PLATON –

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

Deliverable: WP 3.2 Input data formats

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Contents

1 Introduction

The Deliverable 3.2 presents the results of the project work WP3 (Input data formats).

The results of this work package focus on input data formats for software (*ECBus*), which is being developed in a project under thematic "working process and energy consumption of electric buses".

Section 2 is devoted to a general description of data formats for the route as an object that includes three elements: “road”, “bus” and “trip”.

Besides software, the procedure to determine calculated case for energy consumption is developed (Section 3). The procedure involves: 1) a preliminary determination of the routes for assessing energy consumption, 2) the choice of the calculated value of energy consumption based on the probabilistictic representation of possible cases for electric bus operation.

Section 4 demonstrates templates for input data of *ECBus* software.

The ways to use *ECBus* software are presented in Section 5. They relate to organization of using the Software and typical tasks in which the Software can be used.

Section 6 provides an overview of the database being developed.

The Deliverable 3.2 contains two annexes. Annex A (Section 8) gives an example of filling the minimum input data with the user and generating the rest of the input data in *ECBus* software by default. Annex B (Section 9) illustrates directions of development of the database by examples of typical data blocks for modelling bus working process, calculating TCO for electric bus fleet and optimization problems.

2 Input data categories and formats

In the framework of data exchange between components of the PLATON Toolkit there are numerous categories of data to be distinguished. Input data is to be referred as the input to components of the toolkit. These can be output data of other tool components or data from open or proprietary sources. In Figure 1 is shown the information and data architecture between components of the PLATON Toolkit System in the state as of mid-2019. The directed arcs between the green marked tool components represent flows of data objects from their source to their destination including the category and formats which are further described in the following chapter.

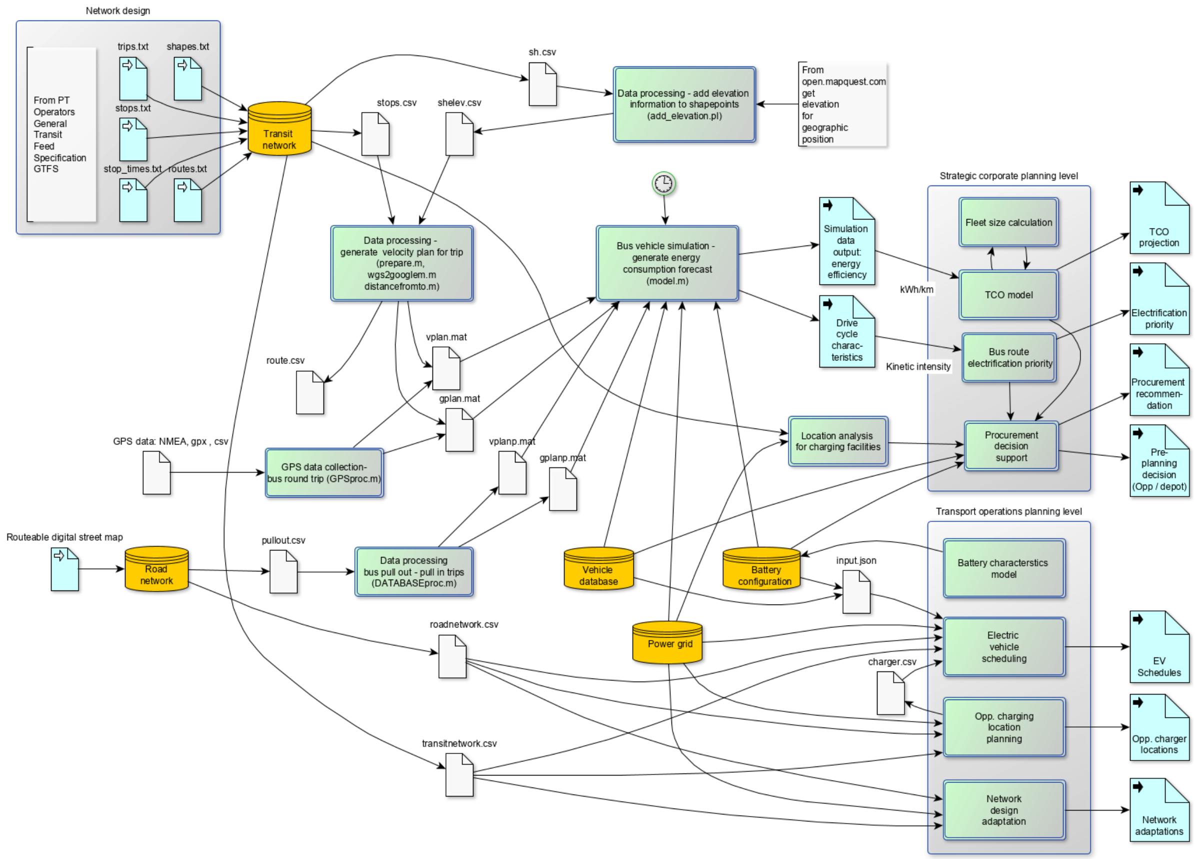


Figure 1 Information and data architecture of PLATON Toolkit System and its components

2.1 Scalar quantities

Input data can be classified by their properties such as type and cardinality. For example, the scalar parameters for the optimization tool component such as boundaries, physical quantities or financial costs are represented by variables with mnemonic names that are collected in and transferred by JSON files. The JSON format was selected for its efficiency with respect to data transfer and parsing capability. Since data structures supported by JSON is also supported by most of the modern programming languages, it makes JSON a very useful data-interchange format.

Table 1 Example of input file input.json with scalar parameters such as yearly capital and operational cost figures


```
{
  "uoc_eur_per_year": 1000000,
  "ucc_eur_per_year": 2500000,
  "poc_kW": 300,
  "cccap_eur": 40000,
  "ccope_eur_per_kWh": 0.21,
  "capb": 97,
  "cvbcap_incl_240kWh_batt": 330400,
  "cvbope_eur_per_km": 0.3,
  "ctjbc_sec": 300,
  "tjdepot_hrs": 9,
  "cbi_eur": 100000,
  "clij_eur_per_meter": 280,
  "irb_mins": 10,
  "cerb_eur_per_km": 0.2,
  "pasr": 150
}
```


2.2 Vectorial quantities

Vectorial quantities like a set of e-bus types or a set of charging station types are represented by arrays in the JSON format as an ordered list of values. A value can be a string, a number, an object, an Array, a Boolean value (i.e. true or false) or Null. This structure can be nested.

Table 2 Example of input file vehicle.json with vectorial quantities such as bus and charger type


```
{
"e_buses":["BKM","VOLVO","SOLARIS"]
"charger":["TIREX","SIEMENS","VOlVO"]
}
```


2.3 Sequences, matrices and other tabular data

Input data of higher cardinality such as sequences, matrices and other tabular data are represented by text files with comma separated values (CSV) that are organized in columns. A preceding header line with mnemonic names is used for column identification. Each row represents an entry of a data object. Typical examples for this type of input data are road networks or transit networks as well as collections of stops and charging facilities.

Table 3 Example of tabular data in Comma Separated Value (CSV) file stops.txt with tabular organized data like geometries, sequences, references, timetable and network data

```
route_id,trip_id,parent_station,stop_id,stop_sequence,stop_lon,stop_lat,x,y
R53,T2822001,S5705901,S5705902,7,11.561104,52.088903,1286976.2,6816216.2
R52,T1932001,S5000701,S5000703,22,11.628128,52.108392,1294437.3,6819747.9
R71,T2377001,S2000201,S2000202,6,11.574198,52.149498,1288433.8,6827201.9
R73,T2636001,S2201,S2207,5,11.639302,52.136404,1295681.2,6824826.7
R55,T2044001,S5500301,S5500301,4,11.586701,52.113503,1289825.7,6820674.3
R59,T2929001,S5901101,S5901102,8,11.620094,52.122899,1293542.9,6822377.7
R55,T2043001,S6100301,S6100302,4,11.594006,52.119298,1290638.8,6821724.9
```

2.4 Geographical data

Geographical data such as the geometries of road and transit networks are represented in the CSV files using the *Well known Text* (WKT) format. A geometric object that is referenced by a data entry is provided in the textual description of object type (LINESTRING) and comma separated intermediate x y coordinate points in the following form:

```
LINESTRING(3680012.4 5779289.3,3680012.2 5779286.5)
```

The x and y coordinates are separated by a blank. The coordinate system of the points can be either geographical (*WGS84*) coordinates or a Cartesian coordinate system such as *Gauss-Krüger* or *Web Mercator*.

2.5 GTFS General Transit Feed Specification

The GTFS specification was introduced by Google, in order to ease the publication and transfer of transit timetables and network information between transit agencies as well as to provide timetable information for users of public transport, especially using the browser of Google Maps.

Many types of applications consume GTFS data, including:

- Trip planning and maps – applications that assist a in planning journeys from one location to another using public transportation and other modes
- Timetable creation – to create a printed list of the agency’s schedule in a timetable format
- Accessibility – applications that assist transit riders with disabilities in using public transportation
- Planning & analysis – applications that assist transit professionals in assessing the current or planned transit network, including ridership forecasting

- Real-time transit information – applications that use GTFS data along with a real-time information source to provide estimated arrival information to transit riders
- Public Information Displays - electronic displays to show schedule information, service advisories, real-time arrivals and/or other information

In Europe, beside GTFS exist the official reference model *Transmodel* for exchange of timetable and network data with two standardized data exchange formats *SIRI* and *NeTEx*. *Transmodel* is the European Reference Data Model for public transport, and constitutes an offer to public transport companies and other providers of services related to the process of passenger transportation (planning, operation and information), to suppliers of software products supporting these processes, and to consultants and other experts acting in the field of public transport in the widest sense. The reference data model, developed at conceptual level, can support the development of software applications, their interaction or combination in an integrated information system, and the system‘s organisation and information management which rules the utilisation of the existing telematics environment in a company (or group of companies) running computer applications supporting the different functional areas of public transport.

In Germany this task is practically solved by the VDV 452 Standard interface network and timetable. In view of the fact that VDV data are mainly available only in Germany and German speaking countries, instead the open availability of GTFS feeds is higher than VDV feeds both in Germany and in many European countries, in PLATON it is considered the use of GTFS as an additional possible source of timetable and public transport network data.

In PLATON GTFS data feed has been used to create a database representing the public transport network and timetable data of the medium sized city of Magdeburg where ifak is based. The database itself is intended to generate simulation input data for energy consumption forecast as a component of the PLATON Toolkit.

2.6 Bus tracking data

Collected data of real trips carried out in buses during duty cycles are stored into GPS-files of different formats. Well known formats are NMEA (National Marine Electronics Association) (see Table 4) and GPX (GPS Exchange Format). Any of the named text based formats can be processed by components of the PLATON Toolkit.

Table 4 Example of an NMEA message $GPGGA Global Positioning System Fix Data as output of an GPS/GNSS receiver to be consecutively stored into an NMEA sequence ASCII text file

```
$GPGGA,hhmmss.ss,llll.ll,a,yyyyy.yy,a,x,xx,x.x,x.x,M,x.x,M,x.x,xxxx*hh
          1         2    3    4     5 6 7  8   9   10 11 12 13  14  15
1    = UTC of Position
2    = Latitude
3    = N or S
4    = Longitude
5    = E or W
6    = GPS quality indicator (0=invalid; 1=GPS fix; 2=Diff. GPS fix)
7    = Number of satellites in use [not those in view]
8    = Horizontal dilution of position
```

```
9    = Antenna altitude above/below mean sea level (geoid)
10   = Meters  (Antenna height unit)
11   = Geoidal separation (Diff. between WGS-84 earth ellipsoid and
       mean sea level.  -=geoid is below WGS-84 ellipsoid)
12   = Meters  (Units of geoidal separation)
13   = Age in seconds since last update from diff. reference station
14   = Diff. reference station ID#
15   = Checksum
```

2.7 Other internal data formats

Data exchange between components of the PLATON Toolkit is also achieved by internal interfaces using *Matlab*/*Octave* MAT files. These files are generated and used by elements of one tool component and are not intended to be used for data exchange between tool components.

3 Input data generation. Route description

The term “route”, used below, is understood as a universal element that can be used for description of any bus trip, including auxiliary transfers.

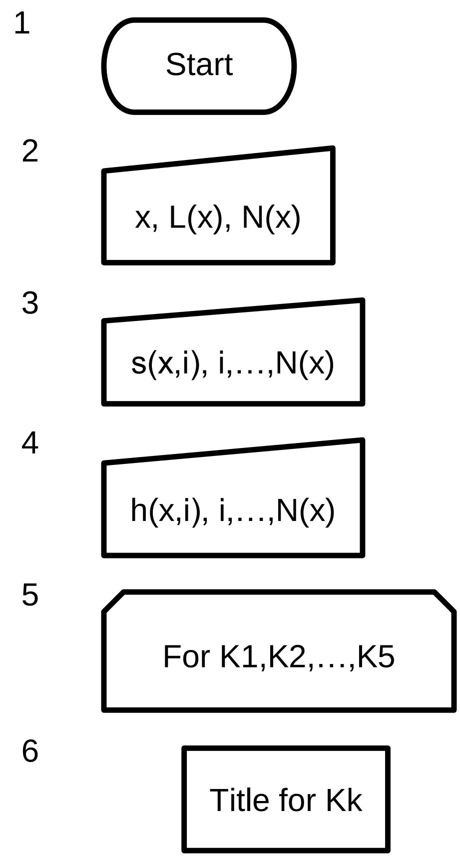
The calculation of the energy consumption of an electric bus on a separate route plays a major role. Based on this calculation, various combinations may be constructed to evaluate energy consumption for the routes cycle containing different set of routes.

All input data to describe the route are divided into three categories: “road”, “bus” and “trip”. In some cases, the input parameters, conditionally related to one category, belong to the two or three mentioned categories. For example, rolling resistance from category "bus" is related to the categories “bus” and “road”.

3.1 Road data

The algorithm for generating road data is shown in Fig. 1.

Road data consist of “General road data” and “Road data in additional”. The first data are always present, and the second ones may be absent.



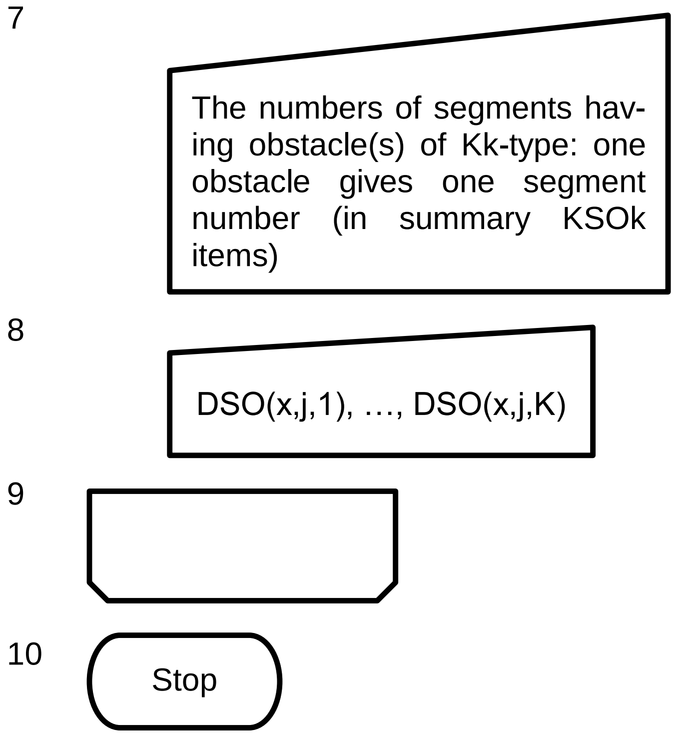


Figure 2 Input data for an object “Road”

General road data

x=IDRoute=Identifier of the route in question

L(x)= Route length, m

*N(*x*)*=Number of the route segments

s(x,i)=Array of Segment lengths (Distances between stopping points) of the route, m, i=1…N+1

h(x,i)=Array of altitudes h(i) at the stopping points, m, i=1…N+1

Road data in additional: traffic obstacles/interferences

K1=identifier of the Turn of road in the segment;

K2=identifier of the Intersection in the segment;

K3=identifier of the Artificial irregularity in the segment;

K4=identifier of the Pedestrian crossing in the segment;

K5=identifier of the Traffic light in the segment.

Blocks 5 and next ones describe the arrays of segment numbers and distances to their obstacles/interferences locations.

KSO(x,Kk,j) = array of the segment numbers related to Kk; j=1,…, KSOk, where KSOk is the number of consecutive nonzero digits in the array Kk of segment numbers

DSO1(x,Kk,j) = array of the j-th distances to obstacles/interference from starting point of considering segment relating to Kk; j=1,…, KSOk, where KSOk is the number of consecutive nonzero digits in the array Kk of segment numbers

3.2 Bus data

Bus data input is shown in Figure 3.

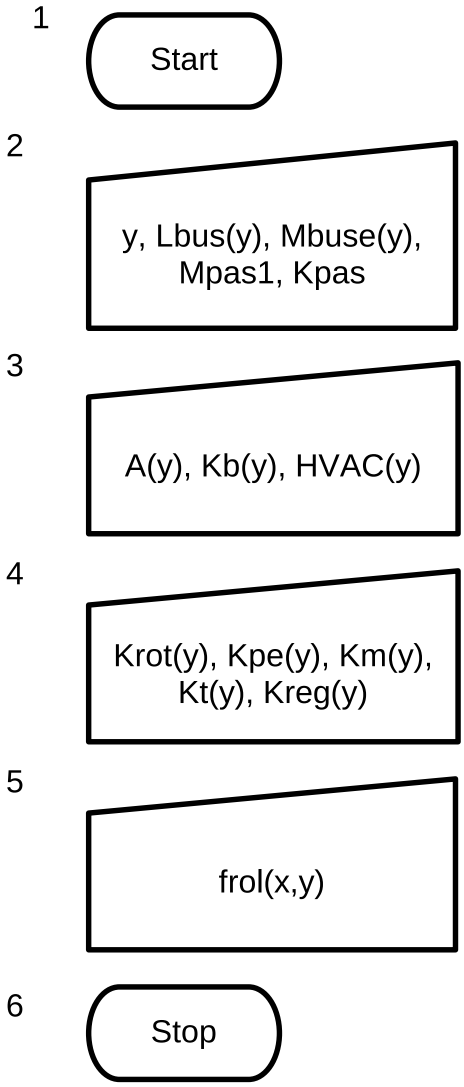


Figure 3 Bus data input

y=IDBus=Identifier of the bus in question

Lbus(y)= Bus length, m (default is 12 m)

Mbuse*(x)*=Bus weight without passengers, kg

Mpas1= One passenger weight, kg (default is 70 kg)

Kpas= Max number of passengers

A(y)= Cross section area (default is 6.6 m^2)

Kb(y)= Drag coefficient (default is 0.4 Ns^2/m^4)

HVAC(y)= Maximum electrical power of auxiliary system or its subsystems with battery energy consumption (default is a=8 kW-for the driver's cabin and ventilation, b=24 kW-for the entire bus)

Krot(y)= Rotation inertia factor (default is 1.05)

Kpe(y)= Average efficiency of the inverter (default is 0.98)

Km(y)= Average efficiency of the motor (default is 0.95)

Kt(y)= Average efficiency of the transmission (default is 0.95)

Kreg(y)= Regeneration (recuperation) factor (default is 0.6)

frol(x,y)= Rolling resistance (for planned types of bus tires and road surfaces) (default is 0.008 in summer)

Some of the input data are original. Others have values that are similar for different electric buses, and they can be taken by default; these data are accompanied by recommendations (in brackets).

For example, Kpe (y), Km(y), Kt(y) serve to obtain TtW(y) during calculation by multiplication:

$$TtW\ (y) = Kpe(y) \cdot Km(y) \cdot Kt(y) \tag{1}$$

So by default, TtW(y) = 0.88.

3.3 Trip data (schedule, passengers loading, stopping times and speed limits)

A trip of an electric bus on the route consist of movement within segments. Each segment includes a passenger boarding and/or alighting phases and a traffic phase that can be interrupted by intersegmental stops (Figure 4).

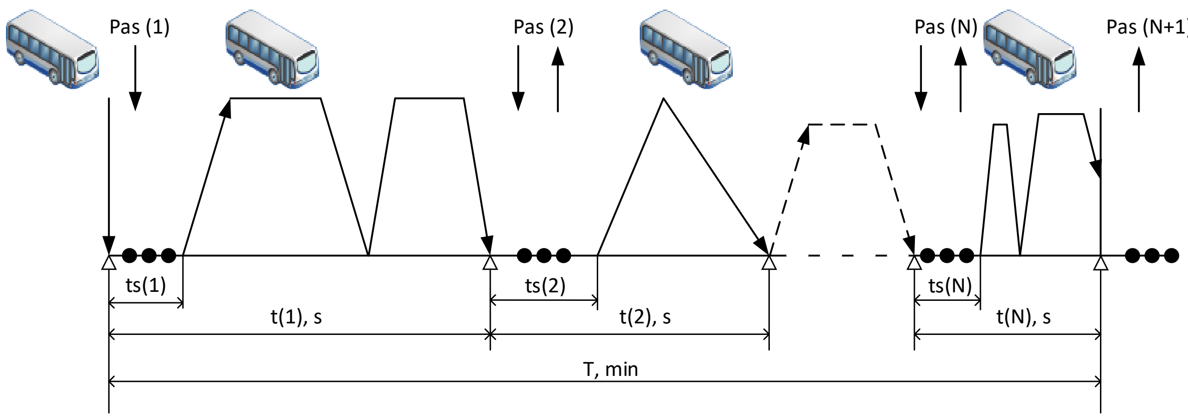


Figure 4 Basic stages in movement of an electric bus on the route

Trip data can be presented by generalized or detailed sets.

Generalized set (Figure 5)

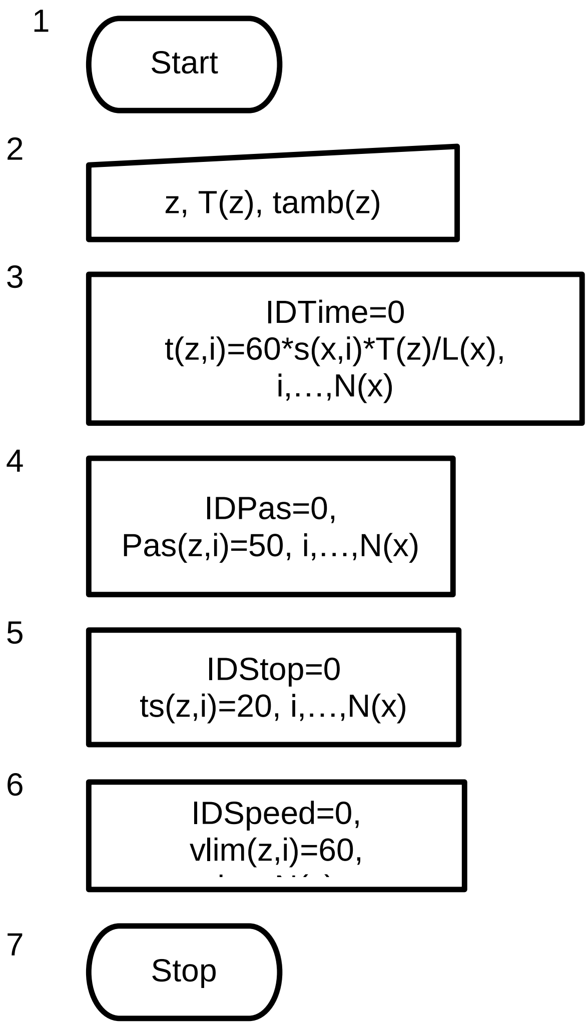


Figure 5 Generalized input data for the object “Trip”

z=IDTrip=Identifier of the bus trip in question

T(z)= Time of trip, minutes

tamb(z)=Ambient temperature, ℃ (default is 15℃)

Generalized input data formats include:

- IDTime=0 and time between arrivals at the i-th and (i + 1)-th stops is calculate by formulas, sec

$$t(z,i)= 60\cdot s(x,i)\cdot T(z)/L(x),\ i,\ldots,N(x) \qquad (2)$$

- IDPas=0 and passenger load for i-th segment is equal Pas(z,i)=50%, i,…,N(x)
- IDStop=0 and stopping times for i-th segment is equal ts(z,i)=20 sec, i,…,N(x)
- IDSpeed=0 and speed limit for i-th segment is equal vlim(z,i)=60 km/h, i,…,N(x)

Detailed set (Figure 6)

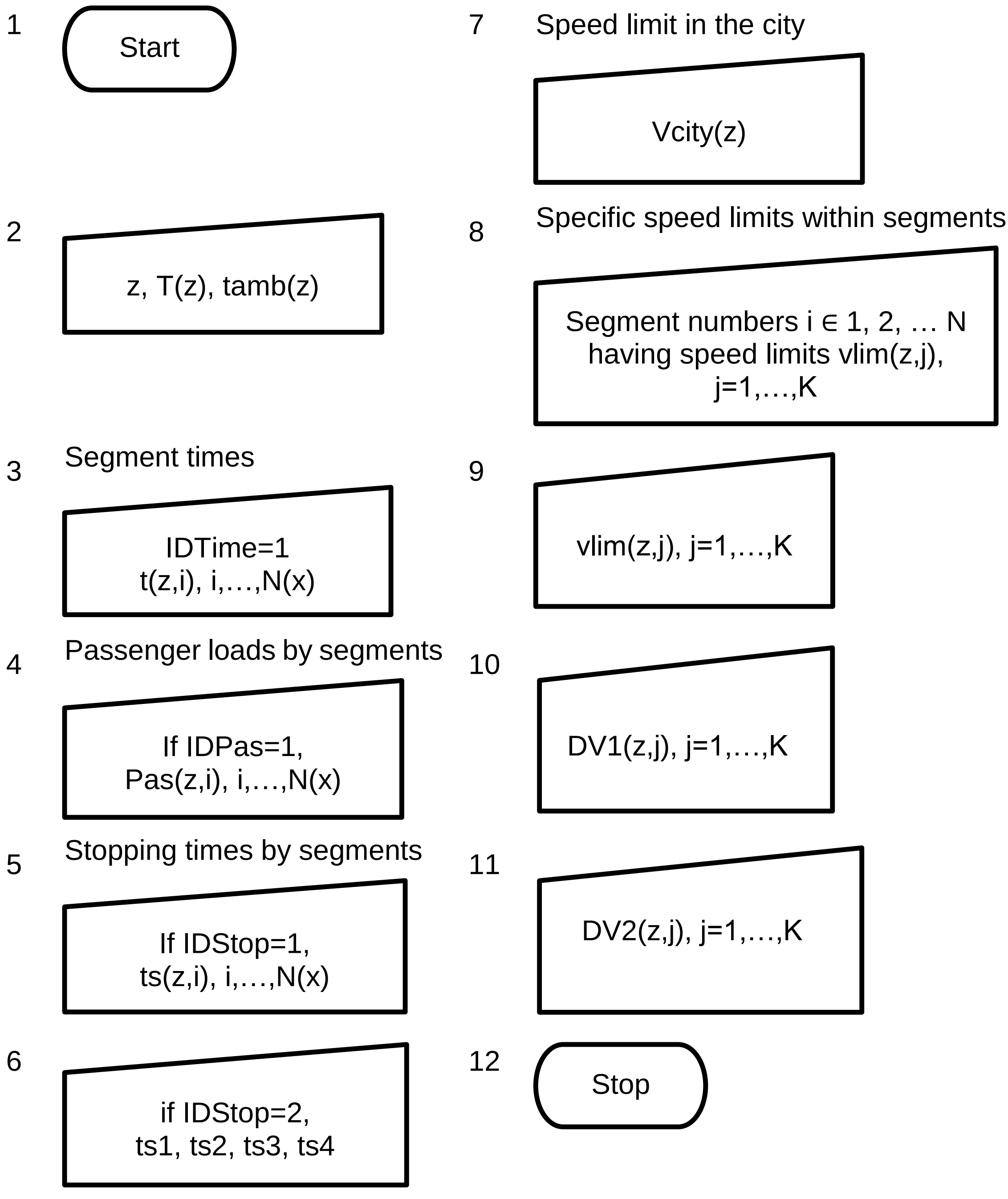


Figure 6 Detailed Input data of the object “Trip”

Detailed Input data formats have the following features.

3 *Segment times*

IDTime=1 and times between arrivals t(z,i), i,…,N+1(x) at the i-th and (i+1)-th stops are entered

4 *Passenger loads by segments*

If IDPas=1, array Pas(z,i), i,…,N(x) are entered

5 *Stopping time if IDStop=1*

If IDStop=1, array ts(z,i), i,…,N(x) are entered

6 *Stopping time if IDStop=2*

If IDStop=2, then ts1, ts2, ts3, ts4 are entered and array ts(z,i) are determined in depending of Pas(z,i) by the following way

- Pas(z,i)≤25%, ts(z,i)= s1 (default is s1=13 sec)
- 25<Pas(z,i) ≤50%, ts(z,i)=s2 (default is s2=18 sec)
- 50<Pas(z,i)≤75%, ts(z,i)=s3 (default is s3=23 sec)
- 75<Pas(z,i)≤100%, ts(z,i)=s4 (default is s3=28 sec)

7 Speed limit in the city for traffic

Vcity=Speed limit in the city for traffic, km/h

8 Specific speed limits within segments

NVmin(z,j) = the array of segment numbers i ∊ 1, 2, … N; j=1,…, K, where K is the number of consecutive nonzero digits in the array of segment numbers NVmin(z,j)

vlim (z,j) = the array of speed limits, km/h, j=1,…, K

DV1(z,j) = the array of distance from starting point of above mentioned segment in the array NVmin(z,j) for beginning the j-th speed limit, m, j=1,…, K

DV2(z,j) = the array of distance from starting point of above mentioned segment in the array NVmin(z,j) for ending the j-th speed limit, m, j=1,…, K

3.4 Identifiers for displaying results

The final section “Results” of the input data set contains a driving style indicator (IDRrive) and lists of displaying calculation results (NResult, NSpof).

IDRriver=1 for calm driver style (as default), 2 — for aggressive one

NResult=The number of calculation type for detailed results output of energy consumption by segments; n ∊ 1, …, 4. NResult is

1 = results for input data entered by the user. Probability of stopping at Pedestrian crossings (PC) and Traffic lights (TL) are assumed 50%. If stopping takes place, then stopping modes includes deceleration and stops for 15 (PC) and 30 (TL) secs respectively at mentioned obstacles (as default)

2 = results without taking into account data concerning obstacle/references (free mode)

3= results without data concerning Pedestrian crossings and Traffic lights (passing through these obstacles without delay)

4 = results with taking into account Pedestrian crossings and Traffic lights: stops for 15 (PC) and 30 (TL) secs respectively at mentioned obstacles after deceleration.

NSprof = array contained numbers of segments, for which data about generated speed profiles are output.

3.5 Minimum set of original input data

The minimum set of original input data for calculating the energy consumption of a bus on a route is as follows.

From category "road"

- *L*(x)=Route length, m
- *N(*x*)*=Number of the route segments
- s(x,i)=Array of Segment lengths (Distances between stopping points) of the route, m, i=1…N+1

The array of altitudes can be represented as h(i)=0 (empty line in the input template).

Also, empty lines can be for other input data. In these cases, input data assigned by default.

From category "bus"

- Mbuse*(*x*)*=Bus weight without passengers, kg
- Kpas= Max number of passengers
- frol(x,y)= Rolling resistance (for planned types of bus tires and road surfaces) (default is 0.008 in summer)

Other parameters from the "bus" category may be accepted by default.

From category "Trip"

- T(z)= Time of trip, minutes
- tamb(z)=Ambient temperature, ℃

Other parameters from the "trip" category may be entered in Generalized input data formats and as default.

From category "Results"

All parameters from the "trip" category may be given as default. The results are presented for cases (as default): IDRriver=1 and NResult=1.

An example of creating full set of input data based on a minimum set of input data is given in Appendix A.

4 Procedure to determine calculated case for energy consumption

The first feature of electric vehicles is the need to monitor the state of their batteries discharge. It is generally recommended for electric buses that the degree of their battery charge should be more than 30%. This recommendation is based on the assumption that bringing the battery to full discharge will reduce its lifetime. However, advances in the technical development of batteries and data of actual operation make it possible to operate batteries at least sometimes with a charge below 30% without loss of lifetime. The described feature complicates the formulation of many problems in which fixed values are used for the permissible discharge of the battery.

The second feature relates to the probabilistic nature of the operating conditions of mobile equipment. Therefore, individual data on energy consumption obtained as a result of calculations or experiments for certain operating conditions, as well as data declared by bus manufacturers are not convincing for decision making. These specific data on energy consumption make it impossible to consider all possible situations and make an informed decision: is the bus suitable for the cycle of routes under consideration. The choice of the calculated (design) energy consumption should be based on a probabilistic approach that describes the possible energy consumption values.

Summarizing both of these features, the **following concept can be formulated**: *the choice of the calculated value of energy consumption should be provided to the decision maker; but possible situations must be demonstrated to him.*

In real practice, the same electric bus can be operated on different routes and route combinations. Therefore, there are two problems: 1) the choice of a combination of trips (determinative routes cycle) for the electric bus, which determines its energy consumption, 2) the choice of the calculated value of energy consumption for the determinative routes cycle.

4.1 Determinative routes cycle

In particular cases, the routes cycle (RC) may correspond to

- the vehicle cycle (for example, in the case “slow depot”)
- several trips followed by recharging (“slow depot+fast terminal“)
- separate route (“fast terminal” at route termini)
- part of urban route (“fast terminal+fast bus stops“), etc. (see set of typical charging configurations in the Deliverable 3.1,Table 5 and [1])

Combinations of routes for the route cycle are organized by the user in a dialogue mode. The goal is to form the so-called “determinative” case in terms of the road aspect.

A choice of determinative routes cycle is not an obvious procedure. For example, shorter trips can have higher energy consumption because of more complicated route profile, schedule, route congestions, etc.

The most complicated case is a choice between the vehicle cycles, which may differ for the same bus.

Vehicle cycle=Operation of a vehicle (van, bus, or train) through the course of a day of transit service.

In this case the user should enter input data taking into account all daily trips such as routes and auxiliary runs. In general case every trips according schedule is individual. It differs by day time, passenger loads, route congestion, ambient temperature, etc.

Full input can be very cumbersome. Therefore, the recommendation is as follows.

1) Divide all trips into typical trips by time periods. For example:

- 1 Morning (N1 trips)
- 2 Middle of a day (N2 trips)
- 3 Evening (N3 trips)
- 4 Late evening & night (N4 trips)

2) Form input data for typical trips and calculate energy consumptions for them.

3) Calculate energy consumption for **Vehicle cycle** using number of trips (Ni) for selected typical trips.

After comparing of results for different variants, the user selects the "determinative" case for task in question.

In various cases, attention can be paid to assessing energy consumption for a route, part of an urban route, a cycle of routes, daily time (vehicle cycle), monthly and annual consumption.

In all the cases, presented above the “route description” is considered as a universal description of any element of interest to the user: the route, auxiliary runs, their parts, etc.

4.2 Calculated value of energy consumption

Probabilistic approach

For electric buses, the distribution of the energy consumption in the relative (dimensionless) form is proposed (see the Delivery 3.1 and [2]).

A parameter ***P* is relative energy consumption** $P=E/E_0$, where E_0 is certain base value, for example, modal value (Modal value=the value that occurs most often, or the most probable energy consumption value).

The original relative curve $f(P)$ corresponds to the normal distribution. The variation coefficient of this curve is 0.25, and the relation between the light loading (*L*-case) and the modal value (*M*-case) is 0.8. Then this distribution is truncated (limited) on the left by the energy consumption value for the case of the bus movement without passengers (No Passengers, *L*-case). As result distribution $f_1(P)$ is created [2].

Typical distributions and their parameters for estimating relative energy consumption are shown in Figure 7. The LN05 is a close analog of the distribution $f_1(P)$. Both distributions reflect wide changes in operating conditions. LN03 refers to cases with a slight change in operating conditions.

LN05 and LN03 are lognormal distributions. They are recommended for future use because of greater convenience compared to truncated normal curves. The parameters for building of lognormal distributions are depicted in Table 5.

Modal value of every mentioned lognormal distribution f(P) is P_0=1.0. To ensure this condition, each initial lognormal distribution Φ(μ, σ) with a modal value x_0 is shifted along the argument axis by the values $\Delta = P_0 - x_0$.

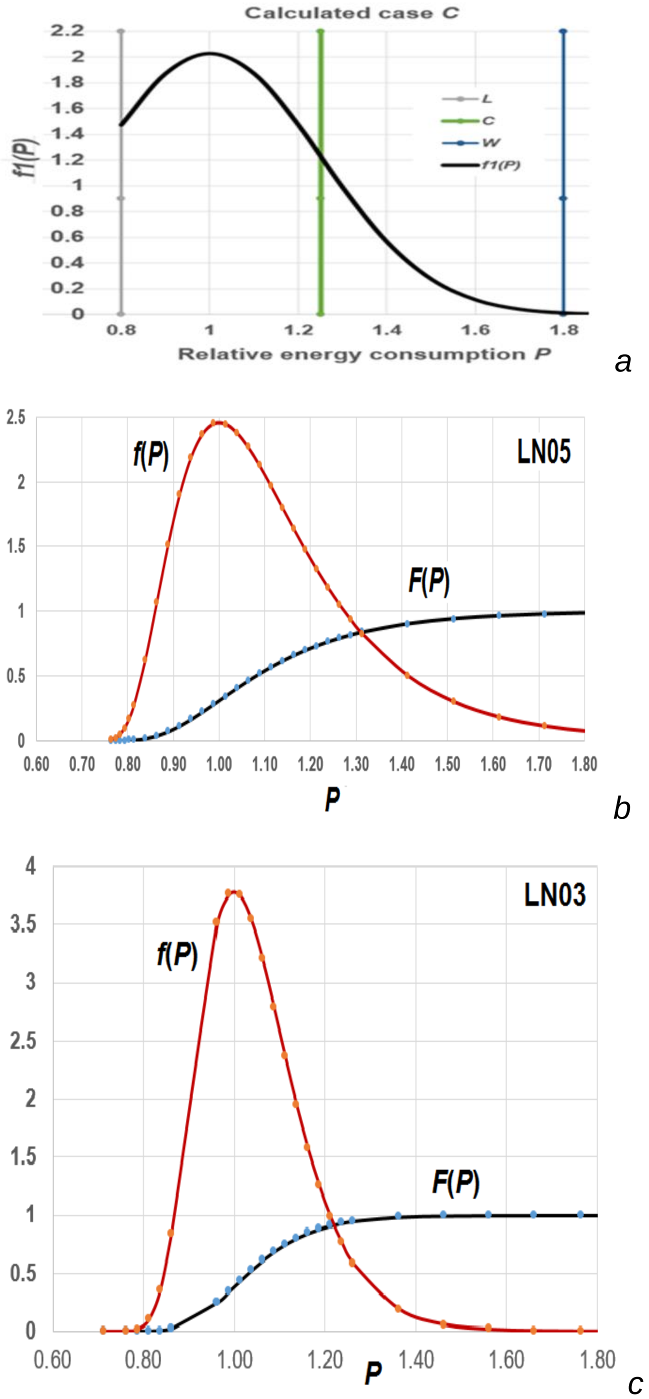


Figure 7 Typical distributions for estimating relative energy consumption (LN05 and LN03 are lognormal distributions)

Table 5 Distributions parameters for design Φ(μ, σ) and transfer to f(P)

Distri-bution	μ=average for ln(x))	σ=standard deviation for ln(x))	x_0=Modal value for f(x), $x_0=\exp(\mu-\sigma^2)$	P_0=Modal value for f(P)	$\Delta=P_0-x_0$
f_{LN05}	−1.00	0.500	0.287	1.00	0.713
f_{LN03}	−1.00	0.300	0.336	1.00	0.664

The LN05 is designed for cases with **wide variation** all factors (all seasons and operation conditions):

- driving style,
- passenger load,
- action of HVAC,
- snow appearance,
- route congestion.

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).

Parameters of distributions are in Table 6. Their standard deviations (0.22 and 0.12) are typical for similar situations in different technical areas. They relate to cases with wide and narrow variation of parameters depending on operation conditions.

Table 6 Parameters of distributions

Distribution	Modal value	Average	Standard deviation	Variation coefficient	Min/Average
*f*1(*P*)	1.00	1.09	0.19	0.17	0.73
LN05	1.00	1.13	0.22	0.20	0.71
LN03	1.00	1.05	0.12	0.11	0.76

Procedure to determine calculated case for energy consumption

The procedure involves two following steps:

1) a preliminary determination of the routes cycle for assessing energy consumption,

2) the choice of the calculated value of energy consumption based on the probabilistic representation of possible cases for electric bus operation.

The first step is to select the “Determinative” routes cycle for obscure situations.

The second step includes calculations the energy consumption for two driving style: calm and aggressive. Then the user should generate one of characteristic value E_X for his case, for example, a modal or average energy consumption value. In this case, the user can use the averaged/modal value according to the calculation results. E_X corresponds to P_X in relative representation (for example, to modal or average value).

The next user operation is selection of distribution (LN05 or LN03) that relates to the case in question (wide or narrow variation of factors corresponds to used input and calculation results).

The user as *decision maker* determines suitable distribution and accepts the probability $F_{LN03/5}(P)$ with which he wants to receive the calculated data on energy consumption.

The data in Table 7 and Table 8 are used to select $P_{C\%}$=P depending on the probability $F_{LN03/5}(P)$.

Table 7 P selection based on probability F(P) for LN05

P	0.99	1.01	1.04	1.06	1.09	1.11	1.14	1.16	1.19
$F_{LN05}(P)$	0.280	0.342	0.402	0.460	**0.515**	**0.566**	**0.614**	**0.657**	**0.695**
P	1.21	1.24	1.26	1.29	1.31	1.41	1.51	1.61	1.71
$F_{LN05}(P)$	**0.730**	**0.762**	**0.789**	**0.814**	**0.836**	**0.901**	**0.940**	0.963	0.977

Table 8 P selection based on probability F(P) for LN03

P	0.86	0.96	0.99	1.01	1.04	1.06	1.09	1.11
$F_{LN03}(P)$	0.021	0.248	0.340	0.434	**0.525**	**0.610**	**0.685**	**0.749**
P	1.14	1.16	1.19	1.21	1.24	1.26	1.19	1.21
$F_{LN03}(P)$	**0.803**	**0.847**	**0.882**	**0.910**	0.932	0.949	0.984	0.995

The final operation is a simple conversion of the energy consumption from the relative to the absolute value: $E_C=E_X P_{C\%}/P_X$.

The sample of the final operation is presented in the Deliverable 3.1.

5 *ECBus* software data template

5.1 Input data template

ECBus (Energy Consumption of the Bus) is software under development that generates a route speed profile and calculates bus energy consumption on a given route.

Input data of *ECBus* sofware are presented as a fixed set of lines. Changing the volume of input data for various tasks and objects is carried out by changing the length of the mentioned lines, which in practice are not limited.

Figure 8 — Figure 11 show templates for input data of *ECBus* software.

	A	B	C	D	E	F	G
1	Calculation identifier						
2							
3	Route description: Road-Bus-Trip						
4	1. Road data						
5	Identifier of the route in question						
6	Route length, m						
7	Number N of route segments						
8	Segments lenghs						
9	Segment numbers 1, 2, …, N						
10	Segment lenghs s(1), s(2),…,s(N)						
11	Altitudes at the stopping points						
12	Stopping points 1, 2, …, N+1						
13	Altitudes at the stopping points h(1), h(2),…,h(N+1)						
14							
15	Road data in additional: traffic obstacles/interferences in segments						
16	Turns of road						
17	Segment numbers i ∊ 1, 2, … N						
18	Distances to Turns of road from starting point of the segment						
19	Intersections						
20	Segment numbers i ∊ 1, 2, … N						
21	Distances to Intersections from starting point of the segment						
22	Artificial irregularities						
23	Segment numbers i ∊ 1, 2, … N						
24	Distances to Artificial irregularities from starting point of the segment						
25	Pedestrian crossings without traffic lights						
26	Segment numbers i ∊ 1, 2, … N						
27	Distances to Pedestrian crossings from starting point of the segment						
28	Traffic lights						
29	Segment numbers i ∊ 1, 2, … N						
30	Distances to Traffic lights from starting point of the segment						

Figure 8 *ECBus* data template for section 1 “Road”

	A	B	C
32	**2. Bus data**		
33	Identifier of the bus in question		
34	Bus length, m (default is 12 m)		
35	Bus weight without passengers, kg		
36	Max number of passengers		
37	One passenger weight, kg (default is 70 kg)		
38	Cross section area (default is 6.6 m^2)		
39	Drag coefficient (default is 0.4 Ns^2/m^4)		
40	Maximum electrical power of auxiliary system or its subsystems with battery energy consumption (default is a=8 kW-for the driver's cabin and ventilation, b=24 kW-for the entire bus)		
41	Rotation inertia factor (default is 1.05)		
42	Average efficiency of the invertor (default is 0.98)		
43	Average efficiency of the motor (default is 0.95)		
44	Average efficiency of the transmission (default is 0.95)		
45	Regeneration (recuperation) factor (default is 0.6)		
46	Rolling resistance (for planned types of bus tires and road surfaces) (default is 0.008 in summer)		
47			

Figure 9 *ECBus* data template for section 2 "Bus"

	A	B	C	D	E	F	G	H
48	**3. Trip data (schedule, passengers loading, stopping times and speed limits)**							
49	Identifier of the trip in question							
50	Time of trip, minutes							
51	Ambient temperature, °C (default is 15°C)							
52	Segment times							
53	Stopping points 1, 2, …, N+1							
54	Times between arrivals, sec							
55	Passenger loads by segments							
56	Segment numbers 1, 2, … N							
57	% of passenger load per segment							
58	Stopping time (IDStop=1)							
59	Segment numbers 1, 2, … N							
60	Stopping times ts(1), ts(2), …, ts(N)							
61	Stopping times (IDStop=2) for dependences on % of passenger load							
62	Stopping times ts1, …, ts4 for dependces on % of passenger load							
63	Pas(z,i)≤25%, ts(z,i)=ts1 (default is ts1=13 sec) 25<Pas(z,i) ≤50%, ts(z,i)=ts2 (default is ts2=18 sec) 50<Pas(z,i)≤75%, ts(z,i)=ts3 (default is ts3=23 sec) 75<Pas(z,i)≤100%, ts(z,i)=ts4 (default is ts3=28 sec)							
64	Speed limit in the city for traffic, km/h							
65	Special speed limits by segments							
66	Segment numbers i ∊ 1, 2, … N							
67	Speed limits within segments, km/h							
68	Distances from starting point segments for **starting** speed limit, m							
69	Distances from starting point segments for **ending** speed limit, m							
70								

Figure 10 *ECBus* data template for section 3 "Trip"

	A	B	C	D	E	F	G	H
71	4. Identifiers for calculation results output							
72	IDRriver							
73	1= calm driver style 2 = aggressive one							
74	NResult							
75	1 = results for input data entered by the user. Probability of stopping at Pedestrian crossings (PC) and Traffic lights (TL) are assumed 50%. If stopping takes place, then stopping modes includes deceleration and stops for 15 (PC) and 30 (TL) secs respectively at mentioned obstacles 2 = results without taking into account data concerning obstacle/references (free mode) 3= results without data concerning Pedestrian crossings and Traffic lights (passing through these obstacles without delay) 4 = results with taking into account Pedestrian crossings and Traffic lights: stops for 15 (PC) and 30 (TL) secs respectively at mentioned obstacles after deceleration.							
76	Nsprof							
77	numbers of segments, for which data about generated speed profiles are output							

Figure 11 *ECBus* data template for section 4 “Results”

5.2 Forming, viewing, editing and saving input data by the user

An example of filling out a template with input data (4 sections) for the developed software is presented in Figure 12 - Figure 15.

	A	B	C	D	E	F
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	1350				
7	Number N of route segments	4				
8	Segments lenghs					
9	Segment numbers 1, 2, …, N	1	2	3	4	
10	Segment lenghs s(1), s(2),…,s(N)	400	300	200	450	
11	Altitudes at the stopping points					
12	Stopping points 1, 2, …, N+1	1	2	3	4	5
13	Altitudes at the stopping points h(1), h(2),…,h(N+1)	216	220	213	225	220
14						
15	Road data in additional: traffic obstacles/interferences in segments					
16	Turns of road					
17	Segment numbers i ∊ 1, 2, … N	1	3			
18	Distances to Turns of road from starting point of the segment	100	150			
19	Intersections					
20	Segment numbers i ∊ 1, 2, … N	2				
21	Distances to Intersections from starting point of the segment	125				
22	Artificial irregularities					
23	Segment numbers i ∊ 1, 2, … N	4				
24	Distances to Artificial irregularities from starting point of the segment	200				
25	Pedestrian crossings without traffic lights					
26	Segment numbers i ∊ 1, 2, … N	5				
27	Distances to Pedestrian crossings from starting point of the segment	75				
28	Traffic lights					
29	Segment numbers i ∊ 1, 2, … N	4				
30	Distances to Traffic lights from starting point of the segment	40				

Figure 12 Filled *ECBus* data template for section 1 “Road”

	A	B
32	**2. Bus data**	
33	Identifier of the bus in question	1
34	Bus length, m	12
35	Bus weight without passengers, kg	1200
36	Max number of passengers	80
37	One passenger weight, kg (default is 70 kg)	70
38	Cross section area (default is 6.6 m^2)	6,6
39	Drag coefficient (default is 0.4 Ns^2/m^4)	0,4
40	Maximum electrical power of auxiliary system or its subsystems with battery energy consumption (default is a=8 kW-for the driver's cabin and ventilation, b=24 kW-for the entire bus)	32
41	Rotation inertia factor (default is 1.05)	1,05
42	Average efficiency of the invertor (default is 0.98)	0,98
43	Average efficiency of the motor (default is 0.95)	0,95
44	Average efficiency of the transmission (default is 0.95)	0,95
45	Regeneration (recuperation) factor (default is 0.6)	0,6
46	Rolling resistance (for planned types of bus tires and road surfaces) (default is 0.008 in summer)	0,008
47		

Figure 13 Filled *ECBus* data template for section 2 "Bus"

	A	B	C	D	E	F
48	**3. Trip data (schedule, passengers loading, stopping times and speed limits)**					
49	Identifier of the trip in question	1				
50	Time of trip, minutes	40				
51	Ambient temperature, °C (default is 15°C)	20				
52	Segment times					
53	Stopping points 1, 2, …, N+1	1	2	3	4	5
54	Times between arrivals, sec	65	70	63	60	66
55	Passenger loads by segments					
56	Segment numbers 1, 2, … N	1	2	3	4	
57	% of passenger load per segment	30	15	50	60	
58	Stopping time (IDStop=1)					
59	Segment numbers 1, 2, … N	1	2	3	4	
60	Stopping times ts(1), ts(2), …, ts(N)	20	10	25	30	
61	Stopping times (IDStop=2) for dependences on % of passenger					
62	Stopping times ts1, …, ts4 for dependces on % of passenger load	15	20	25	30	
63	Pas(z,i)≤25%, ts(z,i)=ts1 (default is ts1=13 sec) 25<Pas(z,i) ≤50%, ts(z,i)=ts2 (default is ts2=18 sec) 50<Pas(z,i)≤75%, ts(z,i)=ts3 (default is ts3=23 sec) 75<Pas(z,i)≤100%, ts(z,i)=ts4 (default is ts3=28 sec)					
64	Speed limit in the city for traffic, km/h	45				
65	Special speed limits by segments					
66	Segment numbers i ∊ 1, 2, … N	2				
67	Speed limits within segments, km/h	4				
68	Distances from starting point segments for **starting** speed limit, m	150				
69	Distances from starting point segments for **ending** speed limit, m	175				

Figure 14 Filled *ECBus* data template for section 3 "Trip"

	A	B	C	D	E	F	G
71	**4. Identifiers for calculation results output**						
72	IDRriver	1					
73	1= calm driver style 2 = aggressive one						
74	NResult	2					
75	1 = results for input data entered by the user. Probability of stopping at Pedestrian crossings (PC) and Traffic lights (TL) are assumed 50%. If stopping takes place, then stopping modes includes deceleration and stops for 15 (PC) and 30 (TL) secs respectively at mentioned obstacles 2 = results without taking into account data concerning obstacle/references (free mode) 3= results without data concerning Pedestrian crossings and Traffic lights (passing through these obstacles without delay) 4 = results with taking into account Pedestrian crossings and Traffic lights: stops for 15 (PC) and 30 (TL) secs respectively at mentioned obstacles after deceleration.						
76	Nsprof	3	4				
77	numbers of segments, for which data about generated speed profiles are output						

Figure 15 Filled *ECBus* data template for section 4 "Results"

After starting the developed application, the window shown in Figure 16.

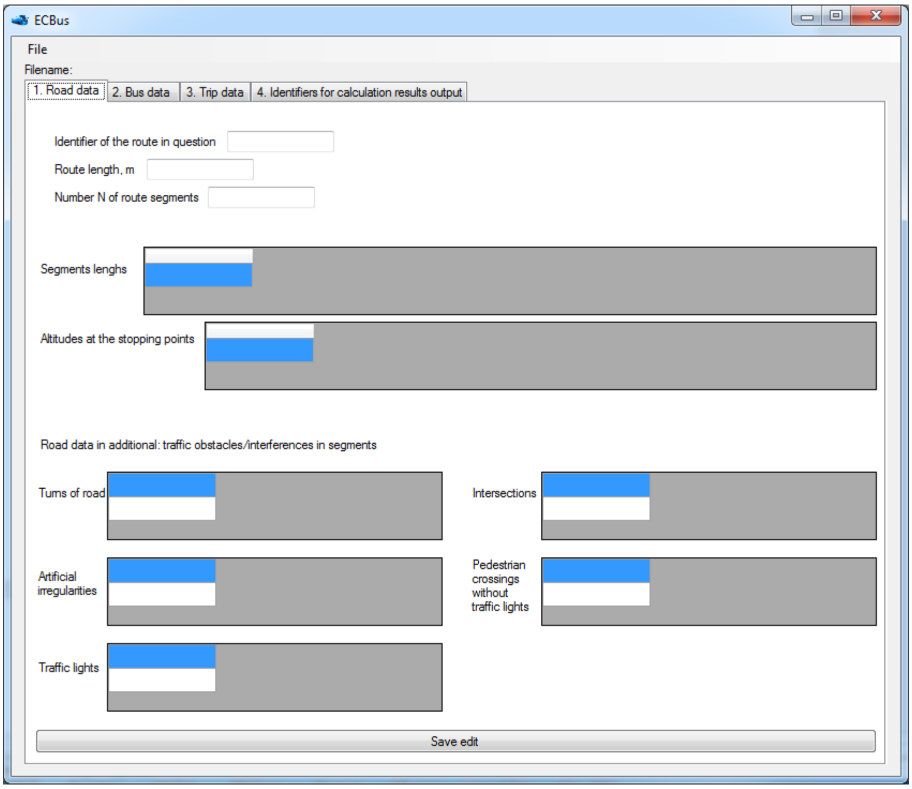


Figure 16 Software window after starting

Input

For the data input, the user needs to open the file with the input data. It is necessary to click File/Open, and select the required Excel file with the * .xls extension.

The result is shown in Figure 17Figure 20, which correspond to the data shown in Figure 12 - Figure 15.

Viewing and Editing

The user can view and edit the entered data and save the changes. But some new data may change the data structure that created under their original forming. Therefore, it is not possible to edit the following data

- the “Number N of route segments”

- in the tab “1. Road data”, top lines in tables:

- “Segment length”,
- “Altitudes at the stopping points”

- the tab “3. Trip data”, top lines in tables

- “Segment times”,
- “Passenger loads % by segments”,
- “Stopping time (IDStop = 1)”,
- “Stopping times (IDStops = 2) dependences on% of passenger load”

Saving

After clicking on the “Save edit” button, the values of the variables in the program are changed for their further use in calculations. New values are also saved in an open file with the source data.

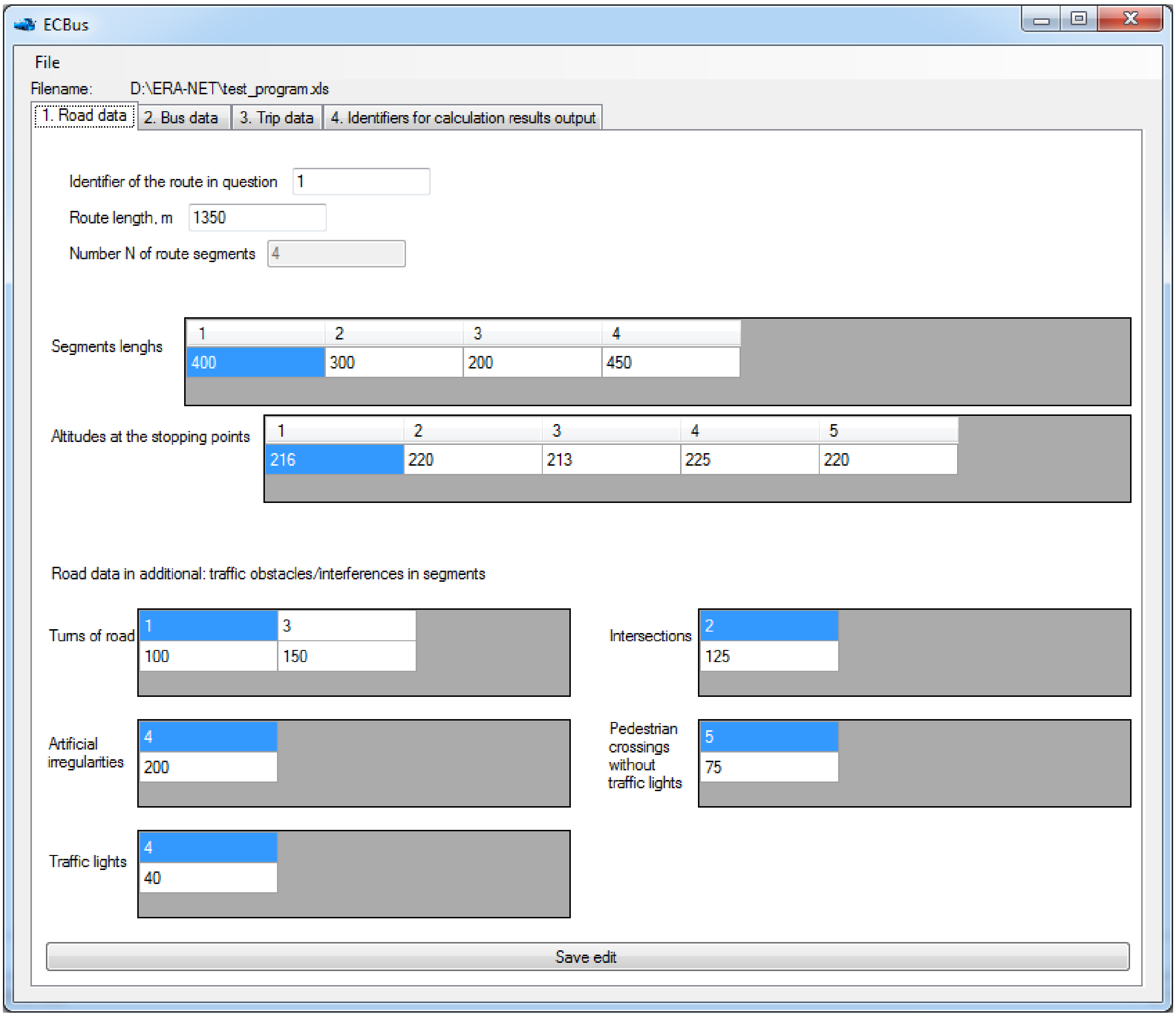


Figure 17 Software window for section 1 “Road”

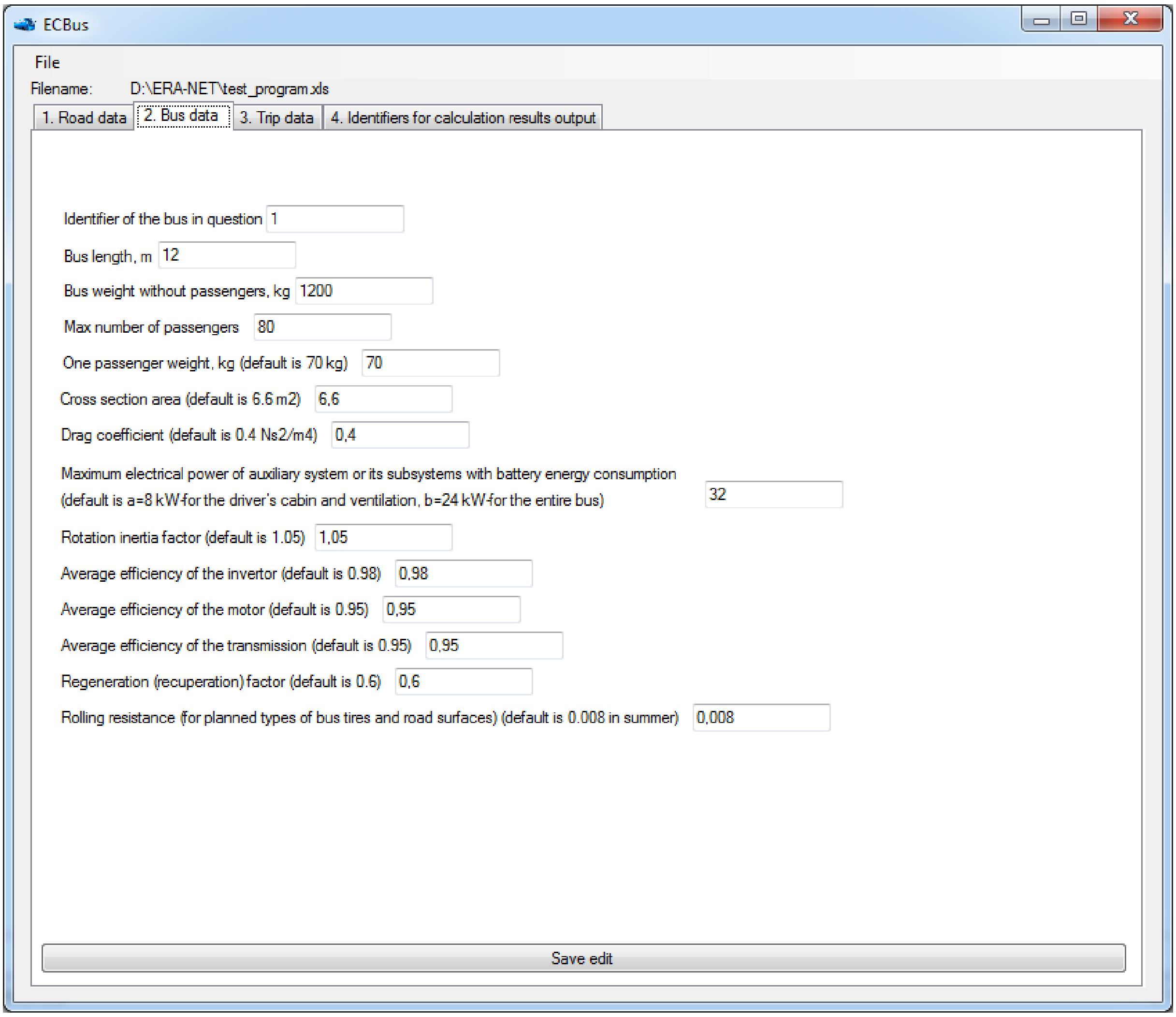


Figure 18 Software window for section 2 “Bus”

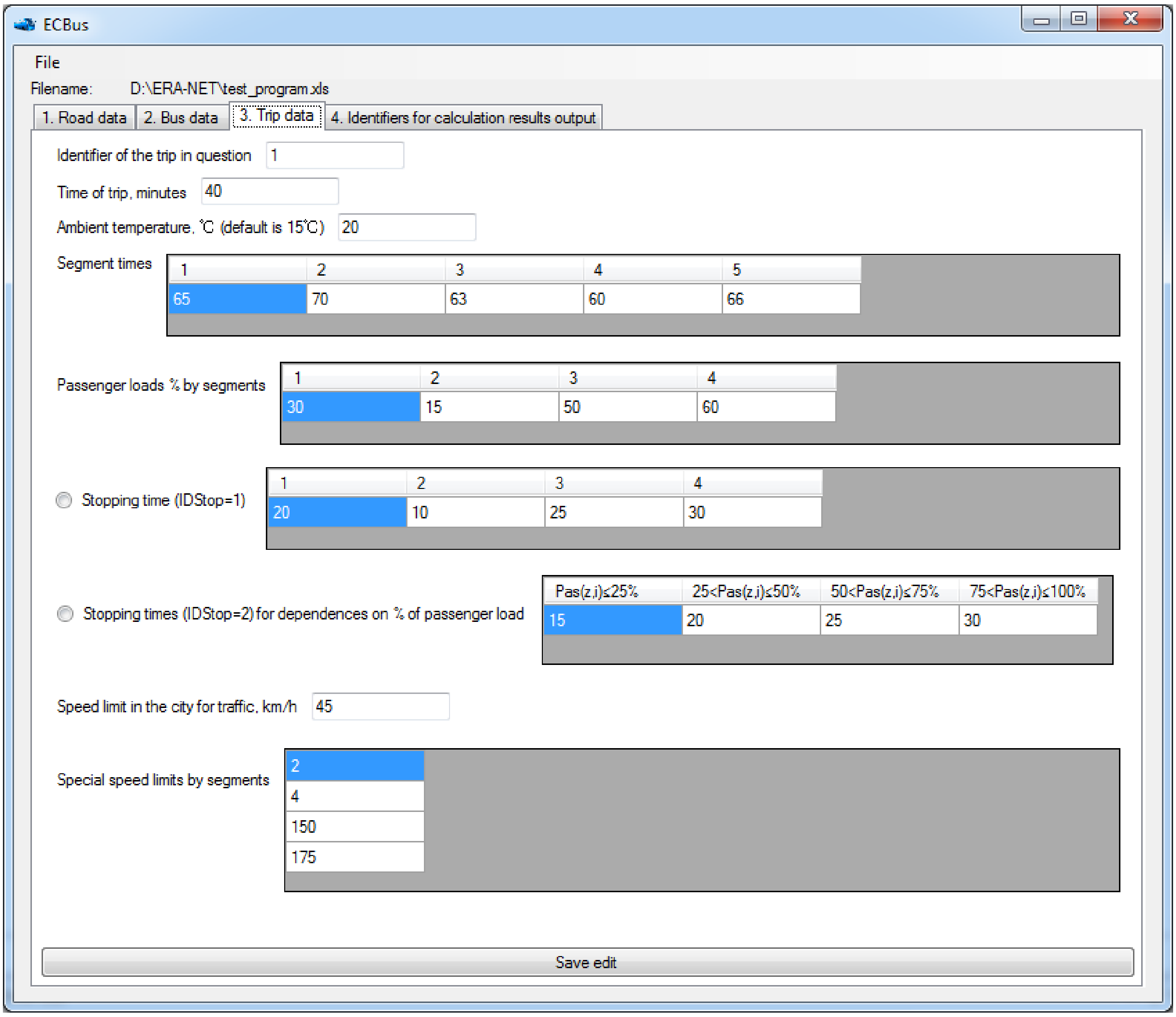


Figure 19 Software window for section 3 “Trip”

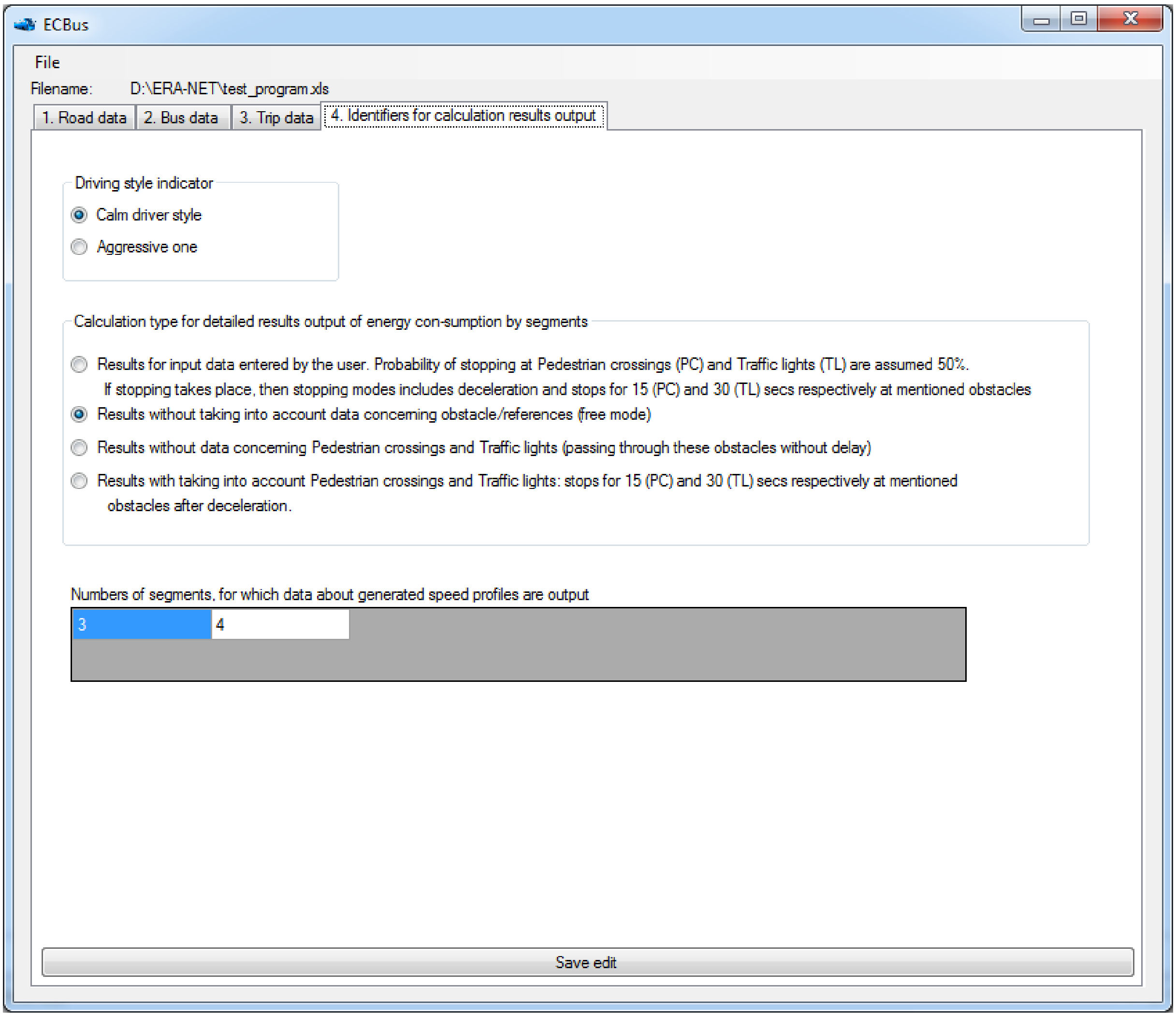


Figure 20 Software window for section 4 “Result”

6 Ways to use *ECBus* software

6.1 Organization of software use

The first way to use *ECBus* software includes two the following steps (Figure 21): user 1) requests the software from the Platon website and 2) gets it at his disposal and uses the *ECBus* on his computer.

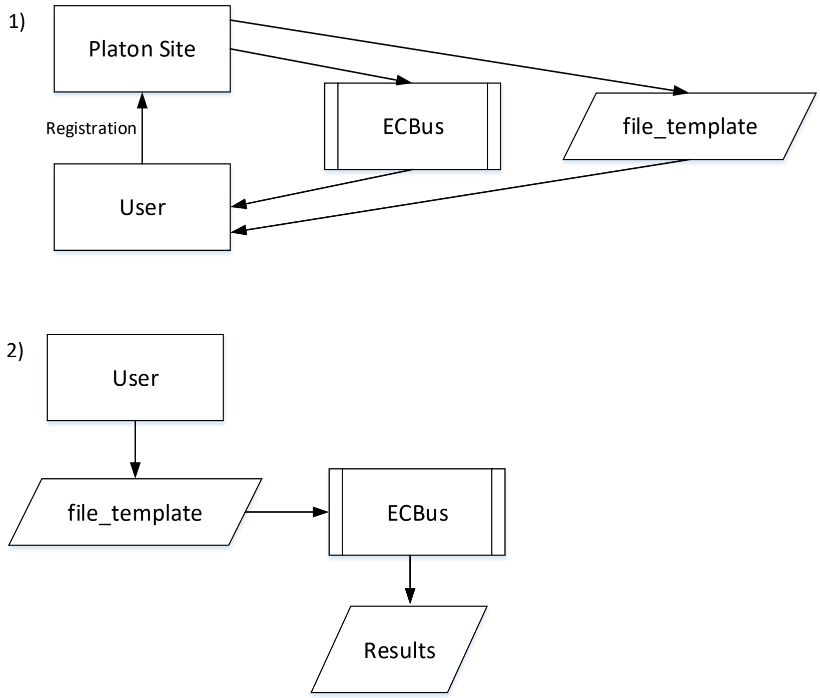


Figure 21 The first way to use *ECBus* software

The second way to use *ECBus* software consists of the following operations (Figure 22): 1) using an algorithm of *ECBus*, software *ECBus*1 is created on the Platon website, 2) then the user communicates with website.

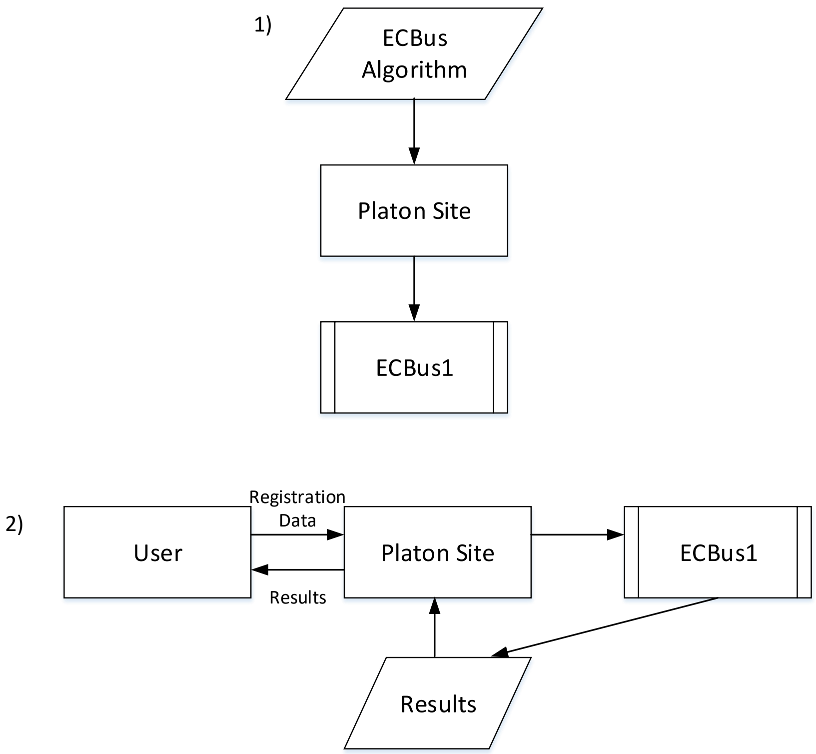


Figure 22 The second way to use *ECBus* software

The third way to use *ECBus* software is based on an approach "software as a service" (SaaS): software *ECBus* is disposed on the Platon sever and user communicates with software through website (Figure 23).

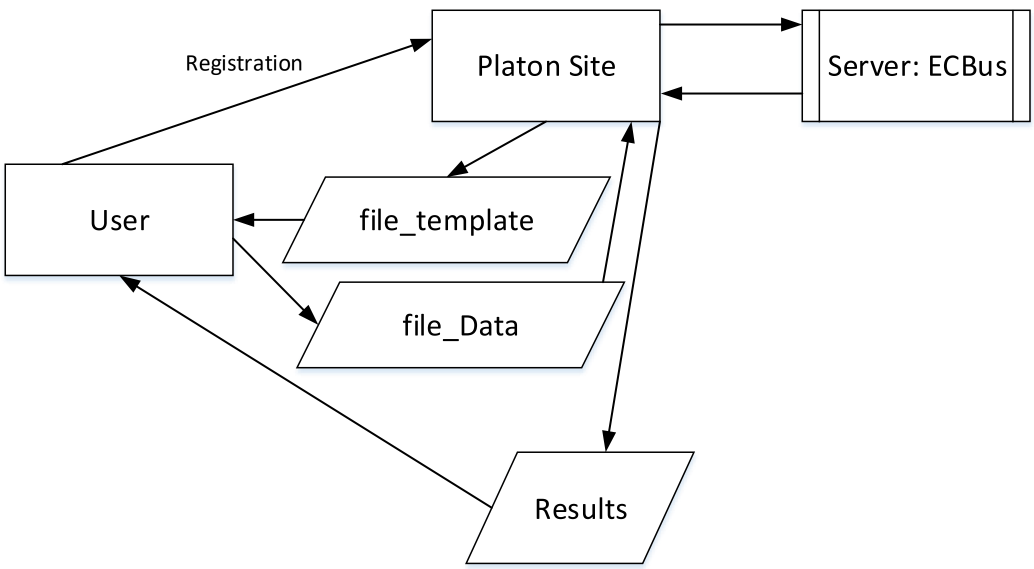


Figure 23 The third way to use *ECBus* software (software as a service, SaaS)

6.2 Solution of typical tasks and their use

There are four main typical tasks for which *ECBus* software can be used effectively.

1. Determination of bus energy consumption on the route

This is a basic task that can be solving

- taking into account various factors: driving style, passenger load, season: HVAC effect and the appearance of snow, traffic congestion. Some of these factors are considered for the first time
- at the same time, the input can contain a simple set of required parameters, and others can be used by default

Data on bus energy consumption can serve **to plan the use of electric buses in different transport cycles.**

2. Determination of the required electric energy volume ant its costs per day, month, year, etc.

The result of solving this problem is usually used in **assessing TCO**, as well as in **optimization problems**, including taking into account energy costs.

3. Choice of bus battery capacity for a specific set of routes

This task is often formulated by a transport company for manufacturers of electric buses in order to obtain a **bus with a minimum capacity (and, accordingly, cost) of a battery** and an electric bus as a whole.

4. Determining the distance that a bus with a known battery capacity can reach along a given route after charging

This task relates to the **location problem for the next charger**.

7 Progress in the database on electric buses and their working process

Database topics are described in Deliverable 3.1.

Annex B contains typical samples of data blocks that presented directions of database development. They are in the following blocks.

1) Complex characteristics of buses

These data provide insights into the economics, emission, energy consumption, operation, infrastructure associated with various types of buses: diesel buses, hybrid electric buses, fuel cell electric buses, battery electric buses and their modifications.

2) Available technology options in electric bus systems

These data are presented in a form of morphological matrix of electric bus systems, covering the following features: energy source, charging/refueling strategy and interface, on-board energy source, drive motor and drive topology, body type, cooling and heating types.

3) Typical data on electric bus from manufactures

As an example, the following list of product characteristics of the world's major bus manufacturers (BYD, Proterra, New Flyer, Complete Coach Works) is presented: Bus Company, Price ($), Range (km), Warranty (years), Efficiency (kWh/km), Gross Weight (ton).

4) Vehicle body and passenger capacity

Typical body types used in EU metropolitan bus services are presented: 12 m single-deck, 18 m articulated, 25 m bi-articulated, 2-axle double-deck, 3-axle double-deck. Their typical parameters include Length [m], Gross vehicle weight [t], Typical empty weight [t], Max. payload [t], Max. no. passengers

5) Battery system

The most common cell types encountered in electric buses are lithium iron phosphate (LFP), lithium titanium oxide (LTO) and lithium nickel manganese cobalt oxide (NMC).

Their parameter are given: Cell voltage [V], Cell capacity [Ah], Energy density [Wh/kg], Charge rate (C-rate), Cycle life (at 100% DoD)

6) Chassis-dynamometer driving cycles for buses with realistic urban drive patterns

For NYBus, ADEME, MAN, BRA, OCC an overview of chassis dynamometer driving cycles parameters are presented: Duration [s], Distance [km], Max speed [km/h], Average vehicle speed [km/h], Average driving speed [km/h], Accelerations per km, Idling time [%], Stops per km, Average stop duration [s].

7) Typical data on modelling bus working process and calculating energy consumption

The first data block contains:

- Large set of parameters, their values and graph illustrating how input data and input parameters are used to calculate the energy demand of electric bus fleet based on real-world data
- Excerpt of the input data for the stops visited during a journey on bus line
- Distribution of the specific energy demand averaged over a journey (terminus to terminus) by vehicle type
- Tornado plots of the sensitivity analysis for the median specific energy demand per journey

The second block contains data on the popular Eco-Driving direction. The structure of energy consumption is described in detail. This provides a basis for assessing the role of the bus and road parameters in the modeling of energy consumption.

8) Factors determining the energy consumption

The variation in the energy consumption of an electric bus on a certain route depends on set of factors. Action of some of them are demonstrated based on operation data and modelling: the passengers loading, ambient temperature, driver’s actions, road conditions (motion mode, average speed, etc.).

9) Method for Evaluating Energy Consumption for an Electric Buses Based on Data for Diesel Buses

The method developed in the process of working on the Platon project is presented.

10) Dependability and maintenance

Currently, there is insufficient data on the dependability of electric buses in operation. Typically, these data are not available in the models for calculating and optimizing total cost of ownership. That is why the data on Availability and Road-calls of electric buses in real operation are important.

Availability (indicator): The number of days the buses are actually available compared to the days that the buses are planned for operation expressed as percent availability.

Roadcall: A failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule.

11) Typical data for calculating TCO for electric bus fleet and complex optimization problem

Data for TCO calculation and optimization problems include the following tabs: General, Financing costs, Energy, Vehicle, E-bus, Charger, ICE, Maintenance, Externalities.

The forecast of battery price for buses (2016-2030) is also presented.

12) Samples of using relative (specific) values for evaluating input data (battery, charger items, maintenance and electricity costs)

These data relate to the use of relative (specific) values:

- for battery and charging infrastructure
- for maintenance and electricity costs

13) Prospect of TCO for different technologies

These data contain:

- Forecast 1 (2012-2030) from point of view 2012
- Forecast 2 (2017-2025) from point of view 2016
- Sensitivity of TCO to daily/annual mileage
- Influence of electricity cost (and carbon grid-intensity)

14) Specific problems in transition to electric bus fleet

This block gives examples of specific research devoted to problem of transition to electric bus fleet.

The combination of charging infrastructure and bus batteries. This study considers a central issue of jointly optimizing the charging infrastructure and battery capacity, relates to transport authorities during the electrification process of the bus fleets and sharpens the focus on infrastructural issues related to the fast charging concept.

TCO and vehicle schedules. Simple substitution of diesel buses with electric buses is often impossible in practice. A vehicle scheduling algorithm is developed that constructs bus schedules to satisfy existing routes and timetables, while considering range limitations and required charging times at terminal stops.

8 Summary

The results of this work package are focused on input data formats for software developed in the Platon project on working process and energy consumption of electric buses.

The Software is designed to generate a speed profile when an electric bus moves along a route and calculate energy consumption. The speed profile is built taking into account real obstacles and speed limits, as well as a calm and aggressive driving styles.

When developing software, the following principles are used:

- Rational schematization of routes, electric buses and trips, focused on the use of widely available source data,
- Many input data can be set by the user “by default” on the basis of generalizations of data from sources contained in the created database,
- The user is given the opportunity to independently create routes for assessing the energy consumption of the electric bus.

Besides software, the procedure to determine calculated case for energy consumption is developed. The procedure involves: 1) a preliminary determination of the routes for assessing energy consumption, 2) the choice of the calculated value of energy consumption based on the probabilistic-tic representation of possible cases for electric bus operation. At the same time, the user himself determines the probability with which he wants to receive the calculated data on energy consumption.

The software *ECBus* being developed can find a wide range of applications. These are

- Determination of energy consumption on the route, taking into account various factors (driving style, passenger load, season: action of HVAC and snow appearance, route congestion),
- Determination of bus energy costs per day, month, year, etc.
- Selection of bus battery capacity for a specific set of routes.
- Determining the distance that a bus with a known battery capacity can travel along a given route after charging (to determine the location for the next charger)

To implement *ECBus* software three ways are considered. The first way includes two the following steps: 1) the user requests software from the Platon web-site and 2) receives it at his disposal. The second way consists of the following operations: 1) using an algorithm of *ECBus*, software *ECBus* is created on the Platon website, 2) then user communicates with website. The third way to use *ECBus* software is based on an approach “software as a service”. Software *ECBus* is disposed on the Platon sever and user communicates with software through website.

The created database on the topic "working process and energy consumption of electric buses" is a necessary element in the decision-making system that accompanies the transition to the fleet of electric buses. The database provides the following

- Systematization of parameters and models of the electric bus working process

- Assessment of the impact of certain factors on operational, economic, environmental and other indicators of electric buses and their fleet
- Summarizing the results of theoretical and experimental studies at all levels of evaluating the parameters of electric buses and buses-analogs
- The accumulation of examples of solutions to problems that arise when considering specific situations in the process of transition to a fleet of electric buses.

Studying such data allows endowing decision makers, researchers, etc. principles and sustainable recommendations for the use of electric buses. An example of such principles is the provision on the use of electric buses, first of all, on routes with high traffic intensity and ensuring their possibly large daily / annual runs. More complex situations can be considered within the framework of TCO estimates of the electric bus fleet and/or optimization problems using parameters and models from the developed database.

9 Annex A. Example of filling minimum input data by the user and forming input data in *ECBus* software by default

9.1 Minimum set of original input data

The minimum set of original input data for calculating the energy consumption of a bus on a route is as follows.

From category “Road”

- L(x)=Route length, m
- N(x)=Number of the route segments
- s(x,i)=Array of Segment lengths (Distances between stopping points) of the route, m, i=1…N+1

From category “Bus”

- Mbuse(x)=Bus weight without passengers, kg
- Kpas= Max number of passengers
- frol(x,y)= Rolling resistance (for planned types of bus tires and road surfaces) (default is 0.008 in summer)

From category “Trip”

- T(z)= Time of trip, minutes
- tamb(z)=Ambient temperature, ℃

From category “Results”

- Nothing.

9.2 Example of filling minimum input data

An example of filling the minimum input template of *ECBus* software is in Figures A1—A4.

	A	B	C	D	E	F	G
1	Calculation identifier						
2							
3	1. Route description (Infrastructure)						
4	Road data						
5	Identifier of the route in question						
6	Route length, m	1350					
7	Number N of route segments	4					
8	Segments lenghs						
9	Segment numbers 1, 2, …, N	1	2	3	4		
10	Segment lenghs s(1), s(2),…,s(N)	400	300	200	450		
11	Altitudes at the stopping points						
12	Stopping points 1, 2, …, N+1						
13	Altitudes at the stopping points h(1), h(2),…,h(N+1)						
14							
15	Road data in additional: traffic obstacles/interferences in segments						
16	Turns of road						
17	Segment numbers i ∊ 1, 2, … N						
18	Distances to Turns of road from starting point of the segment						
19	Intersections						
20	Segment numbers i ∊ 1, 2, … N						
21	Distances to Intersections from starting point of the segment						
22	Artificial irregularities						
23	Segment numbers i ∊ 1, 2, … N						
24	Distances to Artificial irregularities from starting point of the segment						
25	Pedestrian crossings without traffic lights						
26	Segment numbers i ∊ 1, 2, … N						
27	Distances to Pedestrian crossings from starting point of the segment						
28	Traffic lights						
29	Segment numbers i ∊ 1, 2, … N						
30	Distances to Traffic lights from starting point of the segment						

Figure A1 Example of filled data in the template for section 1 “Road”

	A	B
32	2. Bus data	
33	Identifier of the bus in question	
34	Bus length, m (default is 12 m)	
35	Bus weight without passengers, kg	1200
36	Max number of passengers	80
37	One passenger weight, kg (default is 70 kg)	
38	Cross section area (default is 6.6 m^2)	
39	Drag coefficient (default is 0.4 Ns^2/m^4)	
40	Maximum electrical power of auxiliary system or its subsystems with battery energy consumption (default is a=8 kW-for the driver's cabin and ventilation, b=24 kW-for the entire bus)	
41	Rotation inertia factor (default is 1.05)	
42	Average efficiency of the invertor (default is 0.98)	
43	Average efficiency of the motor (default is 0.95)	
44	Average efficiency of the transmission (default is 0.95)	
45	Regeneration (recuperation) factor (default is 0.6)	
46	Rolling resistance (for planned types of bus tires and road surfaces) (default is 0.008 in summer)	0,008
47		

Figure A2 Example of filled data in the template for section 2 “Bus”

	A	B	C	D	E	F
48	3. Trip data (schedule, passengers loading, stopping times and speed limits)					
49	Identifier of the trip in question					
50	Time of trip, minutes	40				
51	Ambient temperature, °C (default is 15°C)					
52	Segment times					
53	Stopping points 1, 2, …, N+1					
54	Times between arrivals, sec					
55	Passenger loads by segments					
56	Segment numbers 1, 2, … N					
57	% of passenger load per segment					
58	Stopping time (IDStop=1)					
59	Segment numbers 1, 2, … N					
60	Stopping times ts(1), ts(2), …, ts(N)					
61	Stopping times (IDStop=2) for dependences on % of passenger					
62	Stopping times ts1, …, ts4 for dependces on % of passenger load					
63	Pas(z,i)≤25%, ts(z,i)=ts1 (default is ts1=13 sec) 25<Pas(z,i) ≤50%, ts(z,i)=ts2 (default is ts2=18 sec) 50<Pas(z,i)≤75%, ts(z,i)=ts3 (default is ts3=23 sec) 75<Pas(z,i)≤100%, ts(z,i)=ts4 (default is ts3=28 sec)					
64	Speed limit in the city for traffic, km/h					
65	Special speed limits by segments					
66	Segment numbers i ∈ 1, 2, … N					
67	Speed limits within segments, km/h					
68	Distances from starting point segments for **starting** speed limit, m					
69	Distances from starting point segments for **ending** speed limit, m					

Figure A3 Example of filled data in the template for section 3 “Trip”

	A	B	C	D	E	F	G
71	4. Identifiers for calculation results output						
72	IDRriver						
73	1= calm driver style 2 = aggressive one						
74	NResult						
75	1 = results for input data entered by the user. Probability of stopping at Pedestrian crossings (PC) and Traffic lights (TL) are assumed 50%. If stopping takes place, then stopping modes includes deceleration and stops for 15 (PC) and 30 (TL) secs respectively at mentioned obstacles 2 = results without taking into account data concerning obstacle/references (free mode) 3= results without data concerning Pedestrian crossings and Traffic lights (passing through these obstacles without delay) 4 = results with taking into account Pedestrian crossings and Traffic lights: stops for 15 (PC) and 30 (TL) secs respectively at mentioned obstacles after deceleration.						
76	Nsprof						
77	numbers of segments, for which data about generated speed profiles are output						

Figure A4 Example of filled data in the template for section 4 “Results”

9.3 Example of forming input data in *ECBus* software by default

An example of input data generation by *ECBus* software by default is shown in Figures A5—A8, which correspond to data on Figures A1—A4.

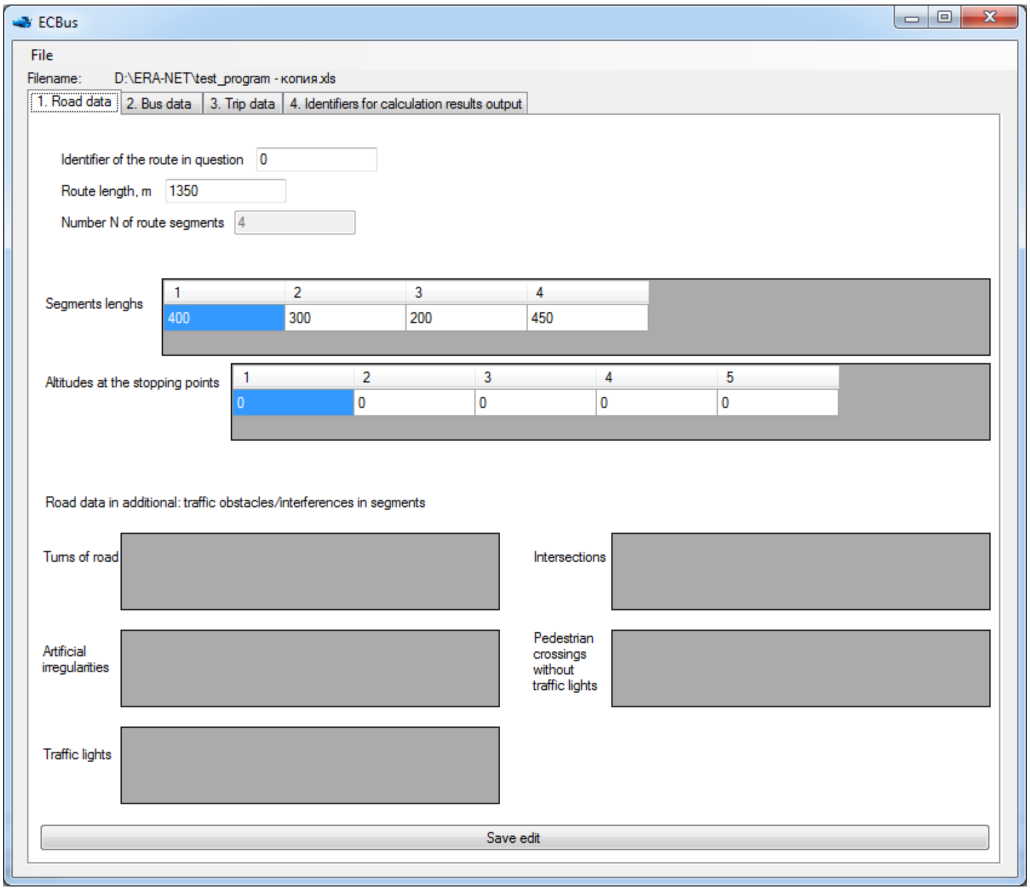


Figure A5 Screening input data for section 1 “Road” in *ECBus* software

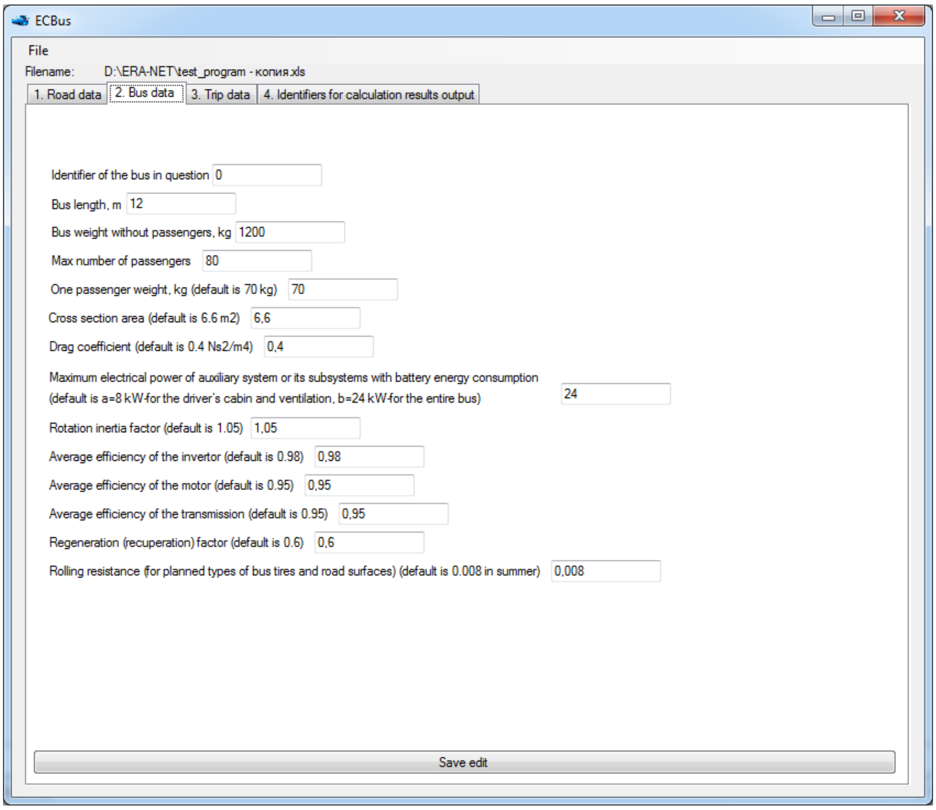


Figure A6 Screening input data for section 2 “Bus” in *ECBus* software

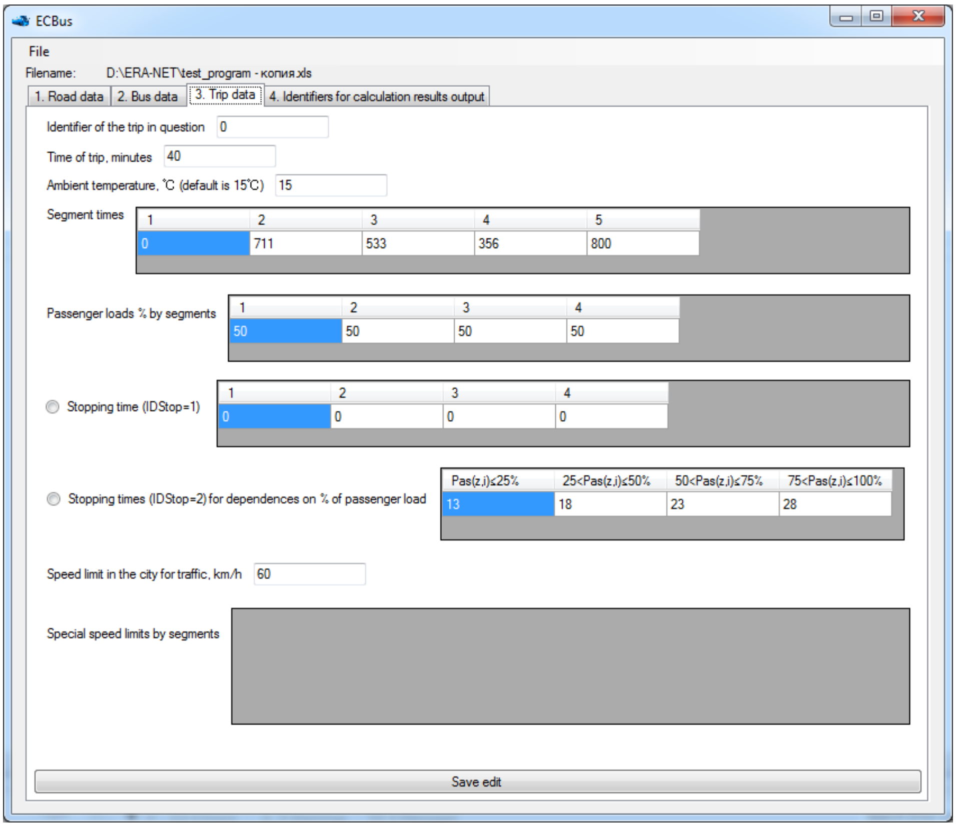


Figure A7 Screening input data for section 3 “Trip” in *ECBus* software

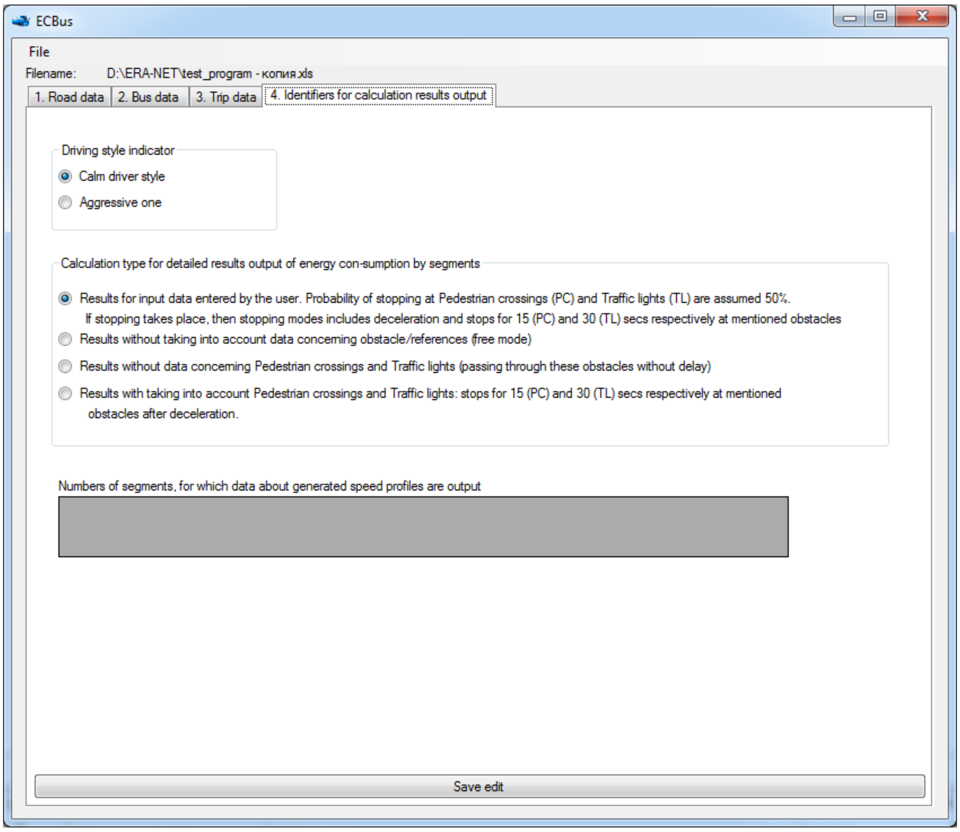


Figure A8 Screening input data for section 4 “Result” in *ECBus* software

10 Annex B. Typical data for modelling bus working process, calculating TCO for electric bus fleet and complex optimization problem

10.1 Complex characteristics of buses

Complex data on popular types of buses is presented in Table B1 [3].

Table B1. Complex data on 12-meter single-deck buses [3] (data are based on [**4**]) *

Parameter	Unit	ICE	HEB - Series	HEB - Parallel	FCEB	BEB-Overnight	BEB-Opportunity
Propulsion technology	Fuel type	Diesel	Diesel	Diesel	Hydrogen - NGSR, WE	Electricity - EU mix, Renewable	Electricity - EU mix, Renewable
Economics							
Bus price	US$	280,000	410,000	445,000	2,000,000	590,000	530,000
Maintenance cost	US $/km	0.38	0.24	0.26	1.20	0.20	0.20
Running cost	US $/km	0.8	0.68	0.76	0.53	0.15	0.15
Infrastructure cost	US $/km	0.04	0.04	0.04	0.16	0.15	0.26
Total cost of ownership	US $/km	2.61	2.98	2.895	5.71	6.83	3.97
GHG Emission							
WTT	gCO2eq/km	218	172	188	320, 305	720, 20	720, 20
TTW	gCO2eq/km	1004	796	870	0	0	0
WTW	gCO2eq/km	1222	968	1058	320, 305	720, 20	720, 20
Energy Consumption							
WTT	MJ/km	3.82	3.45	3.31	7, 4.45	11.9, 3.57	11.9, 3.57
TTW	MJ/km	16.84	10.81	12.81	10.48	6.76	6.76
WTW	MJ/km	20.66	15.26	16.12	17.48, 14.93	18.66, 10.33	18.66, 10.33
Operation							
Range till refueling	km	450	450	450	450	250	40

Acceleration time (0-30 km/h)	Seconds	7.5	8.1	7.9	9.2	10	10
Availability	%	100	100	100	85	90	90
Refueling/Re-charging time	Minutes	5	5	5	10	240	10
Infrastructure							
Infrastructure modification	Nominal	As is	As is	As is	Moderate	Moderate	Major

* in the Table:

- Data collected in Euro are converted to USD using an exchange rate of 1 Euro = 1.241 $, and Kilometers are converted to miles using 1.00 km = 0.62137119 mile,

- The cost estimations represent an average of available data in the literature analyzed in [4],

- Running cost is explicitly identified in some studies as fuel cost, while other studies incorporated fuel and maintenance cost as running/operation cost, hence data obtained from these are excluded [4].

-Acronyms*:*

ATR=Auto Thermal Reforming, CAGR=Compound Annual Growth Rate,

BEB=Battery Electric Bus

CNGB=Compressed Natural Gas Bus,

CNGHEB=Compressed Natural Gas Hybrid Electric Bus, DB=Diesel Bus,

DHEB=Diesel Hybrid Electric Bus, EM=Electric Motor,

FCEB=Fuel Cell Electric Bus, GB=Gasoline Bus,

GHEB=Gasoline Hybrid Electric Bus, GHG=Greenhouse Gas,

GSR=Gas Steam Reforming,

GREET=Greenhouse gases, Regulated Emissions, and Energy use in Transportation,

HEB=Hybrid Electric Bus, H^2-NGSR=Hydrogen - Natural Gas Steam Reforming,

H_2-WE=Hydrogen - Electrolysis of Water,

MJ=Mega-Joules, NGCC=Natural Gas Combined Cycle,

NGSR=Natural Gas Steam Reforming, PHEV=Plugin Hybrid Electric Vehicle,

RED=Renewable Energy Directive, SD=Single-deck bus,

UCs=Ultra Capacitors, USC=Supercritical Steam Cycle,

10.2 Available technology options in electric bus systems

Morphological matrix of available technology options in electric bus systems is depicted in Fig. B1 [5].

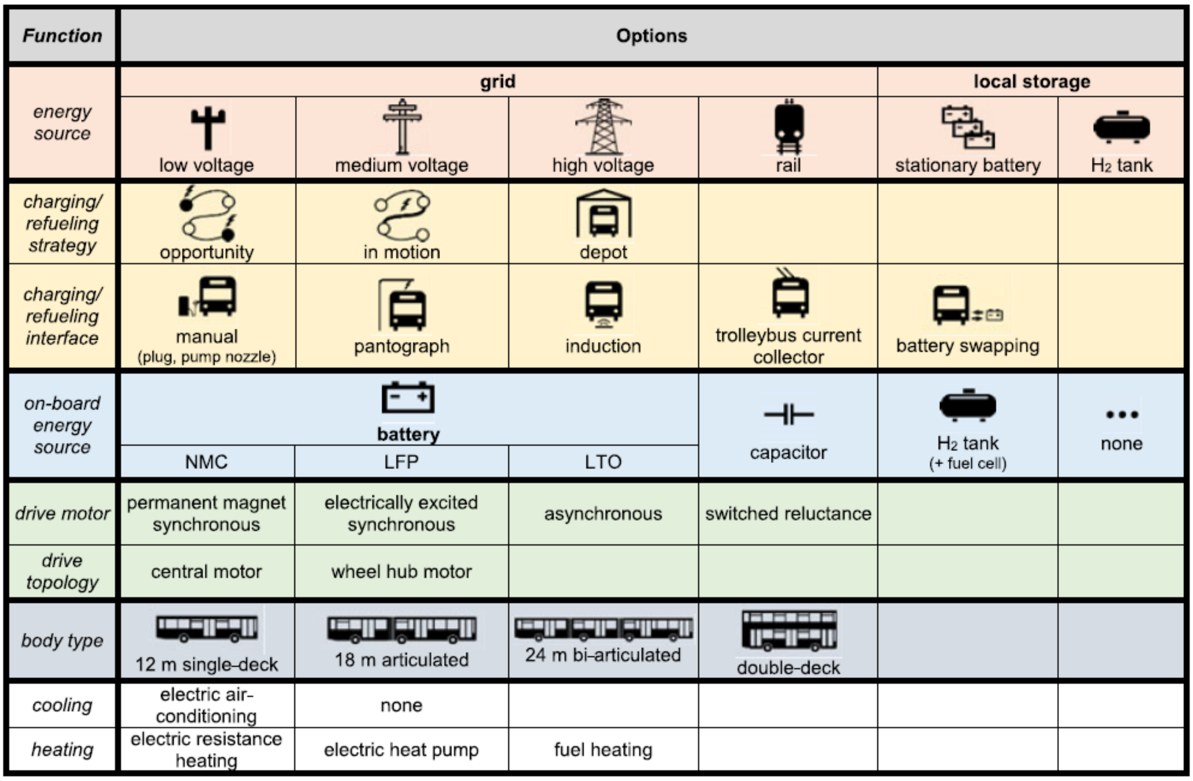


Figure B1 Morphological matrix of available technology options in electric bus systems [5]

10.3 Typical data on electric bus from manufactures

The claimed main economic-technical-operational characteristics of world major bus manufactures are shown in Table B2.

Table B2. Electric bus specifications of world's major bus manufactures (based on [6])

Bus Company	Price ($)	Range (km)	Warranty (years)	Efficiency (kWh/km)	Gross Weight (ton)
BYD	800,000	249+	12	1.19	18.5
Proterra	750,000	154–346	12	1.06	17.7
New Flyer	700,000	193	12	1.14	19.3–20.1
Complete Coach Works	650,000	136–185	12	1.05–1.24	17.1
Average	762,500	151–248	12	1.11	18.3

10.4 Vehicle body and passenger capacity

Electric buses are based on the same vehicle bodies as diesel buses. Table B3 lists typical body types used in metropolitan bus services.

Table B3. Overview of common urban bus body types. Typical empty weight refers to conventional diesel buses [5]

Body type	Length [m]	EU GVW [t]	Typical empty weight [t]	Max. payload [t]	Max. no. passengers
12 m single-deck	12	19.5	11.6	7.9	115
18 m articulated	18-18.75	28	17.3	10.7	156
25 m bi-articulated	24.8	36	22.3	13.7	200
2-axle double-deck	10.5-12	19.5	12.5	7.0	101
3-axle double-deck	12-13.7	26	17.3	8.7	126

Table B3 also specifies the respective gross vehicle weight (GVW) permitted by EU regulations, typical empty masses and the resulting payload and passenger capacity. Although the empty weight is taken from datasheets for diesel buses, it can still serve as a valid basis for electric bus system design because the empty mass of diesel buses and electric buses excluding traction batteries and charging equipment can be assumed to be roughly equal [5].

The weight of an electric bus battery can be on the order of several tons, giving rise to an apparent conflict between battery capacity and passenger capacity. However, it is reasonable to assume that the practical maximum passenger capacity is not limited by payload, but rather by the floor space available to standees. The standee density achieved at full payload represents extreme crush-loading levels that, arguably, do not reflect realistic operating conditions. Designing the vehicle for a passenger capacity determined by floor space leaves ample weight reserve for traction batteries even under crowded conditions, as Fig. B2 illustrates for a 12 m bus. In this example, even assuming a passenger density of 8=m2, a battery weighing close to 1.3 tons could be added without exceeding the GVW of 19.5 tons.

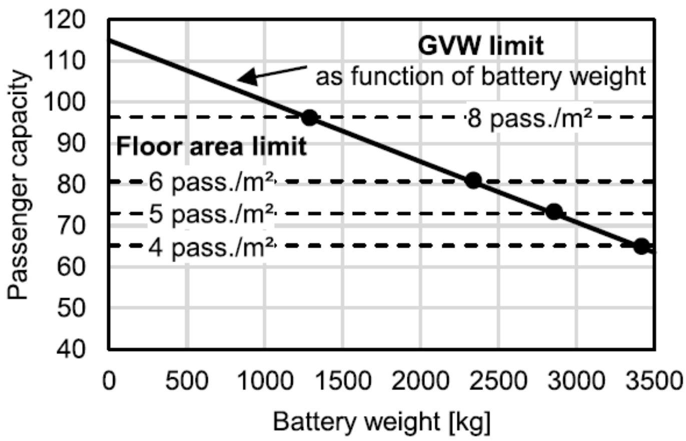


Figure B2. Passenger capacity of a 12 m bus by GVW as a function of added battery weight, and passenger capacity [5]

10.5 Battery system

The most important characteristics of a specific cell type with regard to electric bus operations are energy density, charge rate and cycle life. Currently, lithium iron phosphate (LFP), lithium titanium oxide (LTO) and lithium nickel manganese cobalt oxide (NMC) are the most common cell types encountered in electric buses, as our surveys of electric bus projects indicate. Table B4 shows typical parameters for these cell types from catalogue data. For the sake of comparability, only pouch-type cells are considered [5].

Table B4. Comparison of LFP, LTO and NMC pouch-type battery cells [5] (Sources: Datasheets from EIG, European Batteries, Altairnano, Kokam, Leclanche)

	LFP	**LTO**	**NMC**
Cell voltage V	≈3.2	≈2.3	≈3.6
Cell capacity Ah	14…45	20…65	37…53
Energy density Wh/kg (gravimetric)	115…146	76…77	165…175
Charge rate (C-rate), continuous	1 C	4 C…10 C	2 C…3 C
Cycle life (at 100% DoD)	3000	10,000…20,000	1000…5000

10.6 Chassis-dynamometer driving cycles for buses with realistic urban drive patterns

Data are depicted in Table B5.

Table B5. Overview of chassis dynamometer driving cycles for buses with realistic urban drive patterns [5] (with reference to [7])

	NYBus	ADEME	MAN	BRA	OCC
Duration [s]	600	1898	1089	1740	1909
Distance [km]	0.98	5.68	3.32	10.87	10.5
Max speed [km/h]	49.57	47.9	40.72	58.2	65.39
Average vehicle speed [km=h]	5.94	10.77	10.99	22.5	19.85
Average driving speed [km=h]	17.12	15.5	16.71	29.48	24.7
Accelerations per km	178	12.33	12.63	7.63	8.36
Idling time [%]	65	31	34	24	20
Stops per km	12.13	7.04	6.32	2.76	3.04
Average stop duration[s]	32.67	14.48	17.76	13.73	11.72

10.7 Typical data on modelling bus working process and calculating energy consumption

9.7.1. Estimation of the energy demand of electric bus fleet based on real-world data

The materials of this paragraph demonstrate typical nomenclature of input data, their values and main stage of modeling and calculating energy demand of electric bus fleet by example a work [8].

Nomenclature

A	cross-section area of the vehicle (m^2)
a_+	acceleration rate (m/s^2)
a_-	deceleration rate (m/s^2)
C_d	drag coefficient of the vehicle
D	distance between two consecutively visited bus stops (m)
d_0	distance travelled during the acceleration phase (m)
d_1	distance travelled during the constant speed phase (m)
d_2	distance travelled during the deceleration phase (m)
f	rolling resistance
g	gravitational acceleration (m/s^2)
Δh	elevation difference between two consecutively visited bus stops (m)
M	total mass of the vehicle including load (kg)
M_{curb}	curb mass of the vehicle including battery (without passengers) (kg)
m_{pax}	mass of a passenger (kg)
n_h	number of intermediate halts during a trip
n_{pax}	number of passengers
P_{aux}	auxiliary power (including air-conditioning) (W)
r_{reg}	regeneration factor
Δt_{dwell}	dwell time at a bus stop (s)
Δt_{trip}	trip duration between two consecutively visited bus stops (s)
v_1	coasting speed (m/s)
α	inclination angle of the road
δ	inertia factor
η_m	average efficiency of the motor
η_{PE}	average efficiency of the inverter
η_t	average efficiency of the drivetrain and gearbox
ρ	air density (kg/m^3)

Acronyms

AB	articulated bus
BEB	battery electric bus
DD	double-decker bus
EV	electric vehicle
GHG	greenhouse gases
ICE	internal combustion engine
MAD	median absolute deviation
SD	single-decker bus
WTW	Well to Wheel

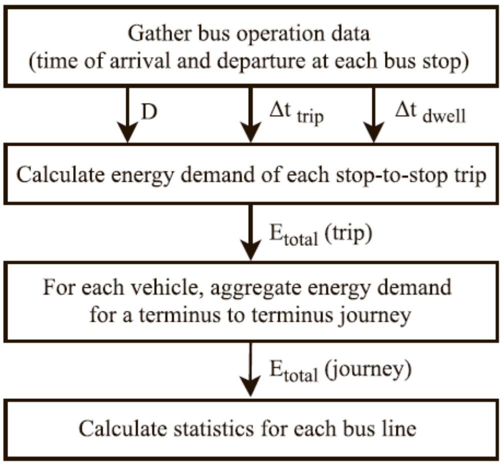


Figure B3 Overview of the steps to calculate the energy demand of a bus fleet based on operation data [8]

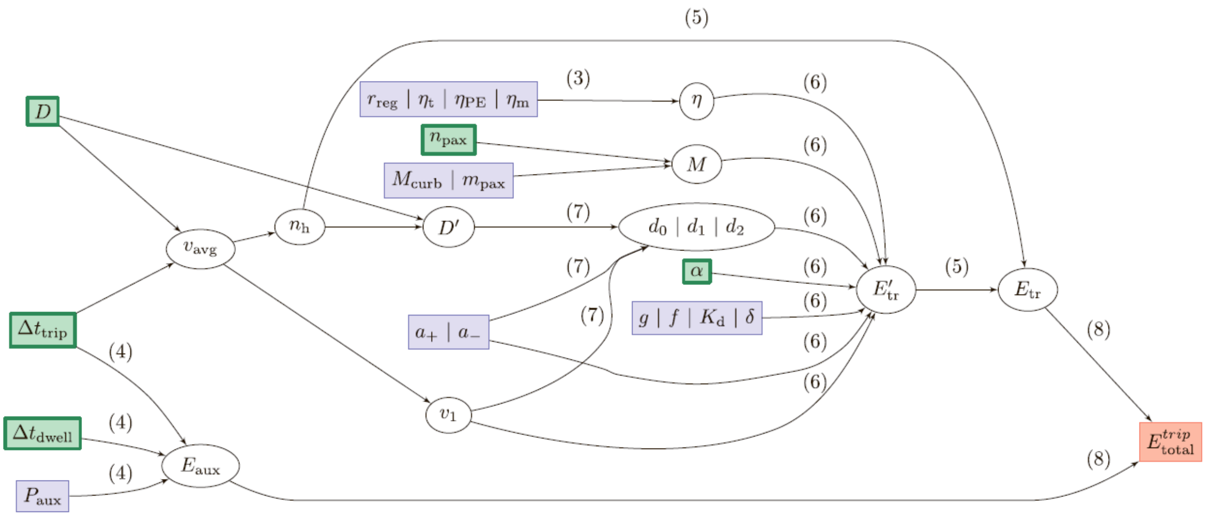


Figure B4. Graph illustrating how input data and input parameters are used to calculate the energy demand. The input data from low-resolution records of bus trips are shown inside green rectangles. The blue rectangles represent the input parameters that are static. Intermediate variables are displayed inside ellipses. The red box represents the total energy demand for one stop-to-stop trip. Numbers in parentheses along the edges correspond to the equation numbers in this paper. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) [8]

Table B6. Excerpt of the input data for the first 5 stops visited during a journey on bus line 100 [8]

Current stop number		11009	11189	11179	11169	11049	...
Arrival time		15:33:01	15:35:34	15:36:55	15:38:02	15:41:25	...
Passengers boarding		7	1	2	11	0	...
Passengers alighting		0	1	0	4	4	...
Delta passengers		7	0	2	7	−4	...
In-vehicle passengers	n_{pax}	7	7	9	16	12	...
Dwell time	Δt_{dwell}	00:00:27	00:00:07	00:00:08	00:00:24	00:00:22	...
Departure time		15:33:28	15:35:41	15:37:03	15:38:26	15:41:47	...
Next stop number		11189	11179	11169	11049	11039	...
Trip distance (m)	D	662	236	600	948	384	...
Trip duration	Δt_{trip}	00:02:06	00:01:14	00:00:59	00:02:59	00:01:09	...
Average trip speed (km/h)	v_{avg}	18.9	11.5	36.6	19.1	20.0	...
Vehicle type		SD	SD	SD	SD	SD	...

Table B7. Constant parameters used in the case study [8]

Parameter	Value	Unit	Parameter	Value	Unit
C_d	0.7	-	δ	1.1	-
ρ	1.18	kg/m^3	r_{reg}	0.6	-
f	0.008	-	m_{pax}	75	kg
η_t	0.97	-	a_+	1	m/s^2
η_{PE}	0.95	-	a_-	-1.5	m/s^2
η_m	0.91	-			

Table B8. Parameters used in this case study depending on vehicle type [8]

Parameter	Vehicle type			Unit
	SD	DD	AB	
M_{curb}	12.5	17.5	18.5	t
A	8.3	10.35	8.3	m^2
P_{aux}	10	15	15	kW

Table B9. Variables derived from the data set [8]

Variable	Description
D	Distance between two consecutively visited stops
Δt_{trip}	Duration of a stop-to-stop trip
Δt_{dwell}	Dwell time at a stop
v_{avg}	Average speed during the stop-to-stop trip
n_{pax}	Number of passengers on the bus
Δh	Difference in elevation between two consecutively visited stops
Vehicle type	Type of the vehicle (SD, DD, AB)

Table B10. Driving statistics for terminus-to-terminus journeys (median value with median absolute deviation shown in parentheses) [8]

	Vehicle type			
	All	SD	DD	AB
Number of buses in the data set	4135	2683	1149	303
Share of total distance driven	100%	68%	25%	7%
Share of total energy demand	100%	59%	32%	9%
Distance per journey (km)	18.4 (10.4)	18.4 (10.6)	20.5 (8.8)	14.4 (10.3)
Speed (km/h)	16.7 (3.5)	16.7 (3.7)	16.6 (3.2)	16.4 (3.3)
Specific energy demand (kWh/km)	1.75 (0.41)	1.62 (0.24)	2.34 (0.34)	2.47 (0.38)
Total energy demand per journey (kWh)	32.2 (19.2)	28.7 (16.6)	45.0 (21.4)	34.2 (20.7)

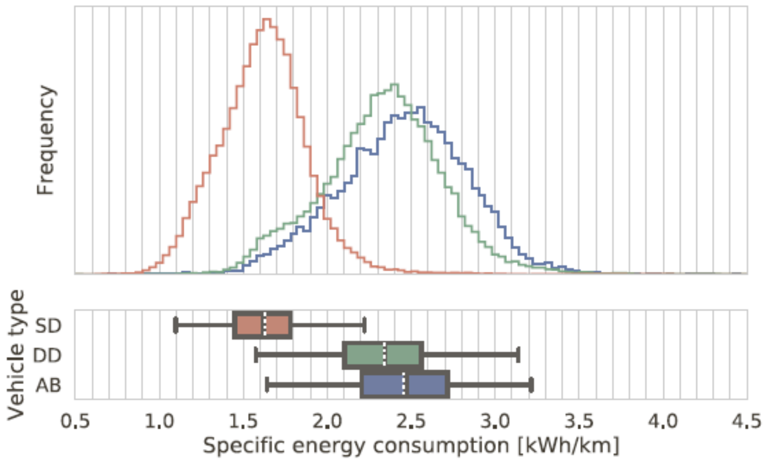


Figure B5 Distribution of the specific energy demand averaged over a journey (terminus to terminus) by vehicle type. (Box plot whiskers set at 2nd and 98th percentiles) [8]

Table B11. Parameters for the sensitivity analysis [8]

Parameter	Low	Base	High	Unit
M_{curb}	10	12.5	15	t
P_{aux}	8	10	12	kW
f	0.006	0.008	0.010	–
r_{reg}	0.5	0.6	0.7	–
a_+	0.7	1	2	m/s^2
a_-	−1	−1.5	−2.5	m/s^2
δ	1.07	1.10	1.13	–
C_d	0.6	0.7	0.8	–
m_{pax}	70	75	80	kg

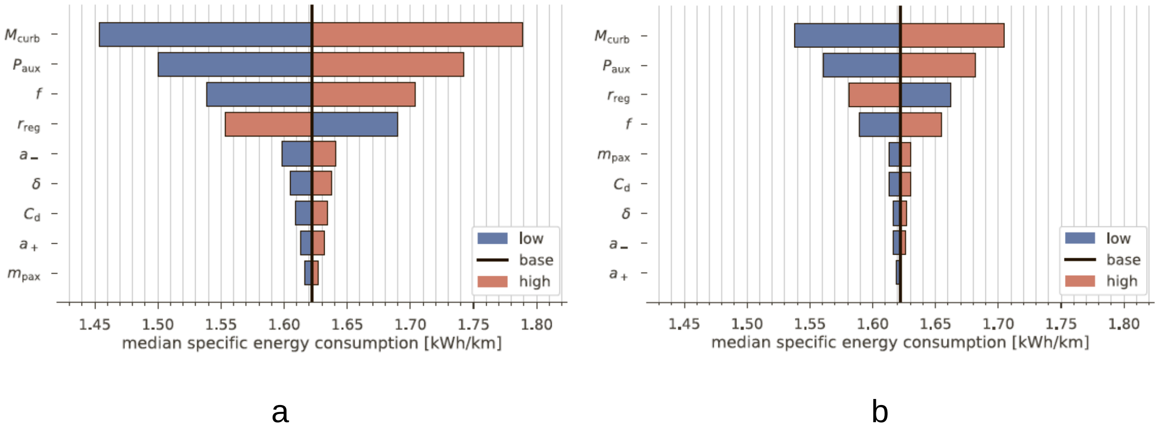


Figure B6 Tornado plots of the sensitivity analysis for the median specific energy demand per journey: a=parameters variation according Table B11; b= parameters variation ± 10% from base value [8]

9.7.2. Eco-driving

This paragraph contains data on the popular Eco-Driving direction [9]. The eco-driving approach employed, which provides reductions in braking similar to EAD technology, was found to provide varying levels of energy savings for different types of vehicles due to differences in drive cycles and vehicle characteristics.

The most interesting data from [9] are presented in Tables B12-B13 and Fig. B7 below. The structure of energy consumption is described in detail. This provides a basis for assessing the role of the bus and road parameters in the modeling of energy consumption.

Table B12. Specifications of electrical vehicle components and key parameters [9]

Component	Parameters	LD Car	Electric Bus	Electric Truck
Aerodynamic drag coeff.	Cd	0.32	0.7	0.62
Rolling resistance coeff.	Crr	0.007	0.009	0.009
Frontal Area	A_f (m^2)	2.01	9.0	9.0
Wheel tire	Wheel radius (m)	0.3125	0.5	0.53
	Inertia (kg-m^2)	0.25	1.0	1.0
Final drive	Final ratio	7.94	7.94	7.94
	Inertia per wheel tire (kg-m^2)	<0.01	<0.01	<0.01
Torque coupler	TC ratio	1.01	1.6	1.6
	Inertia (kg-m^2)	<0.01	<0.01	<0.01
Motor	Max power (kW)	84	212	265
	Continuous power (kW)	42	106	132
	Max torque (Nm)	280	700	874
	Inertia (kg-m^2)	0.03	0.06	0.08
Battery	Capacity (kWh)	24	265	265
	Peak chg power (kW)	148	1500	1500
	Peak dis power (kW)	140	1580	1580
	Normal Voltage (V)	374	581	581
Electric accessory	Constant power (kW)	0.2	5.0	4.0
Vehicle mass	Mass (kg)	1515	14407	15434

Table B13. Key driving characteristics of the passenger car, city bus and delivery truck drive cycles [9]

Vehicle	Passenger Car		City Bus		Delivery Truck	
Drive mode	wo eco-drive	w/eco-driving	wo eco-drive	w/eco-driving	wo eco-drive	w/eco-driving
Max Acceleration (m/s^2)	2.60	2.66	1.29	1.25	1.28	1.27
Average Acceleration (m/s^2)	0.45	0.32	0.28	0.27	0.17	0.15
Max deceleration (m/s^2)	−2.73	−1.48	−2.00	−1.92	−1.72	−0.71
Average deceleration (m/s^2)	−0.42	−0.19	−0.51	−0.14	−0.18	−0.12
Max Speed (mile/hr)	68.57	67.92	41.91	40.67	66.13	66.45
Average Speed (mile/hr)	29.09	29.09	13.51	13.51	40.52	40.53
Distance (mile)	10.89	10.89	21.77	21.75	57.67	57.68
Time (s)	1352	1352	5802	5802	5127	5127
Positive tractive energy (kWhr/km)[a]	0.135	0.091	1.015	0.687	1.090	0.950
Negative tractive energy (kWhr/km)[a]	−0.048	−0.017	−0.561	−0.298	−0.155	−0.045

[a] Estimated based on EVs listed in Table B12.

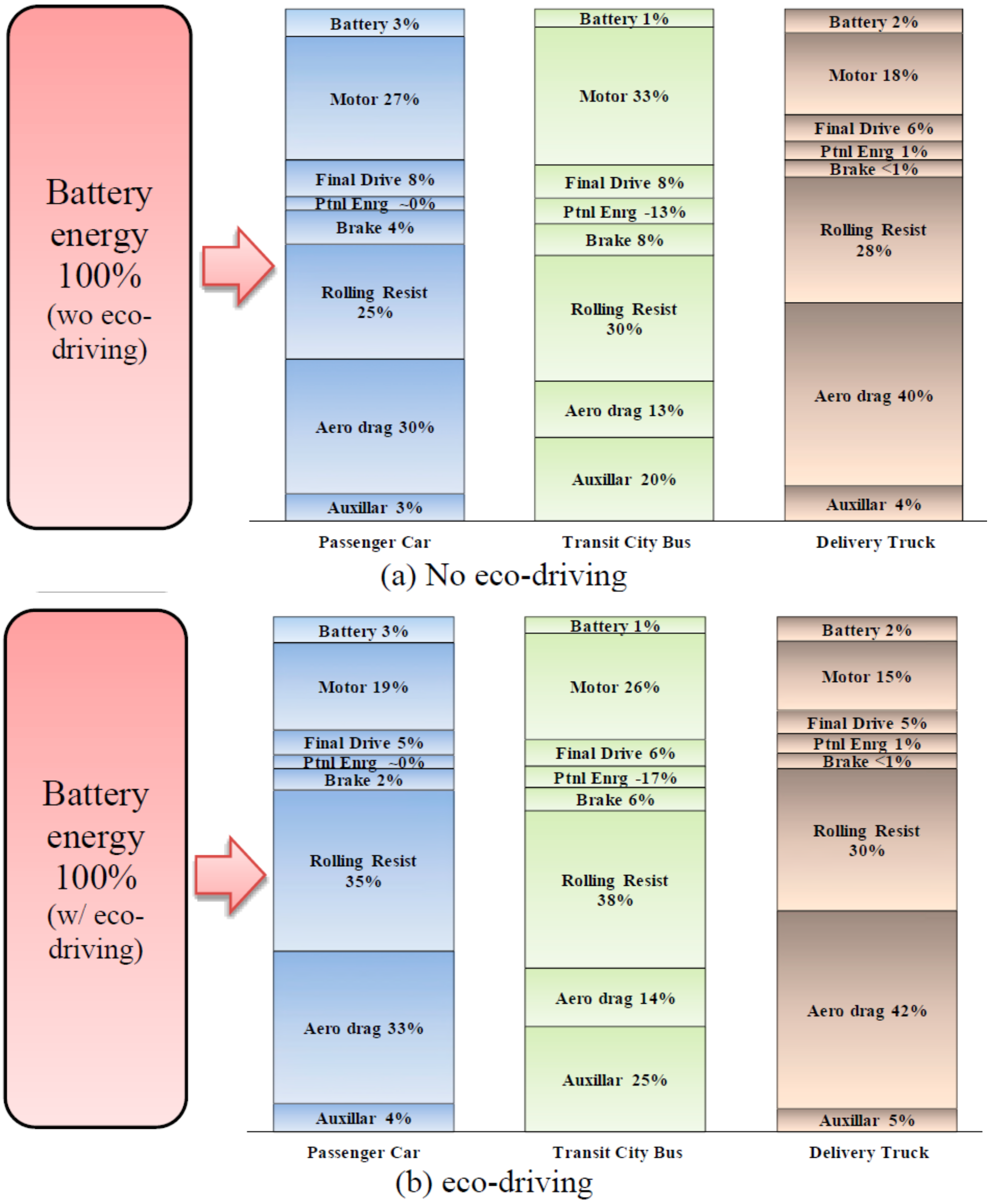


Figure B7 The energy consumption percentage distribution among energy loss factors for the passenger car, transit bus, and delivery truck with and without eco-driving

For a passenger car EV, an E-bus and an E-truck, the model predicts an overall energy savings from eco-driving of 27%, 22% and 8%, respectively. The key component losses of the EVs include aerodynamic drag, rolling resistance, motor loss, and drivetrain loss, as well as accessory loads for buses. In all of these EV cases, the braking energy loss is very nearly eliminated. However, the eco-driving optimized drive cycles do not impact rolling resistance loss. Rolling resistance becomes more important for EVs due to the mass penalty associated with excess battery weight, and since other losses are reduced while rolling resistance remains the same, its relative contribution to the total energy loss becomes more significant. Therefore, low rolling resistance tire technology can have a significant impact on the efficiency of EVs with eco-driving.

The observations show that eco-driving provides a larger reduction in the conventional vehicle's braking energy loss compared to the comparable BEVs. This is due to the

EVs employing regenerative braking. However, the eco-driving leads to frequent engine operation at low loads, corresponding to lower efficiency.

10.8 Factors determining the energy consumption

The variation in the energy consumption of an electric bus on a certain route depends on the passengers (Pas) loading, ambient temperature, driver's actions, road conditions (motion mode, average speed, etc.).

Passenger loading and season factor

Data on rations of energy consumptions of buses on the same route with different Pas loadings, taking into account the season factors, are given in Table B14. These rations are based on the data from Table B15. Action of the factors is presented in Table B16.

Table B14. Relation of energy consumptions vs. passengers (Pas) loading (based on [10])

Season	No Pas/ Av Pas	Max Pas/ Av Pas	Max Pas/ No Pas
Summer	0.82	1.17	1.43
Winter	0.72	1.17	1.62

Table B15. Energy consumption (EC) vs. Pas loading and season factor (based on [10])

Pas loading	Winter, kWh/km	Summer, kWh/km	EC Winter/Summer relation
No Pas	1.19	1.07	1.11
Average Pas	1.64	1.31	1.26
Max Pas	1.93	1.53	1.26

Table B16. Energy consumption (EC) vs. temperature

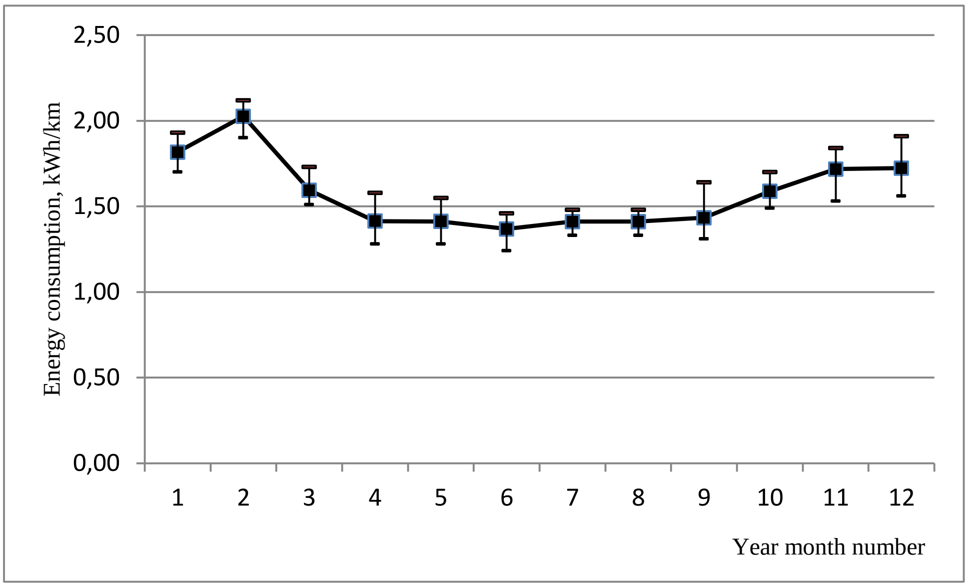
Place	Temperature, ℃	EC, kWh/km	Temperature, ℃	EC, kWh/km	EC max/min relation
Berlin [11]	-17	3.6	18	2.3	1.57
Ontario [12]	35	1.45	10	1.27	1.14

The difference in the max/min rations: 1.57 (Berlin) and 1.14 (Ontario) can be explained by the fact that in Berlin, in addition to the HVAC system (heating, ventilation, air conditioning), there is also an increased movement resistance in winter compared to summer.

Operation data from Belkommunmash

Data reflecting the effect of the seasonal factor from *Belkommunmash operation* are presented in Fig. 29. For their formation, data were used on 15 electric buses that run along the same route.

a



b

jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	annual
−4,5	−4,4	0,0	7,2	13,3	16,4	18,5	17,5	12,1	6,6	0,6	−3,4	6,7

Figure B8 Average energy consumption of 15 electric buses on the same route (*a*) and average temperature in Minsk (*b*) depending on month

The maximum average value is 2.03 kWh / km (February), and the minimum average value is 1.37 kWh / km (June). Their ratio 2.03 / 1.37 = 1.49.

These data can be taken as typical for assessing the impact of the seasonal factor on buses of a similar type. For the type of bus under consideration, it should be noted that:

bus battery is used

- for heating the driver's cab
- manage ventilation

bus battery not used

- for heating the passenger compartment of the bus (Webasto device is used for this)
- for opening and closing doors (for this, a pneumatic system is used)

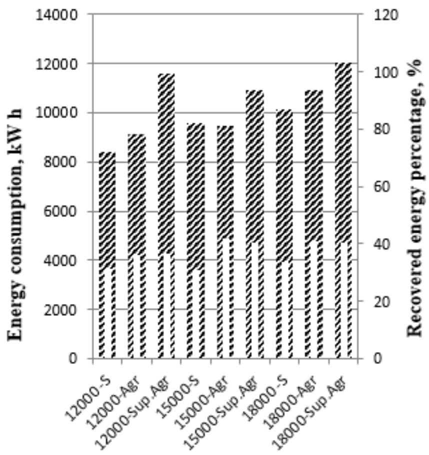
Increasing in energy consumption during winter months can be explained by using bus battery for heating and ventilating operation, but additional factors are

- increasing rolling resistance because of winter tires,
- road coverage (snow is often),
- more complicated traffic condition, and
- harder battery work under minus temperatures.

Energy consumptions and driving cycles (experimental study of Belcommunmach and JIME, 2019).

Data are given in Fig.9.

Driving style	The energy consumption taking into account the recovery, Wh	Recovered energy percentage, %	Power consumption per kilometer, kWh/km	Driving style Factor
	No pass – 12000 kg			
Calm	8422,48	31,40%	0,88	
Aggressive	9152,09	36,30%	0,96	1,09
Super-Aggressive	11583,73	36,60%	1,21	1,38
	Av pass – 15000 kg			
Calm	9564,03	31,00%	1,04 *	
Aggressive	9461,94	41,70%	0,99	0,95
Super-Aggressive	10923,48	40,60%	1,16 *	1,12
	Max pass – 18000 kg			
Calm	10155,55	33,65%	1,11	
Aggressive	10919,13	40,76%	1,14	1,03
Super-Aggressive	12048,43	40,40%	1,25	1,13



Experimental values of energies:

- The energy consumption taking into account the recovery (▨) and
- Recovered energy percentage (□)

Loading	Mass, kg	Energy Consumption, kWh/km
No pass	12 000	0.88/0.96/1.21
Av pass	15 000	1.04*/0.99/1.16*
Max pass	18 000	1.11/1.14/1.25

* Busy hour

Figure B9 Experimental study of 12-m Belkommunmash electric bus E420

Data concerning energy consumptions and driving cycles (Table B17)

Table B17. Vehicle energy consumption (EC) vs. driving cycle

Case study [EC dimensionality]	Driving cycle [13]	EC	EC relation (%)
1) [Wh/km]	HWFET	137	100
	UDDS	165	120
	US06	249	182
2) [Wh/km]	UDDS	125	100
	HWFET	150	120
	US 06	200	160
3) [L/100 km]	HWFET	6.05	100
	EUDC	6.76	112
	NEDC	8.14	135
	FTP	8.39	139
	US 06	8.92	147
	NYBus	16.02	265

Source: 1) mid-size vehicle [14]; 2) Nissan Leaf [15]; 3) Ford Focus [16]

For the bus subject in question, the New York Bus (NYBus) cycle, developed by the US Environmental Protection Agency, is of particular interest. NYBus is cycle test for heavy-duty vehicles, representative of actual driving patterns of transit buses in New York City. The test, developed by the US EPA, attempts to simulate some of the toughest bus driving conditions that existed in the United States in the 1980s. The data for this cycle was collected from a mid-town Manhattan route in New York City. The NYBus test simulates rapid stop-and-go traffic with long passenger transfer times. The cycle consists of very rapid accelerations, followed by rapid decelerations to idle and long idling periods [17].

In well-known SORT approach [18] that is similar to standard driving cycles, a standardized set of trapezes is used. A criterion for the proximity the SORT cycle and real route is the key parameter: the same commercial speed. So the SORT method is intended for measurements of bus performance under standardized on-road cycles, and according to experts such measurements cannot reflect the specific application of buses (vehicle configuration, topography, driver influence, climate, loading conditions, etc.).

Criticism of driving cycles

The disadvantages of standard conditions, including driving cycles, are well known. First of all, these are the slowness (1) and the lack of rises (2). For example, criticism of driving cycles on the example of the popular modern international cycle WLTP (WLTC) is presented in Wikipedia [19]: "Although an improvement over the NEDC, the WLTC cycles are still unrealistically slow. For example, the most rapid 0–50 kilometers per hour time is 15 seconds. Most drivers in Western Europe accelerate from rest to 50 kilometers per hour in 5 to 10 seconds. There is also no hill climbing in the cycles, and modest gradients increase engine loads by 2 to 3 times, with a subsequent increase in pollutants".

Many studies of driving cycles of the vehicles are concentrated on the creation of one typical cycle by consolidating a large set of data. An overview of the features of these works is presented by Kivekas et al. [20], where a new method of synthesis of driving cycles is proposed: generation of changing cycles and number of passengers for the selected bus route based on several measured cycles using the "from stop to stop" segments. At the same time, the possibility of intermediate stops due to the passage of pedestrian crossings and traffic lights is not considered inside the segments. But it is known that the greatest irretrievable losses of energy are associated with the arising intermediate stops. In addition, as in other methods, the severity of the resulting driving cycles is not assessed in terms of driving style and energy consumption.

Data from real operation. These data are free from drawbacks mentioned above of driving cycles. The paper [21] contains the following data. Typical increase of fuel consumption due to aggressive driving compared to defensive driving occurs from 78.5% to 137.3% for petrol vehicles and from 116.3% to 128.3% for diesel vehicles.

Average speed

The effect of the "average speed" *factor* is shown in Fig. B10*a*. The energy consumption is presented in relative form based on data from [22]. Relative energy consumption $P=E/E_0$, where E_0 is certain base value. In this example, it has value of 306.25 Wh/km, that relates to speed of 25 km/h. If the absolute value of energy consumption for any speed becomes known (from calculations or operation), then all the curve can be reproduced in absolute values, as shown in Fig. B10*b*.

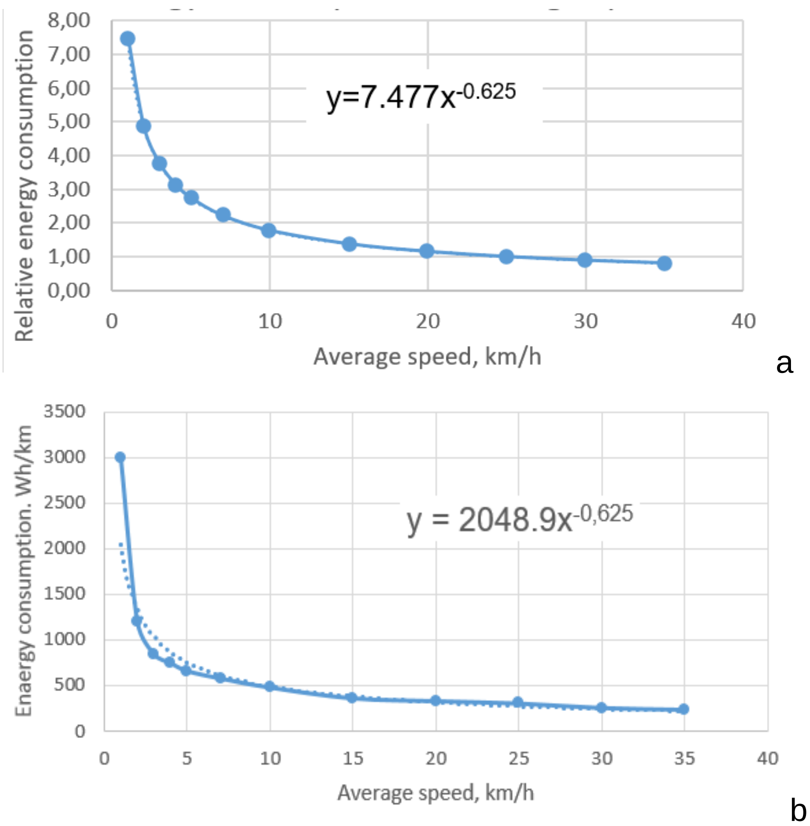


Figure B10 Energy consumption vs. average speed: relative values (a) and absolute values (b)

10.9 Method for Evaluating Energy Consumption for an Electric Buses Based on Data for Diesel Buses

Basic idea [2]

It is assumed that the electric bus operates on the same route as the diesel bus. Diesel bus fuel consumption is known.

To assess the energy consumption of the electric bus, data on the fuel consumption spent on the movement of the similar diesel bus, taking into account its “Tank-to-Wheels” (TTW) losses, are used. Then this energy is recalculated into the energy consumption of the electric bus, taking into account its losses TTW. The effect of energy recuperation for the electric bus during braking is also to be taken into account; this effect can reach 25%. The general idea is illustrated by an example with real parameters, presented below.

Illustrative example

Initial data (actual values): 1) Diesel bus: fuel consumption is 39 l/100 km; calorific value of diesel fuel is 43.12 MJ/l; TTW1=20%; 2) Electric bus: gross weight corresponds to the gross weight of the diesel bus; TTW2=65%; the degree of energy recuperation on the route is 10% from general consumption.

Calculation of the electric bus energy consumption is as follow.

The energy expenditure of a diesel bus per km of the route:

$$0.39 \cdot 43.12 = 16.82 \text{ MJ/km} \tag{3}$$

A part of the energy expenditure to overcome the movement resistance:

$$16.82/0.2 = 3.36 \text{ MJ/km} \tag{4}$$

Energy consumption of the electric bus on the same route:

$$(3.36/0.65(1-0.1) \ = 4.65 \text{ MJ/km} \tag{5}$$

This value (4.65 MJ/km=1.29 kWh/km) can be used for selecting the battery capacity taking into account the available charging configuration.

When evaluating the obtained value, it should be taken into account that due to the higher dynamism of the electric bus, its energy consumption for movement may turn out to be slightly higher. This is confirmed by the results of [23]. The expense for overcoming movement resistances (road resistance, acceleration, air resistance) is 10% higher in the electric bus due to its much more “aggressive” accelerations and higher maximum speeds.

So the final value is

$$E = 1.29 \cdot 1.1 = 1.42 \text{ kWh/km} \tag{5}$$

This value can be considered as average value of energy consumption for the electric bus on a given route.

10.10 Dependability and maintenance

The report [24] provides data on the electric buses Proterra BE35 (Table B18) from April 2014. The report covers two data period: 4/14–7/15 and 8/15–12/16. The data period for the eight new NABI CNG buses used as a baseline comparison begins from October 2014 when the buses were placed into service. Tables B19 and B20 provides a summary of results for several categories of data presented in this report.

Table B18. Proterra BE35 battery electric bus specifications [25]

Bus manufacturer	Proterra
Bus model	BE35
Model year	2014
Total length	10.67 m (35 ft)
Total height	3.28 m (10.75 ft)
Wheelbase	6.02 m (237 in.)
Curb weight	12,555 kg (27,680 lb)
Gross vehicle weight rating	16,928 kg (37,320 lb)
Passenger capacity	35 seated / 18 standing
Battery manufacturer / model	Altairnano / TerraVolt 368
Battery type	368-V lithium titanate
Battery energy/capacity	88 kWh / 60 Ah
Number of packs	8 (6 floor, 2 roof)
Motor manufacturer / model	UQM / PP220
Motor power nominal	120 kW (161 hp)
Motor power peak	220 kW (295 hp)

Fast charging peak power	500 kW
Transmission gear ratios	3.53:1 and 1:1
Cabin air conditioning	Thermoking REH-M6
Cabin heater	11-kW electric resistance

Table B18. Summary of evaluation results [24]

Data Item	BEB		CNG	
Number of buses	12		8	
Data period	4/14–7/15	8/15–12/16	10/14–7/15	8/15–12/16
Number of months	16	17	10	17
Total mileage in data period	401,244	501,037	364,373	656,399
Average odometer	33,437	77,705	45,547	132,405
Average monthly mileage per bus	2,333	2,456	4,555	4,826
Total operating hours	47,462	58,497	—	—
Average speed, including stops (mph)	10.6	8.57	17.6	17.6
Availability (85% is target)	90	90	94	93
Availability (85% is target)	90	90	94	93
Miles between roadcalls (MBRC) – bus[c]	9,331	6,180	45,547	29,165
MBRC – propulsion system only[c]	25,078	16,405	91,093	56,710
MBRC – ESS[d] only[c]	133,748	300,760	—	—
Total maintenance ($/mile)[e]	$0.16	$0.21	$0.18	$0.22
Total maintenance ($/mile without tire costs)	$0.12	$0.14	$0.18	$0.20
Maintenance – propulsion system only ($/mile)	$0.02	$0.02	$0.08	$0.07

[c] MBRC data cumulative from the clean point of April 2014 through December 2016.

[d] Energy storage system.

[e] Work order maintenance cost.

Table B19. Summary of Availability and Unavailability of Buses for Service [24]

Category	BEB	BEB	CNG	CNG

	# Days	%	# Days	%
Planned work days	4,895	90.0	2,512	92.6
Days available	4,406	90.0	2,326	92.6
Unavailable	489	10.0	186	7.4
ESS	15	0.3	—	—
CNG engine	—	—	28	1.1
Electric drive	165	3.4	—	—
Charging issues	17	0.3	—	—
Preventive maintenance	17	0.3	17	0.7
General bus maintenance	227	4.6	136	5.4
Transmission	48	1.0	5	0.2

Terminology

Availability (property of an item) = ability to be in a state to perform as required.

Note: Availability depends upon the combined characteristics of the reliability, recoverability, and maintainability of the item, and the maintenance support performance.

Availability (indicator): The number of days the buses are actually available compared to the days that the buses are planned for operation expressed as percent availability.

Roadcall: A failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule. The analysis includes chargeable roadcalls that affect the operation of the bus or may cause a safety hazard. Non-chargeable roadcalls can be passenger incidents that require the bus to be cleaned before going back into service, or problems with an accessory such as a farebox or radio.

Average driving speed: The average speed of the buses while driving, not including stops and idle time. These data are collected using data loggers.

Miles between roadcalls (MBRC): A measure of reliability calculated by dividing the number of miles traveled by the number of roadcalls. (Also known as mean distance between failures.) MBRC results in the report are categorized as follows:

• Bus MBRC: Includes all chargeable roadcalls. Includes propulsion-related issues as well as problems with bus-related systems such as brakes, suspension, steering, windows, doors, and tires.

• Propulsion-related MBRC: Includes roadcalls that are attributed to the propulsion system. Propulsion-related roadcalls can be caused by issues with the transmission, batteries, and electric drive.

• Energy storage system (ESS)-related MBRC: Includes roadcalls attributed to the energy storage system only.

10.11 Typical data for calculating TCO for electric bus fleet and complex optimization problem

Typical data for calculating TCO are presented in Table B20. displays the battery cost forecast.

Table B20. Data for TCO calculation and optimization problems [26]

Category	Assumption	Value	Unit	Source
General	Daily distance	250	km	Typical electric bus with a long range
	Number of days driven per year	350	days	Choice
Financing costs	Learning rate	4%		in line with the recommended discount rate of the EC
	€/$ exchange rate	1,17		Sep-18
Energy	Diesel price	1,175	€/L	EEA (December 2017) Transport fuel and tax, average
	Electricity price	0,112	€/kWh	Eurostat (2017), Electricity prices for non-household consumers, second half of 2017, Europe average
Vehicle	Capital cost of vehicle body - electric (the vehicle excluding equipment and batteries)	247.863	€	IEA EV Outlook (2018)
	Capital cost of vehicle body-diesel	213.675	€	IEA EV Outlook (2018)
	Depreciation time of battery	8	years	Choice
	Depreciation period of bus	10	years	Choice
	Residual value of bus after 10 years	10%		CE Delft
E-bus	Battery price 2018 (+see Table B21)	335	€/kWh	BNEF (2018) Electric Buses in Cities

	Mark-up for opportunity charging batteries	10,0%		Choice
	E-bus efficiency	1,3	kWh/km	NREL (2017). IEA (2018), CE Delft recommendation Accounts for conservative scenario with utilisation of heat management systems. According to ZeEUS project (ZeEUS final report #2. 2018) values are around 1 kWh/km.
	Cost of other EV equipment	€ 5,860 + €26/kW		Assessment with respect to the EU HDV C02 legislation, TNO (2018)
	Motor power electric bus	150	kW	selection of buses, ZeEUS report #2
	Max usable battery capacity in worse-case scenario	72%		Based on worst case scenario: 20% for degradation and 10% for operational safety margin
Charger	Operational cost 50kW charger	0,14	€/kWh	Assessment with respect to the EU HDV C02 legislation, TNO 2018 (with 8 hours of occupancy per day) Include capital expenditures, maintenance expenditures and operational expenditures
	associated occupancy per day	8	hours	-
	Operational cost 300 kW charger	0,21	€/kWh	CE Delft (on-going study) for 130,000 kWh annually Include capital expenditures, maintenance expenditures and operational expenditures
	associated amount of energy delivered	130000	kWh	-
	Charger maintenance cost	2%	per year	Method to analyze cost effectiveness of different electric bus systems, Oscar Olsson et al., 2016
ICE	Cost of replaced ICE components	€50 + 65€/kW		Assessment with respect to the EU HDV C02 legislation, TNO (2018)

	Engine power	260	kW	Choice based on most sold urban bus Daimler Mercedes Citaro
	Fuel consumption	0,4	L/km	confirmed by CE Delft. TNO (2016), TNO (2015)
	Cost of refuelling infrastructure (dispenser + tank)	78.291	€	BNEF (2018) Electric Buses in Cities
	Depreciation time of refuelling infrastructure	15	years	Choice
	Number of bus per refuelling infrastructure	50		Choice
Maintenance	E-bus maintenance cost	0,183	€/km/year	Olsson, 0., Grauers. A., Pettersson, S. (2016). Methods to analyse cost effectiveness of different electric bus systems, paper for EVS29 Symposium. Montreal, June 19-22,2016 Conservative when compared to IEA (2018) Global EV Outlook 2018 which assumes maintenance cost of e-buses half of those from diesel bus
	ICE bus maintenance cost	0,292	€/km/year	Olsson, 0., Grauers. A., Pettersson, S. (2016). Methods to analyse cost effectiveness of different electric bus systems, paper for EVS29 Symposium. Montreal, June 19-22,2016
Externalities	Air pollution	0,018	€/vkm	Ricardo-AEA, DIW econ, CAU (2014), Update of the Handbook on external costs of transport, London
	Noise	0,087	€/vkm	Ricardo-AEA. DIW econ, CAU (2014), Update of the Handbook on external costs of transport, London Assuming 90% day operation (half dense half thin traffic) and 10% thin night traffic
	Cost of noise reduction ICE vs. Ev	-75%		Turcany, J. (2016), Electric buses and noise, presentation from 02-01-2016, Volvo Buses

				We apply a more conservative factor to the Volvo value (-87%)
	GHG	0,074	€/vkm	Ricardo-AEA, DIW econ, CAU (2014), Update of the Handbook on external costs of transport, London Assumed Euro VI same as Euro V (data N./A.)
	carbon intensity of EU grid	275,9	gC02/kWh	EEA(2017) Overview of electricity production and use in Europe
	carbon price	90	€/ton	Ricardo-AEA, DIW econ, CAU (2014), Update of the Handbook on external costs of transport, London
	GHG cost of a kWh	0,025	€/kWh	Calculated

Table B21. BNEF Forecast of battery prices depending on European demand for e-buses [20]

Battery price for buses (€/kWh)	2016	2018	2020	2022	2024	2026	2028	2030
Low demand in European e-bus	510	333	269	224	194	167	146	129
High demand in European e-bus	510	333	262	204	160	122	102	85
Variation low vs. high demand			-3%	-9%	-18%	-27%	-30%	-34%

10.12 Samples of using relative (specific) values for evaluating input data (battery, charger items, maintenance and electricity costs)

Relative (specific) values for evaluating batteries, chargers, maintenance and electricity costs, etc. are in Tables B22-B23.

Table B22. Use of relative (specific) values for battery and charging infrastructure [3] (based on [27])

Fixed costs	Relative (specific) values
Bus charger	1 €/W
Electricity substation	0.8 €/kW
Cabling in low/medium/dense pars of cities	100/200/300 €/m
Power optimized batteries	1130 €/kWh
Energy optimized batteries	540 €/kWh

Table B23. Use of relative (specific) values for maintenance and electricity costs [3] (based on [27])

Driver cost including dwell time and downtime	35 €/h
Maintenance cost per electric bus (without drivers wages)	0.183 €/km/year
Maintenance cost per bus charger	2 % of bus charger cost/year
Electricity subscription fee per year 400V/10kV	520 €/year / 930 €/year
Power tariff, highest entry per month 400V/10kV	4.12 €/kW/month / 3.42 €/kW/month
Variable energy fee 400V/10kV	0.0068 €/kWh / 0.0031 €/kWh
Energy costs	0.075 €/kWh

10.13 Prospect of TCO for different technologies

Forecast 1

The paper [4] with reference to [28] reports that the TCO for some electric buses will drop significantly by 2030 with an average of 30–50 % for FCEB and BEB (Overnight & Opportunity). The TCO for HEB (series and parallel) and diesel buses is also expected to drop by an average of 1–5 % in 2030 as highlighted in Fig. B11.

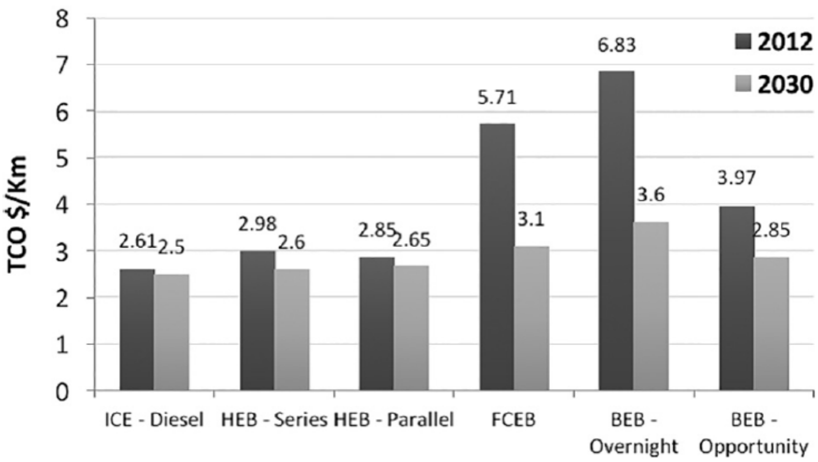


Figure B11 TCO of buses 2012/2030 [4] with reference to [28]

Forecast 2

Fig. 12 shows the TCO values for electric 12 m buses compared to conventional buses under operational and technical parameters obtained in [5].

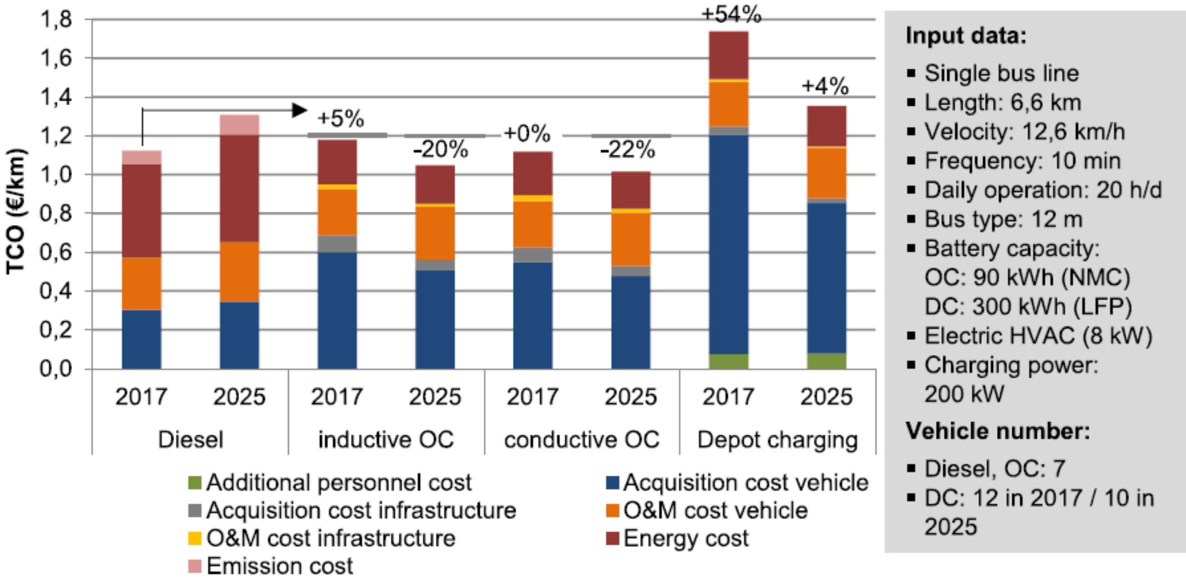


Figure B12 TCO assessment of different technologies for 2017 and 2025 (forecast trend scenario) [5]
(O&M cost = Operation and Maintenance cost)

Fig. 13 [5] shows possible probability distribution of future TCO outcomes for different technologies in the year 2025, allowing a risk assessment for technology decisions. The spread of each histogram indicates the degree of cost uncertainty. For instance, the conventional diesel bus features the highest uncertainty due to the dependency on fossil fuel.

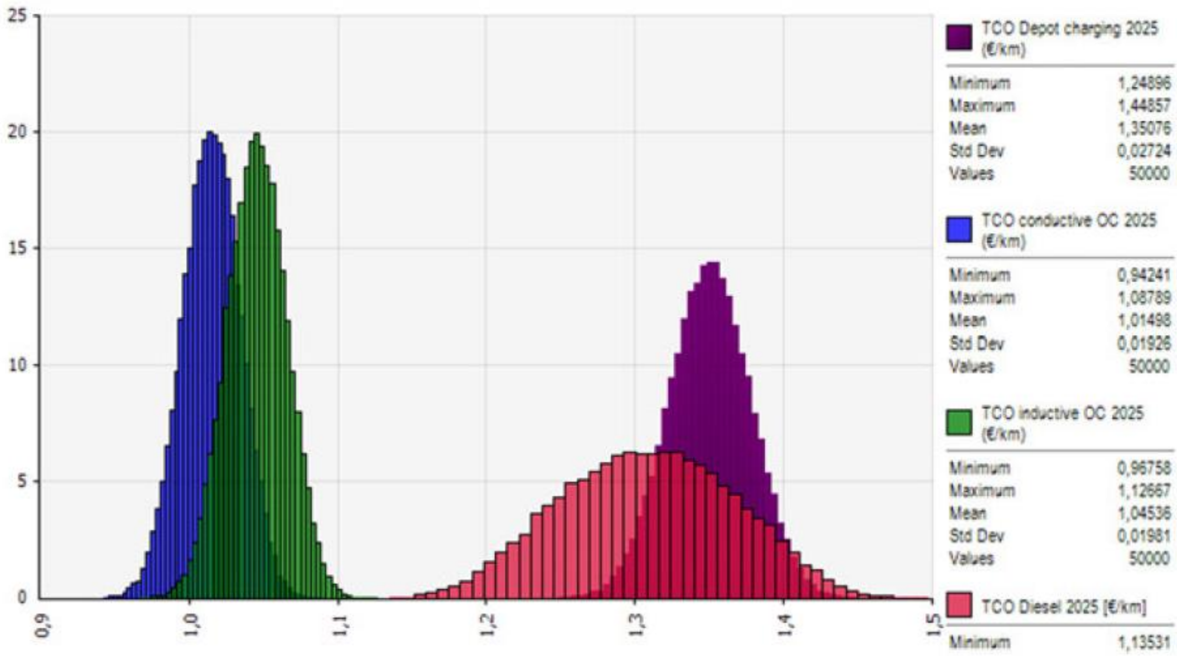


Figure B13 Stochastic TCO simulation for a bus procurement in 2025 based on selected route [5]

Sensitivity of TCO to daily/annual mileage

- **Today**, electric buses can be slightly more expensive on shorter routes [26].

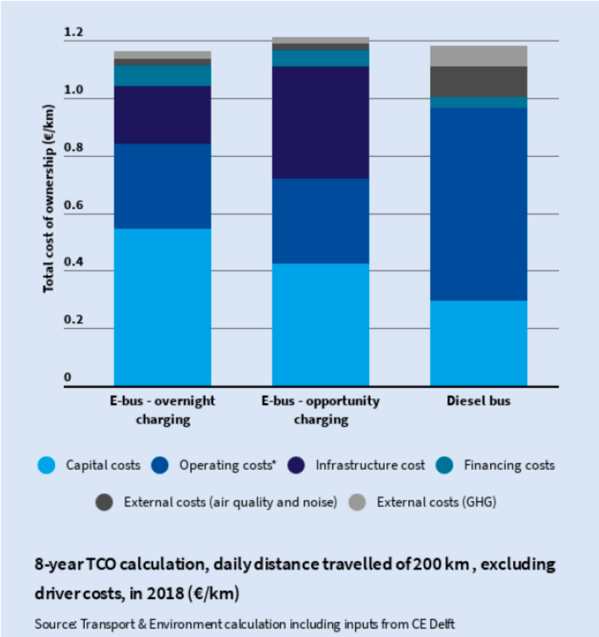
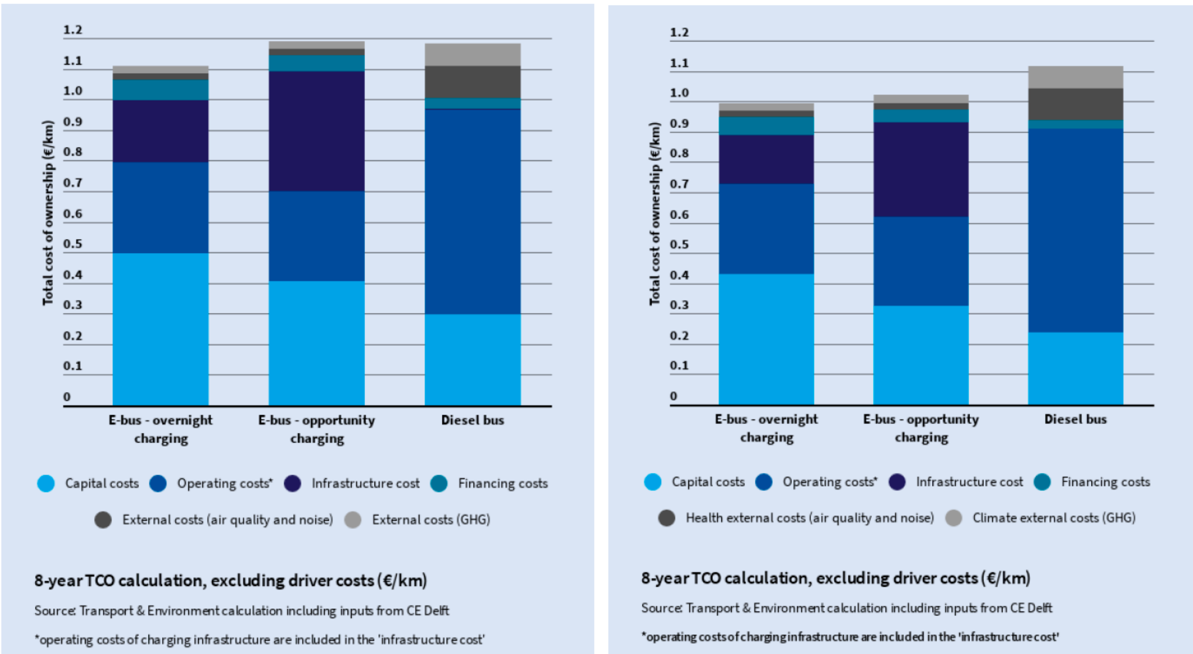


Figure B14 TCO comparison with 200 km travelled per day (sensitivity analysis) [26]

- **TCO in 2020:** Overnight charging electric buses will become increasingly competitive as battery prices decrease (Fig. B15).



a *b*

Figure B15 TCO comparison in 2020 (sensitivity analysis)
a = 200 km travelled per day, b =250 km travelled per day [26]

- **TCO vs. bus annual mileage**

TCO of any vehicles depends heavily on their annual mileage if the period for calculating TCO is fixed. This is usually done.

To describe the trend of "TCO vs. bus annual mileage" is suggested to use the following approach [3]. First, a typical mathematical dependence is constructed. Before using this dependence, it is adjusted to a certain TCO value corresponding to the annual run. The dependency graph can be shifted vertically as a result of the adjustment. Then, the corrected dependence is used for the prediction.

It is suggested to describe typical mathematical dependence in the form

$$y = ax^b + c \quad (6)$$

where x = annual mileage (km), y = TCO ($ / km).

The values of parameters *a* and *b* are presented in Table B24.

Table B24. Parameters *a*, *b* for electric buses with different battery capacities [3]

Trend line	Battery capacity, kWh	*a*	*b*
1	110–250	39,156	−0,978
2	≥350	59,157	−1,049

For using dependence (6) it is necessary to have supporting point (x_0, y_0). If TCO y_0 is known (or defined) for the annual mileage x_0, then the parameter *c* is equal to

$$c = y_0 - ax_0^b \quad (7)$$

Fig. B16 shows lines 1 and 2, which are plotted for the values x_0=33 km and y_0=1,539 $/km (line 1) as well as for x_0 =33 km and y_0=1.830 $/km (line 2).

In presented cases, there are *c*=0.258 (line 1) and *c*=0.318 (line 2) respectively. The above parameters can be used if any information (supporting point) is absent.

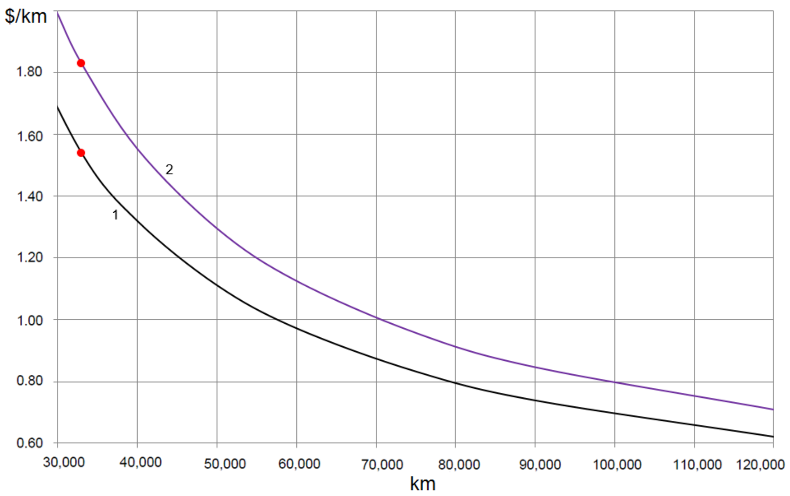
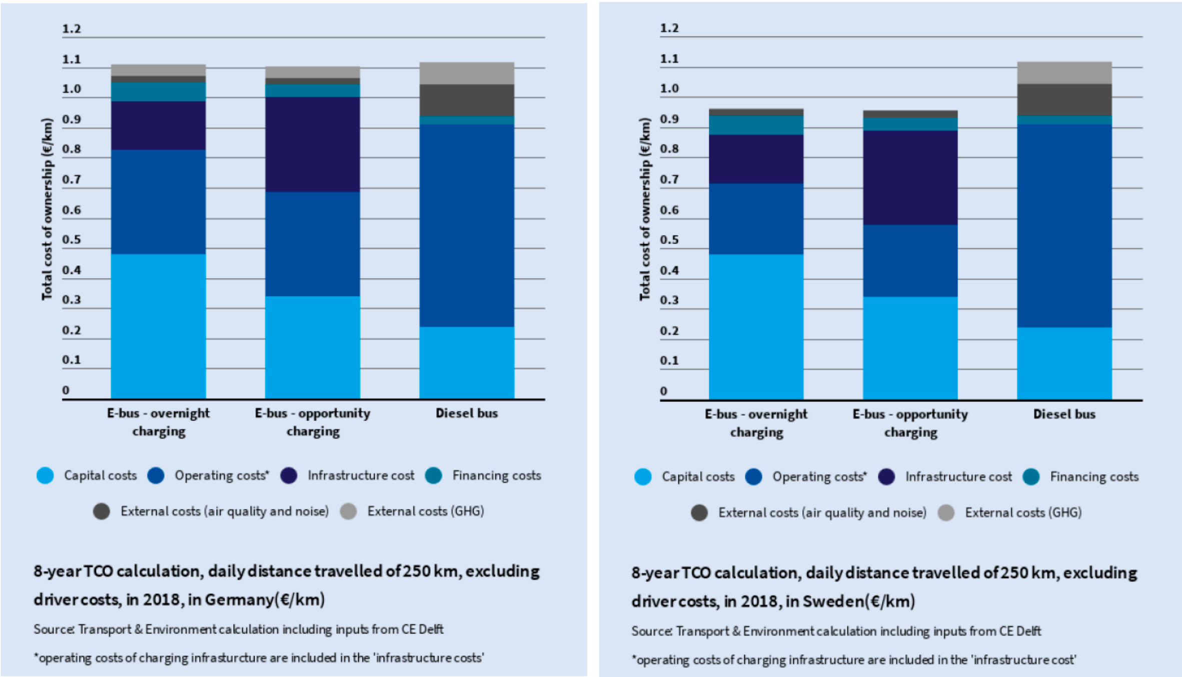


Figure B16.TCO ($/km) vs. bus annual mileage (km) [3]

Influence of electricity cost (and carbon grid-intensity) [26]

High cost: example of Germany and low cost: example of Sweden (Fig. 17)

- Germany electricity cost: 0.151€/kWh, C02 intensity of the grid: 424.9 g/kWh
- Sweden electricity cost: 0.065 €/kWh, C02 intensity of the grid: 10.5 g/kWh



a *b*

Figure B17 TCO comparison with 250 km travelled per day (sensitivity analysis): a= in Germany, b= in Sweden

10.14 Specific problems in transition to electric bus fleet

The combination of charging infrastructure and bus batteries

An efficient layout of the charging infrastructure and an appropriate dimensioning of battery capacity are crucial to minimize the total cost of ownership and to enable an energetically feasible bus operation.

In [29], the central issue of jointly optimizing the charging infrastructure and battery capacity is described by a capacitated set covering problem. A mixed-integer linear optimization model is developed to determine the minimum number and location of required charging stations for a bus network as well as the adequate battery capacity for each bus line. The bus energy consumption for each route segment is determined based on individual route, bus type, traffic, and other information. Different scenarios are examined in order to assess the influence of charging power, climate, and changing operating conditions. The findings reveal significant differences in terms of required infrastructure. Moreover, the results highlight a trade-off between battery capacity and charging infrastructure under different operational and infrastructure conditions.

Table 25 provides a network overview of key figures under the assumptions of the baseline scenario. Electrifying the examined network requires a total number of 24 charging stations. The charging points are located at terminal stops as well as at bus stops en route. All charging stations that are installed en route are located at intersection with other bus lines and thus realize synergies.

Table B25. Network overview for the simulated baseline scenario [29]

Bus line	Bus type	Line length (km)	No. of buses	Battery capacity (kWh)	Charging points used	Utilization of available charging time (%)
186	DD	27.87	12	90	3	80
188	SB	11.27	4	60	1	70
282	DD	19.32	8	90	2	64
283	SB	17.65	6	60	1	78
284	SB	16.83	4	60	2	62
285	DD	26.21	6	90	3	60
M48	DD	33.35	12	90	3	85
M82	DD	13.61	8	90	2	64
M85	DD	32.67	14	90	4	73
100	DD	15.64	10	90	4	95
110	SB	19.64	4	60	3	67
200	DD	23.61	10	90	5	91
204	SB	12.73	4	60	3	50
245	DD	15.62	10	90	3	76
249	AB	13.89	6	90	3	98
X09	AB	15.56	6	90	3	43
X10	DD	34.58	10	90	3	66
Total		350.02	134			

Figures B18 and B19 present some results from [29].

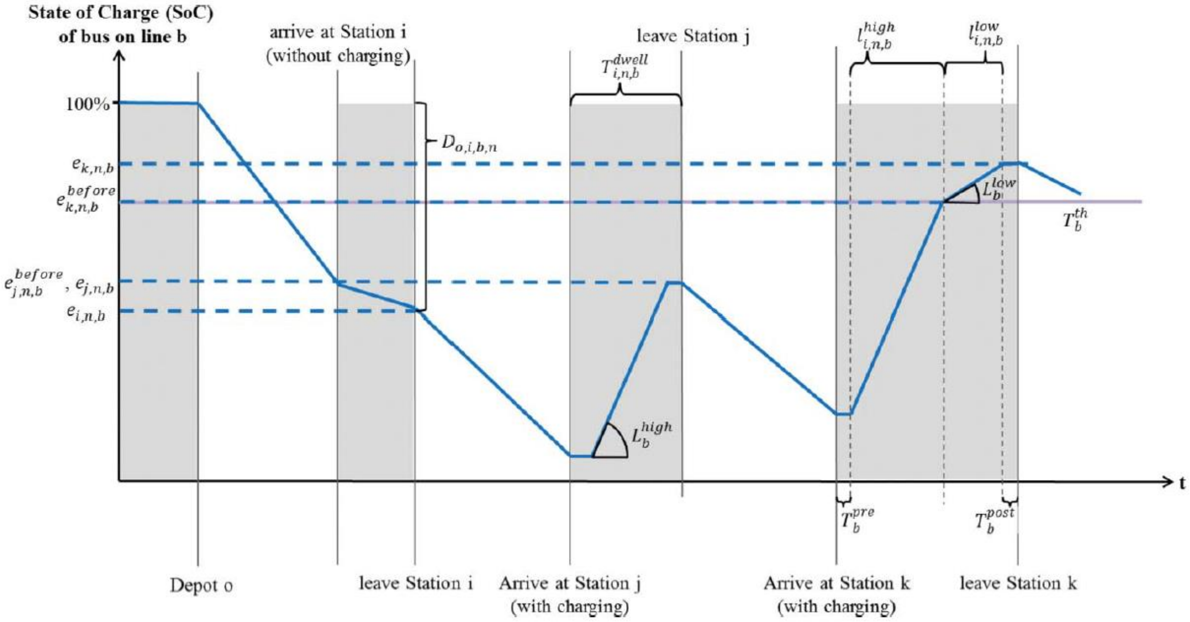


Figure B18 State of Charge of a bus over time during service on a line, including discharge on the route, and charging at stations [29]

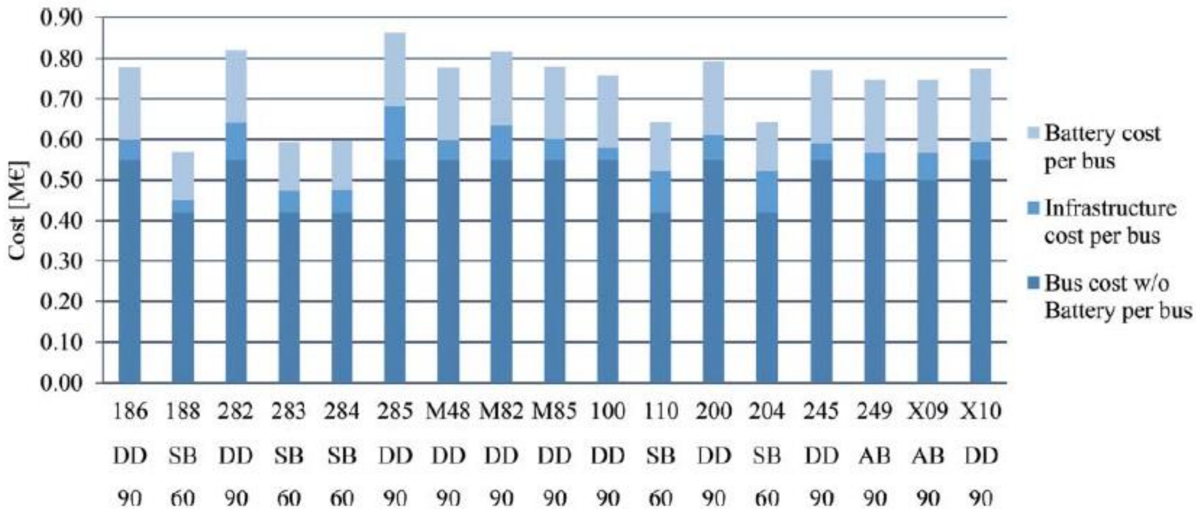


Figure B19 System costs per bus and bus route for the baseline scenario.
The bus type and the battery capacity in kWh are given below the bus line number [29]

TCO and vehicle schedules

The paper [30] introduces a methodology for an advanced TCO (total cost of ownership) analysis of electric bus systems and presents results for a set of real-world bus lines. An electric bus system simulation model is developed. Simulations on the basis of existing vehicle schedules demonstrate that simple substitution of diesel buses with electric buses is often impossible in practice. Thus, a vehicle scheduling algorithm is developed that constructs bus schedules to satisfy existing routes and timetables, while considering range limitations and required charging times at terminal stops. The resulting schedules form the basis to determine the cost of bus network electrification.

Figures B20 — B22 show some intermediate data from [30].

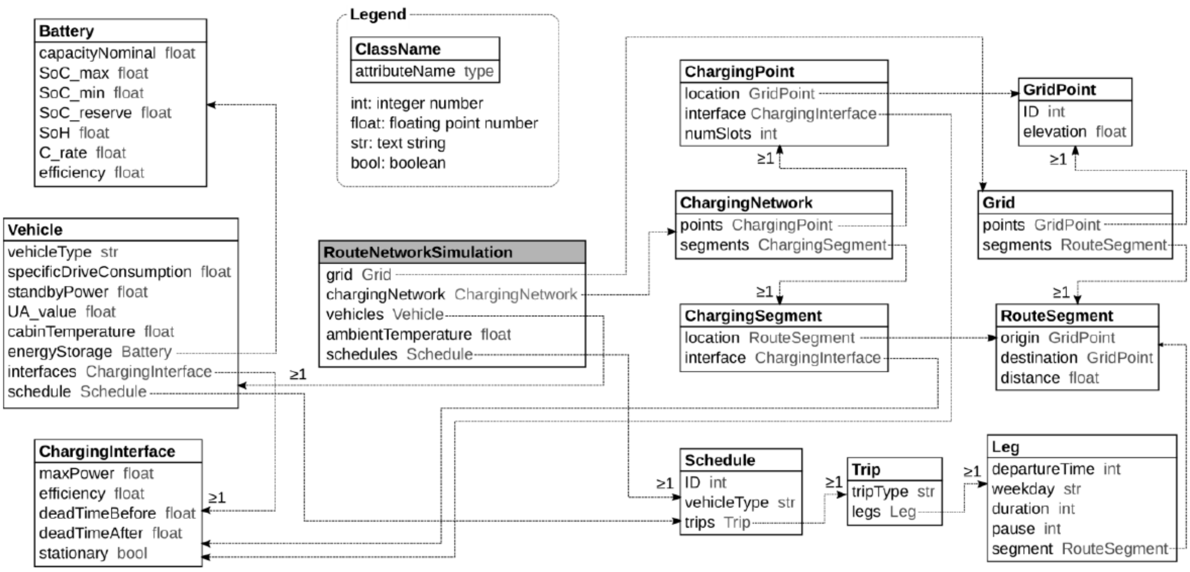


Figure B20 Simplified class diagram depicting the most important classes and parameters (attributes) for bus route network simulation [30]

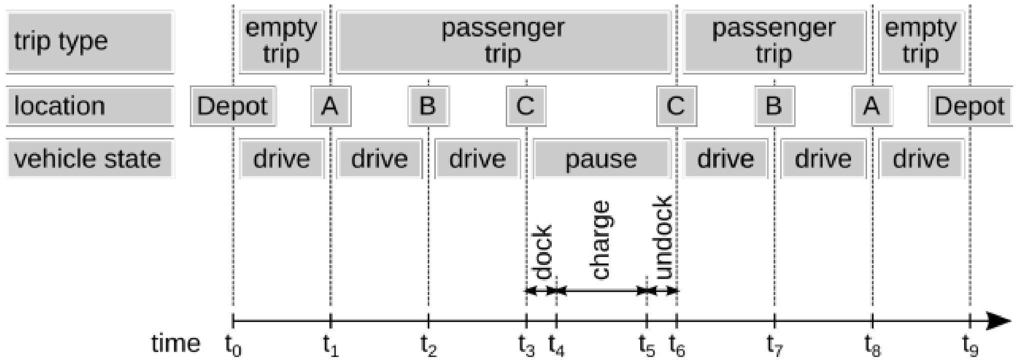


Figure B21 Time intervals used for energy flow calculation [30]

	2018 unit cost	Lifetime (a)
Vehicle base (18 m)	530,000 €	12
Battery: OC (NMC)	800 €/kWh	6
Battery: DC (LFP)	430 €/kWh	6
Fast charging station	500 €/kW	20
Slow charging station	60,000 €	20

a

	2018 unit cost	Escalation
Electricity	0.15 €/kWh	3.27% p.a. until 2020; 2.17% p.a. after 2020
Driver	33 €/h	1.5% p.a.

b

Figure B22 Accepted from literary sources, data for capital (a) and operation (b) expenses [30]

Obtained results (Table B26) for an opportunity charging (OC) and a depot charging (DC) scenario indicate that the TCO gap between the two systems is narrow, with the depot charging system incurring a slightly higher cost of 2.3% [30].

Table B26. TCO values from literature and this work. If more than one number is stated, the values correspond to different scenarios [30]

Source	TCO		Diff.
	OC	DC	
Bi et al. [1, 2]	0.99 $/km	1.06 $/km	7%
Lajunen and Lip-man [3]	0.88-1.10 €/km	1.03-1.18 €/km	7-19%
Pihlatie et al. [4]	0.87 €/km	1.15 €/km	32%
Vilppo and Markkula [5]	2.911 M€	3.121 M€	7%
Kunith [6]	2.49-2.92 €/km	3.18-3.51 €/km	20-28%
Rogge et al. [7]	–	2.46-3.29 €/km	–
Fusco et al. [8]	576-616 M€	–	–
This work	4.29 €/km	4.39 €/km	2.3%

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