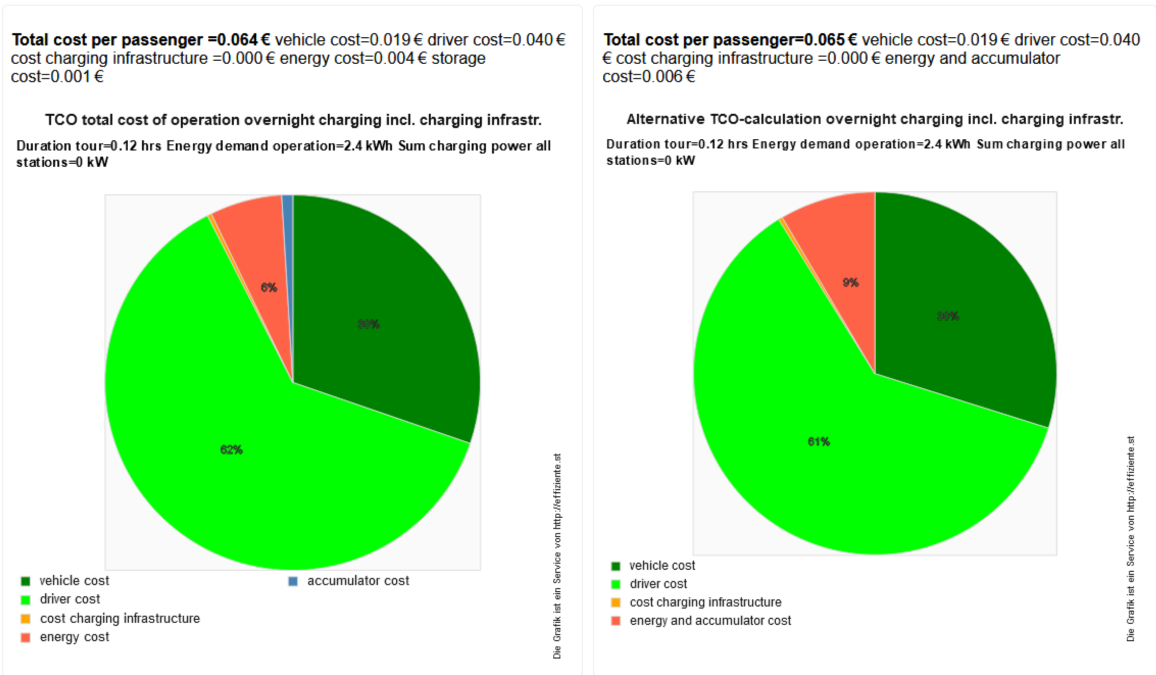


Figure 70 Comparing TCO models