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Possibilities of energy demand reduction in trolleybus transportation

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Contents

1. The current state of trolleybus service in DPMB (Brno office of public transportation)

1.1 Trolleybus fleet of DPMB

The trolleybus fleet is composed exclusively of Skoda cars, counting 152 vehicles in total. The most common types are non-articulated cars of the older 14 Tr or 14 TrM type, 67 vehicles altogether. The second most common type is newer low-floor 21 Tr type - 60 pieces. The less common articulated trolleybuses are represented by 25 cars. There are 8 cars of the oldest 15 Tr type, 8 cars of the newer low-floor 22 Tr type and 9 cars of the newest low-floor 25 Tr type. The 25 Tr trolleybus is based on Iveco bus body, equipped with electric drive by Skoda Electric. The newest cars are from the year 2009. Delivery of 30 new low-floor cars of the 31 Tr type is expected in 2015, which will replace the oldest type 14 Tr.

1.2 Supply network

For supplying the DPMB, a.s. tram and trolleybus lines, there are 29 converter stations with a total rated power of 100 MVA. Converter stations are supplied from a common 22 kV distribution network. For a better reliability of electrical supply, converter stations are connected in “loops” on their primary sides, this allows a supply from two sides. In case of primary supply failure, the loop can be divided into 2 parts and ensures a primary supply from one side without any limitation of service (the faulty section is disconnected).

In the central part of the city, converter stations usually contain more units (3 to 5 transformers). In the peripheral parts of the city, stations usually contain one transformer, they are used to improve the quality of electrical supply and as a backup – for more details see further description of DC part of converter stations. The nominal trolley voltage for trams and trolleybuses is 600 V DC. In Brno the trolley voltage is negative (-600 V). In converter stations the 22 kV AC voltage is transformed down to 525 V AC. The AC voltage is rectified by solid-state diode rectifiers (one rectifier for each transformer) into DC voltage. This voltage is carried out by a feeder line from which the individual tram or trolleybus line sections are supplied through circuit breakers. In case of inability of excess energy consumption during regenerative braking in one section, the energy is fed back to the converter station and then through the feeder line to another section where it is required. The energy can be interchanged between tram and trolleybus networks. To ensure reliability of traction power supply during failure of a converter station’s 22 kV primary supply, the converter stations in Brno are since the 50 s interconnected, either through the supply sections or directly by special cables carrying the 600 V DC voltage. In practice the system works as follows: During the failure of a primary supply to a converter station, the station has a dead primary part, only the DC output part is live – supplied from other stations – and through the feeder line the direct current is distributed to supply sections with power consumption. Converter stations are currently rated so that even during a failure of a multi-unit station, full service without limitation is possible. The byproduct of this interconnection is the ability to distribute the regenerative braking energy to other converter stations and supply remote locations. This ability is limited only by the resistance of trolley and cable network. All converter stations are in automatic mode monitored from central supervisory service with the ability of remote control of individual stations through the “SAT”

control network. During emergency it is possible to locally manually operate each station, but this is used only during failure of communication with the control system or during special occasions with large supply demands (such as during fireworks festival).

1.3 Energy requirements of trolleybuses

The most energy consuming are the oldest trolleybuses, types 14 Tr / 14 TrM and the articulated 15 Tr type, which is electrically and power wise 2x 14 Tr. These trolleybuses utilize DC motors and a low-loss SCR converters to control traction and braking, however they don't allow recovering the braking energy back to the trolley.

The more modern 21 Tr types are less energy demanding, they use DC motors and SCR converters as well and originally they were able to return the braking energy to the trolley, however because of reliability problems this possibility was disabled and the braking energy supplies only self-consumption. DPMB, a. s. also runs two trolleybuses of the 21 Tr AC type with AC induction motors, which are able to regenerative brake back to the trolley.

Probably the least energy demanding (in comparison to the 15 Tr type) are trolleybuses of the 22 Tr type with SCR controlled DC motors (electrically and power-wise the same as 2 x 21 Tr) which allow regenerative braking and the newest 25 Tr trolleybuses with AC induction motors, which allow recovery of braking energy as well.

The energy demand of individual types is best described by the specific annual planned energy consumption in kWh/km, which can be seen in Tab. 1.1.

Tab. 1.1 Planned trolleybus annual specific energy consumption in DPMB

Trolleybus type	**Rated power**	**Average annual specific consumption of electric energy in kWh/km**
14 Tr / 14 TrR	100 kW	1.856
15 Tr	200 kW	2.887
21 Tr	140 kW	1.759
22 Tr	264 kW	2.510
25 Tr	240 kW	2.510

The energy consumption of the new 21 Tr AC types was not yet specified due to the short run time of about 2 months.

1.4 Regenerative braking possibilities

As can be seen from Chap. 1.3, it is possible to divide the trolleybuses into 3 groups with respect to braking energy recovery possibilities:

- Do not allow regenerative braking - oldest 14 Tr/14 TrM a 15 Tr types
- Energy recovery only to self-consumption –21 Tr type
- Allow regenerative braking back to the trolley – mainly 21 TrAC, 22 Tr and 25 Tr types

2. Experience with ultracapacitor and battery applications in realized projects

2.1 Hybrid trolleybus of the Barnimer Busgesellschaft (Eberswalde)

The Barnimer Busgesellschaft mbH company (Barnim office of bus transportation, ltd.) operates trolleybus transport in Germany for the longest time. The Barnim district is situated on the east of the federal country Brandenburg and its capital city is Eberswalde. The use of regenerative braking is common since the year 1983.

„Hybrid trolleybuses“, which use a combination of trolley supply, Li-ion cells and ultracapacitors as the energy source (for traction converter, auxiliary drives and other self-consumption) were commissioned into service in June 2012. It’s the first system of its kind in Europe. The manufacturer of these articulated trolleybuses is the Solaris company, the traction system was supplied by the Cegelec company (total 12 pieces).

The development of this system was sponsored by the TROLLEY project (http://www.trolley-project.eu) and co-financed by the ERDF (European Regional Development Fund).
A study containing basic information on measured and simulated energetic balances, efficiencies and dimensioning of the ultracapacitor and battery system (in German) can be found on the below mentioned URL. The study was written in the Dresden Fraunhofer Institute on the order of Barnim bus company.

http://www.bbg-eberswalde.de/downloads/trolley/TROLLEY-TEIL-B.pdf

Although the mentioned document does not contain technical details (e.g. exact calculations), authors come to similar conclusions as in our study.

For the purpose of independent driving capability (without a trolley supply) the system contains $LiFeYPO_4$ (lithium-iron-yttrium-phosphate) battery. The battery details are in Tab. 2.1.

Tab. 2.1Traction battery of Solaris Trollino 18 AC articulated trolleybus

Battery type	EVC-LYP200/108A
Number of cells	108 in series, 2 branches in parallel, 216 total
Capacity of one cell	200 Ah
Voltage of one cell. (min., nom., 85% charge,100% charge)	2.8 V/ 3.2 V/ 3.43 V/ 3.65 V
Total voltage of the battery	308 V/ 352 V/ 377 V/ 395 V
Max. single cell charge/discharge current	0.5 C/2C, 100 A/ 400 A
Max. total battery charge/discharge current	200 A/ 800 A
Maximum battery stored energy	70.4 kWh
Utilizable energy (SOC 25% to 85%)	42.2 kWh
Maximum discharge power	120 kW
Weight of bare cells	756 kg

Weight of whole battery	1020 kg
Charging time from 25% to 85%	75 min
Charging time for 5 km independent drive	ca. 20 min
Expected lifetime (25% to 85% cycles)	3000 cycles
Expected lifetime (partial cycles for 5km drive)	12000 cycles

As can be seen from Tab. 2.1, the battery is dimensioned for high energy – apparently for the purpose of long independent driving without the need for a trolley supply. In the study and in other documents concerning the TROLLEY project, information about average energy consumption of 2.5 kWh/km can be found.

Note: Our study comes to the number of 1.3 kWh/km. This result was obtained from a measurement on a smaller and lighter trolleybus 21 Tr, see Chap. 4.2.4, equation (4.8).

Further, a corresponding action radius of 70.4/2.5 = 28 km is specified in the study. However, as in our study, authors recommend to use the battery only with partial charge/discharge cycles while keeping the SOC (state of charge) in the range of 25 to 85 %. It is recommended to avoid deep discharging of the battery but also avoid full recharging to extend battery life. In this range the utilizable capacity is only 42.2 kWh and a corresponding action radius of around 17 km, however this is still more than enough.

Note: The study states that before delivery to Eberswalde (June 2012), the trolleybuses were able to drive 18 km without a trolley during a test drive in Ostrava.

For a driving range of 5 km, energy of around 5 x 2.5 = 12.5 kWh is sufficient. For periodic driving on a 5 km detour section during closure, in the drive-recharge-drive regime, it is possible to keep the SOC in the range of around 67 to 85 % (18 % utilizable energy or around 12.5 kWh). This further avoids deep discharging of the battery and a lifetime of 4 times more cycles than in the 25 to 85 % regime is expected – see Tab. 2.1.

Ultracapacitors are used as a second energy storage device in the system. There are two reasons for this arrangement (combination of battery and ultracapacitor):

1) The allowable peak power (current) of a battery is directly related to its Ah-capacity. The $LiFePO_4$ or $LiFeYPO_4$ cells offer an excellent maximum current to capacity ratio. Even so the selected cell type (see Tab. 2.1) allows a maximum discharge power of only 120 kW while the rated power of the trolleybus is 250 kW. For independent traction without power limitation, the battery would have to be rated at twice the capacity, which would be unused (range of independent drive needlessly long). The battery would be too heavy and expensive. For this reason it is better to use a smaller battery rated not for the peak power, but for the required independent drive range. An ultracapacitor, which has a much lower internal resistance than the battery, is then used to cover up the required power peaks. However the specific energy density of the ultracapacitor is about an order of magnitude lower than for the battery so the ultracapacitor alone would have insufficient energy for the required drive range.

2) With ultracapacitors the efficiency of braking energy storage will increase, because the charging efficiency of ultracapacitor is a few percent higher compared to a battery (given by higher internal resistance and the character of electrochemical reactions in a battery). This also helps to decrease losses in the battery, resulting in easier cooling. Momentary power peaks of both polarities (charge/discharge) will then be covered by ultracapacitors and the lower average long-term power with higher energy will be supplied by the battery.

However, these details are not transparently stated in the study (know-how). There's a remark about using the ultracapacitor alone for short distance driving (e.g. in the depot), but this is clearly not the main reason for using the ultracapacitor.

The disadvantage of the battery / ultracapacitor combination is its complexity and price of the system.

Note: In our study, for the 21 Tr trolleybus (in case of choosing the battery variant) we recommend using a battery which is able to deliver higher peak powers for a given capacity, then the use of ultracapacitor is not required to reach full power during independent traction.

Tab. 2.2 shows the basic parameters of an ultracapacitor used in theoretical calculations and simulations in the Fraunhofer Institute study.

Tab. 2.2 On-board ultracapacitor (parameters used in the Fraunhofer study for simulations and calculations)

Manufacturer	LS Mtron
Cell type	LS3000
Maximum ultracapacitor voltage	790 V
Minimum ultracapacitor voltage	519 V
Total capacitance	10.2 F
Utilizable energy	500 Wh
Total weight	ca 320 kg
Efficiency of DC/DC converter	ca 0.95

The capacitor is sized only with respect to accumulation of braking energy. In comparison to Chap. 6.2.1 we can see that our study comes to similar energy rating.

Further, a possibility of stationary energy storage tank (in the converter station) is discussed in the Fraunhofer study. With respect to the fact that large energy capacity of this energy storage tank is not required (compared to on-board use for independent traction), ultracapacitor is the best solution – efficiency will be higher than with a battery because of lower internal resistance. The larger weight and dimensions are not a problem in a stationary application.

The ultracapacitor type discussed in this part of the study is the type BCAP3000 P270 by Maxwell. It's the same capacitor type as proposed in our study (see Chap. 6.2.1).
As with the above mentioned LS Mtron capacitor (see Tab. 2.2) and other designs presented in the study (including the stationary application), the minimum capacitor voltage is chosen about half the maximum voltage. The reason for this lies in worse efficiency of the DC/DC converter for lower voltages, see Chap. 6.2.1.

Even though the maximum voltage of the Maxwell ultracapacitor cell is 2.7 V, the Fraunhofer study recommends only 2.5 V which results in longer lifetime. Lowest voltage is chosen at 1 V (a bit lower than the mentioned one half).

An interesting conclusion mentioned in the study is the calculated efficiency of storing the braking energy into the ultracapacitor at 91 %. Considering that the average efficiency of the DC/DC converter can be guessed at 95 %, the charging efficiency of the ultracapacitor itself then comes out to 96 %, which is a realistic estimation (of course this depends on the charging current – a higher current will result in lower efficiency).

2.2 Trolleybuses of PKT Gdynia

Gdynia is a city located in the north of Poland, near Baltic Sea. The PKT Gdynia company (Przedsiębiorstwo Komunikacji Trolejbusowej Sp. z o.o. w Gdyni – office of trolleybus transportation in Gdynia) was founded in 1998 as an autonomous company operating only trolleybus transport in Gdynia. This company manages 87 trolleybuses operating on 12 routes, the total length of trolleybus routes is approximately 90 km. The percentage of trolleybus transport (from the whole mass transportation) is there more than 25 % [1].

Approximately 50 % of the trolleybuses allow returning of braking energy back to the trolley, while the ratio of returned energy to withdrawn energy is 20 % [2] – similar result as in our study (see Chap. 4.2.4).

2.2.1 Trolleybuses with batteries for the purpose of independent driving capability

The first trolleybuses of the type Solaris Trollino 12 with independent driving capability were put into service in 2009. It must be noted that the batteries installed into the vehicles serve solely for the purpose of independent traction, not for braking energy storage. These vehicles use NiCd cells of the STH 800 type, manufactured by SAFT. Tab. 2.3 shows the basic parameters of the battery.

Tab. 2.3 Traction battery of the Solaris Trollino 12 trolleybus [3]

Nominal voltage	201.6 V
Capacity	80 Ah
Stored energy at full charge	16.1 kWh
Weight (including converter)	800 kg
Maximum power (battery operation)	70 kW
Maximum speed (battery operation)	40 km/h
Number of partial cycles – SOC 100 % to 80 %	15000

As can be seen, the stored energy is more than 4 times lower than for the trolleybuses with $LiFeYPO_4$ batteries in Eberswalde (see Chap. 2.1), however the weight is similar – NiCd batteries have a considerable disadvantage in the form of a very low energy density (weight related). Lifetime for partial cycles is similar to the before mentioned $LiFeYPO_4$ battery.

The Solaris Trollino 12 trolleybuses with NiCd batteries are also equipped with a device for recording selected parameters related to the use of battery during operation. Tab. 2.4 shows measurement results of important parameters. Values are presented for “standard operation” (planned route changes) and “emergency operation” (trolley damage, converter station failure etc.), during this operation the specific energy consumption per km is higher because of more complex traffic situations and resulting lower speed.

Tab. 2.4 Selected measured parameters from Solaris Trollino 12 trolleybus battery operation [3]

	Standard operation	Emergency operation
Driving range for 20 % battery discharge	2.28 km	1.63 km
Average energy consumption	1.51 kWh/km	1.86 kWh/km
Lowest energy consumption	0.83 kWh/km	0.68 kWh/km
Highest energy consumption	2.36 kWh/km	2.72 kWh/km
Longest recorded independent drive	2.164 km	7.105 km

The 1.51 kWh/km figure of average energy consumption roughly agrees with the result in our study of 1.3 kWh/km (see Chap. 4.2.4).

So far the trolleybuses in the Gdynia city use only NiCd batteries. Within the frame of the „CIVITAS DYNAMO“ project, PKT Gdynia company plans to buy 2 new trolleybuses with Li-Ion batteries or convert older buses into trolleybuses with Li-Ion batteries [1].

2.2.2 Ultracapacitors

Ultracapacitors are not yet installed into vehicles in the Gdynia city. An ultracapacitor was installed into a converter station on the Wielkopolska street in April 2014. This location was selected due to hilly terrain and resulting higher ratio of regenerative braking energy.

Sources:
http://gitmot.uib.es/SummerUniversityII/documentos/presentaciones/Day%202/2.3-%20Marta%20Woronowicz.pdf
http://www.ceec.uitp.org/sites/default/files/1-s2.0-S0378779614000716-main.pdf
http://www.depot.ceon.pl/bitstream/handle/123456789/4181/ee13-proceedings.pdf?sequence=1

2.3 Hybrid trolleybuses in Rome

Rome manages trolleybuses of the Sollaris Trollino 18 type, with NiMH batteries installed. The batteries are used to overcome a 1.6 km long section Termini – Porta Pia (on the route 90). The maximum energy capacity of the battery is 38 kWh, due to the above mentioned lifetime reasons the capacity is used only in partial cycles. In 2013 these trolleybuses were already successfully running for 8 years. Ultracapacitors are not used there.

Sources:
http://www.asstra.it/eventi/download_allegato/801.html
http://www.zkmgdynia.pl/admin/__pliki__/TROLLEY_ebook_2013_.pdf
http://www.trolley-project.eu/fileadmin/user_upload/download/TROLLEY_PR6_Core_Output_Reference_Guide_Trolleybus_Tram_PP05_LVB.pdf

3. General comparison of ultracapacitor and $LiFePO_4$ cells

3.1 Characteristics of ultracapacitors and $LiFePO_4$ batteries

The advantage of ultracapacitors is their almost 100 % charge / discharge efficiency (a more accurate estimation is 96 to 97 % at maximum current) and the ability to withstand large peak currents (powers) even at low capacitances (given by extremely low internal resistance (ESR)).

As will be explained further, the internal resistance of an ultracapacitor with 4 kWh utilizable energy and rated voltage of 600 V is only 8.3 mΩ, while for a $LiFePO_4$ battery with approximately 3.5 times more energy and the same voltage rating the ESR would be 180 mΩ, or about 22 times more. However as will also be shown, this advantage is not very relevant, as the losses are in both cases negligible compared to the average motor power.

During charging of ultracapacitors there is no chemical reaction delay as with standard batteries, this also increases the charging efficiency. There is some chemical reaction delay with the $LiFePO_4$ cells, however it is very short compared e.g. to common lead acid batteries. Considering the dynamics of assumed charge / discharge processes (trolleybus operation), this chemical delay does not present a substantial problem with respect to efficiency of braking energy storage.

An advantage of the ultracapacitors is their long lifetime. For example, Maxwell Technologies states up to 10 years or 1 million cycles, though at a temperature of 25 °C (for details see further – e.g. for maximum temperature of 65 °C the lifetime is only 1500 hours). For batteries the lifetime (in years) is not explicitly stated. However, based on the further mentioned experiments and long-term testing, we can conclude that with proper care of the batteries a lifetime of 5 years is achievable, and with great probability even more (e.g. 8 years, for details see Chap. 6.6). The number of full charge/discharge cycles is usually vaguely stated as “more than 1000” – much less than for an ultracapacitor. However, during normal operation, the battery would work with partial cycles with only a small energy exchange (because it would be sized to allow longer detour independent driving, not only to accumulate the much lower braking energy). Due to this fact the problem of limited full cycles is not substantial, the battery would rarely be discharged deeply (only during the longest detours). The very small partial cycles cannot be thought of as limiting for the lifetime of the battery (see further described long term practical tests in Chap. 6.5)

A smaller disadvantage of the ultracapacitor is that its voltage during charging and discharging is not nearly constant like with a battery, but it’s proportional to the stored charge (like for any capacitor). During operation the voltage varies in a wide range, which results in limited usable energy range – see note about DC/DC converter in Chap. 3.2. With an ultracapacitor the converter will then operate with a somewhat lower overall efficiency than with the $LiFePO_4$ battery.

A significant disadvantage of the ultracapacitor lies in its ca. 23-times lower mass related energy density in comparison to the $LiFePO_4$ battery (4.3 Wh/kg for ultracapacitor, 99 Wh/kg for $LiFePO_4$ battery). For the same energy the ultracapacitor is then 23 times heavier than the $LiFePO_4$ battery.

Note: The mentioned values of energy densities are valid for the selected ultracapacitors and battery cells, see further. For the selected ultracapacitors the datasheet value of mass related energy density is higher (6 Wh/kg), but it must be taken into account that to keep acceptable efficiency of the DC/DC converter, the ultracapacitor cannot be discharged to zero but only to about half the rated voltage.

Considering the temperature range, for the assumed climate of application (in Czech Republic) and operating conditions, both variants come out similar – $LiFePO_4$ -30 °C to +55 °C, ultracapacitor -40 °C to +65 °C. Due to high internal resistance of the $LiFePO_4$ cells at low temperatures, it is not recommended to use them at freezing temperatures (e.g. -5 °C and lower). However the cells quickly heat up by the current flowing through them (low volume and mass of the battery) and the internal resistance drops.

3.2 The requirement for “matching” DC/DC converter

A two-quadrant (“two way”) DC/DC converter connected between the energy storage tank and DC-link of the traction converter (which is basically the trolley supply – approx. 600 to 750 V) will be required in both cases (ultracapacitor or battery).

The ultracapacitor voltage will be variable according to the actual charge (state of charge). The maximum voltage of the ultracapacitor will be the same as voltage of the mentioned DC-link (or it can be limited to a specified maximum value, e.g. 600 V, by regulating the DC/DC converter). The lowest voltage should be limited to about half – around 300 V. It is not recommended to use a lower minimum voltage value because of lower efficiency of the mentioned DC/DC converter (non-optimal operation – higher currents required at lower voltages).

In the case of battery the DC/DC converter must be used as well. The battery voltage however varies only slightly with state of charge so the converter will always operate in more optimal conditions with respect to its efficiency. The battery voltage in discharged state can be only slightly lower than the DC-link (trolley) voltage.

4. Measurement on the 21 Tr trolleybus

4.1 Measurement apparatus

For the purposes of logging the energetic balances, regenerative braking and losses on the trolley / supply network, an automatic measurement apparatus allowing long-term measurements and recording of required values was installed into the 21 Tr trolleybus. The apparatus is based on a measuring and logging device “CompactRIO” from National Instruments. The exact configuration was following:

- Controller - NI cRIO9022
- Reconfigurable chassis - cRIO-9113
- Analog inputs card - NI 9222
- Digital inputs card - NI 9401

The apparatus was mounted in a space containing the “Regulator” for traction converters in the vehicle. The required 24 V DC supply voltage was delivered from an internal supply present in the Regulator. One more circuit board containing circuits for signal conditioning and level matching for the CompactRIO was mounted in the apparatus housing.
The following quantities were measured:

- Actual DC current drawn from the trolley

For the purpose of current measurement a galvanically isolated transducer (already present in the vehicle) with resistor shunted current output was used. The shunt is located in the Regulator housing. The voltage from this shunt was carried out through free pins in a connector on the Regulator directly to a first analog input of the NI 9222 module. The current-to-voltage transfer ratio was precisely known (current transfer ratio of the transducer and value of the shunt, which was confirmed by measurement). The measurement sample rate was set to 100 kHz and an average value of the samples was saved every 0.5 seconds. This way a true average current value was saved even if the real waveform would contain high frequency ripple caused by converter thyristors switching.

- Actual DC trolley voltage

This voltage is in the 21 Tr trolleybus measured by galvanically isolated voltage transducer with resistor shunted current output. The shunt is located in the Regulator housing as well. The voltage from this shunt was carried out through free pins in a connector on the Regulator to a second analog input of the NI 9222 module. The voltage transfer ratio was precisely known (shunt value confirmed by measurement). This way a true average voltage value was saved even if the real waveform would contain high frequency ripple caused by converter thyristors switching.

- Actual rms current through the braking resistor

The braking resistor current is not directly measured in the 21 Tr trolleybus. For this purpose a galvanically isolated current transducer ("LEM") was installed into the braking resistor area. The current range of this transducer is 2000 A with DC – 100 kHz bandwidth. The transducer requires a ±24 V symmetric supply and it has a current output. The supply for the transducer was fed by a shielded cable from the Regulator and its current output was connected by the same cable to an auxiliary circuit board with an appropriate shunt resistor on it. The voltage from this shunt was fed through an RC filter with a time constant of approximately 4 µs (8.2 kΩ metalized resistor and 470 pF ceramic capacitor) to a third output of the NI 9222 module. The time constant of the filter was selected very low to avoid distortion of the measured current pulses. The filter served only to suppress RF interference.

To determine the power (energy) lost on the shunt resistor, it is not enough to know the average (DC) value of current, because the shunt resistor is controlled by a switching converter resulting in current pulses with variable amplitude, frequency and duty cycle. As the real power on a resistor is proportional to the square of rms current value, this value of the current pulses needed to be measured accurately. For this reason the sample rate was set to 100 kHz to capture the variable current pulses with adequate resolution (fundamental frequency to a few kHz). The rms value from these samples was then calculated:

$$I_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} i_n^2} \tag{1.1}$$

Where i_n is the n-th current sample and N is the total number of samples during the 0.5 s saving period.

- Actual vehicle speed

A pulse output from the speed sensor was carried out from the Regulator through free pins on a connector to the auxiliary circuit board, where an appropriate voltage divider was realized to match the voltage level to the digital input of the NI 9401 digital measurement card.

The results were written to an USB flash disk every minute. The trolleybus was then put into regular service on selected routes and data from the flash disk were regularly (once a day) copied and then processed in MATLAB software. For the purpose of calculating losses on the trolley supply network, a relationship between actual resistance of the trolley network and the position on a particular route needs to be known (details see Chap. 4.2.2). Based on this procedure the following results were obtained:

Set of graphs 1 (for each route):

- Energy delivered from the trolley vs. time
- Energy wasted on the braking resistor vs. time
- Energy wasted on supply internal resistance vs. time
- Vehicle speed vs. time
- Driven distance vs. time

Set of graphs 2 (discrete, for each route):

- Total energy delivered from trolley vs. consecutive number of drive (whole route loop)
- Total energy delivered from trolley vs. consecutive number of drive (whole route loop)
- Total energy wasted on the braking resistor vs. consecutive number of drive (whole route loop)
- Total energy wasted on trolley supply resistance vs. consecutive number of drive (whole route loop)
- Peak value of trolley current vs. consecutive number of drive (whole route loop)
- Peak value of rms current through the braking resistor vs. consecutive number of drive (whole route loop)

For the purpose of energy storage tank dimensioning, considering the ability of independent traction (for details see Chap. 5.1), another discrete graph set was created:

- Maximum energy delivered from trolley for any 2 km section vs. route number and consecutive number of drive
- Total energy wasted on the braking resistor for the above selected section vs. route number and consecutive number of drive
- Maximum rms current through the braking resistor for the above selected section vs. route number and consecutive number of drive

4.2 Measurement results

4.2.1 Examples of recorded data

An example of measured data (actual trolley voltage, actual trolley current, actual rms braking resistor current, speed) can be seen in Fig. 4.1. A detailed graph of trolley current and braking resistor current can be seen in Fig. 4.2.

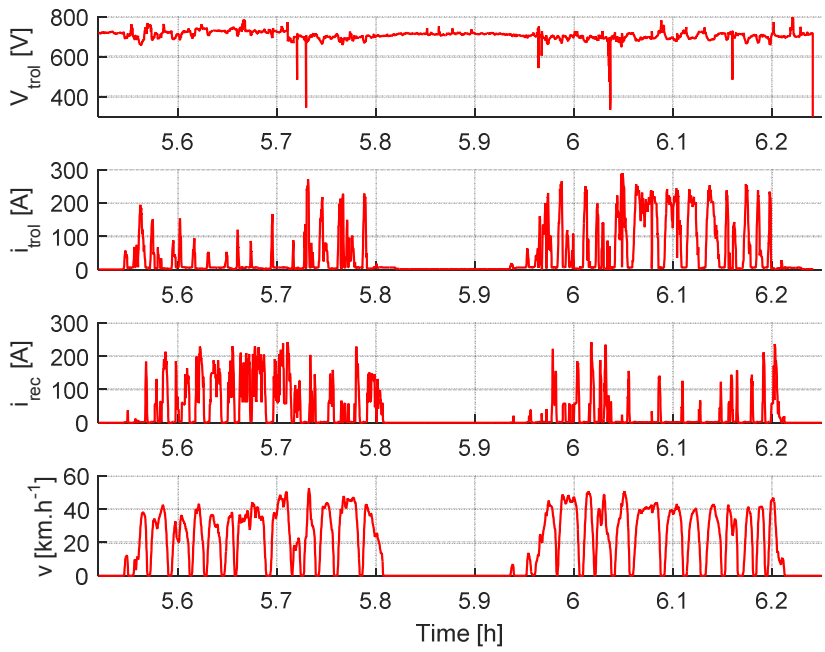


Fig. 4.1 Example of measured data

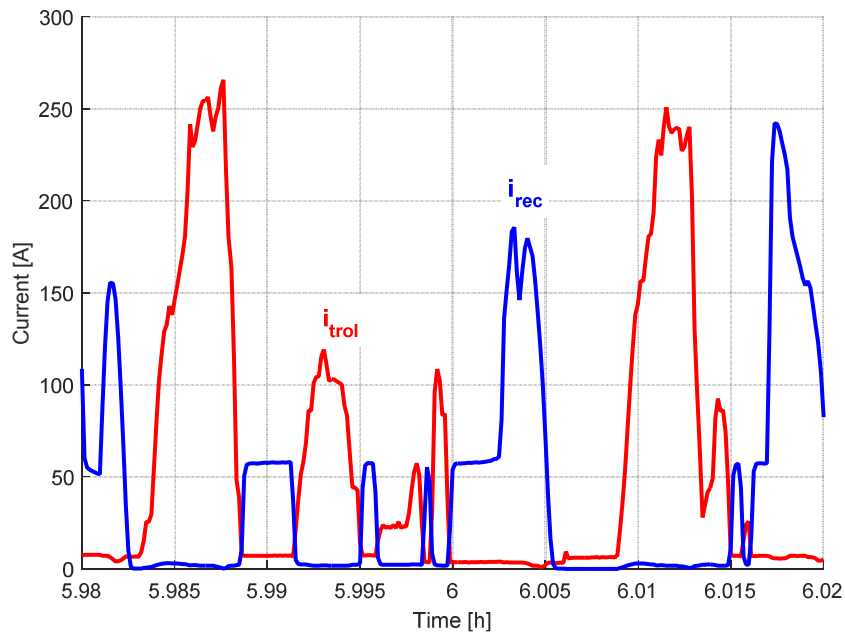


Fig. 4.2 Detail of trolley current (average value, red) and braking resistor current (rms value, blue)

4.2.2 Calculation of supply network internal resistance

A knowledge of the supply resistance is necessary for analysis of losses on the supply network. The DPMB trolleybus trolley supply network is divided into several separately supplied sections. The feeder lines for individual sections have different lengths and further there are often situations like doubled lines etc. The resistance varies continuously throughout the length of a particular section (in the feeder line connection the resistance is minimal). This complex situation was approximately resolved by calculating an average resistance value of supply network for every supplied section (calculated by DPMB). Results are given in Tab. 4.1.

Tab. 4.1 Average resistance of supply network for each supplied section (by Ing. Jan Kopřiva, DPMB)

Section number	***Route number***	***Localization***	***Average resistance / Ω /***	***Section length /m /***
11	25, 26, 35, 37	Mendlovo namesti	**0.079**	320
13	25, 26	Uvoz	**0.11**	1042
50	32, 34, 36	Brandlova - Kounicova	**0.147**	489
51	32, 34, 36	Kounicova	**0.101**	610
52	32	Chodska	**0.136**	1400
53	32	Charvatska – Srbska	**0.14**	1271
54	30	Palackeho - KPN	**0.07**	981
65	34, 36	Tabor	**0.052**	987
66	34, 36	Kounicova	**0.052**	725
68	34, 36	Korejska - Vychodilova	**0.065**	1224
69	30	Kralovopolska - Skacelova	**0.112**	1306
80	38, 39	Komenskeho namesti – Udolni	**0.033**	744
81	25, 26, 35, 38, 39	Uvoz	**0.047**	670
82	25, 26, 37	Hlinky	**0.078**	1100
82	25, 26, 35, 37	Mendlovo namesti - Hlinky	**0.034**	280
83	25, 26, 37	Hlinky – Pisarecka	**0.046**	1136
84	37	Ant. Prochazky - Libusina trida	**0.081**	938
85	37	Libusina trida	**0.07**	704
86	37	Libusina trida	**0.092**	1151
87	37	Libusina trida - Jirovcova	**0.096**	1212
88	35, 38, 39	Tvrdeho	**0.184**	567
88	35, 39	Barvicova	**0.125**	1026
88	38	Preslova	**0.13**	1272
109	25, 26	Rybnicka	**0.173**	1227
111	25, 37	Osova - Netroufalky	**0.173**	1476
133	30, 36	Kroftova - Stursova	**0.136**	750
134	30,36	Hlavni	**0.065**	1073
135	30	Namesti 28. dubna - Bystrcka	**0.12**	2191
136	30	Odbojarska – Namesti 28. dubna	**0.072**	800
137	30	Cerneho	**0.181**	1067
151	25, 26	Pionyrska - Drobneho	**0.158**	483

152	25, 26	Drobneho - Provaznikova	**0.113**	1070
153	25, 26	Provaznikova	**0.163**	846
158	25, 26	Kotlarska – Pionyrska	**0.097**	688
159	25, 26	Provaznikova - Svatoplukova	**0.093**	1100
160	25, 26, 27	Svatoplukova	**0.186**	677
161	25, 26, 27	Rokytova – Zarosicka	**0.131**	1007
162	25, 26, 27	Zarosicka – Vestonicka	**0.165**	1909
163	25, 26	Novolisenska - smycka	**0.126**	970
164	36	Hlavni – Komin smycka	**0.21**	1171
167	25, 26	Petra Krivky – Rybnicka	**0.091**	1377
168	26, 37	Kamenny Vrch smycka - Petra Krivky	**0.052**	984
169	37	Chironova	**0.112**	960

For the purpose of calculating losses on the supply network for each route number, a constant (equivalent) resistance value was calculated individually for each route as a weighted average value (weights based on section lengths) of resistances of sections included in the route of interest. The results are given in Tab. 4.2.

Tab. 4.2 Equivalent constant resistance values for individual route numbers

route	***resistance / Ω /***
25	0.117
26	0.112
27	0.159
30	0.108
32	0.133
34	0.075
35	0.104
36	0.102
37	0.077
38	0.101
39	0.096

4.2.3 Energy balance vs. time

In Fig. 4.3 an energy delivered from trolley vs. time (E_{trol}), energy wasted on the braking resistor (E_{rec}) and energy wasted on supply resistance (E_{trans}) for route number 25 can be seen in the upper graph. Driven distance vs. time is displayed in the middle graph and speed vs. time is plotted in the bottom graph.

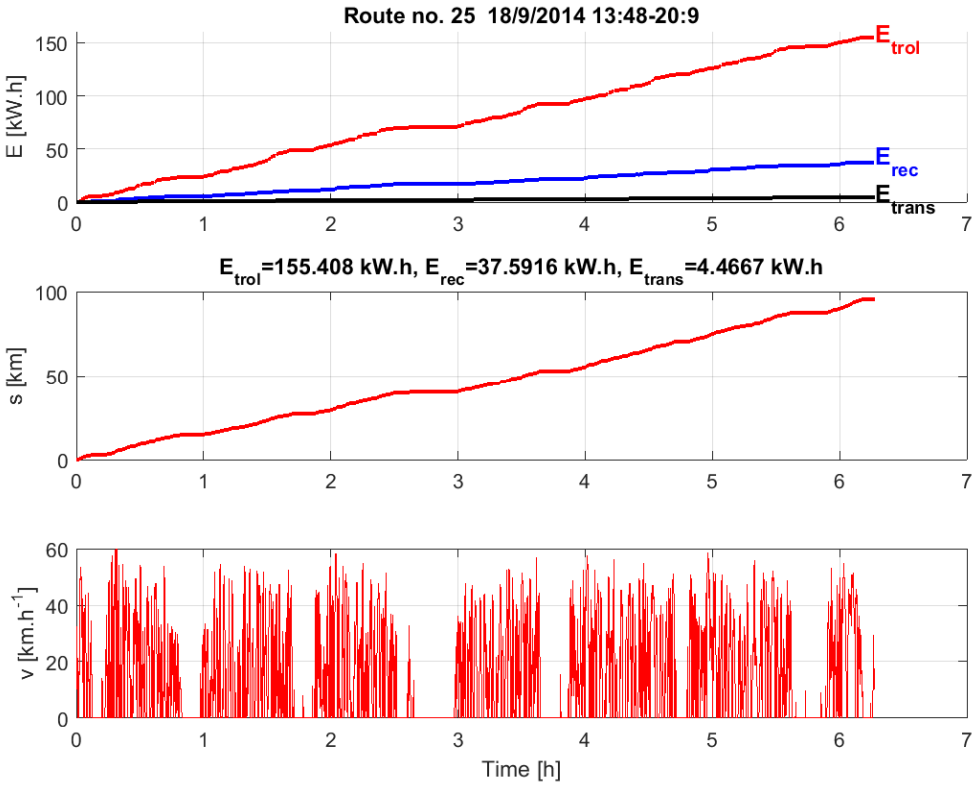


Fig. 4.3 Energy balance – route number 25

The results mentioned above were calculated from measured currents, voltage and speed, see Chap. 1. Energy E_{trol} is a time integral of actual power delivered from the trolley – a product of instantaneous trolley voltage and instantaneous trolley current:

$$E_{trol} = \int p_{trol}(t)dt = \int v_{trol}(t) \cdot i_{trol}(t)dt \tag{4.1}$$

Energy E_{rec} is a time integral of instantaneous power loss on the braking resistor, which is given as a product of braking resistor resistance and square of instantaneous current:

$$E_{rec} = \int p_R(t)dt = \int R \cdot i_R^2(t)dt \tag{4.2}$$

where R is resistance of the braking resistor.

The current through the braking resistor has a shape of approximately rectangular pulses with variable height, frequency and duty cycle. As shown in Chap. 4.1, the software in CompactRIO continuously performed calculations of actual rms current value through the braking resistor (related to the short time interval of 0.5 s). Considering this the equation (4.2) can be rewritten as:

$$E_{rec} = \int p_R(t)dt = \int R \cdot i_R^2(t)dt = R \cdot \sum_{n=1}^{K} \Delta t \cdot I_{rms,n}^2 \tag{4.3}$$

where K is number of all measured (calculated) rms current value samples and Δt is the sample calculation period (0.5 s).

The energy E_{trans} is a time integral of instantaneous power loss on the supply network, which is given as a product of supply network resistance (trolley resistance) and square of instantaneous current drawn from the trolley:

$$E_{trans} = \int p_{trans}(t)dt = \int R_{trans} \cdot i_{trol}^2(t)dt \tag{4.4}$$

The speed is recalculated from the output of a speed sensor in the vehicle. The driven distance is then a time integral of speed.

In Fig. 4.4 to 4.9 are similar graphs for other route numbers – 26, 30, 32, 34, 36 and 37. These are measurement results for particular time intervals. Other results for the same route numbers but for different time intervals are shown in the attachment. The difference in results for the same route number is caused by number of passengers, traffic and driving style (actual driver).

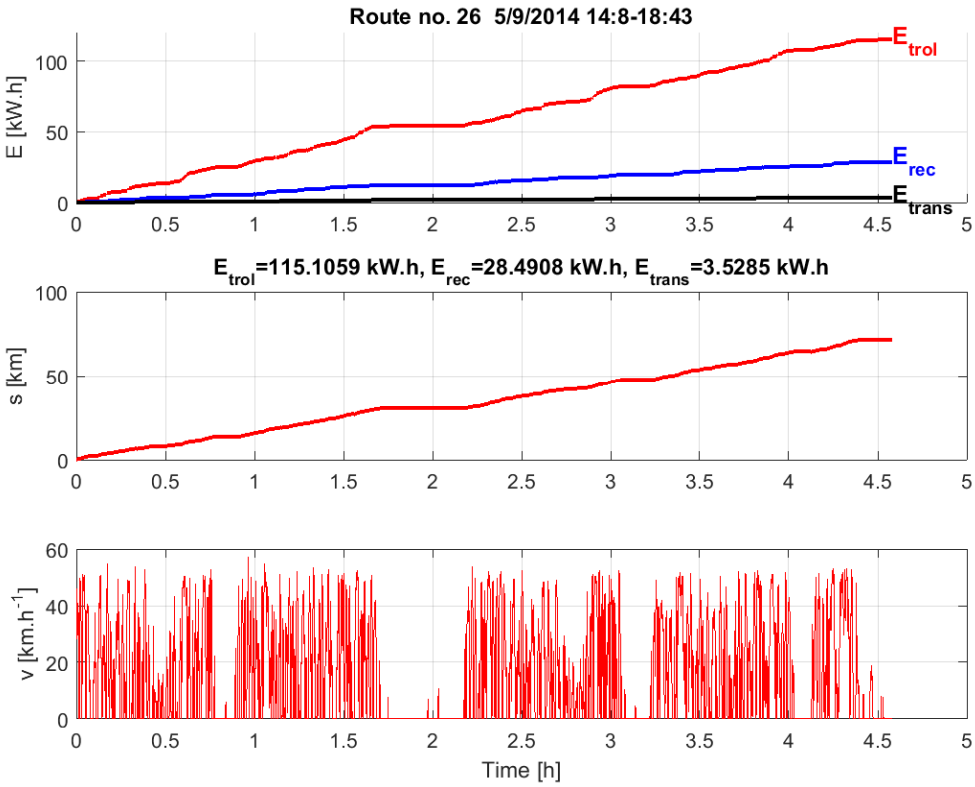


Fig. 4.4 Energy balance – route number 26

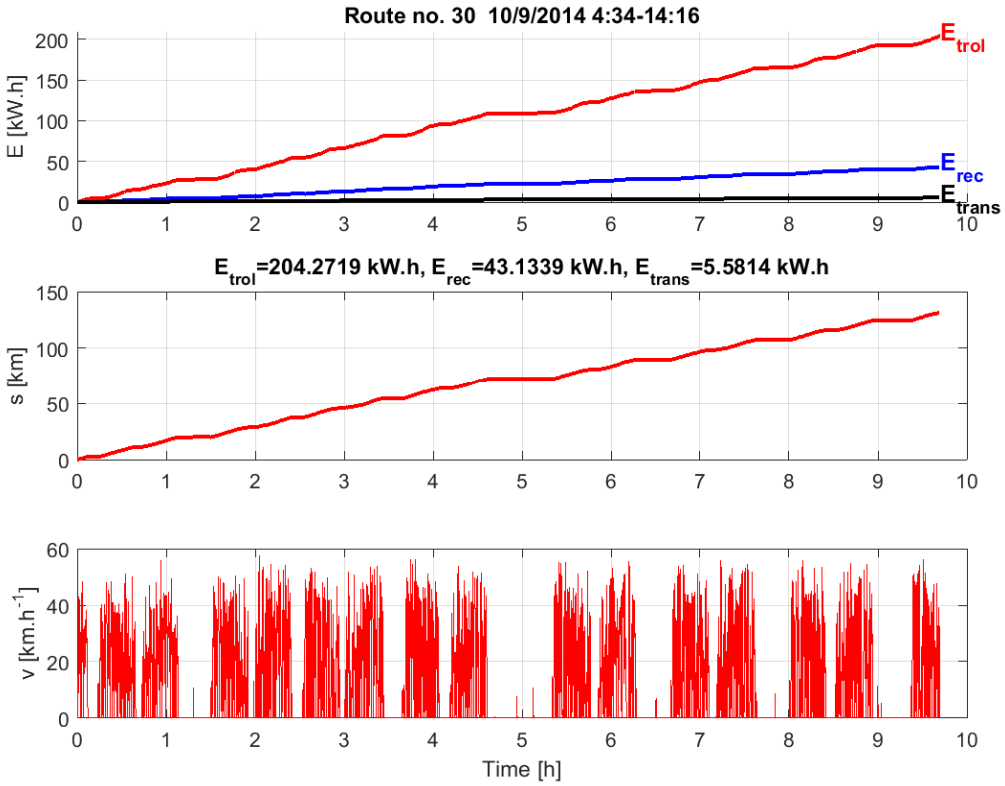


Fig. 4.5 Energy balance – route number 30

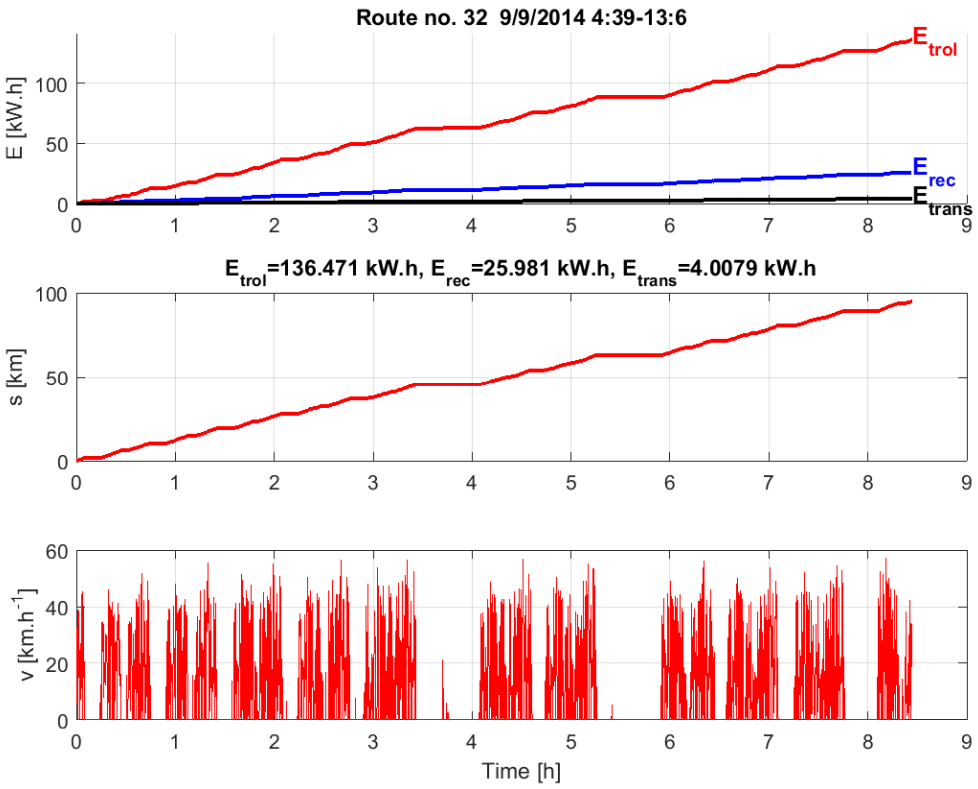


Fig. 4.6 Energy balance – route number 32

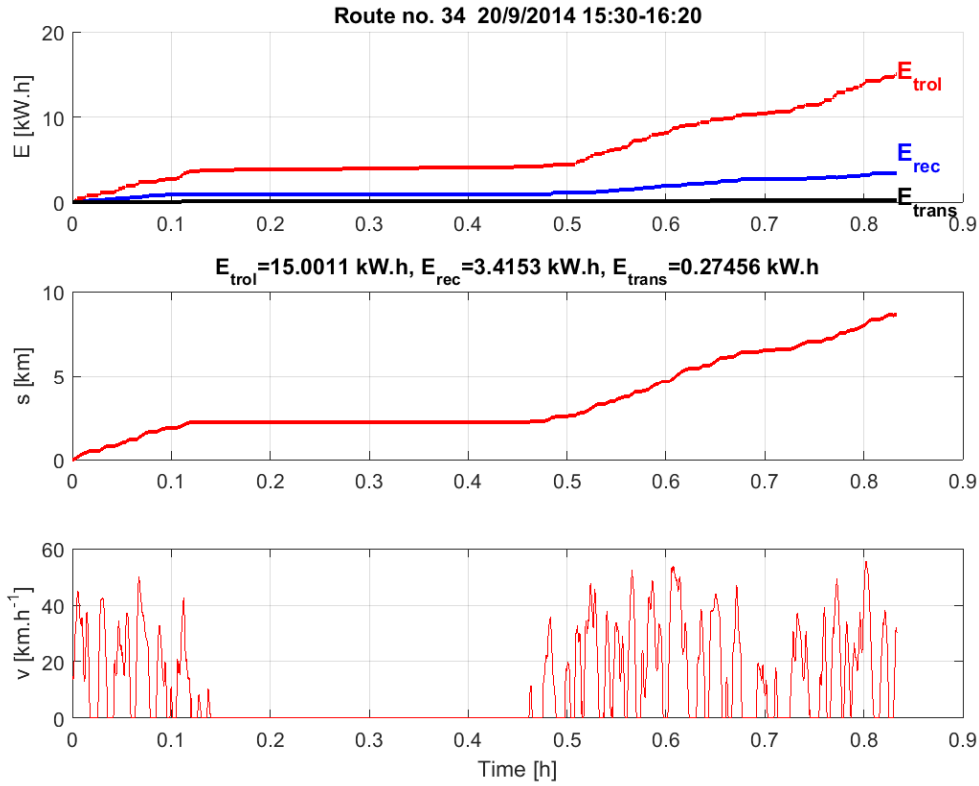


Fig. 4.7 Energy balance – route number 34

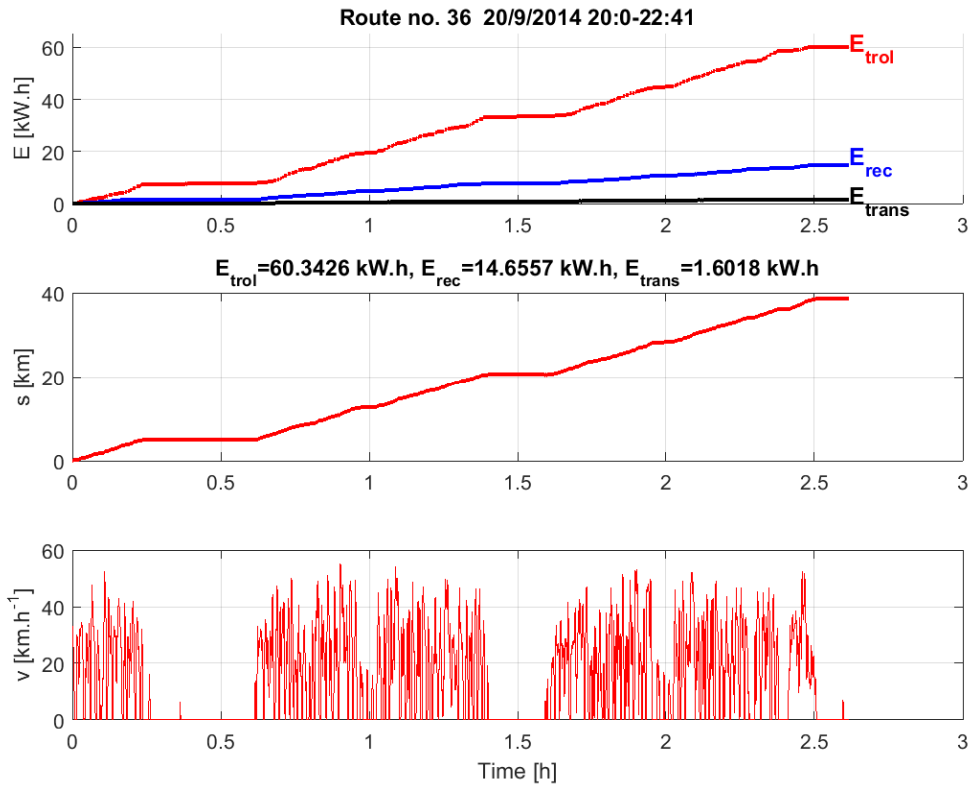


Fig. 4.8 Energy balance – route number 36

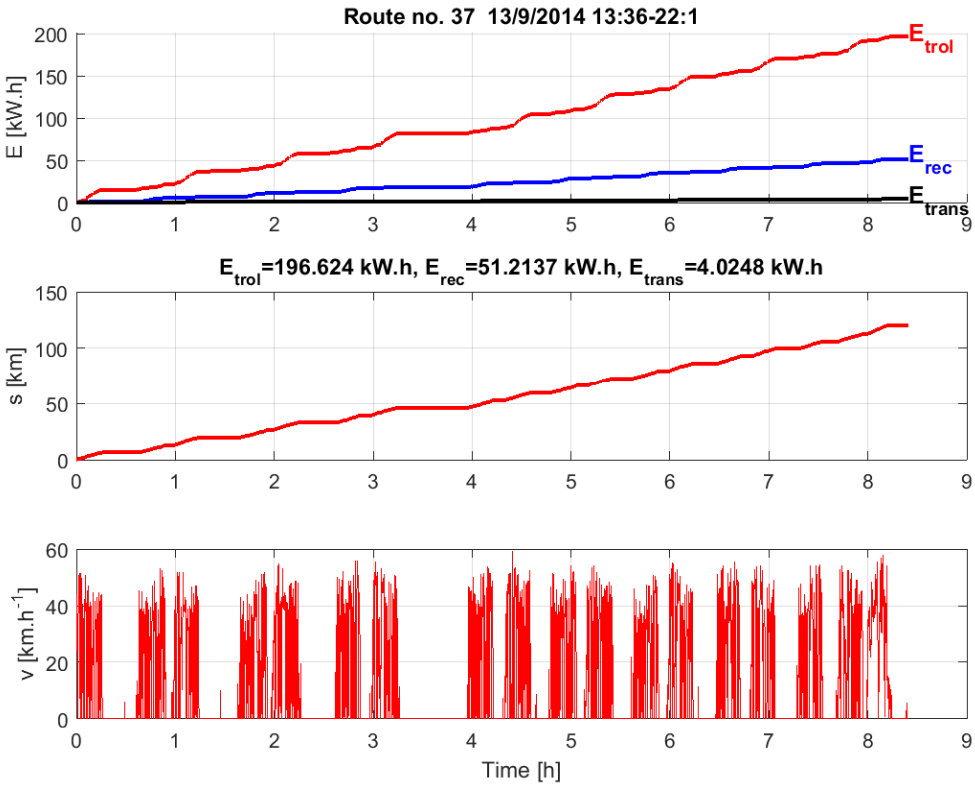


Fig. 4.9 Energy balance – route number 37

4.2.4 Processing of measurement results

Summarized measurement results are in Tab. 4.3. Here the total (final) energies E_{trol}, E_{rec} and E_{trans} for various work shifts on all measured routes are stated (together with the highest rms current of the braking resistor and the total driven distance). The energy E_{rec} wasted in the braking resistor is expressed also relatively – as a percentage of the energy E_{trol} delivered from the trolley.

Tab. 4.3 Total energy balance for various routes and work shifts

Route	Date	Course	From	Till	Driver	E_{trol} [kW.h]	E_{rec} [kW.h]	E_{rec}/E_{trol} [%]	E_{trans} [kW.h]	s [km]
25	4.9.2014	02529	6:16	9:38	Dostal Rudolf	90.93	23.76	26.13	2.83	54.77
25	4.9.2014	02521	13:48	20:09	Parenica Milan	150.21	36.68	24.42	4.54	93.81
25	12.9.2014	02529	6:16	9:38	Valenta Petr	87.24	20.10	23.04	2.32	54.87
25	12.9.2014	02521	13:48	20:09	Valenta Milan	150.99	33.47	22.17	4.03	95.13
25	18.9.2014	02529	6:16	9:38	Tupy Michal	87.87	21.71	24.71	2.64	54.82
25	18.9.2014	02521	13:48	20:09	Josefik Pavel	155.41	37.59	24.19	4.47	95.49
26	4.9.2014	02529	4:49	6:16	Dostal Rudolf	34.07	7.16	21.00	0.84	22.21
26	5.9.2014	02621	4:39	9:09	Julinek Petr	128.97	34.57	26.81	3.96	75.84

26	5.9.2014	02621	14:08	18:43	Spacek Jan	115.11	28.49	24.75	3.53	71.68
26	12.9.2014	02529	4:49	6:16	Valenta Petr	34.44	6.23	18.09	0.81	22.20
26	15.9.2014	02621	4:39	9:09	Spacek Jan	127.09	30.67	24.13	4.17	75.73
26	15.9.2014	02621	14:08	18:43	Novak Ladislav	115.12	27.91	24.24	3.46	72.08
26	18.9.2014	02529	4:49	6:16	Tupy Michal	38.54	8.05	20.88	1.10	22.92
30	3.9.2014	03019	5:42	14:43	Kozak Jiri	193.94	41.05	21.17	4.21	122.34
30	3.9.2014	03019	14:43	23:23	Tucek Petr	193.70	43.64	22.53	5.52	119.76
30	8.9.2014	03009	4:34	14:16	Carvas Vojtech	194.94	38.73	19.87	4.88	131.14
30	8.9.2014	03009	14:16	23:04	Navratil Vilem	173.24	36.93	21.32	4.46	120.41
30	10.9.2014	03009	4:34	14:16	Winkler Zdenek	204.27	43.13	21.12	5.58	131.65
30	10.9.2014	03009	14:16	23:04	Mlcoch Lubomir	175.28	37.92	21.63	4.49	120.23
32	9.9.2014	03201	4:39	13:06	Dolezal Frantisek	136.47	25.98	19.04	4.01	94.88
32	9.9.2014	03201	13:06	21:24	Petlach Jiri	148.64	32.25	21.69	4.96	94.53
32	16.9.2014	03207	14:41	19:21	Tyrner Miroslav	87.67	16.78	19.14	2.70	56.98
32	19.9.2014	03201	4:39	13:06	Vlacil Zdenek	165.98	37.24	22.44	5.86	94.65
32	19.9.2014	03201	13:06	21:24	Bukacek Pavel	175.92	43.36	24.65	6.64	95.60
32	21.9.2014	03201	14:34	21:24	Petlach Jiri	126.01	26.84	21.30	4.01	86.25
32	21.9.2014	03201	7:40	14:34	Sevela Rostislav	121.95	24.87	20.39	3.69	86.65
34	20.9.2014	03601	9:30	10:20	Sterc Richard	15.13	3.48	23.01	0.27	8.75
34	20.9.2014	03601	11:30	12:20	Sterc Richard	15.47	3.68	23.76	0.29	8.47
34	20.9.2014	03601	13:30	14:20	Sterc Richard	15.41	3.72	24.17	0.29	8.60
34	20.9.2014	03601	15:30	16:20	Navratil Vilem	15.00	3.42	22.77	0.27	8.68
34	20.9.2014	03601	17:30	18:20	Navratil Vilem	17.05	3.85	22.60	0.34	9.05
34	20.9.2014	03601	19:30	20:00	Navratil Vilem	14.29	3.17	22.21	0.27	8.93
36	20.9.2014	03601	5:44	9:30	Sterc Richard	92.84	20.78	22.38	2.15	56.07
36	20.9.2014	03601	10:20	11:30	Sterc Richard	23.17	5.20	22.45	0.52	13.99
36	20.9.2014	03601	12:20	13:30	Sterc Richard	26.69	6.27	23.48	0.67	14.66
36	20.9.2014	03601	14:20	14:35	Sterc Richard	8.57	2.23	26.03	0.24	4.59
36	20.9.2014	03601	14:35	15:30	Navratil Vilem	16.97	3.66	21.58	0.41	9.80
36	20.9.2014	03601	16:20	17:30	Navrátil Vilém	26.03	5.98	22.97	0.69	13.99
36	20.9.2014	03601	18:20	19:30	Navratil Vilem	24.82	5.71	23.02	0.66	14.18
36	20.9.2014	03601	20:00	22:41	Navratil Vilem	60.34	14.66	24.29	1.60	38.59
37	5.9.2014	02621	9:09	9:47	Julinek Petr	10.12	2.59	25.63	0.15	9.18
37	5.9.2014	02621	13:15	14:08	Spacek Jan	23.29	5.94	25.51	0.52	13.07
37	6.9.2014	03703	6:10	14:46	Buchta Jan	198.25	53.65	27.06	3.92	120.36
37	6.9.2014	03703	14:46	23:14	Stancl Rostislav	206.90	52.84	25.54	4.40	120.28
37	7.9.2014	03709	6:40	14:26	Mlcoch Lubomir	172.24	46.53	27.01	3.46	107.61
37	7.9.2014	03709	14:26	22:59	Kozak Jiri	194.43	48.03	24.70	3.16	119.68
37	11.9.2014	03707	5:36	14:51	Havranek Vladimir	220.61	55.81	25.30	3.92	133.65
37	11.9.2014	03707	14:51	23:29	Ancinec Jiri	236.66	54.18	22.89	4.84	137.82
37	13.9.2014	03701	6:08	13:36	Kozak Jiri	173.84	43.09	24.78	2.78	103.90
37	13.9.2014	03701	13:36	22:01	Mlcoch Lubomir	196.62	51.21	26.05	4.02	120.53
37	14.9.2014	03703	6:10	14:46	Navratil Vilem	197.10	52.35	26.56	4.11	121.27
37	14.9.2014	03703	14:46	23:14	Hasa Boris	193.09	46.08	23.87	3.47	120.44

37	15.9.2014	02621	9:09	9:47	Spacek Jan	11.84	3.98	33.61	0.24	10.20
37	15.9.2014	02621	13:15	14:08	Novak Ladislav	21.95	5.05	23.01	0.41	13.79
37	17.9.2014	03707	5:36	14:51	Eichler Stanislav	235.52	63.75	27.07	5.14	133.82
37	17.9.2014	03707	14:51	23:29	Grygar Oldrich	234.28	59.02	25.19	4.57	137.61

Further the ratio between the sum of all energies wasted on the braking resistors and the sum of all energies delivered from the trolley was calculated (average percentage of the regenerative braking energy for all measurements):

$$A = \frac{\sum E_{rec}}{\sum E_{trol}} \cdot 100 = \frac{1495.02}{6312.52} \cdot 100 = 23.7\% \tag{4.5}$$

Also the ratio between the sum of all energy losses in the trolley and the sum of all energies delivered from the trolley was calculated:

$$B = \frac{\sum E_{trans}}{\sum E_{trol}} \cdot 100 = \frac{157.49}{6312.52} \cdot 100 = 2.5\% \tag{4.6}$$

From the measurement results in Tab. 4.3 the average value of the consumed energy per 1 km was calculated using following equation (4.7):

$$E_{km} = \frac{1}{N} \sum_{i=1}^{N} E_{trol,i} / s_i = 1.66 \text{ kWh/km} \tag{4.7}$$

This energy would be decreased utilizing the braking energy using the energy storage tank (at a theoretical efficiency of 100%) to the following value:

$$E'_{km} = \frac{1}{N} \sum_{i=1}^{N} \left(E_{trol,i} - E_{rec,i}\right) / s_i = 1.268 \text{ kWh/km} \tag{4.8}$$

However the equation (4.8) does not assume losses in the matching DC/DC converter (which is necessary for the energy storage tank) and losses in the energy storage tank itself (charging/discharging efficiency). These losses must be taken into consideration in the case of storing the energy to the storage tank and also in the case of backward energy delivery to the system. The corrected calculation of the average consumed energy per 1 km can be expressed by (4.9) for the case of battery and (4.10) for the case of ultracapacitor as the energy storage tank:

$$E'_{km-BAT} = \frac{1}{N} \sum_{i=1}^{N} \left(E_{trol,i} - E_{rec,i} \cdot \eta_{DC/DC}{}^{2} \cdot \eta_{BAT}{}^{2}\right) / s_i = 1.37 \text{ kWh/km} \tag{4.9}$$

$$E'_{km-CAP} = \frac{1}{N} \sum_{i=1}^{N} \left(E_{trol,i} - E_{rec,i} \cdot \eta_{DC/DC}{}^{2} \cdot \eta_{CAP}{}^{2}\right) / s_i = 1.33 \text{ kWh/km} \tag{4.10}$$

Where η_{BAT} is the battery efficiency, see chap. 6.3.1 and η_{CAP} is the ultra-capacitor efficiency, see chap. 6.2.1.

4.2.5 Conclusions from the energy balance measurement

1) The measurement of energy balance was performed for a long time on 7 chosen routes 25, 26, 30, 32, 34, 36 and 37. These routes were chosen by DPMB as representative ones. It can be deduced from the performed calculation (4.5) that the average percentage of braking energy being wasted in the braking resistors of the trolleybuses is about 24% from the total energy delivered to these trolleybuses from the trolley.

2) When including also the losses in the trolley - by the calculation of the ratio $E_{rec}/(E_{trol} + E_{trans})$ instead of E_{rec}/E_{trol} – certainly a lower value of the braking energy percentage is obtained because not only the total energy delivered to the trolleybuses is used in the percentage calculation but also the energy wasted in the trolley during supplying the trolleybuses. Since the total energy wasted in the trolley is only 157.5 kWh a similar result as in 1) is obtained – namely 23.1 %.

3) The energy loss in the trolley represents only ca. 2.5 % of the energy delivered from this trolley to the trolleybuses. However this result is too optimistic - it is true only if just one trolleybus is driving in the trolley section. The trolley loss power is proportional to the square of total delivered current which is certainly more than the sum of squares of individual currents (for more trolleybuses in one trolley section).

5. Estimation of required usable energy and peak power of the energy storage tank

5.1 Energy of the storage tank with respect to the regenerative braking

An example of regenerative braking must be found in the measurement results where the maximum energy was wasted in the braking resistor. Certainly this must be the minimum energy dimensioning of the energy storage tank.

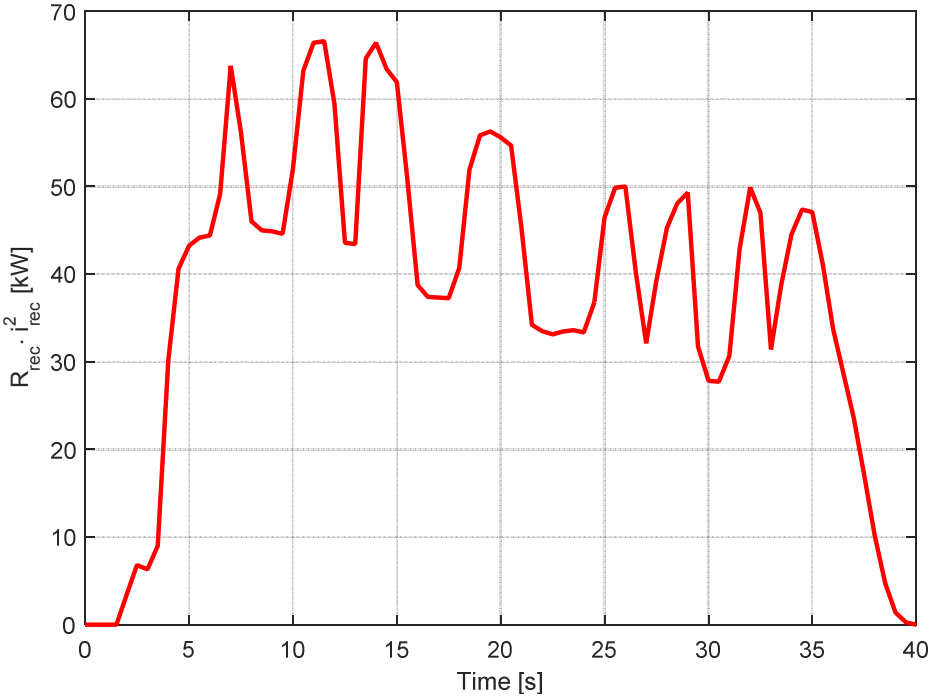


Fig. 5.1 Waste power of the braking resistor – found representative example with maximum waste energy (found in route 37)

The case of regenerative braking which can be assumed as a representative one can be observed in Fig. 5.1. This situation was found in the route no. 37 and the highest braking energy wasted in the braking resistor was calculated at 0.425 kWh (time integral of the power during the braking time - area under the power curve in Fig. 5.1.).

Therefore the energy dimensioning of about 0.5 kWh would be enough without respect to the demand of an independent drive without trolley.

5.2 Energy of the storage tank with respect to independent drive

The requirement on independent drive without trolley can be taken into consideration when dimensioning the energy storage tank. Firstly an adequate detour distance must be determined and the energy of the tank must be matched to it.
The per cent representation of detours according to their driving distances is in Tab. 5.1. It is clear from Tab. 5.1 detour distances are shorter than 2 km in 94 % of all cases. This is why the distance of 2 km was chosen as a criteria for the energy dimensioning of the energy storage tank with respect to the detour driving (without trolley).

Tab. 5.1 Statistics of detours in years 2012 - 2013

Detour distance	Number of detours	Per cent representation in the whole number of detours
to 100 m	5	11%
101 m – 200 m	7	15%
201 m – 400 m	4	9%
401 m – 600 m	7	15%
601 m – 1000 m	4	9%
1001 m – 1500 m	10	22%
1501 m – 2000 m	6	13%
2001 m and more	3	6%

The energy situation in the most energy-demanding section of 2 km for each route and also for each work shift in each route is in Fig. 5.2. The energy delivered from trolley in this section, energy wasted in the braking resistor in this section and also the peak rms current of the braking resistor in this section are displayed. All these quantities are dependent on the corresponding route and work shift on the route.

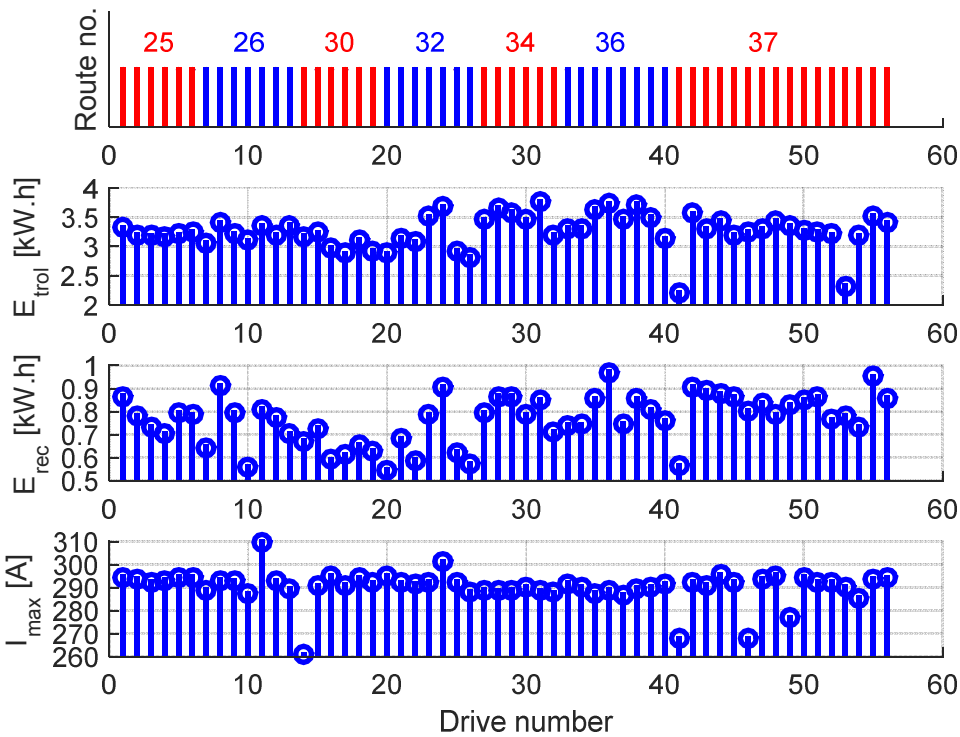


Fig. 5.2 Energy situation in the most energy-demanding section of 2 km for each route and route work shift

The energy of the storage tank necessary for supplying the trolleybus in the mentioned 2 km section can be obtained subtracting the wasted braking energy E_{rec} from the energy delivered from the trolley. Analyzing the Fig. 5.2 we can find the worst case with the maximum energy demand which is about 3 kWh (difference of the energy delivered from trolley and energy wasted in the braking resistor).
Therefore we choose the usable energy of the storage tank ca. 4 kWh to ensure some robustness.

5.3 Peak power and current of the energy storage tank

5.3.1 Charging during regenerative braking

From Fig. 5.2 it is obvious that the maximum measured rms current of the braking resistor is approx. 300 A (the singular peak 310 A is considered to be a measurement inaccuracy caused by interference).

The variable voltage of the braking resistor is generally different from the voltage of the energy storage tank. This is why the mentioned resistor current must be re-calculated to the charging current of the energy storage tank. The storage tank (ultracapacitor or $LiFePO_4$ battery) will be connected to the DC link (trolley) through a bi-directional DC/DC converter which performs (theoretically) a lossless power transfer form one voltage level to another. Therefore we calculate firstly the peak regenerative braking power (being actually wasted in the resistor):

$$P_{rec,\max} = R \cdot I_{RMS,\max}^2 = 1{,}69 \cdot 300^2 = 152.1 \text{ kW} \tag{5.1}$$

If the ultracapacitor will be used then its voltage will be varying from approx. 300 V to approx. 600 V (see Chap. 3.2 and Chap. 6.2.1 b) for explanation). If a battery will be used then the voltage will be approx. 600 V (constant).

In the case of ultracapacitor the maximum charging current will be at the minimum voltage of 300 V:

$$I_{C,\max} = \frac{P_{rec,\max}}{V_{C,\min}} = \frac{152.1 \cdot 10^3}{300} = 507\text{A} \tag{5.2}$$

Therefore at the nominal ultracapacitor voltage of 600 V the current will be only half – approx. 250 A.

In the case of battery with nominal voltage of 600 V the current corresponding to the maximum charging power of 152 kW will also be 250 A.

5.3.2 Discharging

In the discharging process the energy storage tank will be dimensioned for the maximum power delivered normally from the trolley found out in the measurement. This way the independent drive without the trolley will be guaranteed without necessity of modification of the traction converter control circuits to decrease the traction power. Analyzing the measured trolley currents we find out the maximum DC trolley current of ca 300 A. Considering trolley voltage of 600 V this represents a peak power of 180 kW.

Note: A higher peak power delivered from the trolley was found out during the measurements (over 200 kW) because the trolley voltage was usually higher – about 700 V, up to 750 V. However during the independent drive without trolley we can limit the power slightly just to 180 kW by control of the DC/DC converter connected between the energy storage tank and DC-link of the traction converter (trolley).

In the case of ultracapacitor with a voltage near to the minimum value of 300 V this power corresponds to a discharging ultracapacitor current of 600 A. In the case of $LiFePO_4$ battery with a nominal voltage of 600 V the corresponding maximum discharging current will be 300 A.

6. Energy storage tank

6.1 Basic requirements and usage

A storage tank with an energy capacity of 0.5 kWh (only the regenerative braking energy will be stored) or 4 kWh (not only the regenerative braking energy will be stored but also an independent drive to 2 km distance is considered) is demanded according to the measurement results.

A peak discharge power of 180 kW and a peak charge power of 152 kW must be allowed. **It is obvious from these values that an energy tank with high ratio of demanded peak power to the accumulated energy is required (power of 180 kW, energy only 0.5 kWh respectively 4 kWh).**

Conventional batteries (lead-acid, NiCd etc.) are absolutely not able to reach these contradictory parameters. Much higher capacity (energy) of these batteries than demanded would be necessary to allow the demanded power. This would cause an unrealistic weight and price. There are only two solutions acceptable from the technical and economical point of view: **Ultracapacitors or $LiFePO_4$ batteries.**

6.2 Ultracapacitor design

6.2.1 Suitable cells selection and dimensioning of the ultracapacitor

a) Cells selection

At least 30 companies in the world produce ultracapacitors. A parameter overview of cells from some manufacturers is in Tab. 6.1. Only cells with sufficient capacitance and acceptable low internal resistance are included. The relatively low cell voltage is a common property of all cells (see Tab. 6.1).

Tab. 6.1 Ultracapacitor cell parameters – various manufacturers

Manufacturer	Cell cap. [F]	Cell nom. voltage [V]	Cell int. resist. [mΩ]	Energy density [Wh/kg]
CDE	3000	2.7	0.29	6
Elton	10000	1.5	0.5	4.2
Illinois	3500	2.7	0.29	5.9
Ioxus	3000	2.7	0.26	6.0
Korchip	400	2.7	12	6.1
LS Mtron	3000	2.8	0.25	5.9
Maxwell	**3400**	**2.7**	**0.29**	**6.0**
Nichicon	6000	2.7	2.2	4
NCC	2300	2.5	1.2	4.1
Samwha	3000	2.7	0.28	5.6
Skeleton	**3500**	**2.85**	**0.2**	**10.1**
VinaTech	800	3.0	10	6.3
WIMA	6500	2.7	0.18	4.3
YEC	400	2.7	12	5.5
Yunasko	1700	2.7	0.17	5.8

Note.: The real usable energy density considering the capacitor discharging from the nominal voltage to one half of the nominal voltage (not to zero – with respect to the efficiency of the matching DC/DC converter) is a bit lower than shows Tab. 6.1, see equation (6.1) for explanation.

The manufacturers mentioned in Tab. 6.1 produce also cells with a lower capacitance, however the volume- and weight-energy density of these cells is lower (influence of packaging and contacts). Also whole modules i.e. series-parallel packs with a larger number of cells including balancing circuits and with a compact packaging are available in the market. However the nominal voltage of these modules is usually lower than 150 V. We assume it is more advantageous from price and also building-in reasons to construct an individual module (purchasing only the cells).

Special attention should be paid to the cells from the German company **Skeleton Technologies, GmbH.** The company was founded in Dresden in March of 2013 and it is supposed to be a strategic supplier of ultracapacitors in Germany (respectively in the whole European Union). The massive financial support to the development department of this company from European Union resources supports this claim. Already today the Skeleton cells provide a weight energy density about 70 % higher and also rather lower internal resistance than proved cells from **Maxwell (representing a world standard).** According to the available information the company Skeleton sells their cells only by itself – they are not available from various distributors of electronic components or batteries (see http://skeletontech.com/where-to-buy). Their price is not higher in comparison e.g. with the Maxwell cells, probably Skeleton is slightly cheaper. With respect to future applications it is suitable to observe the production of Skeleton, already now their capacitors offer the best weight- energy density in the world (see Tab. 6.1). Also the rectangular housing of Skeleton cells is advantageous for achieving lower total dimensions of a pack containing a larger number of cells.

Nevertheless the cells from Californian Maxwell Technologies (http://www.maxwell.com) with factories not only in USA but also in Swiss, Germany, China and South Korea were used in further designs and calculations. Maxwell is a traditional world manufacturer with proved quality, reliability and mass production. Also we can see in Tab. 6.1 that the Maxwell cells belong to the best ones (disregarding the excellent new Skeleton) – i.e. they provide a low

internal resistance and high energy density at a given capacitance value. Comparable to these parameters are e.g. cells Cornell Dubilier Electronics (CDE) and Ioxus.

The ultracapacitor can be advantageously completed using cells Maxwell Technologies 3000 F with nominal voltage 2.7 V (maximum steady-operation DC voltage of the cell), type BCAP3000 P270 K04. Technical parameters of the cell BCAP3000 are in Tab. 6.2.

Tab. 6.2 Technical parameters of the cell BCAP3000 (3000 F/ 2.7 V Maxwell)

Nominal capacitance (begin of life-tome)	3000 F
Internal resistance (begin of life-time)	0.29 mΩ
Nominal voltage	2.7 V
Peak voltage (max. 1 sec, non-repetitive)	2.85 V
Leakage current at the nominal voltage, steady state after 72 hours and temperature 25 °C	5.2 mA
Operation temperature	-40 °C to +65 °C
Storage temperature	-40 °C to +70 °C
Weight	510 g
Dimensions	cylinder – diameter ca 61 mm, length 138 mm
Short-circuit current (charged to nominal voltage), do not use as working current	9300 A
Maximum RMS current for temperature increasing 15 °C	130 A
Maximum RMS current for temperature increasing 40 °C	210 A
Life-time at the nominal voltage and temperature +65 °C	1500 h (2 months)
Intended life-time at the nominal voltage and temperature +25 °C	10 years

b) Capacitance dimensioning of the ultracapacitor

With respect to a sufficient efficiency of the matching DC/DC converter it is necessary to ensure that the operating ultracapacitor voltage never decreases under ca. one half of its full (nominal) voltage 600 V. Considering this condition the usable energy of the ultracapacitor can be calculated:

$$W = \frac{1}{2}C\left(V_{\max}^2 - V_{\min}^2\right) = \frac{1}{2}C\left(V_{\max}^2 - \frac{V_{\max}^2}{4}\right) = \frac{3}{8}CV_{\max}^2 \tag{6.1}$$

In this chapter the usable energy will be designed according to the demand of storing the regenerative braking energy. Knowing our actual values V_{max} = 600 V and W = 1.8 MJ (0.5 kWh) the necessary capacitance is:

$$C = \frac{8W}{3V_{\max}^2} = \frac{8 \cdot 1.8 \cdot 10^6}{3 \cdot 600^2} = 13.3\ \text{F} \tag{6.2}$$

c) Ultracapacitor dimensioning – number of cells in series-parallel configuration

A series connection of 230 cells 3000 F/ 2.7 V will be suitable to achieve the required voltage of 600 V. Then the nominal voltage will be 621 V and the safety reserve 21 V i.e. 0.09 V per cell enables an advantageous simplification of balancing circuits. The total capacitance will be 3000/230 = 13 F (convenient value).

d) Resulting internal resistance, charging and discharging efficiency, losses

The resulting internal resistance of the ultracapacitor will be 230 x 0.29 mΩ =66.7 mΩ (theoretically, without considering the contact resistances).

The charging and discharging efficiency is given by the following formulas:

$$\eta_{CAP,char} = \frac{I \cdot V_i}{I \cdot (V_i + R_i I)} = \frac{V_i}{V_i + R_i I} \tag{6.3}$$

$$\eta_{CAP,dis} = \frac{I \cdot (V_i - R_i I)}{I \cdot V_i} = \frac{V_i - R_i I}{V_i} \tag{6.4}$$

Where V_i is the internal voltage of the ultracapacitor (no-load voltage), I is the actual charging/discharging current and R_i is the internal resistance of the ultra-capacitor.

From equations (6.3) and (6.4) it is clear the charging and discharging efficiency decreases with increasing current (power). Average values of power and losses during the charging/discharging pulses would be necessary to calculate to perform an exact calculation of the total efficiency of storing/returning the ultracapacitor energy. This would require a necessity of integral calculation considering the true curve of the actual current. Moreover the efficiencies at a given current depend on the actual value of the internal voltage V_i. At lower voltage and the same current the efficiencies are lower.

It will be suitable to consider some representative average value of efficiency for the purposes of energy and following economy calculations. This value should correspond to an estimated average current being ca 300 A (statistically most often approximate value of ultracapacitor current). Further also the average value of internal voltage will be supposed which is 450 V (600 V max., 300 V min.).

Then the mentioned average efficiencies can be calculated:

$$\eta_{CAP,char} = \frac{V_i}{V_i + R_i I} = \frac{450}{450 + 66.7 \cdot 10^{-3} \cdot 300} = 95.7\% \tag{6.5}$$

$$\eta_{CAP,dis} = \frac{V_i - R_i I}{V_i} = \frac{450 - 66.7 \cdot 10^{-3} \cdot 300}{450} = 95.6\% \tag{6.6}$$

Therefore identical values for charging and discharging efficiency η_{CAP} 96 % will be considered in further energy and economy calculations.

As mentioned in Tab. 6.2, the temperature rise of the cell about 40°C corresponds to the rms current of 210 A (no ventilator, long-time steady state). In our application the current will be varying in range from 0 to 600 A. Even without calculating the real rms current value it can be supposed that the designed solution lies on the border of feasibility and therefore most probably an additional ventilator will be necessary.

A huge peak loss power of 24 kW appears at the full charging/discharging current of 600 A. However the true average loss power will be much lower: At the efficiency η_{CAP} 96 %, considering the measured energy recovery percentage A = 23.7 % (sum of all recovered energies to sum of all energies delivered from trolley, see chap. 4.2.4) and at a representative average power delivered from trolley of P_{av} = 50 kW (commonly it will be lower) the average loss power of the ultracapacitor will be:

$$\Delta P_{CAP} = A \cdot P_{av} \cdot (1 - \eta_{CAP}) = 0.237 \cdot 50 \cdot 10^3 \cdot (1 - 0.96) = 474 \text{ W} \tag{6.7}$$

A loss power of ca 0.5 kW (2.2 W per cell) can be considered.

6.2.2 Weight and price of the 13 F/ 621 V ultracapacitor assembled from BCAP3000 cells

The BCAP3000 cell is placed in a cylindrical housing – diameter of 61 mm, length of 138 mm. The weight of one cell is 510 g. Considering the usage of 230 cells the total weight will be 117 kg (cells itself). The built-up volume is ca. 118 l.

The price of one BCAP3000 cell is ca 45 EUR when purchasing over 200 pcs. This price is valid at the distribution company Mouser Electronics.
http://cz.mouser.com/ProductDetail/Maxwell-Technologies/BCAP3000-P270-K04/?qs=sGAEpiMZZMuDCPMZUZ%252bYl4vDGR228uRDhgVZbUDv3h0%3d

Purchasing 230 cells the total price is 230 x 45 = 10 350 EUR i.e. ca. 279 450 CZK.

6.3 Design of $LiFePO_4$ battery

$LiFePO_4$ batteries provide a high efficiency of fast surge charging in contrast to lead-acid or NiCd batteries. Due to the low internal resistance they are able to operate with high currents (powers) at a low capacity. However they do not reach the quality of ultracapacitors in this point of view.

$LiFePO_4$ batteries (lithium-iron-phosphate) provide a high weight- energy density (see below) similarly like Li-ion (lithium-ion). But in contrast to Li-ion they ensure a significantly lower internal resistance which enables e.g. a cell with capacity of 2.3 Ah to provide steady safe current of 70 A (i.e. ca “30C” without decreasing the capacity – this was quite unthinkable in

conventional batteries up to now). Only these batteries seem to be strongly suitable for our application.

6.3.1 Selection of suitable cells and dimensioning of the battery

a) Selection of cells

The company A123 Systems is always the top manufacturer of $LiFePO_4$ batteries, although significant changes in the ownership of this company were performed. Most probably some economical problems appeared in the company but its technical know-how and good production potential remained unchanged. Considering general positive references and also personal experiences of the BUT team, we propose the $LiFePO_4$ just from the manufacturer A123 Systems (www.a123systems.com).

Note: Chinese $LiFePO_4$ batteries Thundersky are known among constructors and users of electric vehicles (E-cars, various carriages, garden tractors etc.). According to available information their quality is unstable and we do not recommend to use them.

According to required parameters (4 kWh, 600 V, 300 A) the cells ANR 26650M1-B from the recommended company A123 Systems were chosen as the most suitable. Their basic parameters are in Tab. 6.3. The manufacturer even notes in the datasheet one of suitable applications: “Transportation - advanced energy storage for electric drive vehicles” (with an illustration view of an electric bus).
http://www.a123systems.com/Collateral/Documents/English-US/A123%20Systems%20ANR26650%20Data%20Sheet.pdf)

Tab. 6.3 Basic technical parameters of the cell ANR 26650M1-B (manufacturer A123 Systems)

Nominal capacity	2.3 Ah
Nominal voltage	3.3 V
Internal resistance (DC)	10 mΩ
Recommended steady fast-charging current	10 A
Maximum allowed steady discharging current	70 A
Maximum pulse discharging current (10 sec)	120 A
Life-time	More than 1000 full charging/discharging cycles
Operating temperature range	-30 °C to +55 °C
Storage temperature range	-30 °C to +60 °C
Weight	76 g
Dimensions	diameter 26 mm, length 65 mm

Estimating the limit of charging/discharging current of one cell

At the cell internal resistance of 10 mΩ the reported steady discharging current of 70 A represents a surprisingly high loss power 70 x 70 x 0.01 = 49 W. It is obvious that an unacceptably high temperature (cell over-heating) would correspond to this loss power in thermal steady state (after charging the thermal capacity of the cell) since the thermal resistance of the cell to the ambient is high (the cell is relatively small, see Tab. 6.3). However the current of 70 A is allowed, because the cell will be quickly discharged in 2 minutes at the small capacity of 2.3 Ah and therefore the heat can be still accumulated into the thermal capacity of the cell since the thermal time constant is surely longer than the mentioned 2 minutes.

A much lower current of 10 A is allowed for the charging. The reason lies certainly in the efficiency of charging (electro-chemical problem). The loss power at the internal resistance at the current of 10 A is only 1 W – this cannot damage the cell thermally.

A compromise between the cell charging current (charging efficiency) and capacity of the whole battery must be found for the proposed application (lower current of one cell – more parallel-connected cells – higher capacity – even higher than demanded). **A choice of one cell peak charging current of 25 A seems to be a reasonable compromise** (2.5-times higher than the reported steady charging current).

b) Battery dimensioning – number of cells in the series-parallel configuration, capacity

It is necessary to use 182 series connected blocks to achieve the nominal voltage of 600 V at the cell nominal voltage of 3.3 V. Considering the peak charging current of 250 A and the chosen peak charging current per one cell of 25 A the resulting number of parallel cells in each of 182 series blocks must be 250/25 = 10 pcs. Then the whole battery will be assembled from 1820 cells.

Due to the necessity to reduce the peak charging current of one cell to 25 A using 10 parallel cells, the Ah-capacity of the battery will be 10 x 2.3 = 23 Ah. **Therefore the energy capacity must be 23 Ah x 600 V = 13.8 kWh (instead of the required only 0.5 kWh, respectively 4 kWh for independent drive).** From this we can see the ability of $LiFePO_4$ battery to provide high power at low capacity is not optimal.

c) Resulting internal resistance, charging/discharging efficiency, losses

Assembling blocks with 10 parallel cells and connecting 182 these blocks in series the resulting internal resistance will be 182 x 10 mΩ/10 = 182 mΩ (theoretically, without influence of contact resistances).

The charging and discharging efficiency is given by following equations (not considering the electro-chemical processes):

$$\eta_{BAT,char} = \frac{I \cdot V_i}{I \cdot (V_i + R_i I)} = \frac{V_i}{V_i + R_i I} \tag{6.5}$$

$$\eta_{BAT,dis} = \frac{I \cdot (V_i - R_i I)}{I \cdot V_i} = \frac{V_i - R_i I}{V_i} \tag{6.6}$$

Where V_i is the battery internal voltage (no-load), I is the actual charging/discharging current and R_i is the battery internal resistance.

It will be suitable to consider some representative average value of efficiency for the purposes of energy and following economy calculations. This value should correspond to an estimated average current being ca 200 A.

Note: This value is lower than at the ultracapacitor (300 A) since the battery voltage is approximately constant (600 V), unlike the ultracapacitor voltage being variable in range of 300 V to 600 V. Then at the minimum (half) voltage the current was twice higher at the same power (ensured with the DC/DC converter).

Further the nominal value of battery internal voltage will be considered approximately 600 V. Then the mentioned average efficiencies can be calculated:

$$\eta_{BAT,char} = \frac{V_i}{V_i + R_i I} = \frac{600}{600 + 182 \cdot 10^{-3} \cdot 200} = 94.3\% \tag{6.7}$$

$$\eta_{BAT,dis} = \frac{V_i - R_i I}{V_i} = \frac{600 - 182 \cdot 10^{-3} \cdot 200}{600} = 93.9\% \tag{6.8}$$

Therefore identical values for charging and discharging efficiency η_{BAT} 94 % will be considered in further energy and economy calculations.

At the full charging/discharging current of 250 A/ 300 A the peak loss power of 11.4 kW / 16.4 kW appears (6.3 W/ 9 W per cell).

However the average loss power will be again much lower: Let’s consider the above calculated efficiency of 94 %. Further considering the measured energy recovery percentage A = 23.7 % (sum of all recovered energies to sum of all energies delivered from trolley, see Chap. 4.2.4)

and at a representative average power delivered from trolley of P_{av} = 50 kW (commonly it will be lower) the average loss power of the battery will be:

$$P_{bat} = A \cdot P_{av} \cdot (1 - \eta_{BAT}) = 0.237 \cdot 50 \cdot 10^3 \cdot (1 - 0.94) = 711\,\mathrm{W} \tag{4.4}$$

A loss power of ca. 0.7 kW (0.4 W per cell) can be considered.

Note: If the traction power (discharging current) in the independent drive without trolley will be not limited (during detour driving) then it will be most probably suitable to design the battery cooling really for 16 kW (long and fast up-hill driving without trolley).

6.3.2 Weight and price of the 600 V/ 23 Ah battery assembled from ANR 26650M1-B cells

The ANR 26650M1-B cell is placed in a cylindrical housing – diameter of 26 mm, length of 65 mm. The weight of one cell is 76 g. Considering the usage of 1820 cells the total weight of the battery pack is 138 kg which is acceptable. The built-up volume of 80 l is acceptable too.

The price of one ANR 26650 cell is ca. 16.0 USD when purchasing over 100 pcs. (Reference: http://www.batteryspace.com/a123-system-nanophosphate-lifepo4-26650-rechargeable-cell-3.2v-2500-mah.aspx). Purchasing 1820 cells the total price is 1820 x 16 = 29120 USD i.e. ca. 630 000 CZK.

6.4 Ability of independent drive without trolley

For the ultracapacitor dimensioning in Chap. 6.2, we assumed only the regenerative braking energy of 0.5 kWh (not the higher energy demanded for the independent drive). The same assumption was in Chap. 6.3 when dimensioning the battery. However there it was found that the battery must be dimensioned for a much higher energy capacity to allow the required high peak currents. The ability of the battery to provide high currents at low capacity is not as high as with the ultracapacitor. This predetermines the battery also for the purposes of independent driving capability (same currents, higher required capacity).

In this chapter we focus on finding out the action radius of the independent drive using the battery designed in Chap. 6.3 and ultracapacitor designed in Chap. 6.2. We also perform a design of a larger ultracapacitor to achieve the required action radius (2 km).

6.4.1 Action radius with the $LiFePO_4$ battery designed in Chap. 6.3

Knowing the battery energy capacity of 13.8 kWh and the energy of 4 kWh required for driving the most energy demanding section of 2 km, the action radius with this battery will be 13.8/4 x 2 km = ca. 7 km. In practice the battery will be not fully discharged (lifetime considerations). On the other hand the energy demand of the independent drive will certainly not be the highest during its whole length. Considering this we can estimate a length of 7 km as a realistic average achievable value.

6.4.2 Action radius with the ultracapacitor designed in Chap. 6.2

Knowing the ultracapacitor usable energy of 0.5 kWh and the energy of 4 kWh required for driving the most energy demanding section of 2 km, the action radius with this ultracapacitor will be only 0.5/4 x 2 km = ca. 0.25 km. We can see an insufficient value was obtained with respect to practical utilization.

6.4.3 Ultracapacitor design for action radius of 2 km

The capacitance of the ultracapacitor has to be increased in the ratio of 4 kWh to 0.5 kWh in order to achieve the 2 km action radius with energy demand of 4 kWh. This means 8-times higher capacitance in comparison to the actual value of 13.3 F (Chap. 6.2). Using the same cells (BCAP3000 P270 K04) the required capacitance will be achieved by parallel connection of 8 cells and 230 of these parallel combinations in series. The total number of cells will then be 1840.

The weight of this ultracapacitor (cells itself) will be also 8-times higher than the previous variant, i.e. about 938 kg (see Chap. 6.2.2), the built-in volume will be 945 l and price 82 800 EUR i.e. about 2 235 600 CZK. A problem with ultracapacitor placing into the trolleybus might arise – built-in volume of almost1 m^3 with an additional weight of almost 1 ton (even more considering the mechanical construction parts). Also the price would be unacceptably high. Therefore we do not recommend this solution.

6.5 Result summary of ultracapacitor and $LiFePO_4$ battery design

Tab. 6.4 Comparison of designed energy storage tanks

	$LiFePO_4$ battery	“large ultracapacitor”	“small ultracapacitor”
usable energy	13.8 kWh	4 kWh	0.5 kWh
internal resistance	182 mΩ	8.3 mΩ	66.7 mΩ
average losses	711 W	60 W	474 W
action radius	about 7 km	about 2 km	about 250 m
weight	138 kg	938 kg	117 kg
price	632 000 CZK	2 293 000 CZK	280 000 CZK

6.6 Practical experience with Li-ion battery operation, long lifetime considerations

This chapter presents an information about changes of operating parameters (aging) of a Li-ion battery used in an electric bike with an induction motor (developed in BUT, Department of power electrical and electronic engineering) during 8 years (with a total driven distance of 14 000 km). The aim of this chapter is to inform about the performance of the Li-ion battery (analogically also $LiFePO_4$) which reached a long lifetime.

6.6.1 Battery description and performance

The battery pack is a series-parallel connection of Li-ion cells CGR18650C (Panasonic) with a nominal voltage of 3.6 V and nominal capacity of 2.15 Ah. BMS circuits of custom design are included in the battery. They disconnect the load when the voltage of any cell drops below the allowed value. Further if any cell reaches the maximum charging voltage then the BMS circuits send this information via a 1 bit logical signal to the external charger. Using this signal the master voltage control of the charger is realized.

The presence of BMS circuits in all types of Li-ion batteries (also $LiFePO_4$) is necessary. The cells are extremely sensitive to deep discharging (significant decreasing of lifetime, danger of damage, risk of fire in some types) and also to overcharging (similar risks).

The CGR18650C cells used in the described battery are commonly used especially in notebook PCs. The battery was assembled from new cells bought in March of 2005. The total retail price of 147 pcs of cells used in the battery was ca 25 000 CZK including VAT. The battery was used from 2005 till 2013 without any repairs or service and till now it shows minimum degradation (see later). The total driven distance with this bike was about 14 000 km. About 50 – 70 km corresponds to 1 full charging cycle of the battery (depending on the profile of the trail and driving style). Therefore the battery wearing corresponds to ca. 190 full charging cycles.

However it is well known that the Li-ion batteries degrade also without charging or discharging – just during the time (e.g. storage). Often this process ends their life-time earlier than the expected number of full charging cycles is completed. The degradation of the described battery was slowed down probably by 3 main reasons:

1) Simple but precise BMS circuits developed for this battery protect each cell reliably against overvoltage and undervoltage. The minimum voltage is chosen higher than the manufacturer allows and the maximum voltage lower (see below for details).

2) Usage of brand-name cells (here namely Panasonic) – there are big quality differences among the Li-ion cells. The manufacturer A123 Systems proposed for the application in the trolleybus belongs to the best ones too.

3) The full capacity of the battery is not used, i.e. the battery is not discharged deeply. The charging is realized as soon as there is a possibility, not after the battery is completely discharged. This means that the battery operates with many partial charging cycles. Also the users of notebooks know the significant positive influence of this way of operation on the battery lifetime.

The battery is assembled as a series connection of 7 blocks, each block containing 21 cells in parallel. Parameters of this battery are in Tab. 6.5.

Tab. 6.5 Electrical parameters of the battery used in the electric bike

Nominal voltage (3.6 V per cell)	25.2 V

Minimum voltage (3.1 V per cell)	21.7 V
Maximum voltage (4.1 V per cell)	28.7 V
Maximum steady discharging current (2 A per cell)	42 A
Maximum charging current (1.4 A per cell)	29.4 A
Usable capacity (1.9 Ah per cell)	40 Ah
Internal resistance (120 mΩ per cell)	40 mΩ

The connection of 7 series blocks represents the necessity to use 7 protecting circuits to check the voltage of each cell. The parallel connection of cells in each block contributes to some “averaging” – similar capacity and actual voltage value of each block is statistically ensured.

The manufacturer of used Li-ion cells allows a maximum cell voltage of 4.2 V and minimum voltage of 3 V. The nominal capacity corresponds to these limits. Slightly stricter limits for minimum and maximum 3.1 V and 4.1 V were used in order to prolong the battery lifetime. This way the usable capacity is decreased to ca 90 % of the nominal value, but after years of operation these limits seem to be very useful for the increasing of lifetime.

6.6.2 Reference measurement of the new battery

First proving measurement of battery capacity and internal resistance was done after only 540 km traveled by the bicycle in 2005. Two modes, constant discharging with 20 A current for 10 minutes (i.e. ca 1 A per cell) and zero current (no-load) for 3 minutes were alternated during the measurement. The constant voltage in the end of three minute no-load mode (before another discharging mode) was measured as well as the voltage in the end of 10 minutes (discharging) interval (measured still under load). The V_{20A} voltage under load time dependence was obtained with the above described technique as well as V_0 in no-load state during discharging interval. Due to constant current it is easy to find the time dependence of the electric charge (capacity) taken from the battery. The results of proving measurement are presented in Fig. 6.1. (Three minute intervals – where the discharging was stopped – are extracted from the graph).

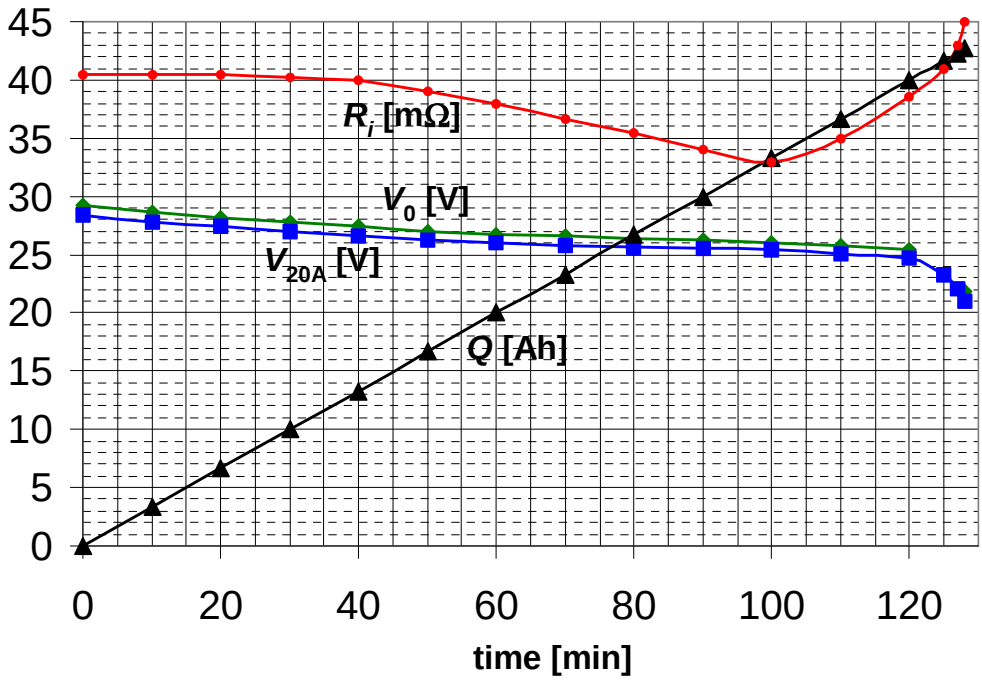


Fig. 6.1 Measurement of new battery (after 540 km traveled)

The maximum no-load voltage per cell of 4.2 V(i.e. maximum battery voltage of 29.4 V) was used in these measurements. If only 4.1 V is assumed then the discharge time is reduced by 10 minutes (compared to Fig. 6.1), which means reduction of usable capacity from 42.5 Ah to 39.2 Ah.

Internal resistance is the lowest when about 80 % of energy is already taken from fully charged battery. After that, the resistance rises and it is also higher with higher state of charge (see Fig. 6.1).

6.6.3 Periodical measurements during the battery lifetime

Periodical measurement of battery capacity and internal resistance (with voltage range from initial value of 28.7 V to final value of 21.7 V) are being done since 2005. Results of capacity measurements are summarized in Tab. 6.6.

Tab. 6.6 Periodical measurements of capacity and internal resistance of battery

Date of measurement	Total distance traveled [km]	Capacity [Ah]	Internal resistance [mΩ]
10. August 2005	540	39.2	40
26. July 2006	1 666	37.7	40
30. January 2008	4 667	35.0	40

21. October 2008	9 192	35.0	40
7. July 2009	10 847	34.3	40
7. May 2010	12 074	33.0	40
4. March 2011	13 865	33.0	40
10. December 2013	ca. 14 000	32.7	44.5

6.6.4 Battery measurement conclusion

The battery was not significantly degraded even after eight years of operation. The capacity decreased only by approx. 16.6 % and internal resistance increased by approx. 11 %. On the other hand, the internal resistance increased significantly during the last year which might indicate coming end of battery lifetime.

The battery exceeded all expectations. On the other hand, only careful handling of the battery was assumed in terms of battery ageing. Expected number of full cycles was not performed (declared value of used type is ca. 300 cycles) due to low intensity of bicycle use.

$LiFePO_4$ battery will also be kept in charged state (and with only partial cycles) in suggested application and high lifetime of the battery is expected if the battery voltage level is appropriately chosen. Moreover, the $LiFePO_4$ batteries have longer lifetime (higher number of charging cycles) than measured Li-ion cells. We also expect battery lifetime in fully-operational state of about 8 years.

6.6.5 BMS system for $LiFePO_4$ battery

Schematic of BMS circuitry is shown in Fig. 6.2. Due to the possible non-symmetry (aging) of each block it is not sufficient to monitor total battery voltage but it is necessary to monitor voltage of each series connected battery block. There are plenty of various “professional” BMS devices available on the market, which can be used with particular cell types.

Experience of BUT researchers shows that the reliability of these devices differs a lot and most of them are unnecessarily complex (excess of visualization elements, complex circuitry, microprocessors). The following simple solution was verified by eight year operation of the electric bicycle as mentioned above. We suggest realizing similar BMS solution in suggested trolleybus application.
Basic block includes comparators evaluating overvoltage and undervoltage. These comparators are part of modules shown in Fig. 6.2 and marked “BL 1” to “BL 7” (seven series connected blocks were used in this application).

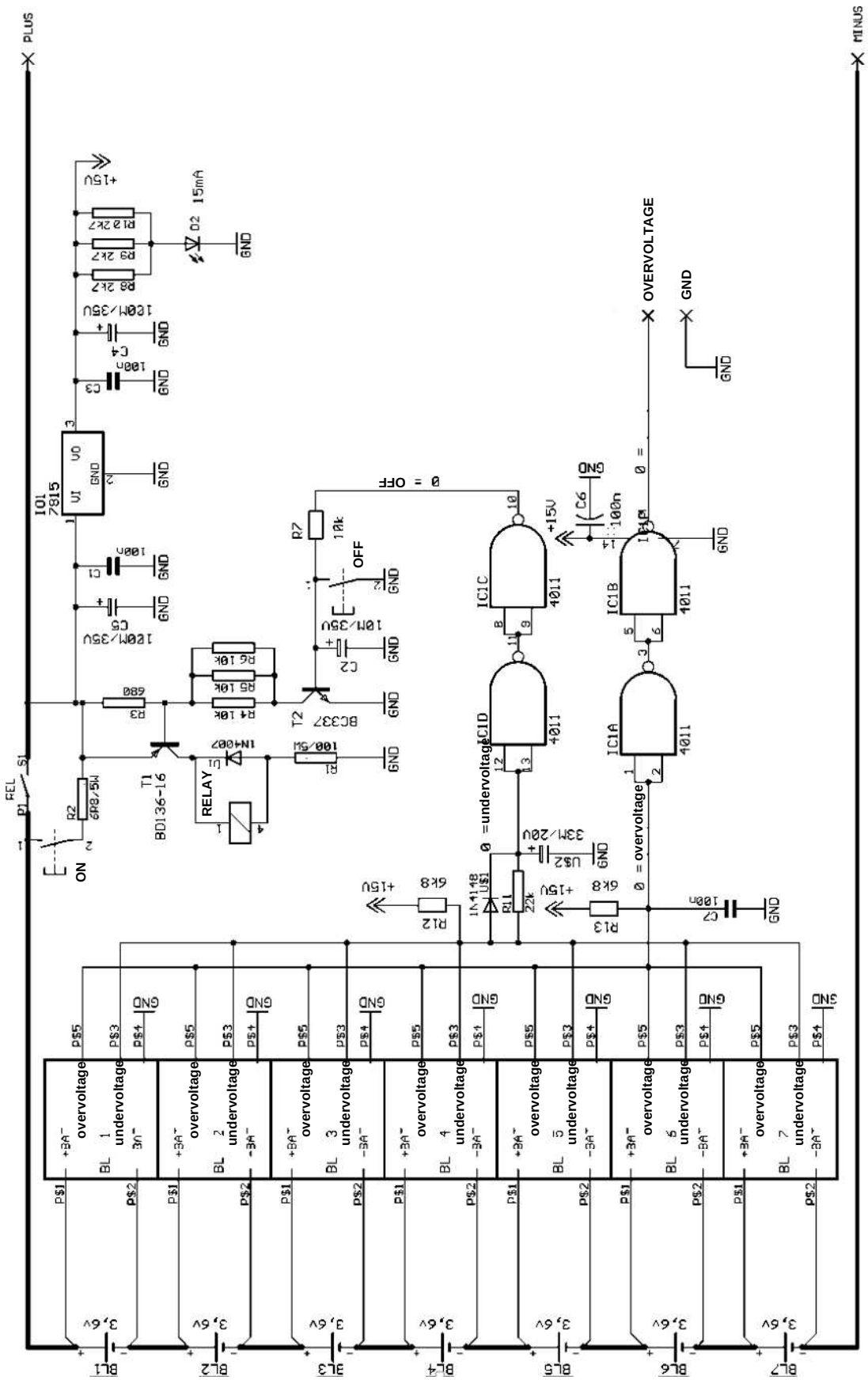


Fig. 6.2 Possible solution of protection circuits – illustrative diagram (solution used in mentioned application of electric bicycle battery)

Schematic of comparator modules (BL 1 – BL 7) is shown in Fig. 6.3. Each circuit is supplied from corresponding battery block. Two output logic signals give information about undervoltage and overvoltage of the battery block. These signals are galvanically isolated from the battery block. Logic outputs realized as open collector allow parallel connection of signals from all modules.
If undervoltage is detected on any of battery blocks then the logic output signal "UNDERVOLTAGE" becomes immediately logical 0. Control circuit of the relay is disconnected as well as the positive output contact of the battery. The power supply for protective circuits is also disconnected and the battery is then discharged only with small comparator modules supply current. The battery can also be disconnected manually via a push button as shown in Fig. 6.2. Battery can be re-activated by another push button. Pushing this button short-circuits contacts of the relay and reconnects the power supply to protective circuits of the battery. If no undervoltage is present as well as the switch off button is not pressed then the power contact of the relay will switch on and the battery is permanently connected to the power circuit.

Note: Possible short term impulses of logical zero (caused by pulse battery current and interference) are eliminated by using a RCD (resistor, capacitor, diode) network, see Fig. 6.2.

If higher voltage level than maximum allowed voltage occurs on any of battery block then logic output signal "OVERVOLTAGE" becomes logical 1 (TRUE). Signal is passed to a converter which consequently reduces or even disables regenerative braking.

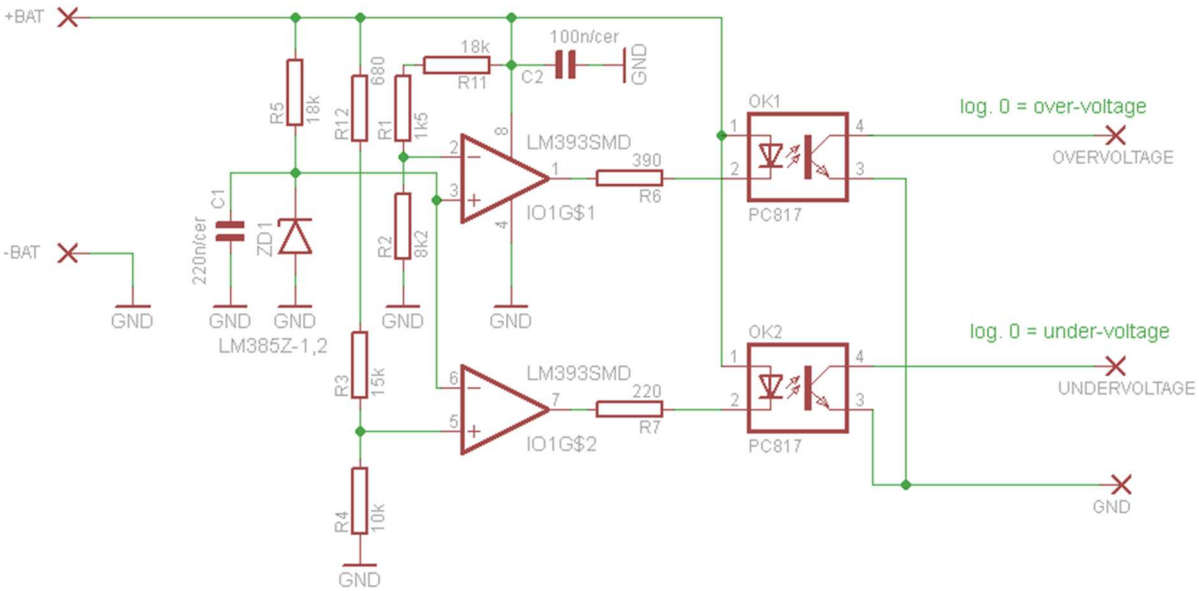


Fig. 6.3 Realization of comparators module (BL 1 to BL 7 in Fig. 6.2)

6.6.6 Control techniques of battery charging, balancing

“OVERVOLTAGE” signal, which was described in the end of previous chapter, is passed to matching DC/DC converter and works as feedback signal to battery voltage regulator. Voltage control works in principle as a parallel voltage control of all battery blocks. If a failure occurs (short circuit or disconnection) on a connection between protection circuits of the battery and matching converter then logical zero appears on this connection and the inverter evaluates this failure as a permanent overvoltage and disables the charging process. There is no risk of overcharging resulting in battery damage.

Principle of matching converter is clear from Fig. 6.4. Inner block “Battery management system” represents BMS circuits as described before. Their output called “OVERVOLTAGE” is fed to a RC network with a sufficient time constant which works as a low-pass filter and outputs average value of input pulsed logic signal. This filtered value is used as required current value in inner current control loop. Superior voltage regulation is then realized only with help of BMS circuits – it is a parallel control of all cells voltages (i.e. not only total voltage of the whole battery). The overvoltage output signal oscillates between logical values 1 and 0 during the final stage of charging and every cell is protected from overcharging.

If some cell has a lower capacity or higher internal resistance in comparison to others (e.g. due to unequal aging processes) then this cell will reach maximum voltage first and will set the logical output “OVERVOLTAGE” to zero. Charging current will then be reduced to avoid overcharging of this weakest cell. However, the charging process continues but it takes a longer time.

Despite common belief, we can see that in this case there is no need to use any special circuits (BMS) to prevent possible overvoltage.

Note: A necessary condition is that all series blocks are identically loaded and have the same values of leakage currents. All claims were verified with long time operation of described battery.

Of course, utilization of BMS circuit will slow down charging process due to higher deviation in capacity or internal resistance of some possibly damaged battery cell. But if the charging process is slowed down significantly, it is clear, that the damaged cell limits total capacity of the battery and has to be removed anyway, whether the BMS circuit is used or not.

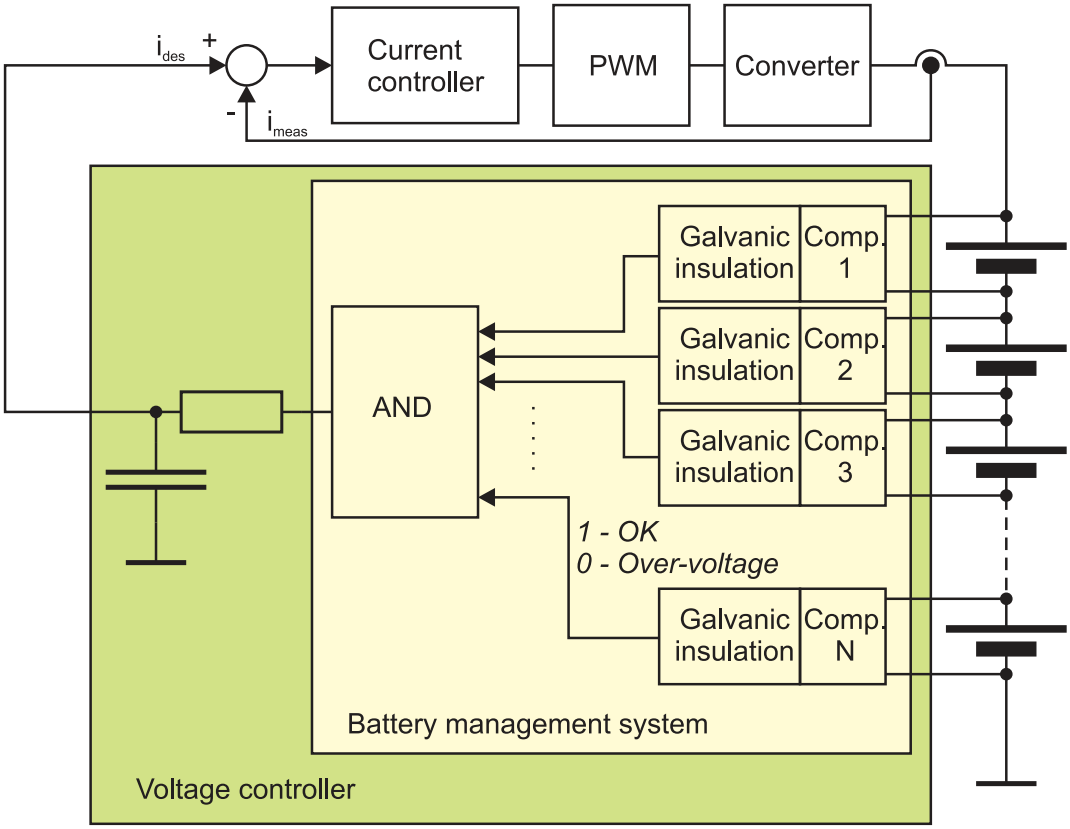


Fig. 6.4 Control strategy of Li-ion battery charging process

7. Control strategy for matching DC/DC converter with respect to reduction of trolley overvoltage

There are plenty of strategies for the control of energy storage system (ultracapacitor or battery). This chapter describes some control strategies which are simple but effective with respect to following requirements:

1) Energy savings in trolleybus drive (utilization of regenerative braking energy, trolley loss reduction)
2) Elimination of trolley overvoltage
3) Possibility of independent drive without trolley

7.1 Ultracapacitor control strategy

Direct parallel connection of the ultracapacitor to DC link of traction inverter is not possible. This arrangement does not allow to vary ultracapacitor voltage in a wide range and only small amount of energy is transferred from or into the ultracapacitor (charging/discharging).

It is necessary to place a two-quadrant converter between the DC link and ultracapacitor according to Fig. 7.1.
It allows (theoretically) lossless bidirectional energy transfer between ultracapacitor C_U and DC link. If the top transistor is switched then the energy is delivered from DC link trough choke L_U into the ultracapacitor. If the bottom transistor is switched then the energy is transferred from the ultracapacitor to the DC link.

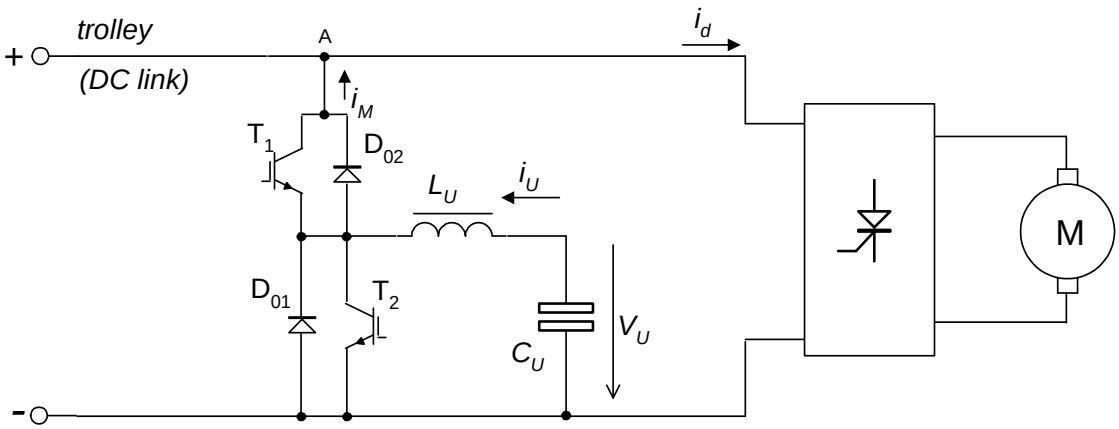


Fig. 7.1 Ultracapacitor connection via a two-quadrant DC/DC converter

At very low ultracapacitor voltage level V_U, the DC/DC converter needs to operate with a very low duty cycle (resulting from basic principle of operation). Then the required average value of the current I_M is achievable only with extremely high peak current. In such case, transistors operate with high voltage and high current which increases losses in the converter and reduces its efficiency. This phenomenon was already mentioned in Chap. 5.2. Minimum value of the ultracapacitor voltage was defined as a half of the DC link voltage to avoid this situation.

Control circuits have to ensure:

- Absorption or supplying of current from/to the traction inverter.
- Keeping the ultracapacitor voltage on required level.

It is clear that these requirements can be opposite to each other but the first requirement is primary. Ultracapacitor voltage control can be relatively slow. Cascade control structure is used. Standard control scheme with inner current loop is used. Current loop of the ultracapacitor is essential. Required current as an input signal is obtained from derivative module connected to a trolley current sensor.

This way a feedback control to zero change of trolley current value is performed. It means that the inverter sets appropriate ultracapacitor current to smooth trolley current (short-term trolley current peaks filtrating to long-term average value).

To obtain the required ultracapacitor current value, an output of the ultracapacitor voltage controller is added to the output of the previously mentioned derivative controller. The slew rate of the voltage controller is limited. It is practical to set the ultracapacitor voltage inversely proportional to actual vehicle speed. Then an optimal ultracapacitor utilization can be ensured. Of course the minimum permissible voltage has to be taken in account. It means to charge the ultracapacitor to maximum voltage at zero speed to ensure sufficient amount of energy for acceleration and to reduce the ultracapacitor voltage at maximum speed to allow for absorption of braking energy.

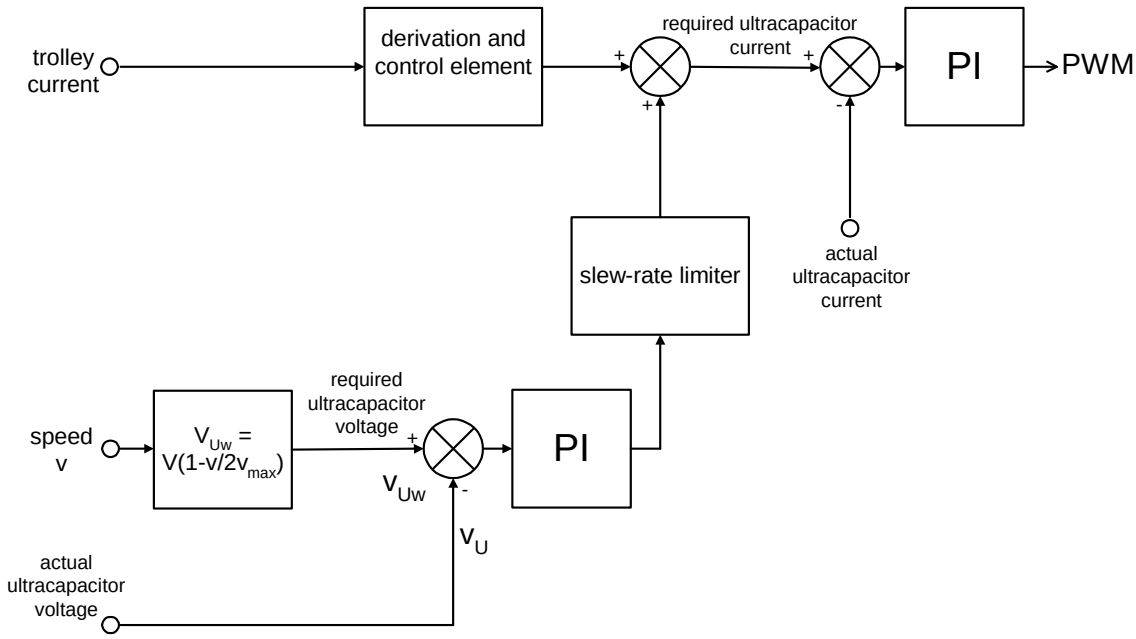


Fig. 7.2 Control structure with an ultracapacitor

Designed control strategy compensates fast changes in trolley current value and polarity (caused by drive/regenerative braking). The energy is absorbed during regenerative braking and quickly supplied at higher load (acceleration).

The smooth trolley current is essential. It reduces trolley voltage over-shoots especially short term over-shoots caused by fast current changes and by trolley inductances. In addition the smooth current reduces the rms value and therefore less power is lost in trolley resistances.

Real power of constant voltage source with variable current is given by multiplication of its voltage and its average current value. Real power of the trolley is directly proportional to the average current value due to constant trolley voltage. In contrary, Joule losses are dependent on rms current value. If the high current spikes are eliminated and the average current value remains unchanged then the same real power is consumed but the rms value is reduced as well as the Joule losses.

The suggested solution also reduces trolley average current value (i.e. long term trolley average input power) due to utilization of regenerative braking energy.

7.2 Control strategy with $LiFePO_4$ battery

It is possible to assume principally the same control strategy for the battery as for the ultracapacitor. Therefore the control structure with matching DC/DC converter is identical to the structure shown in Fig. 7.2.

The main difference in comparison with previous strategy is that it is not possible to use a voltage loop for battery state-of-charge (SOC) control. Battery voltage dependence on state-of-charge is very flat – large change in battery charge corresponds to a very small change in voltage value in considered operational SOC range. This voltage further depends on temperature, internal resistance and actual battery current. It is not possible to estimate battery state-of-charge from its voltage unlike with the ultracapacitor.

The state-of-charge will be controlled instead of voltage via outer control loop. Maximum usable energy of the designed battery is approx. 13.8 kWh and maximum measured regenerative braking energy is only 0.425 kWh. Therefore it is sufficient to keep the battery SOC at around 80 % of its maximum value. Dynamics of this control loop will be reduced as well, as mentioned in previous control strategy with ultracapacitor, see Fig. 7.3.

Desired SOC value of 80 % was determined with respect to permanent capability to use the trolleybus for independent drive without trolley (detour drive). Higher SOC value is not recommended because then the battery is not able to absorb higher amounts of energy (unacceptable voltage rise can occur).

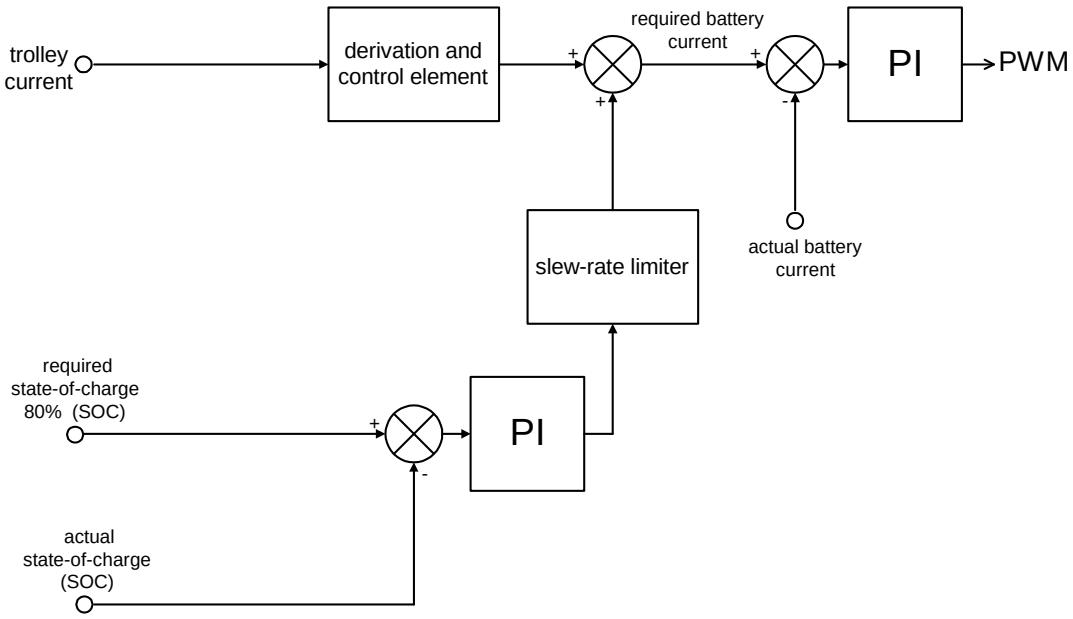


Fig. 7.3 Control structure with battery

7.3 Charging and discharging control with respect to vehicle range capability

From previous chapter 7.2 it is clear that the battery state-of-charge will be kept at around 80 % of its value during driving. Maximum regenerative braking energy is only 3.6 % of maximum battery energy. Battery will always be ready for independent traction and no manual action in charging strategy will be required before this mode.

8. On-board installation of ultracapacitor or $LiFePO_4$battery

8.1 Theoretical analysis

System for regenerative energy purposes can be installed into trolleybus of any type in principle, if its traction motor is able to operate in generator (braking) mode. All electrical machines (DC PM/wound motor, induction motor, PMSM, Switched reluctance motor …) are able to operate in generator mode in principle. However the control strategy is more important in terms of regenerative energy usage – i.e. it depends more on inverter/converter topology or on system of contractors and resistors if dissipative control strategy is used. Some topologies do not allow transfer of the regenerative braking energy back to DC link. Although the motor is able to brake, i.e. operates in generator mode, the energy is wasted in resistor.

Assessment of a concrete trolleybus type and its operational data showed that installation of regenerative energy storage system has no economical reasonability due to low economic returns on investment of such installation. Not only the costs of regenerative energy storage system, but also additional costs of old inverters modification (to be able to deliver the regenerative braking energy) have to be taken into account.

Similar economic results are also expected when assessing the regenerative energy storage system installation into new trolleybuses. For possible realization another reasons have to be assumed such as possibility of independent drive without trolley.

8.2 Assessment of installation into older trolleybus (21 Tr)

8.2.1 Possible complication with using regenerative braking energy in the 21 Tr trolleybus

According to Fig. 4.2 it is obvious that the trolley current almost never falls to zero, i.e. not even during regenerative braking interval. Theoretically it would be possible that it was caused with some misleading *offset* in the graph (real current value is moved up against zero axis in the graph), but this is not probably this case in fact, because the offset value is too high and the current drops to zero in some intervals in the graph. The trolleybus probably consumes some low current from the trolley even during regenerative braking. We suppose that this represents the trolleybus electrical systems own consumption and all the regenerative braking energy is wasted in braking resistors – no energy is transmitted back to DC link.

According to power circuit schematic, it is obvious that the regenerative braking to DC link is possible. This situation probably occurs only at a too low DC link voltage, in other case all regenerative braking energy is most likely wasted in resistors, as mentioned before. If our assumptions are right then **the regenerative braking energy cannot be reused most of the time, without modification of control circuits.**

8.2.2 Installation of the energy storage system into the 21 Tr trolleybus

The total weight of the whole regenerative energy storage system is about 170 kg (including converter and other auxiliary design elements) and this value is valid for both options – small ultracapacitor according to Chap. 6.2 or small battery according to Chap. 6.3. Ultracapacitor installation is quite simple. It is possible to place it into a container on the trolleybus roof. Roof placement of the $LiFePO_4$ batteries is not optimal due to temperature fluctuations. Therefore the battery has to be placed somewhere else in trolleybus. The on-board installation volume of about 80 liters is not large to cause any special problems with the installation and the battery can be moreover split to smaller blocks placed anywhere in the vehicle.

8.3 Installation of the energy storage system into new trolleybuses

Installation of energy storage system is easier into new trolleybuses in terms of technical challenges, because the proportion of the energy storage system can be already considered at trolleybus design and manufacture. It is essential to define the expected benefits of this kind of installation first and to choose appropriate technology which will be demanded at the purchase of new vehicles. We can expect that all established producers have sufficient experience with such technologies.

9. Installation of stationary energy storage system in converter station

Chap. 10 explains that economic returns on investments of energy storage system into vehicle are unacceptably long, comparable to the trolleybus lifetime. On the other hand energy savings, current spikes reduction and ability of independent drive are beneficial.

It is clearly more favorable to return the braking energy into trolley than into energy storage tank (ultracapacitor, $LiFePO_4$ battery) in economic point of view. Most of the braking energy is consumed by another vehicles connected into the same trolley section in macroscopic point of view. Therefore a common stationary energy storage system in converter station can be designed to a significantly lower energy than is the sum of all energies of storage systems in vehicles. It is obvious according to Chap. 3 and Chap. 6, that utilization of ultracapacitor allows to increase energy transfer efficiency in comparison with $LiFePO_4$ battery with the same nominal value of stored energy. The battery has to be designed for a higher energy capability than needed due to high required peak power. Larger dimensions and weight of ultracapacitor are not limiting in stationary application. Therefore the ultracapacitor is more beneficial than $LiFePO_4$ battery for converter stationary application.

Stationary application of energy storage system does not bring any benefit in terms of independent drive due to absence of energy storage systems installed directly into vehicles as

well as reduction of trolley current and voltage spikes. Furthermore, the trolley loss reduction is not possible (lower trolley rms current given by “smoothing” of trolley current waveform).

DPMB supply network is not suitable for installation of stationary energy storage systems into converter station (mutual trolley connection, many vehicles powered from common power source). Utilization of stationary energy storage systems is more beneficial in converter stations which supply smaller isolated sections where the excess regenerative braking energy is available because it is often not consumed by another vehicle.

10. Model of economical return on investments (system on-board installation)

Average calculated values of consumed energy per 1 km drive (with and without energy storage tank) are summarized in Tab.10.1. These results are obtained according to equations (4.7) – (4.10) defined in Chap. 4.2.4.

Tab. 10.1 Average consumed energy

E_{km}	1.66 kWh/km
$E'_{km\text{-}BAT}$	1.37 kWh/km
$E'_{km\text{-}CAP}$	1.33 kWh/km

Average year mileage of the trolleybus in DPMB is about 50 000 km. The cost of one kWh is 2.2 CZK. It is possible to calculate energy and cost savings according to data in Tab. 10.1 if the braking energy storage tank is used.

Yearly energy costs of the trolleybus without utilization of regenerative braking energy is as follows:

$$\text{costs}_{1year} = E_{km} \cdot T_{km} \cdot \text{price}_{kWh} = 1.66 \cdot 50\,000 \cdot 2.2 = 182\,449 \text{ CZK} \tag{10.1}$$

where
T_{km}……..year average mileage in kilometers
price_{kWh}…..price of one kWh

Yearly costs for electric energy consumption of the trolleybus assuming utilization of battery or ultracapacitor can be evaluated according to following equations:

$$\text{costs}_{1year-BAT} = E_{km-BAT} \cdot T_{km} \cdot \text{price}_{kWh} = 1.37 \cdot 50\,000 \cdot 2.2 = 150\,325 \text{ CZK} \tag{10.2}$$

$$\text{costs}_{1year-CAP} = E_{km-CAP} \cdot T_{km} \cdot \text{price}_{kWh} = 1.33 \cdot 50\,000 \cdot 2.2 = 145\,949 \text{ CZK} \tag{10.3}$$

Electric energy savings per year can be then enumerated according to following equations:

$$\text{saving}_{1year-BAT} = \text{costs}_{1year} - \text{costs}_{1year-BAT} = 182\,449 - 150\,325 = 32\,125 \text{ CZK} \tag{10.4}$$

$$\text{saving}_{1year-CAP} = \text{costs}_{1year} - \text{costs}_{1year-CAP} = 182\,449 - 145\,949 = 36\,501 \text{ CZK} \tag{10.5}$$

Electric energy costs and saving of fifteen years of trolleybus operation are summarized in Tab. 10.2. This calculation does not assume energy price fluctuations. Energy saving and costs assuming 3 % yearly inflation rate increase in price per kWh are summarized in Tab. 10.3.

Tab. 10.2 Electric energy costs and savings

	1 year	10 years	15 years
costs	182 449 CZK	1 824 494 CZK	2 736 740 CZK
$costs_{BAT}$	148 172 CZK	1 481 716 CZK	2 222 574 CZK
$costs_{CAP}$	146 697 CZK	1 466 974 CZK	2 200 462 CZK
$saving_{BAT}$	34 278 CZK	342 778 CZK	514 167 CZK
$saving_{CAP}$	35 752 CZK	357 519 CZK	536 279 CZK

Tab. 10.3 Electric energy costs and saving assuming yearly inflation rate 3 % in price per kWh

	1 year	10 years	15 years
costs	182 449 CZK	2 091 578 CZK	3 393 360 CZK
$costs_{BAT}$	148 172 CZK	1 698 621 CZK	2 755 831 CZK
$costs_{CAP}$	146 697 CZK	1 681 722 CZK	2 728 413 CZK
$saving_{BAT}$	34 278 CZK	392 956 CZK	637 529 CZK
$saving_{CAP}$	35 752 CZK	409 856 CZK	664 947 CZK

Electric energy savings of the fifteen years trolleybus operation are summarized in Tab. 10.2 and in Tab 10.3. The investment costs of the energy storage system ($LiFePO_4$ battery/ultracapacitor and matching converter) have to be subtracted from these values. The retail price of ultracapacitor is 279 450 CZK according to Chap. 6.2.2 and the price of the battery can be estimated to 632 000 CZK according to Chap. 6.3.2. These are retail prices in both cases and the final price will be lower in case of wholesale price but probably not more than by 30 %.

Also additional investment costs of matching inverter have to be taken into account. Converter price is hard to enumerate due to the fact that it is hard to find converter for this particular application available on the market. Its minimal price can be estimated according to every single components price of the converter and with some practical experience in the field. This converter price assumed in case of mass production is approximately 100 000 CZK. This price would be accessible only if there already was a mass produced converter (developed for other purposes but with the same or similar parameters) available on the market. In case of custom production focused only on DPMB needs, the converter development price will be approximately several million CZK. The qualified estimation is approximately 4 000 000 CZK.

Some assumed economical returns on investments are summarized in Tab. 10.4 - Tab. 10.7. No increase in electrical energy purchasing costs is assumed. The data were calculated according to following equations:

$$\text{Balance for purchasing of energy storage system}_{BAT/CAP} = \text{saving}_{BAT/CAP} - (\text{system purchase cost}_{BAT/CAP} - \text{quantity discount}) - \text{system purchase cost}_{DC/DC} \quad (10.6)$$

$$\text{Balance for development of energy storage system}_{BAT/CAP} = \text{balance for purchasing of energy storage system}_{BAT/CAP} \times \text{number of trolleybuses} - \text{development costs} \quad (10.7)$$

Tab. 10.4 Economical return on investments of energy storage system without assuming increase in electrical energy purchase cost

Number of trolleybuses	costs	1 year	10 years	15 years
1	*System purchase$_{BAT}$*	-607 722.21 CZK	-299 222.12 CZK	-127 833.19 CZK
	System purchase$_{CAP}$	-253 698.07 CZK	68 069.34 CZK	246 829.01 CZK
	System development$_{BAT}$	-4 607 722.21 CZK	-4 299 222.12 CZK	-4 127 833.19 CZK
	System development$_{CAP}$	-3 964 248.07 CZK	-3 642 480.66 CZK	-3 463 720.99 CZK
10	*System development$_{BAT}$*	-10 077 222.12 CZK	-6 992 221.23 CZK	-5 278 331.85 CZK
	System development$_{CAP}$	-6 536 980.66 CZK	-3 319 306.57 CZK	-1 531 709.86 CZK
20	*System development$_{BAT}$*	-16 154 444.25 CZK	-9 984 442.47 CZK	-6 556 663.70 CZK
	System development$_{CAP}$	-9 073 961.31 CZK	-2 638 613.15 CZK	936 580.28 CZK

Tab. 10.5 Economical return on investments of energy storage system without assuming increase in electrical energy purchasing cost and assuming lower battery purchasing cost due to quantity discount 30 %

System development		1 year	10 years	15 years
1	*System purchase$_{BAT}$*	-418 122.21 CZK	-109 622.12 CZK	61 766.81 CZK
	System purchase$_{CAP}$	-169 863.07 CZK	151 904.34 CZK	330 664.01 CZK
	System development$_{BAT}$	-4 418 122.21 CZK	-4 109 622.12 CZK	-3 938 233.19 CZK
	System development$_{CAP}$	-3 964 248.07 CZK	-3 642 480.66 CZK	-3 463 720.99 CZK
10	*System development$_{BAT}$*	-8 181 222.12 CZK	-5 096 221.23 CZK	-3 382 331.85 CZK
	System development$_{CAP}$	-5 698 630.66 CZK	-2 480 956.57 CZK	-693 359.86 CZK
20	*System development$_{BAT}$*	-12 362 444.25 CZK	-6 192 442.47 CZK	-2 764 663.70 CZK
	System development$_{CAP}$	-7 397 261.31 CZK	-961 913.15 CZK	2 613 280.28 CZK

Tab. 10.6 Economical return on investments of energy storage system assuming increase in electrical energy purchasing price by yearly inflation rate 3 %

Number of trolleybuses		1 year	10 year	15 year
1	*System purchase$_{BAT}$*	-607 722.21 CZK	-249 043.58 CZK	-4 470.38 CZK
	System purchase$_{CAP}$	-253 698.07 CZK	120 405.86 CZK	375 497.15 CZK
	System development$_{BAT}$	-4 607 722.21 CZK	-4 249 043.58 CZK	-4 004 470.38 CZK
	System development$_{CAP}$	-3 964 248.07 CZK	-3 590 144.14 CZK	-3 335 052.85 CZK
10	*System development$_{BAT}$*	-10 077 222.12 CZK	-6 490 435.79 CZK	-4 044 703.79 CZK
	System development$_{CAP}$	-6 536 980.66 CZK	-2 795 941.41 CZK	-245 028.54 CZK
20	*System development$_{BAT}$*	-16 154 444.25 CZK	-8 980 871.58 CZK	-4 089 407.58 CZK
	System development$_{CAP}$	-9 073 961.31 CZK	-1 591 882.81 CZK	3 509 942.93 CZK

Tab. 10.7 Economical return on investments of energy storage system assuming increase in electrical energy purchasing price by yearly inflation rate 3 % together with assuming battery purchasing cost due to quantity discount 30 %

Number of trolleybuses		1 year	10 years	15 years
1	*System purchase*$_{BAT}$	-418 122.21 CZK	-59 443.58 CZK	185 129.62 CZK
	System purchase$_{CAP}$	-169 863.07 CZK	204 240.86 CZK	459 332.15 CZK
	System development$_{BAT}$	-4 418 122.21 CZK	-4 059 443.58 CZK	-3 814 870.38 CZK
	System development$_{CAP}$	-3 964 248.07 CZK	-3 590 144.14 CZK	-3 335 052.85 CZK
10	*System development*$_{BAT}$	-8 181 222.12 CZK	-4 594 435.79 CZK	-2 148 703.79 CZK
	System development$_{CAP}$	-5 698 630.66 CZK	-1 957 591.41 CZK	593 321.46 CZK
20	*System development*$_{BAT}$	-12 362 444.25 CZK	-5 188 871.58 CZK	-297 407.58 CZK
	System development$_{CAP}$	-7 397 261.31 CZK	84 817.19 CZK	5 186 642.93 CZK

11. Continuous monitoring of important system parameters

On-board installed equipment should be extended with measurement and logging system (data-logger). Actual voltage, trolley current, consumed power, traction power, state of charge of energy storage system could be measured and logged for further evaluation. Especially integral measurement of energy delivered from trolley and energy delivered from energy storage system can be used for long-term evaluation of energy storage system benefits.

12. Final assessments

12.1 Economic benefits

Energy system installation into trolleybus (e.g. 21 Tr) gives no positive economic benefits according to results presented in Chap. 10. Economical return on investment represents an unacceptable long time considering electric energy costs for DPMB and therefore it is unreasonable from economic point of view.

Moreover the costs calculations presented in Chap. 10 do not reflect additional modification of traction converter and additional costs related to verification and homologation processes, etc.

12.2 Choosing the type of energy storage system – ultracapacitor vs. battery $LiFePO_4$

According to Chap. 6.2.1 and 6.3.1, it is obvious that utilization of ultracapacitor gives more benefits in terms of efficiency – ca. 96 % in comparison to battery – ca. 94 %. (Basically, battery efficiency will be even lower with respect to electrochemical processes).

If no longer than 250 m drive without trolley is desired then the utilization of ultracapacitor is more beneficial (purchasing price 280 000 CZK, ca. 120 kg) in comparison to battery (purchasing price 632 000 CZK, ca. 140 kg).

But assumed battery is able to store energy of 13.8 kWh in contrary to ultracapacitor 0.5 kWh. Battery driving range is at least 7 km without trolley in contrary to 250 m by using ultracapacitor.

On the other hand, reduced lifetime of battery has to be taken into consideration if the battery will be used not only for independent drive purposes but also for periodical transfer of regenerative braking energy.

12.3 Conclusions and final recommendations

Installation of ultracapacitors or $LiFePO_4$ battery systems can reduce energy costs on trolleybus operations as follows:

- Consumed electric energy savings
  - Ultracapacitor – ca. 20 % assuming converter efficiency 95 % and charging efficiency 96 %
  - $LiFePO_4$ battery – ca. 19 % assuming converter efficiency 95 % and battery efficiency 94 %
  - Reduction of trolley losses and voltage overshoots

In case of installation of energy storage system into converter stations, some benefits in terms of energy savings can be expected. These savings will be slightly lower due to trolley losses

(between trolleybus and converter station) in comparison with trolleybus on-board installation. Reduction of trolley voltage overshoots (generated in trolley due to inductances and high current slopes) will not be performed.

Installation of energy storage system (ultracapacitor of $LiFePO_4$ battery) into trolleybuses is not rentable from economic point of view (see Chap. 10), because economic return on investment is unacceptable long considering current electric energy costs.

A significant benefit of these technologies (especially batteries) is the possibility to drive without trolley. This can be used:

- where the trolley installation is not possible (i.e. historical parts of cities)
- where the trolley installation is not economically acceptable (peripheries of cities with low traffic density)
- at special cases where the trolley drive cannot be temporarily used (detours)

The on-board installation of battery system (at least into several trolleybuses) can be accepted with respect to these reasons.

Choosing ultracapacitor or $LiFePO_4$ battery:

First, it is essential to determine expected benefits of installation of energy storage system, and after that to choose final technology in terms of these findings, which will be purchased as a part of new vehicles. It is assumed that almost all established producers have some experience with these technologies.

If the electric energy saving is priority in contrary to drive without trolley then it is more suitable to choose ultracapacitor in terms of lifetime.

If the $LiFePO_4$ battery is used in configuration designed in previous chapters then the drive range without trolley is approximately 7 km. In this case we recommend not to use battery for energy recovery purposes (shorter battery lifetime). If the energy recovery is not utilized, it is possible to design the battery capacity to one third (it means ca. 4.6 kWh), because lower charging current is required. Lower weight and purchasing cost of battery are achieved.

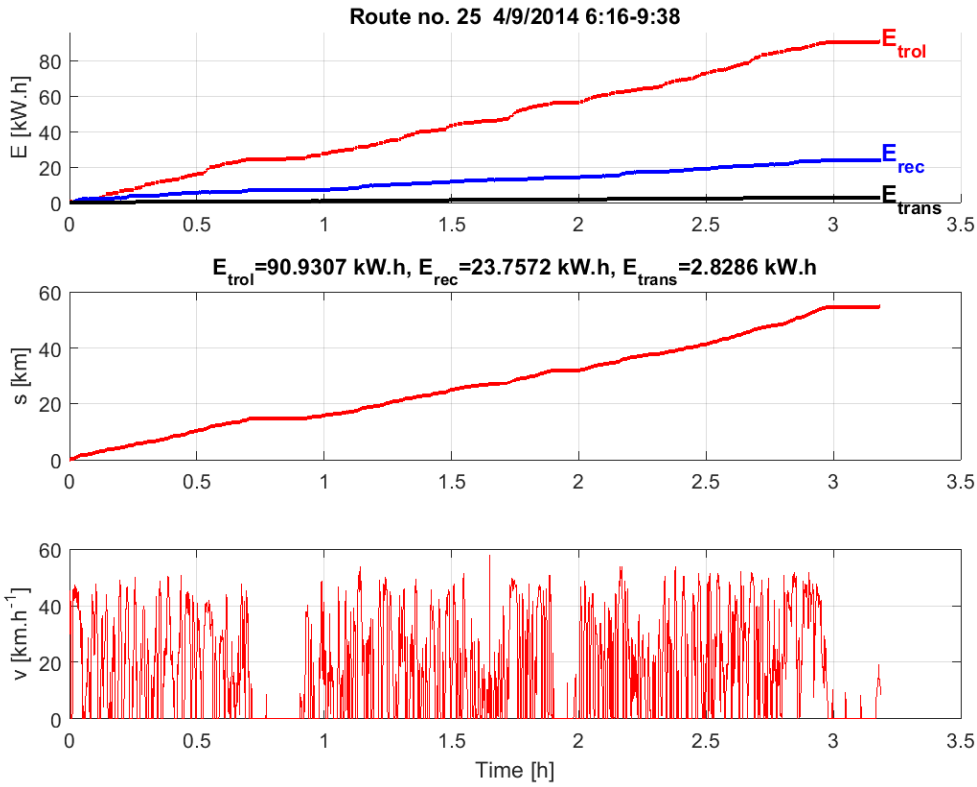
Final recommendation:

There is no general recommendation for utilization of either ultracapacitor or battery. Always a concrete assessment of particular drive application has to be provided. If these technologies will be finally used then the utilization of the battery seems more beneficial due to possibility of independent drive without trolley. On-board installation of the technology is not acceptable from the economic point of view without additional technical requirements or reasons.

Recommendation for 21 Tr trolleybuses:

21 Tr trolleybuses were able to return braking energy back into trolley but this features was disabled due to poor reliability (thyristor failures). Solving reliability issue would be more beneficial instead of installation of electric energy storage system for utilization of braking energy.

13. Appendix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E_rec
E_trans
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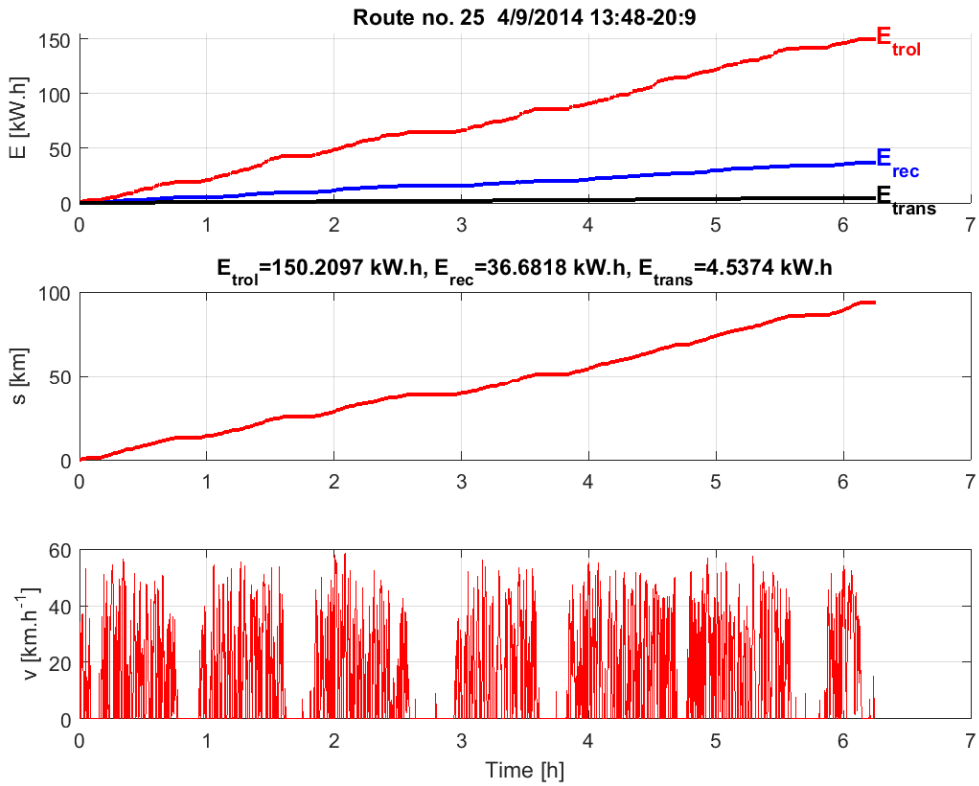
s [km]
v [km.h^-1]
Time [h]


Route no. 25 4/9/2014 13:48-20:9
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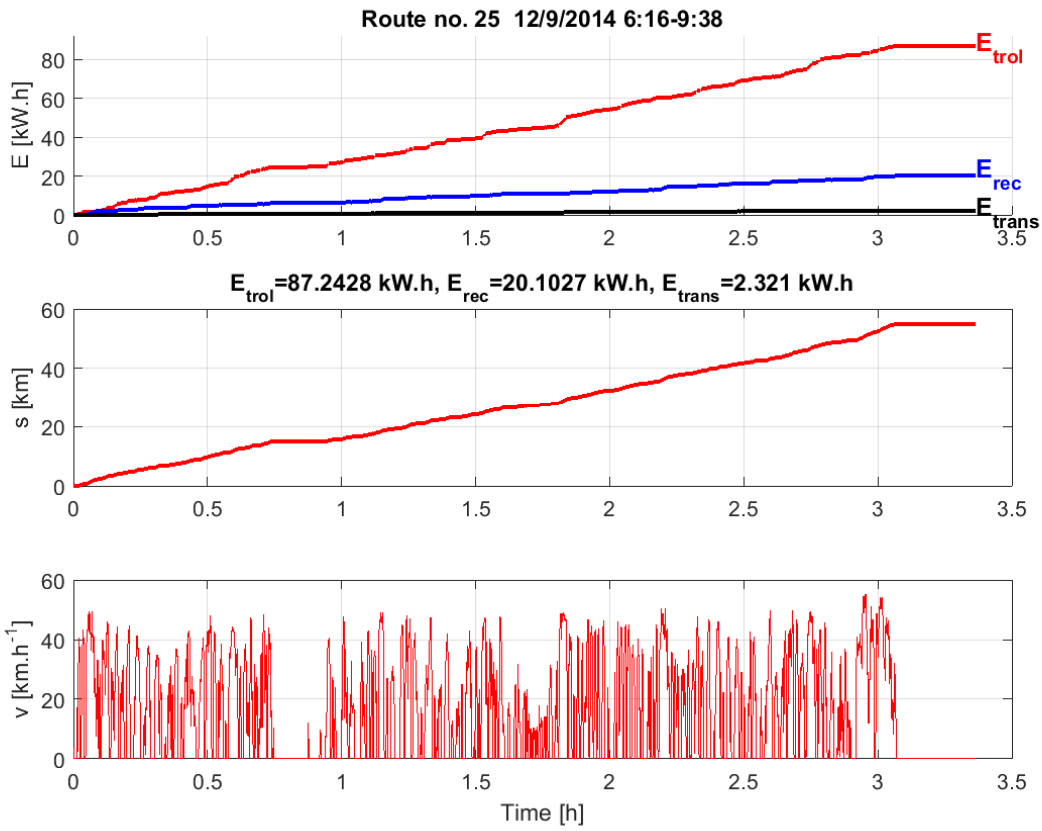
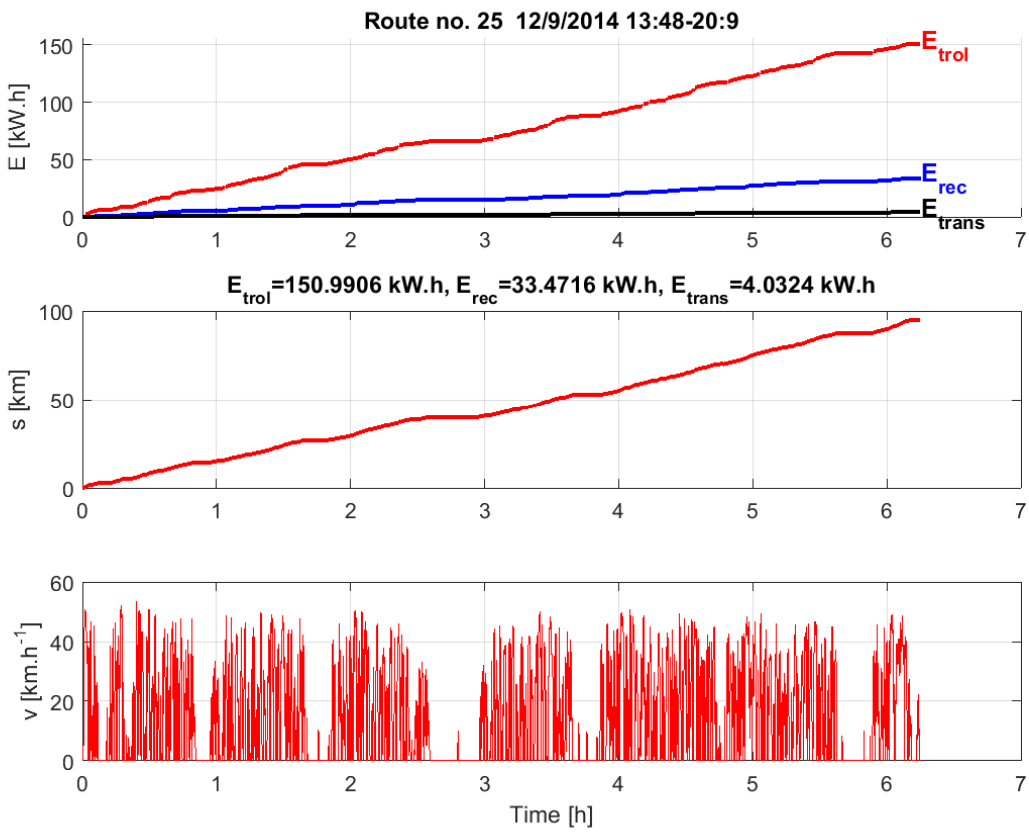
E_trol
E_rec
E_trans
E_trol=150.2097 kW.h, E_rec=36.6818 kW.h, E_trans=4.5374 kW.h
s [km]
v [km.h^-1]
Time [h]


Route no. 25 12/9/2014 6:16-9:38
E [kW.h]
E_trol
E_rec
E_trans
E_trol=87.2428 kW.h, E_rec=20.1027 kW.h, E_trans=2.321 kW.h
s [km]
v [km.h^-1]
Time [h]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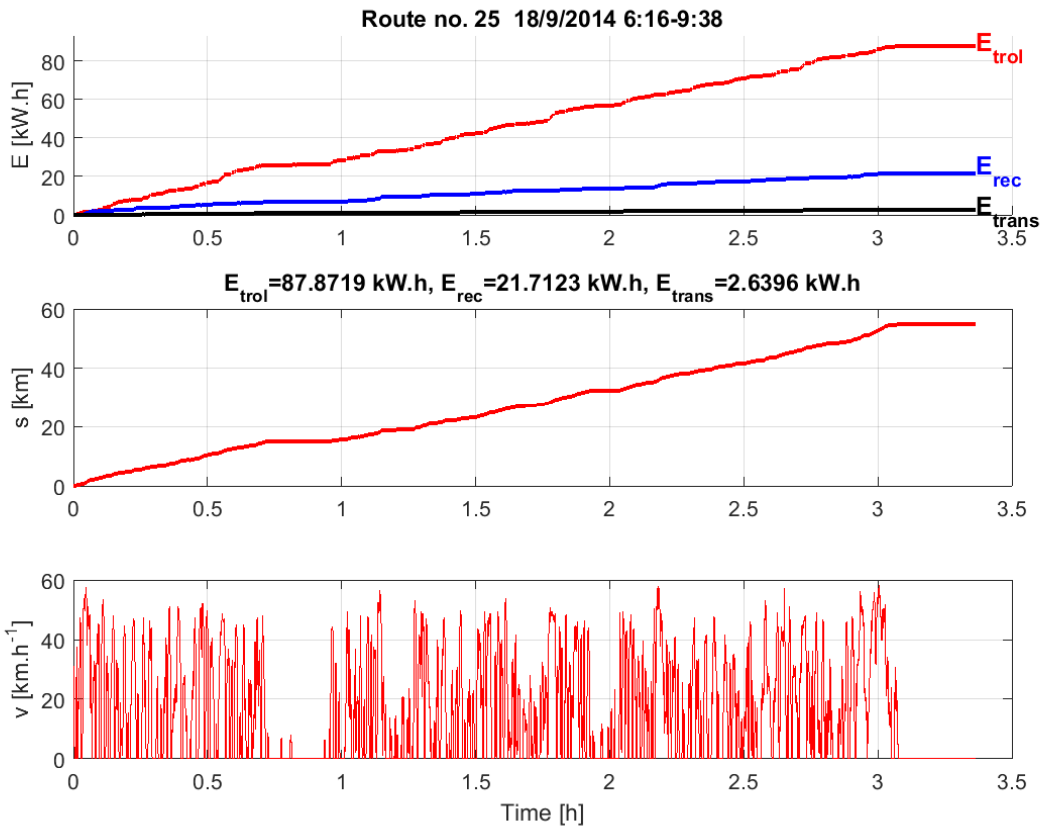
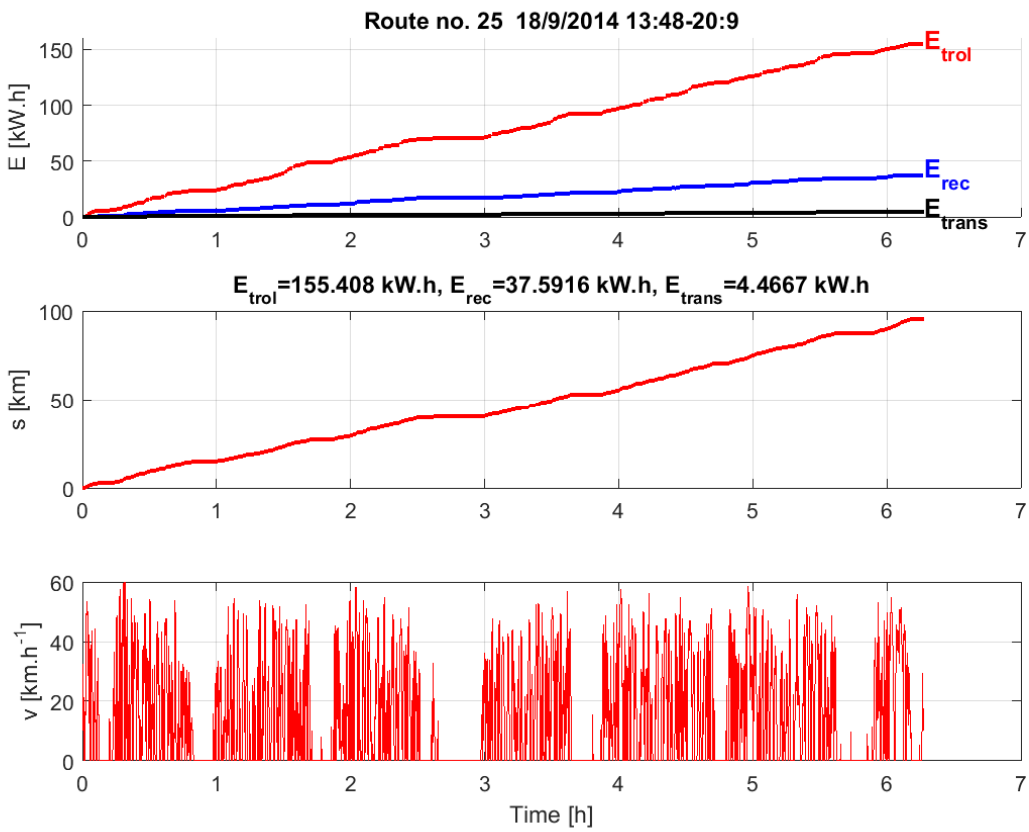
E_trol
E_rec
E_trans
E_trol=150.9906 kW.h, E_rec=33.4716 kW.h, E_trans=4.0324 kW.h
s [km]
v [km.h^-1]
Time [h]


Route no. 25 18/9/2014 6:16-9:38
E [kW.h]
E_trol
E_rec
E_trans
E_trol=87.8719 kW.h, E_rec=21.7123 kW.h, E_trans=2.6396 kW.h
s [km]
v [km.h^-1]
Time [h]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E_trol
E_rec
E_trans
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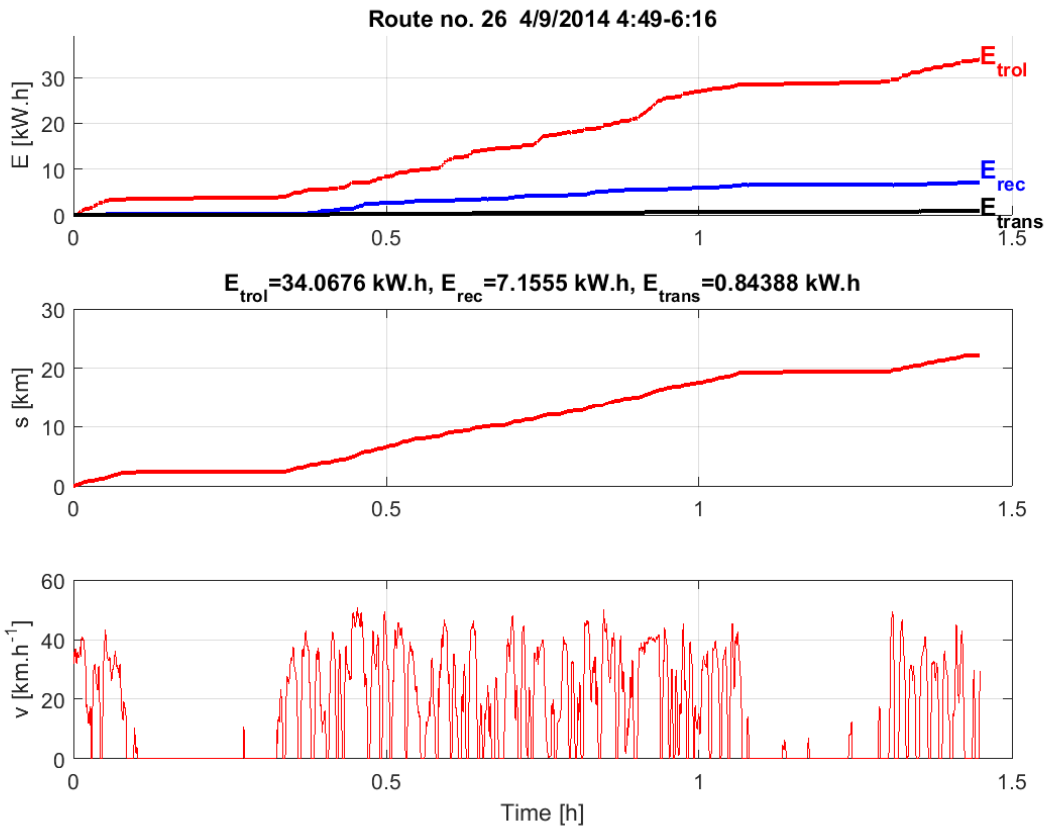
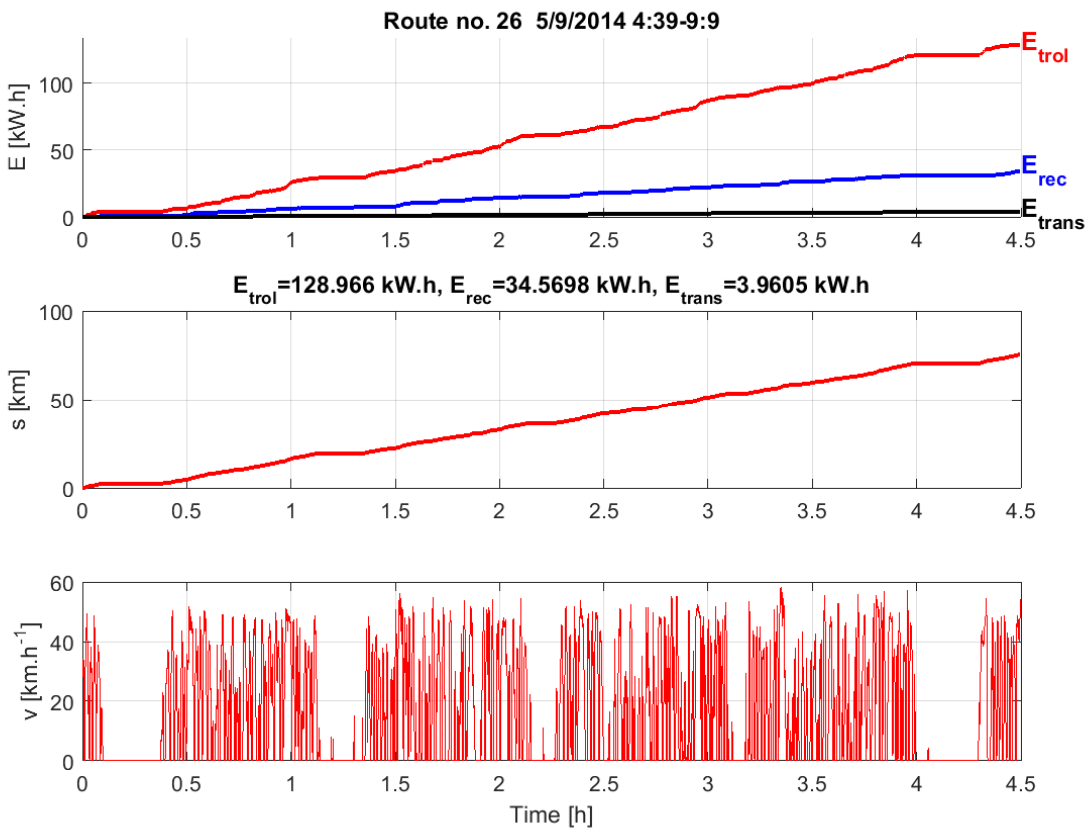
s [km]
v [km.h^-1]
Time [h]


Route no. 26 4/9/2014 4:49-6:16
E [kW.h]
E_trol
E_rec
E_trans
E_trol=34.0676 kW.h, E_rec=7.1555 kW.h, E_trans=0.84388 kW.h
s [km]
v [km.h^-1]
Time [h]


Route no. 26 5/9/2014 4:39-9:9
E [kW.h]
E_trol
E_rec
E_trans
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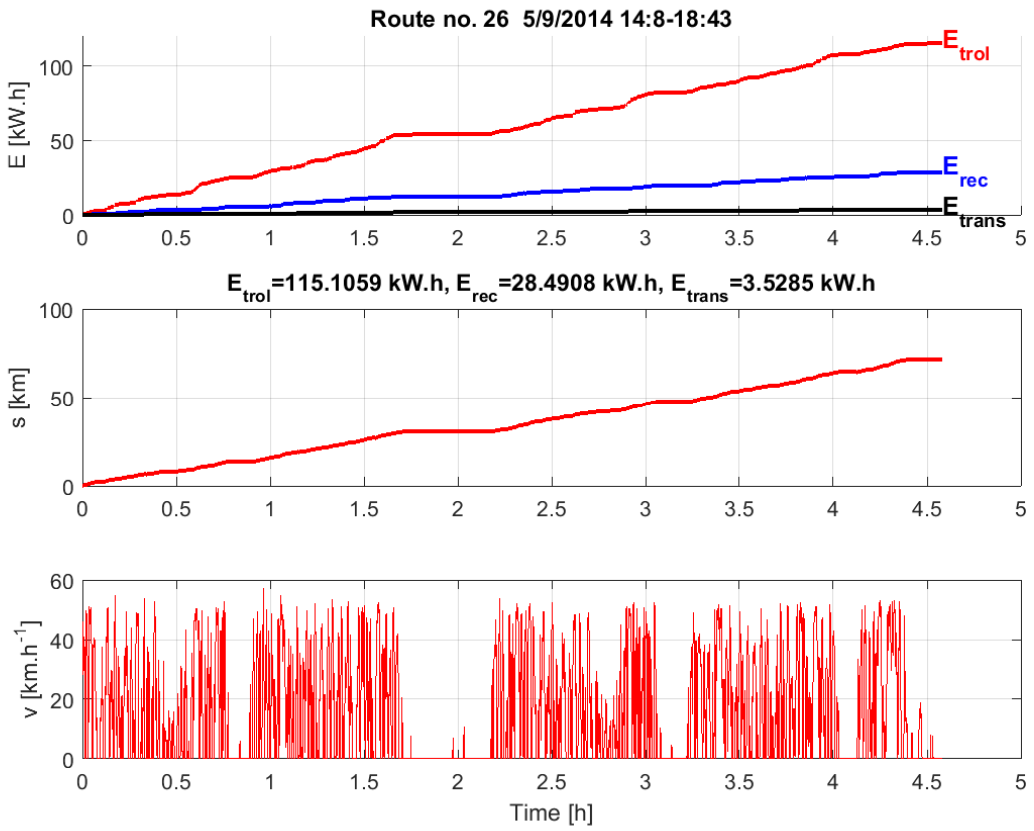
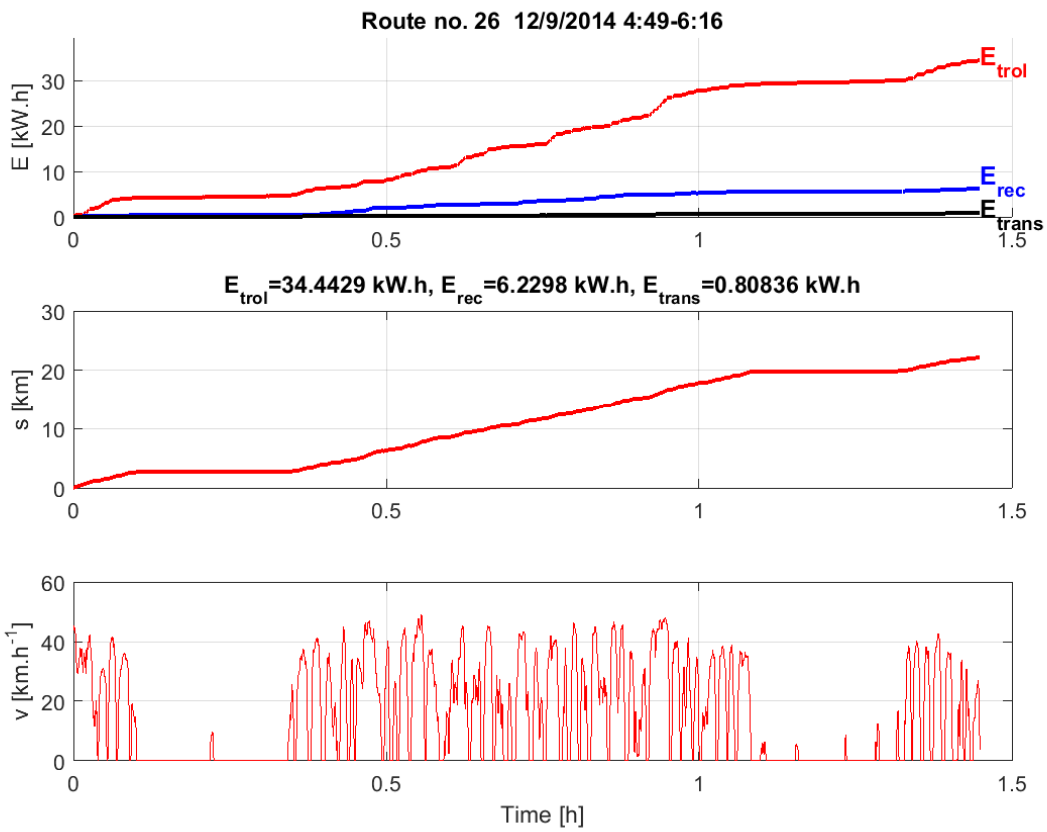
s [km]
v [km.h^-1]
Time [h]


Route no. 26 5/9/2014 14:8-18:43
E [kW.h]
E_trol
E_rec
E_trans
E_trol=115.1059 kW.h, E_rec=28.4908 kW.h, E_trans=3.5285 kW.h
s [km]
v [km.h^-1]
Time [h]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E [kW.h]
E_trol
E_rec
E_trans
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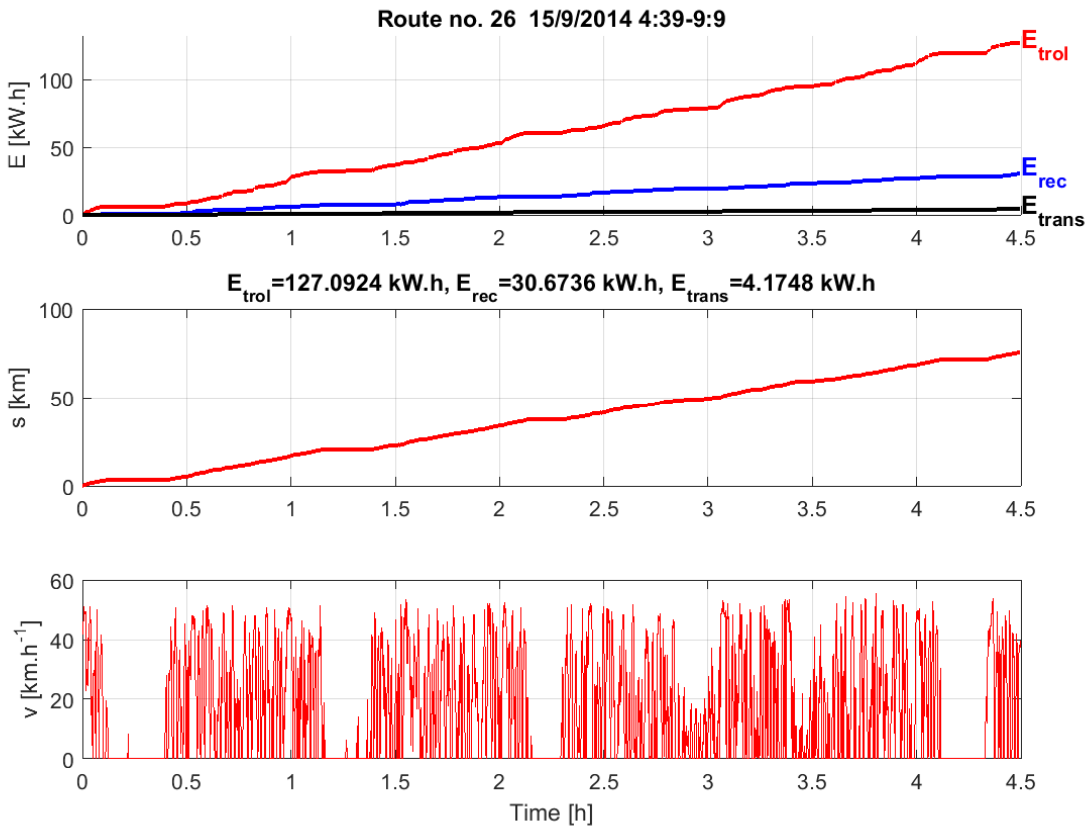
s [km]
v [km.h^-1]
Time [h]


Route no. 26 15/9/2014 4:39-9:9
E [kW.h]
E_trol
E_rec
E_trans
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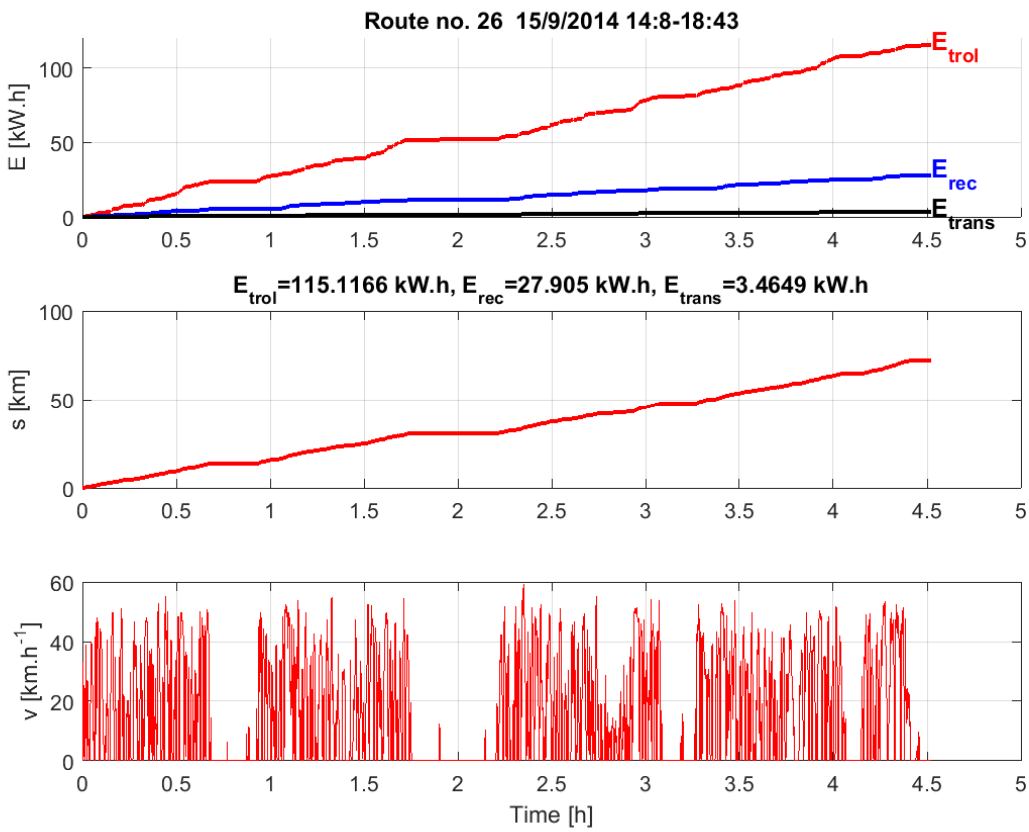
s [km]
v [km.h^-1]
Time [h]


Route no. 26 15/9/2014 14:8-18:43
E [kW.h]
E_trol
E_rec
E_trans
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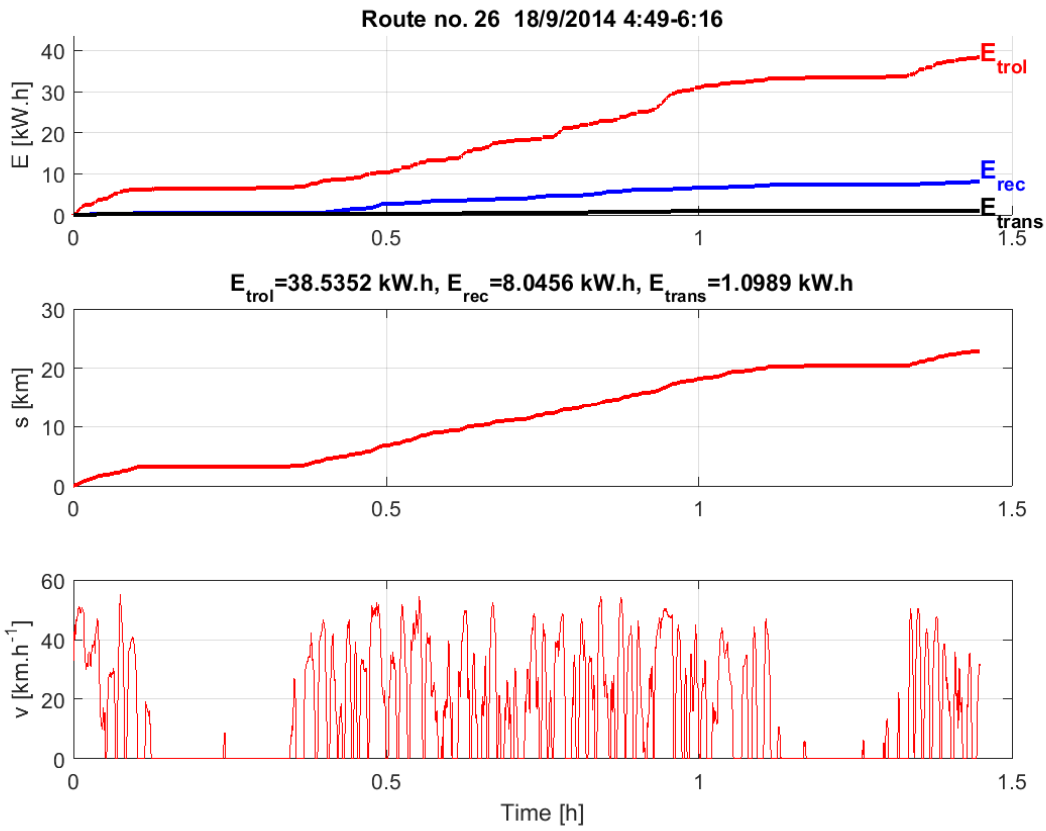
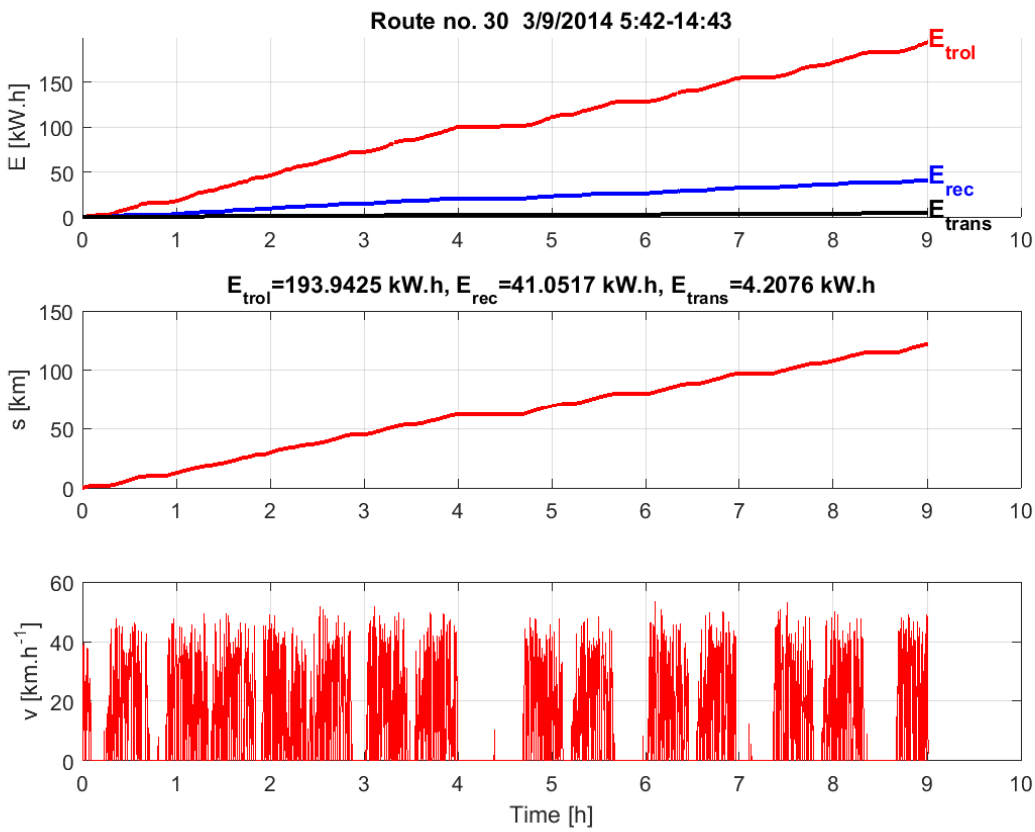
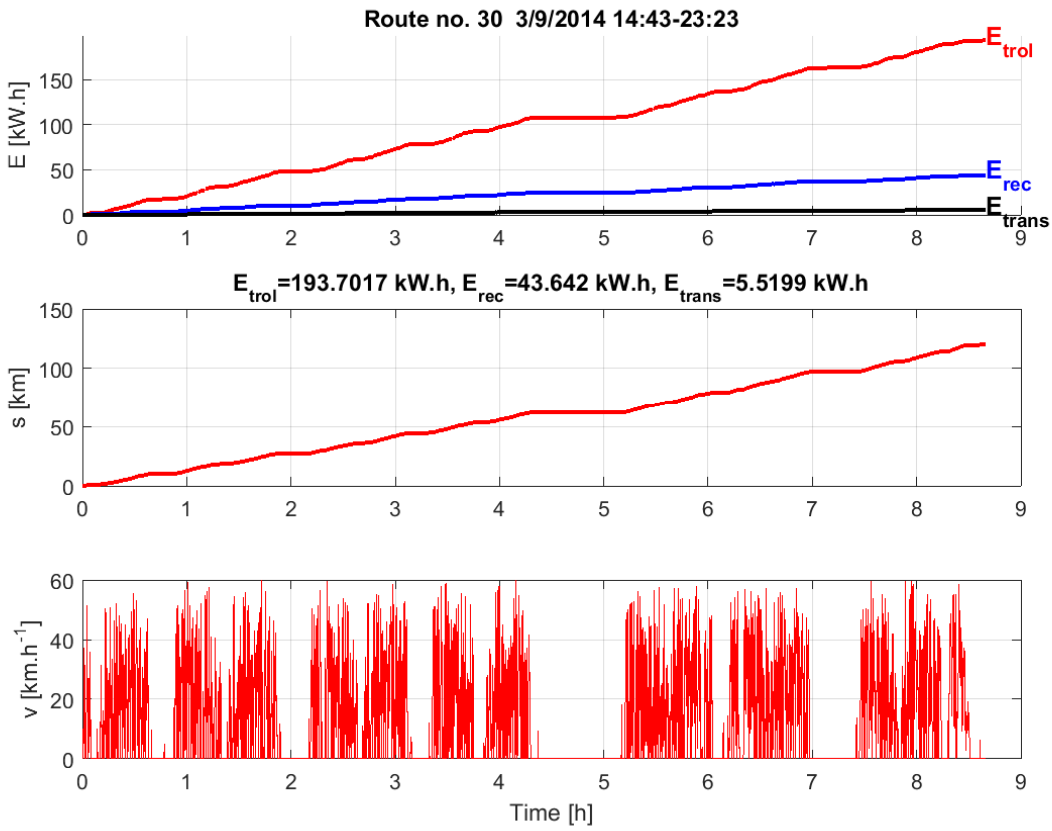
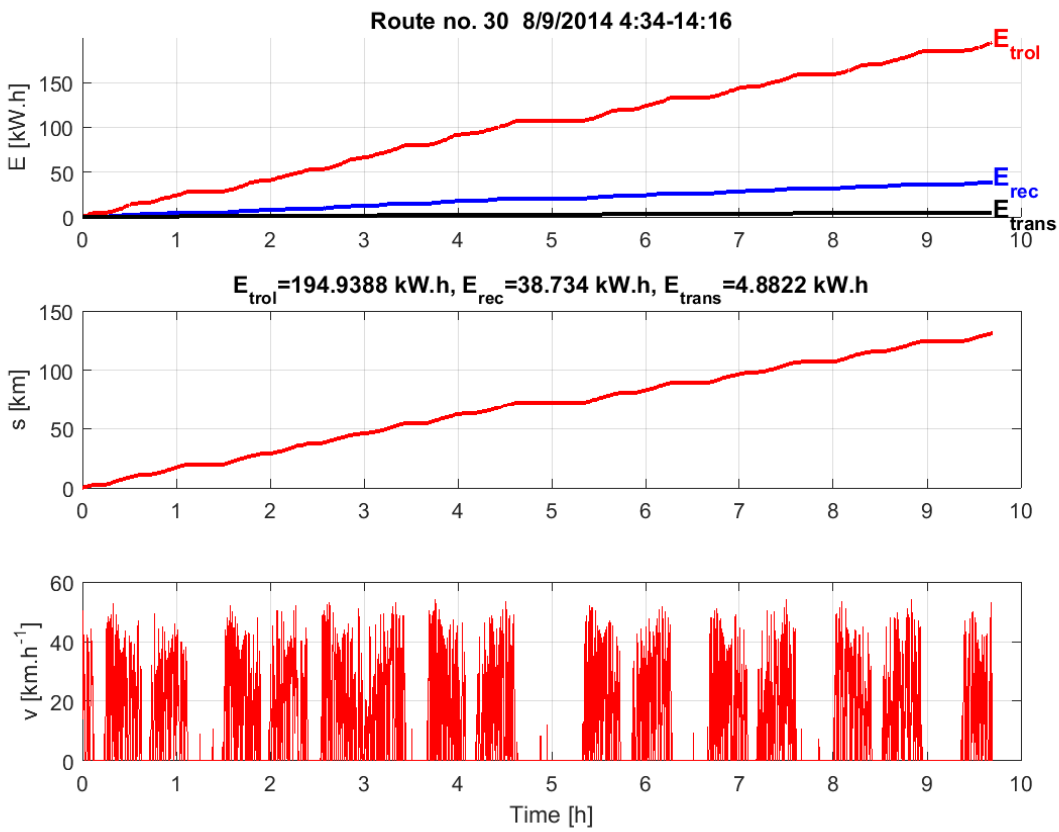
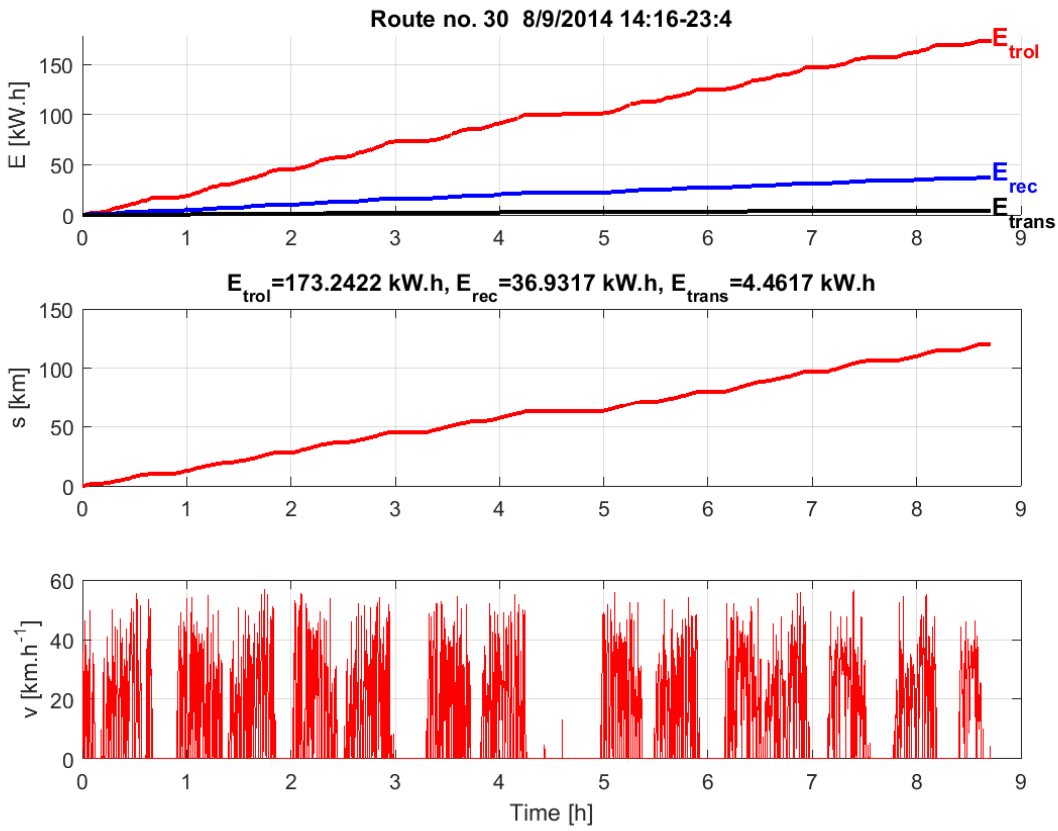
s [km]
v [km.h^-1]
Time [h]

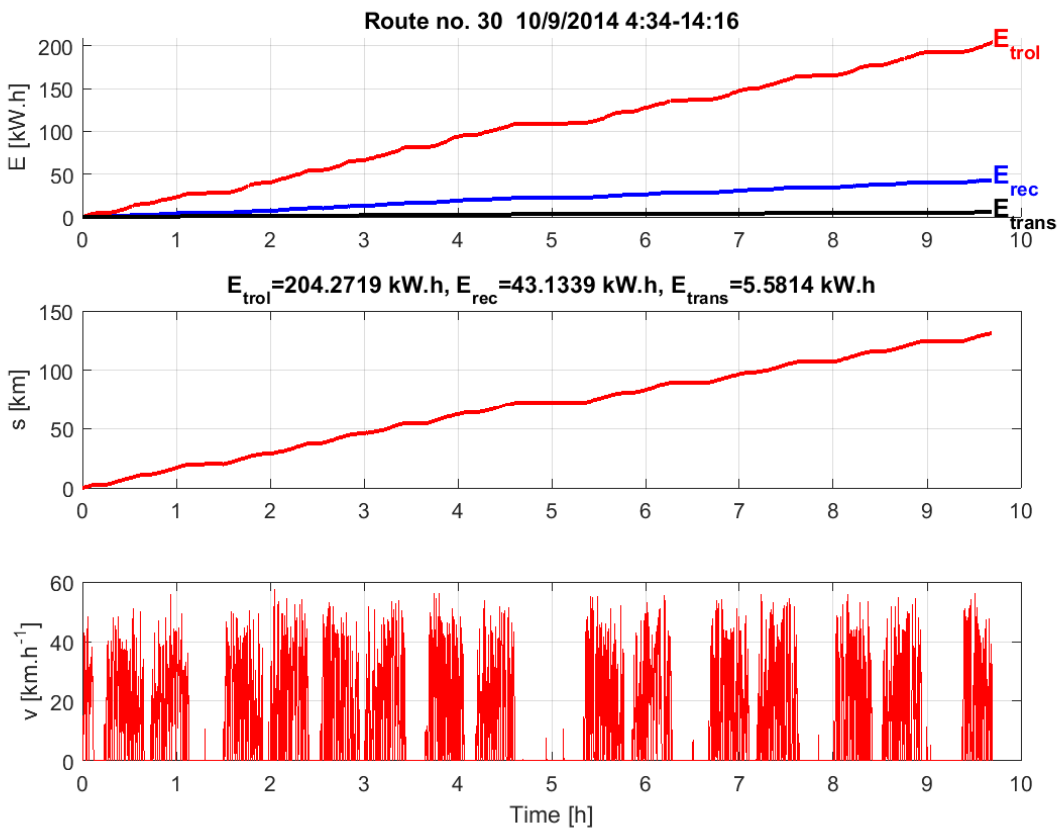

Route no. 26 18/9/2014 4:49-6:16
E [kW.h]
E_trol
E_rec
E_trans
E_trol=38.5352 kW.h, E_rec=8.0456 kW.h, E_trans=1.0989 kW.h
s [km]
v [km.h^-1]
Time [h]

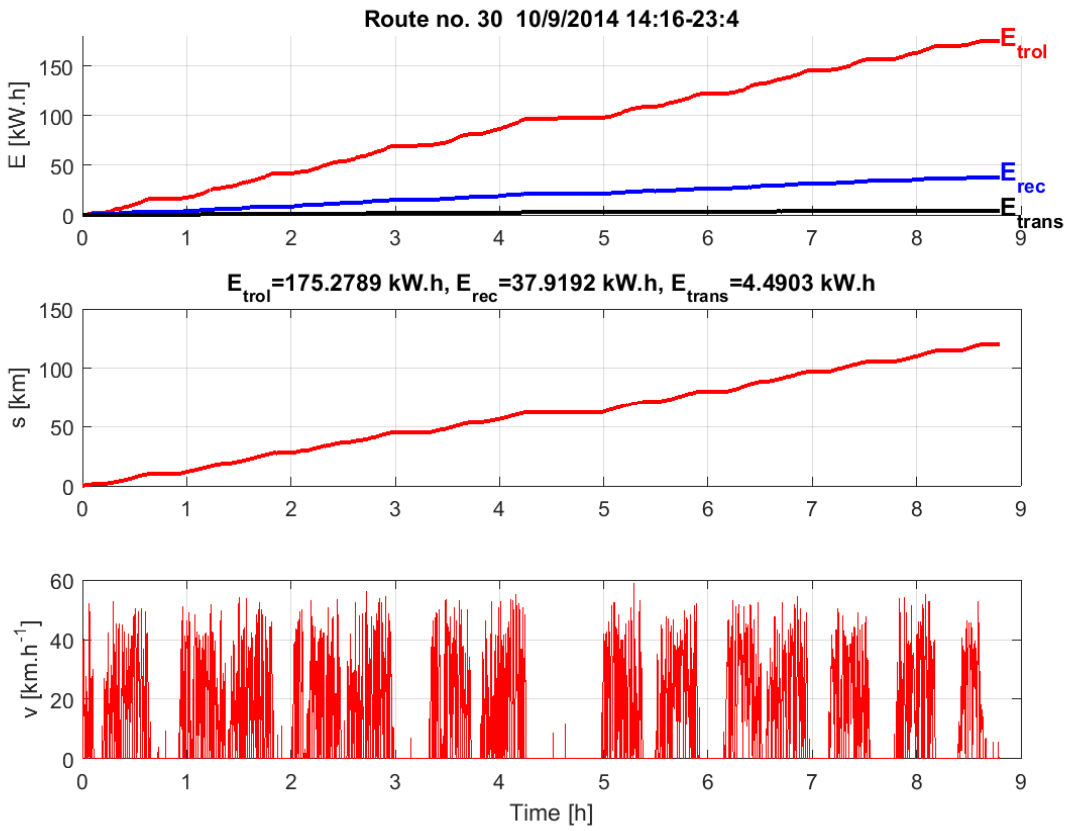

Route no. 30 3/9/2014 5:42-14:43
E [kW.h]
E_trol
E_rec
E_trans
E_trol=193.9425 kW.h, E_rec=41.0517 kW.h, E_trans=4.2076 kW.h
s [km]
v [km.h^-1]
Time [h]

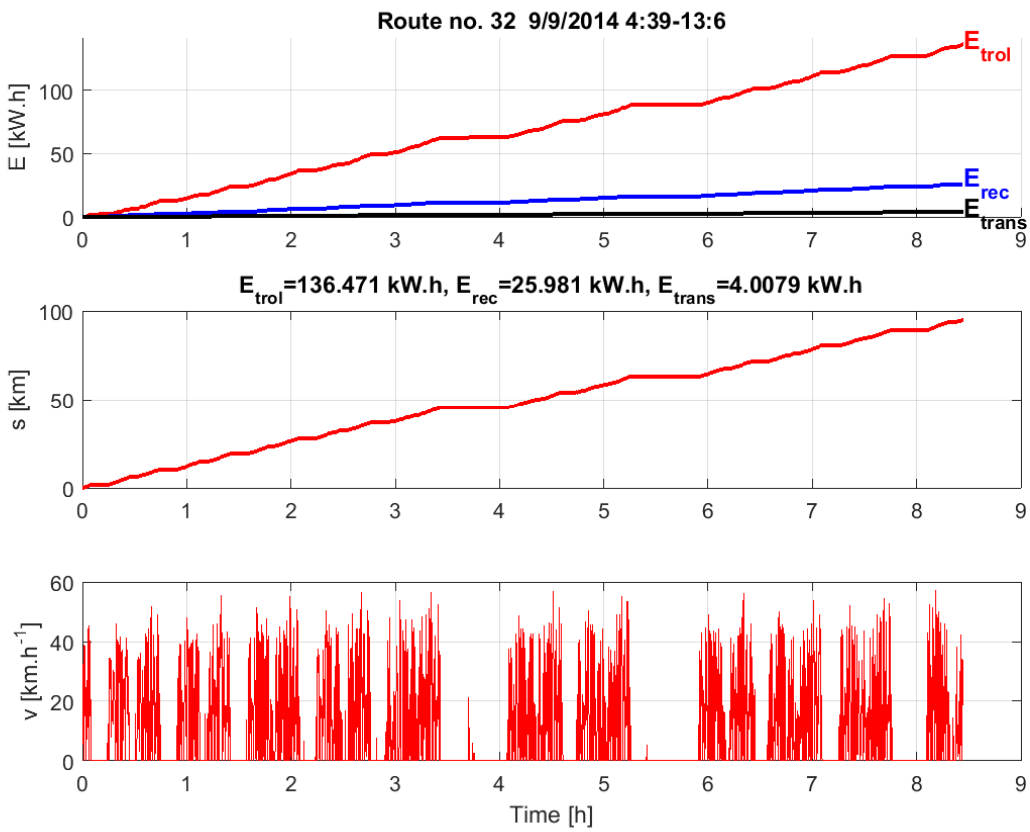

Route no. 30 3/9/2014 14:43-23:23
E [kW.h]
E_trol
E_rec
E_trans
E_trol=193.7017 kW.h, E_rec=43.642 kW.h, E_trans=5.5199 kW.h
s [km]
v [km.h^-1]
Time [h]

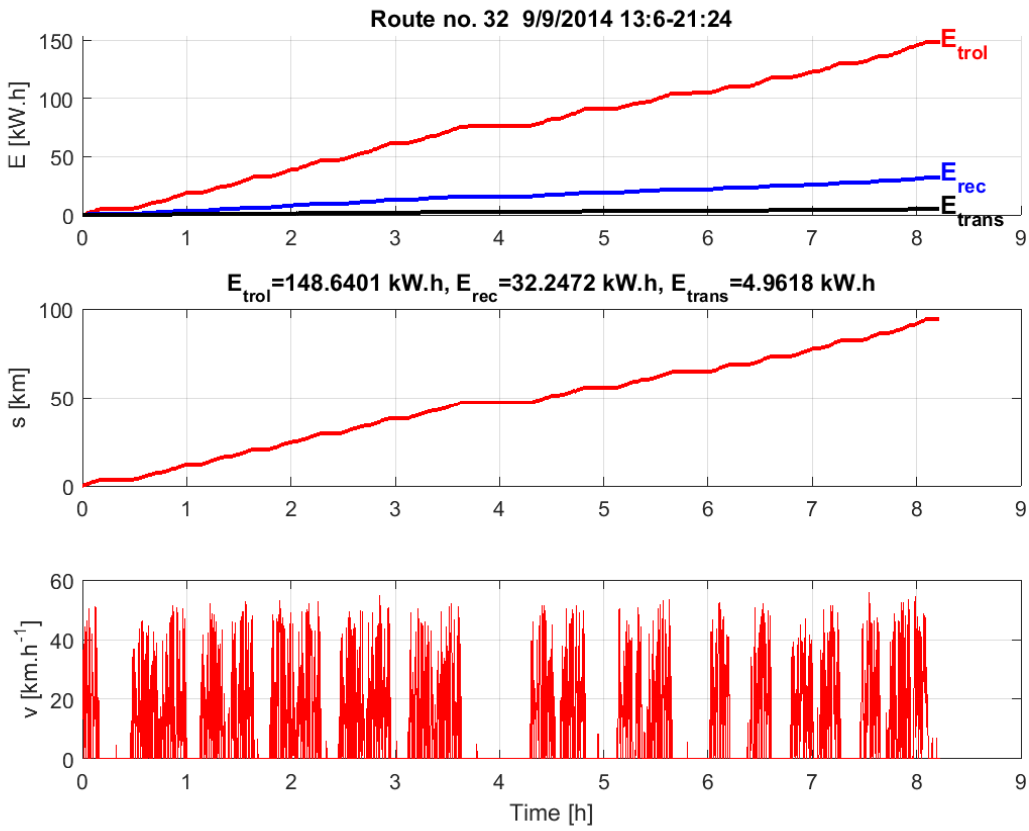

Route no. 30 8/9/2014 4:34-14:16
E [kW.h]
E_trol
E_rec
E_trans
E_trol=194.9388 kW.h, E_rec=38.734 kW.h, E_trans=4.8822 kW.h
s [km]
v [km.h^-1]
Time [h]

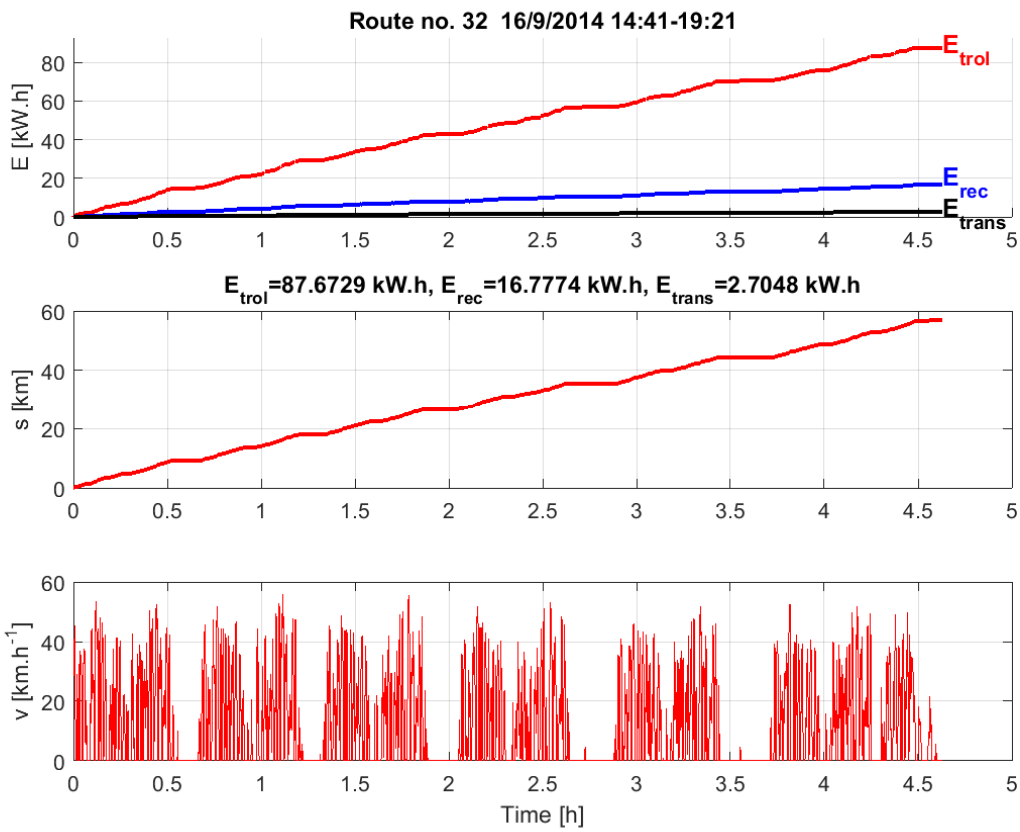

Route no. 30 8/9/2014 14:16-23:4
E [kW.h]
E trol
E rec
E trans
E trol=173.2422 kW.h, E rec=36.9317 kW.h, E trans=4.4617 kW.h
s [km]
v [km.h-1]
Time [h]

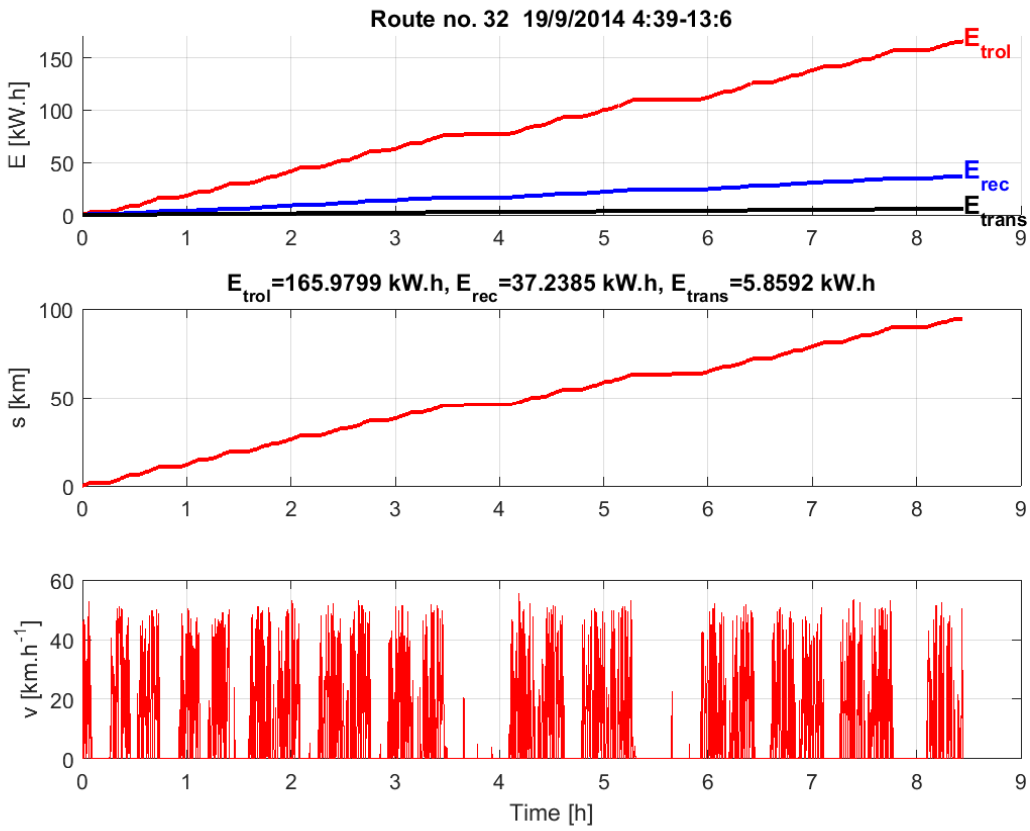

Route no. 30 10/9/2014 4:34-14:16
E [kW.h]
E trol
E rec
E trans
E trol=204.2719 kW.h, E rec=43.1339 kW.h, E trans=5.5814 kW.h
s [km]
v [km.h-1]
Time [h]

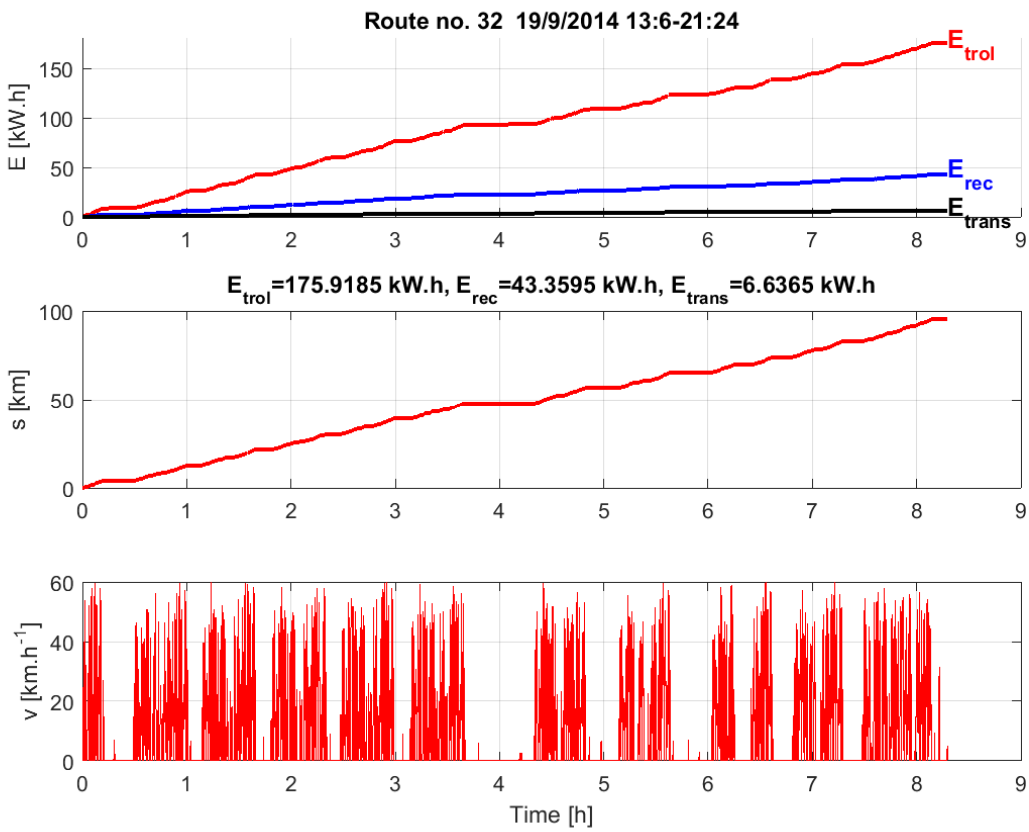

Route no. 30 10/9/2014 14:16-23:4
E [kW.h]
E_trol
E_rec
E_trans
E_trol=175.2789 kW.h, E_rec=37.9192 kW.h, E_trans=4.4903 kW.h
s [km]
v [km.h^-1]
Time [h]

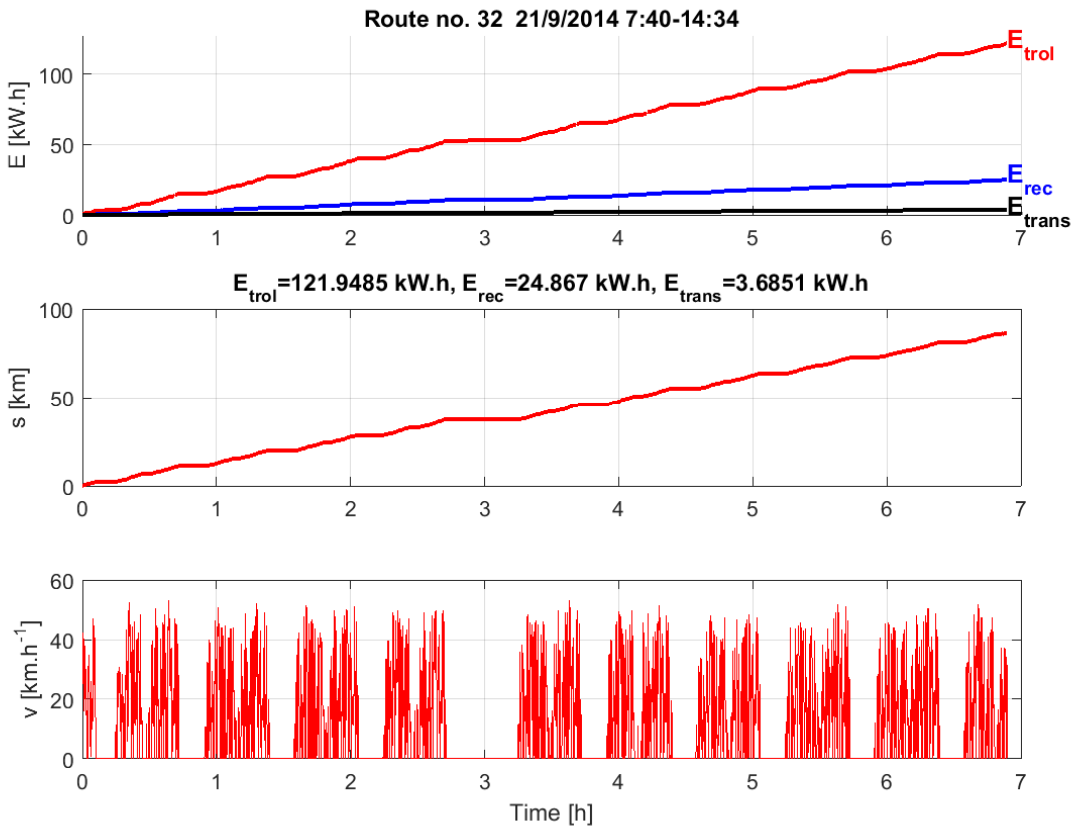

Route no. 32 9/9/2014 4:39-13:6
E [kW.h]
E_trol
E_rec
E_trans
E_trol=136.471 kW.h, E_rec=25.981 kW.h, E_trans=4.0079 kW.h
s [km]
v [km.h^-1]
Time [h]

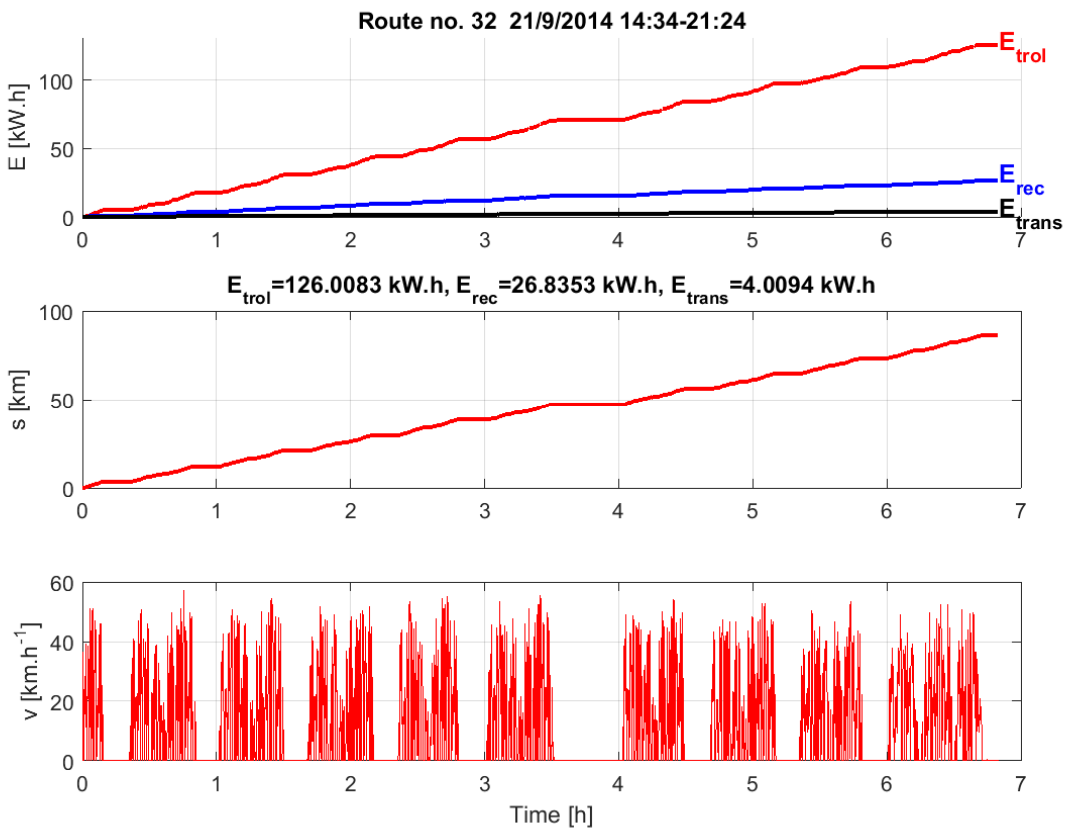

Route no. 32 9/9/2014 13:6-21:24
E [kW.h]
E trol
E rec
E trans
E trol=148.6401 kW.h, E rec=32.2472 kW.h, E trans=4.9618 kW.h
s [km]
v [km.h-1]
Time [h]

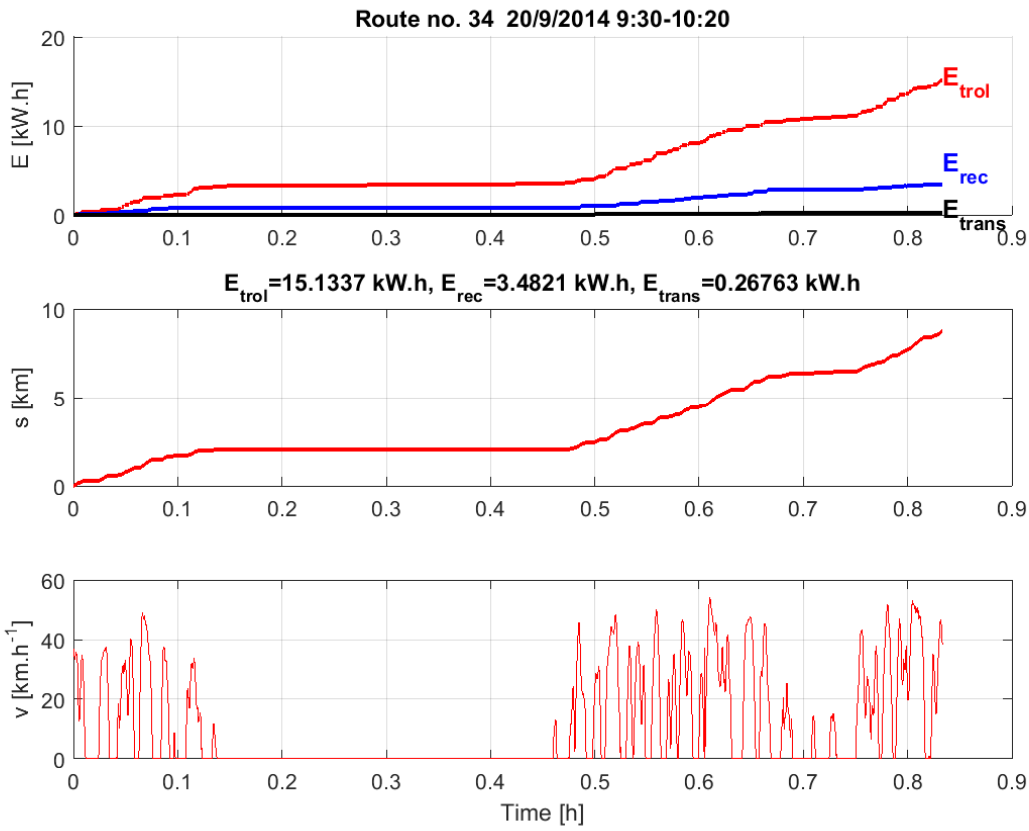

Route no. 32 16/9/2014 14:41-19:21
E [kW.h]
E trol
E rec
E trans
E trol=87.6729 kW.h, E rec=16.7774 kW.h, E trans=2.7048 kW.h
s [km]
v [km.h-1]
Time [h]

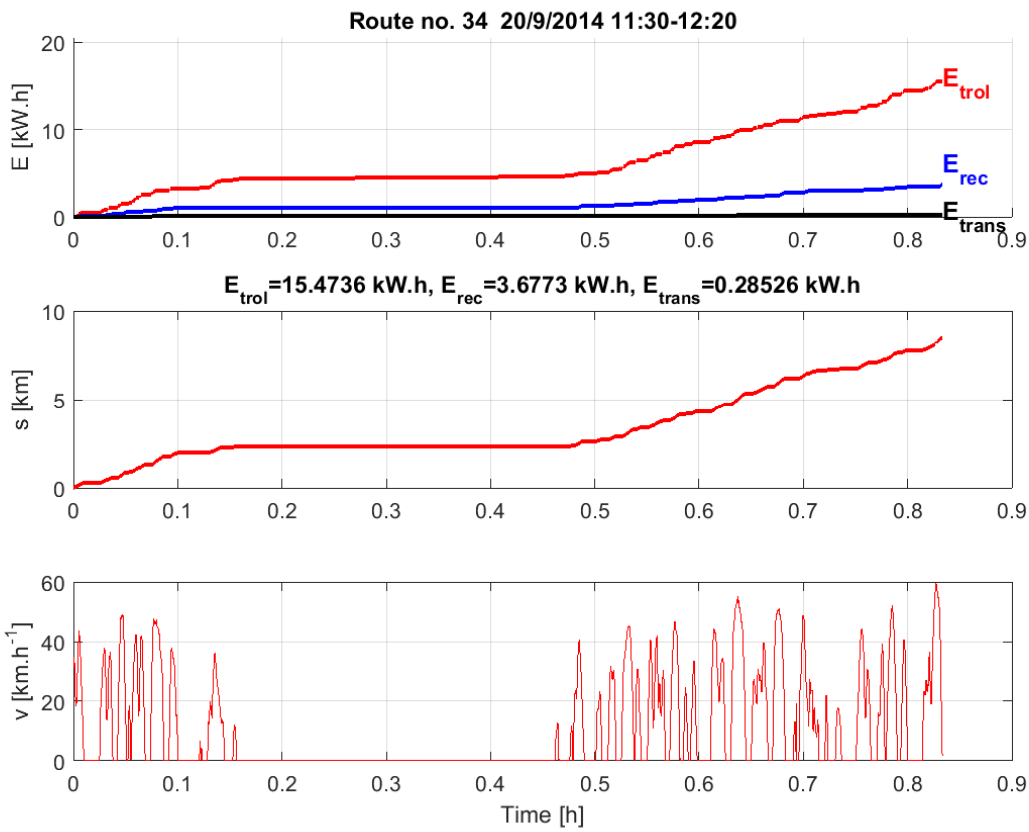

Route no. 32 19/9/2014 4:39-13:6
E [kW.h]
E_trol
E_rec
E_trans
E_trol=165.9799 kW.h, E_rec=37.2385 kW.h, E_trans=5.8592 kW.h
s [km]
v [km.h^-1]
Time [h]

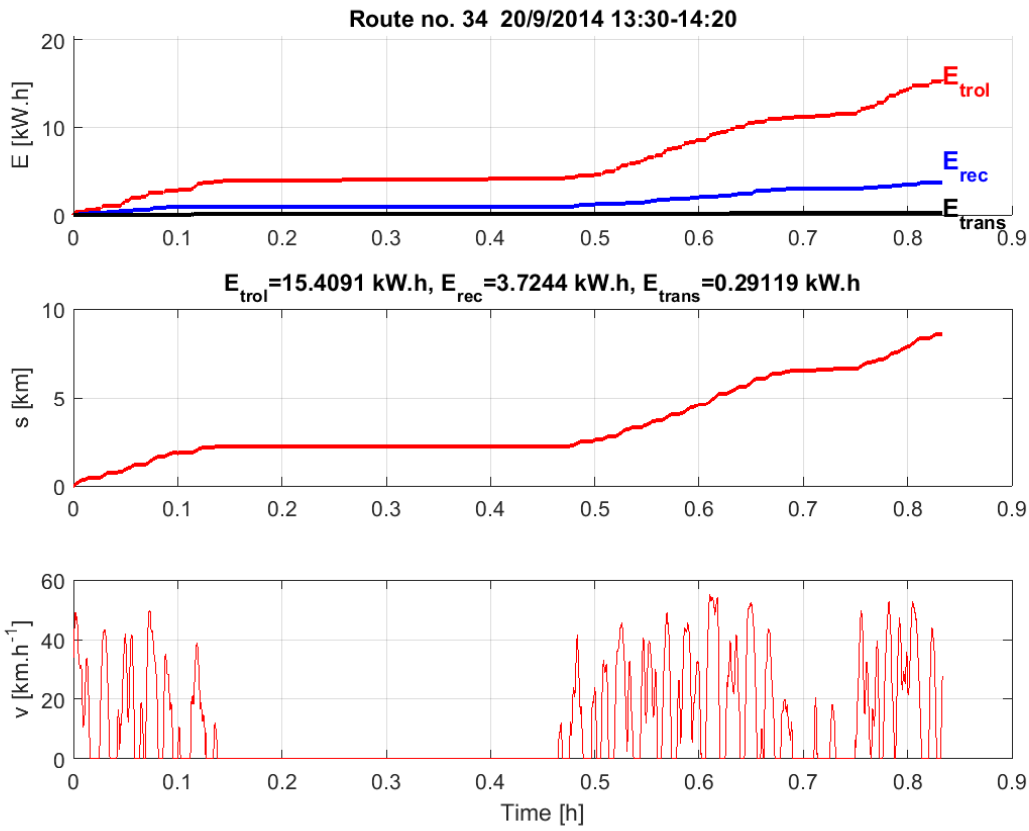

Route no. 32 19/9/2014 13:6-21:24
E [kW.h]
E_trol
E_rec
E_trans
E_trol=175.9185 kW.h, E_rec=43.3595 kW.h, E_trans=6.6365 kW.h
s [km]
v [km.h^-1]
Time [h]


Route no. 32 21/9/2014 7:40-14:34
E [kW.h]
E trol
E rec
E trans
E trol=121.9485 kW.h, E rec=24.867 kW.h, E trans=3.6851 kW.h
s [km]
v [km.h-1]
Time [h]


Route no. 32 21/9/2014 14:34-21:24
E [kW.h]
E trol
E rec
E trans
E trol=126.0083 kW.h, E rec=26.8353 kW.h, E trans=4.0094 kW.h
s [km]
v [km.h-1]
Time [h]


Route no. 34 20/9/2014 9:30-10:20
E [kW.h]
E_trol
E_rec
E_trans
E_trol=15.1337 kW.h, E_rec=3.4821 kW.h, E_trans=0.26763 kW.h
s [km]
v [km.h^-1]
Time [h]


Route no. 34 20/9/2014 11:30-12:20
E [kW.h]
E_trol
E_rec
E_trans
E_trol=15.4736 kW.h, E_rec=3.6773 kW.h, E_trans=0.28526 kW.h
s [km]
v [km.h^-1]
Time [h]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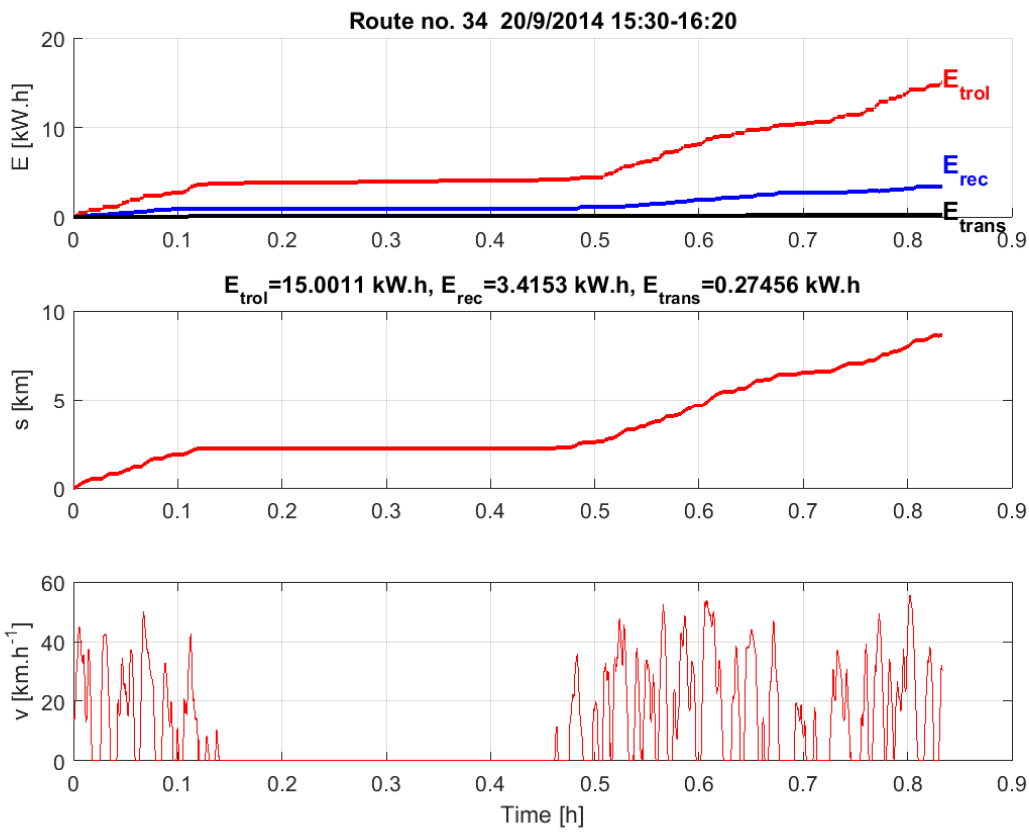
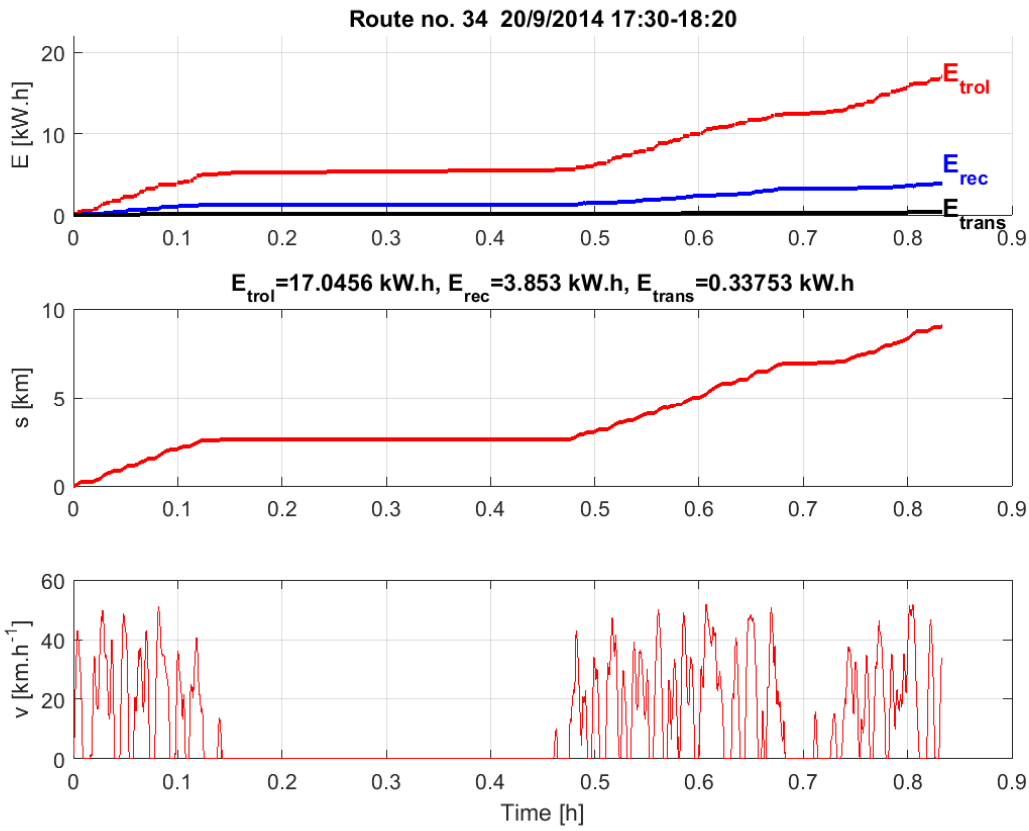
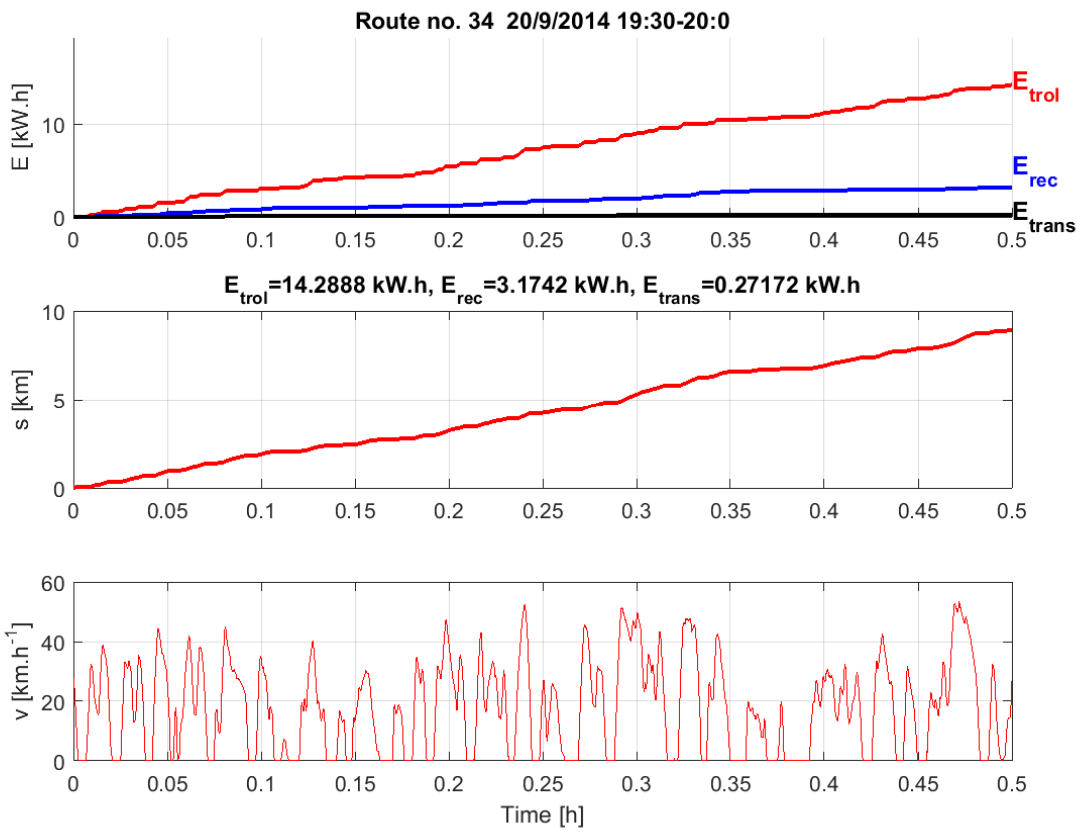
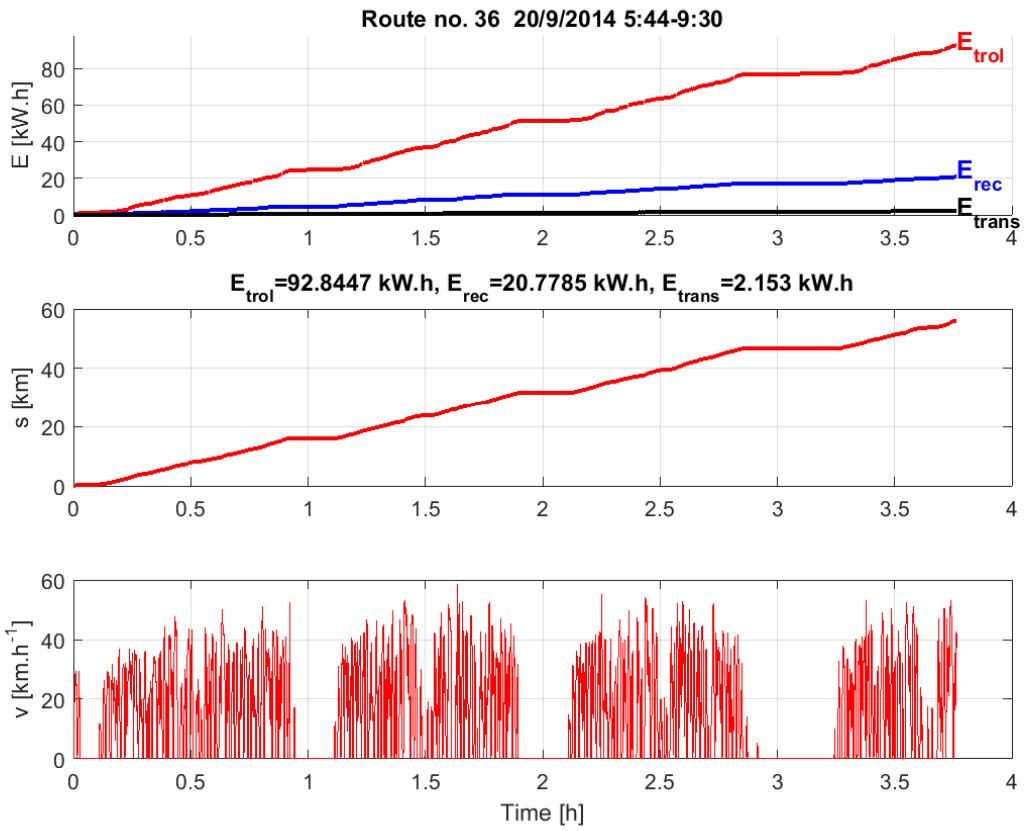
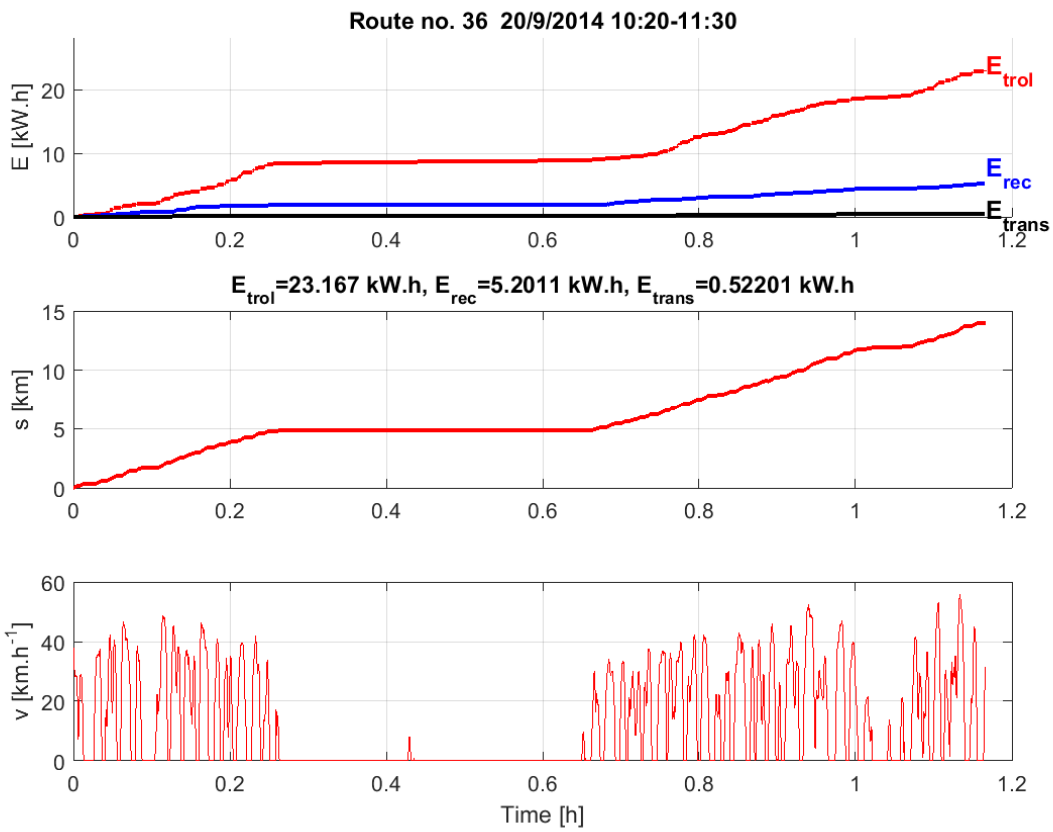
E [kW.h]
E_trol
E_rec
E_trans
E_trol=15.4091 kW.h, E_rec=3.7244 kW.h, E_trans=0.29119 kW.h
s [km]
v [km.h^-1]
Time [h]

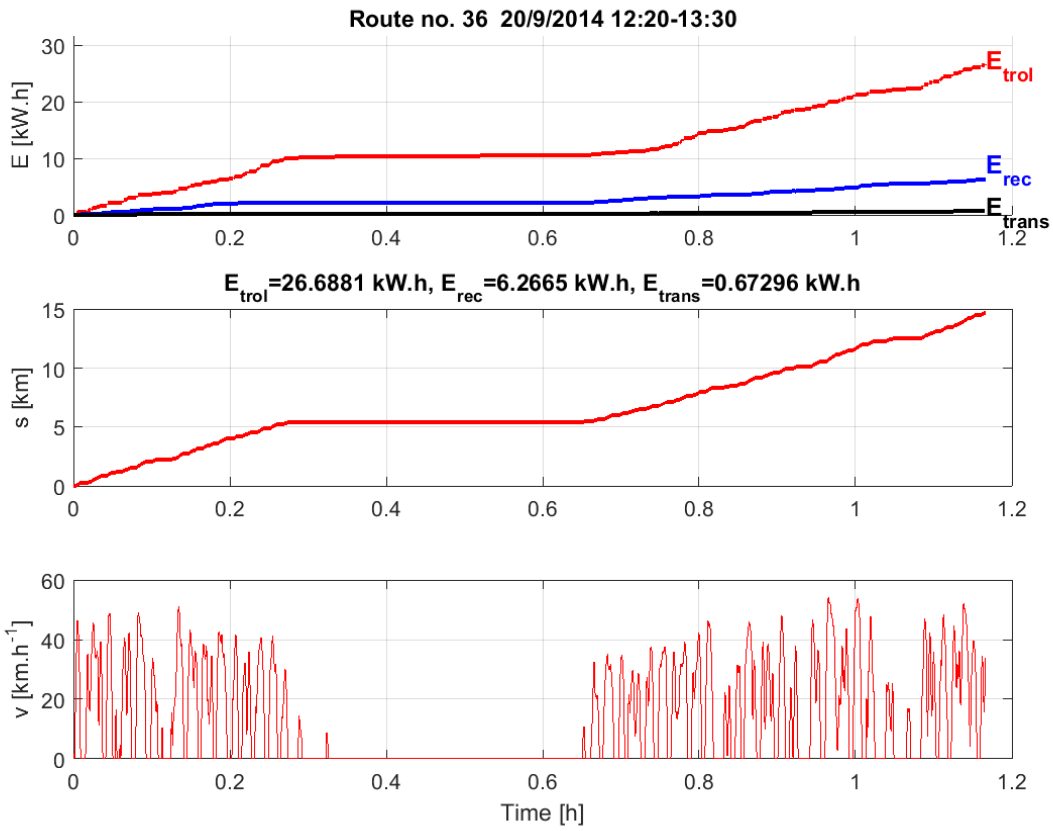

Route no. 34 20/9/2014 15:30-16:20
E [kW.h]
E_trol
E_rec
E_trans
E_trol=15.0011 kW.h, E_rec=3.4153 kW.h, E_trans=0.27456 kW.h
s [km]
v [km.h^-1]
Time [h]

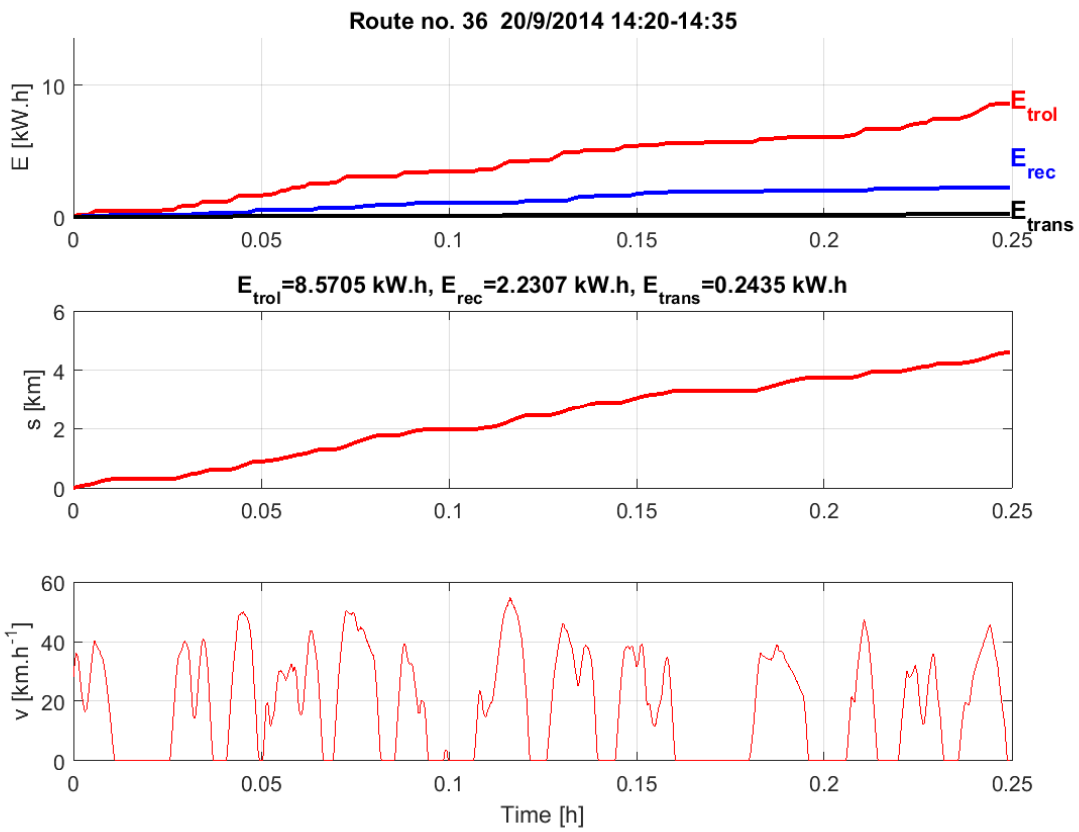

Route no. 34 20/9/2014 17:30-18:20
E [kW.h]
E_trol
E_rec
E_trans
E_trol=17.0456 kW.h, E_rec=3.853 kW.h, E_trans=0.33753 kW.h
s [km]
v [km.h^-1]
Time [h]

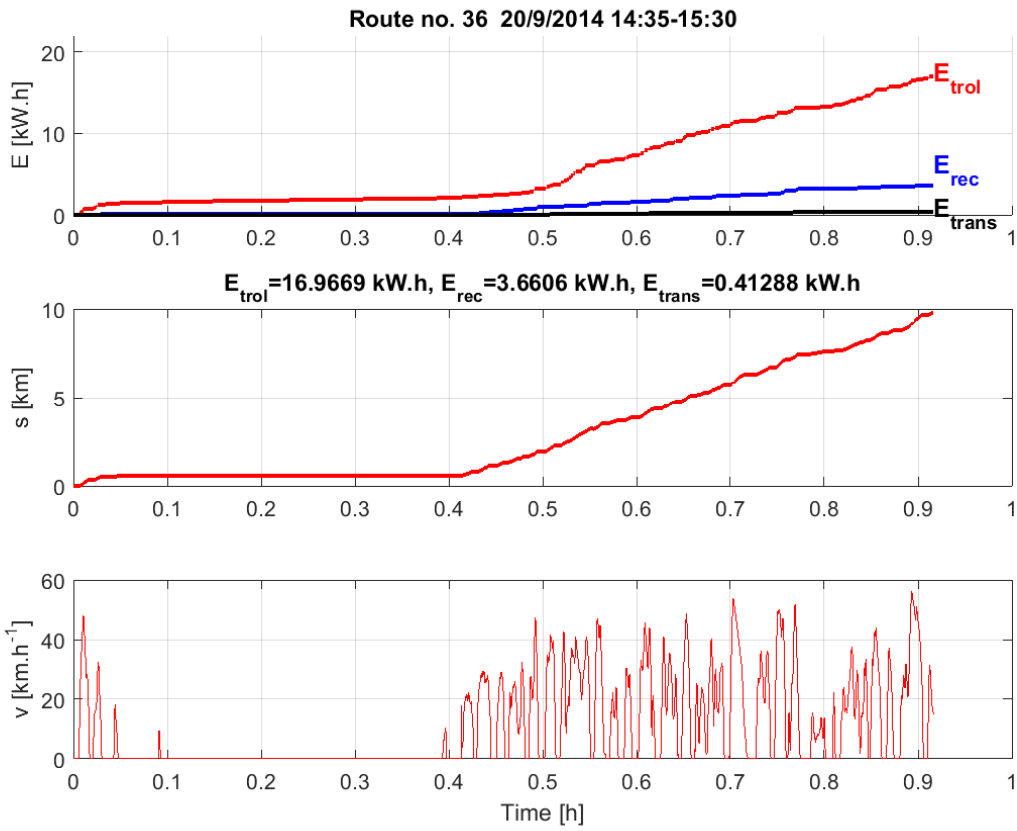

Route no. 34 20/9/2014 19:30-20:0
E [kW.h]
E_trol
E_rec
E_trans
E_trol=14.2888 kW.h, E_rec=3.1742 kW.h, E_trans=0.27172 kW.h
s [km]
v [km.h^-1]
Time [h]

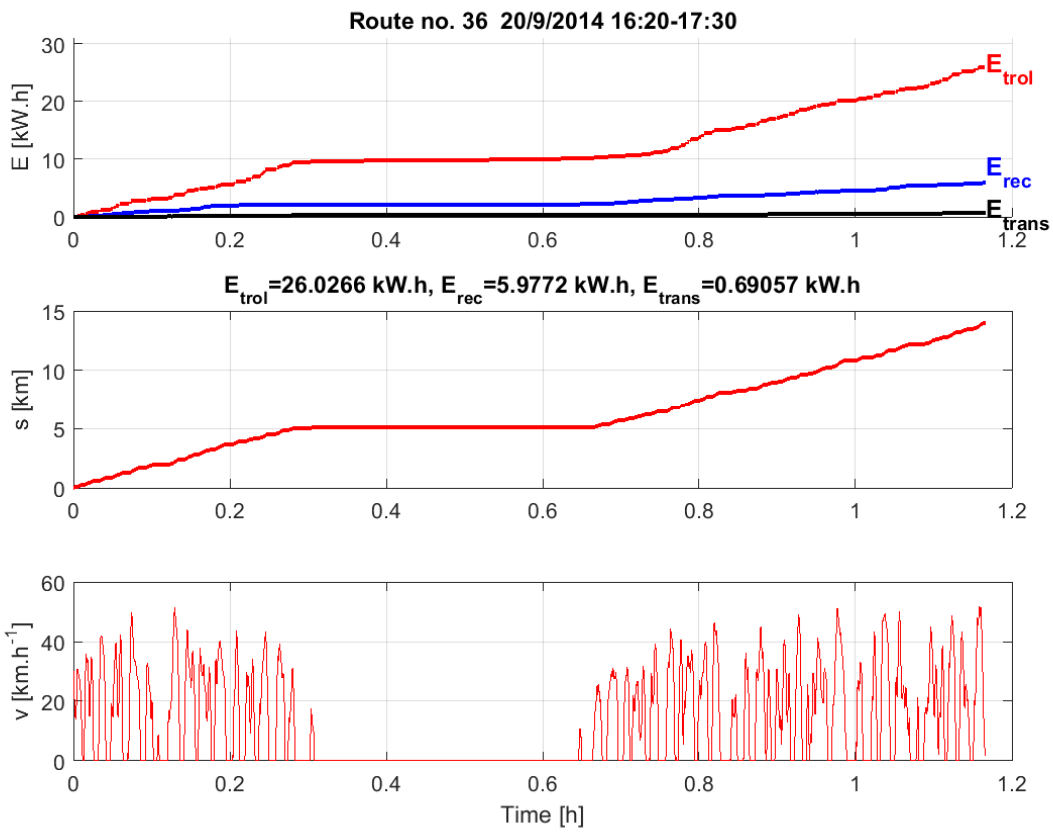

Route no. 36 20/9/2014 5:44-9:30
E [kW.h]
E_trol
E_rec
E_trans
E_trol=92.8447 kW.h, E_rec=20.7785 kW.h, E_trans=2.153 kW.h
s [km]
v [km.h^-1]
Time [h]

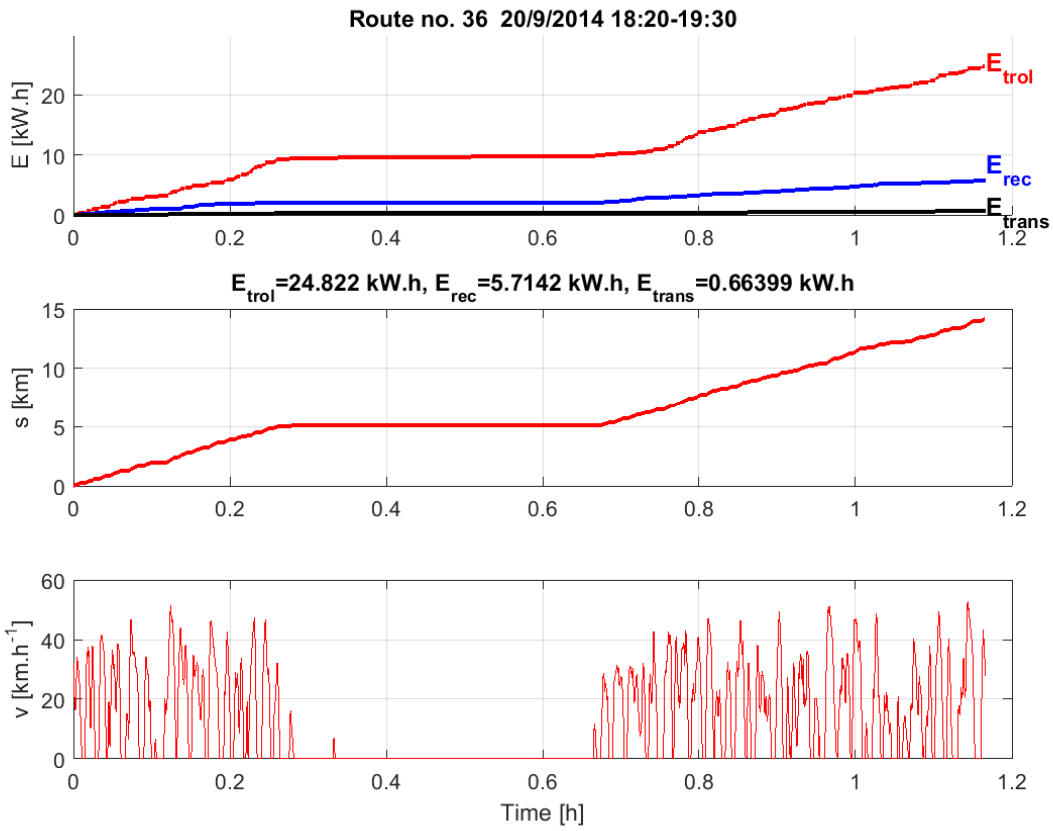

Route no. 36 20/9/2014 10:20-11:30
E [kW.h]
E_trol
E_rec
E_trans
E_trol=23.167 kW.h, E_rec=5.2011 kW.h, E_trans=0.52201 kW.h
s [km]
v [km.h^-1]
Time [h]

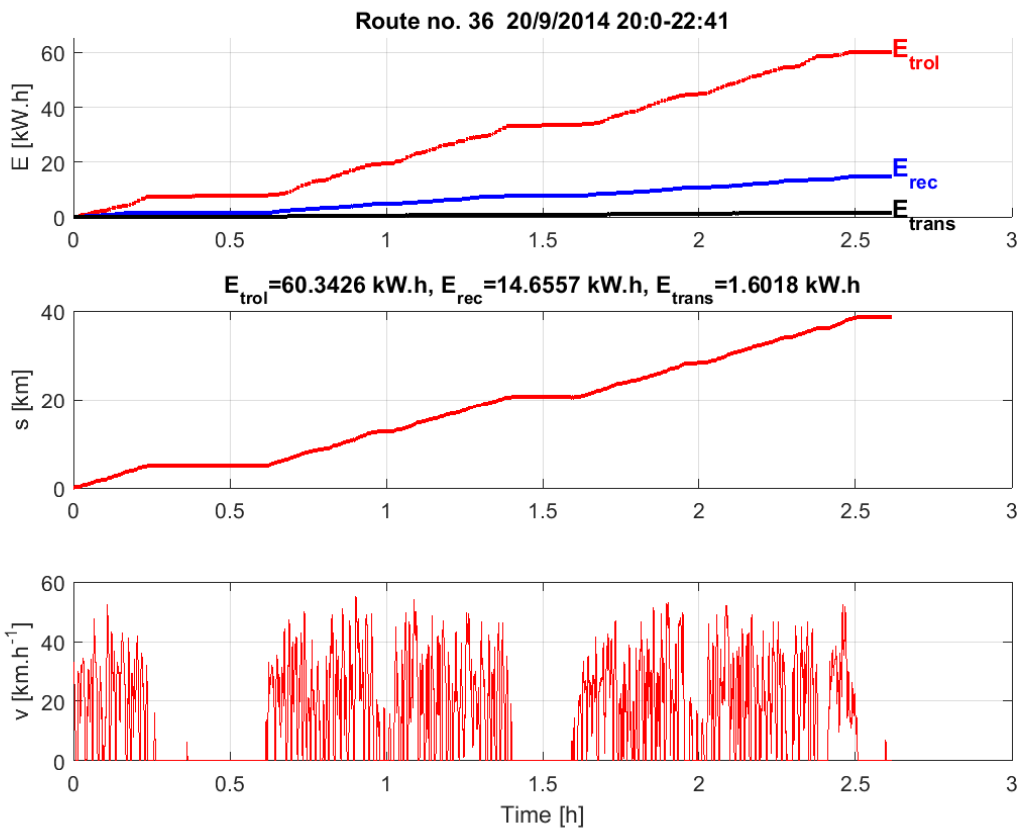

Route no. 36 20/9/2014 12:20-13:30
E [kW.h]
E_trol
E_rec
E_trans
E_trol=26.6881 kW.h, E_rec=6.2665 kW.h, E_trans=0.67296 kW.h
s [km]
v [km.h^-1]
Time [h]

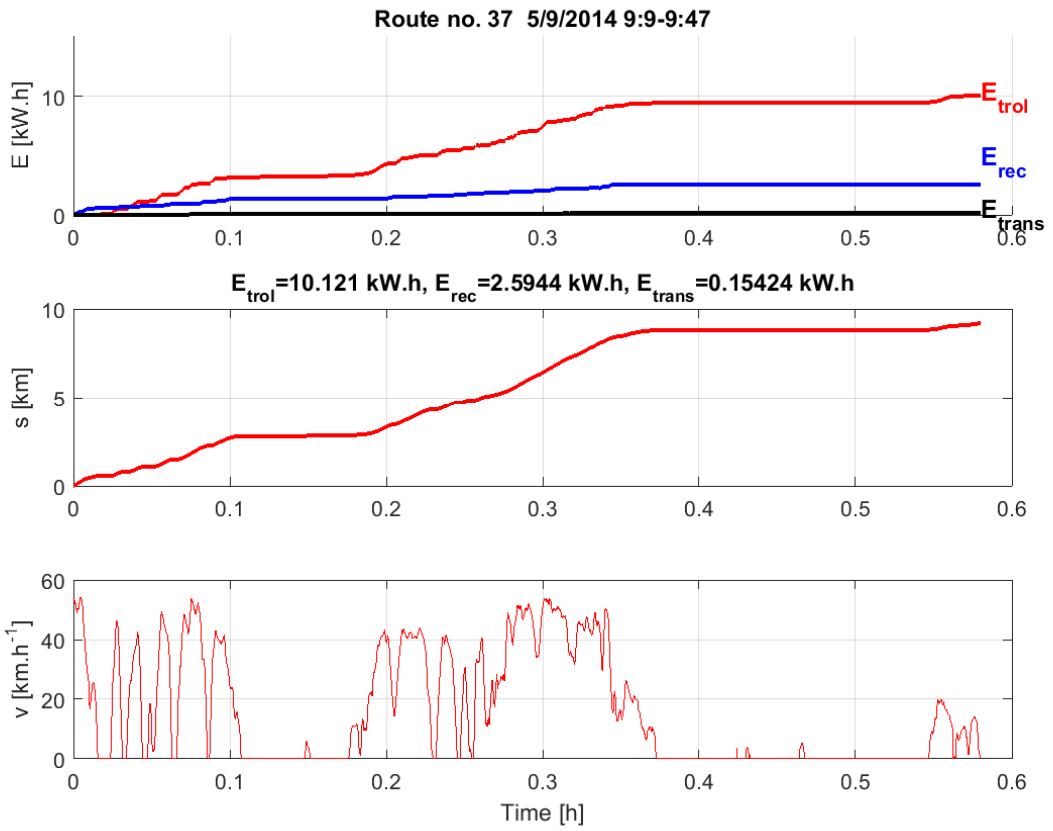

Route no. 36 20/9/2014 14:20-14:35
E [kW.h]
E_trol
E_rec
E_trans
E_trol=8.5705 kW.h, E_rec=2.2307 kW.h, E_trans=0.2435 kW.h
s [km]
v [km.h^-1]
Time [h]

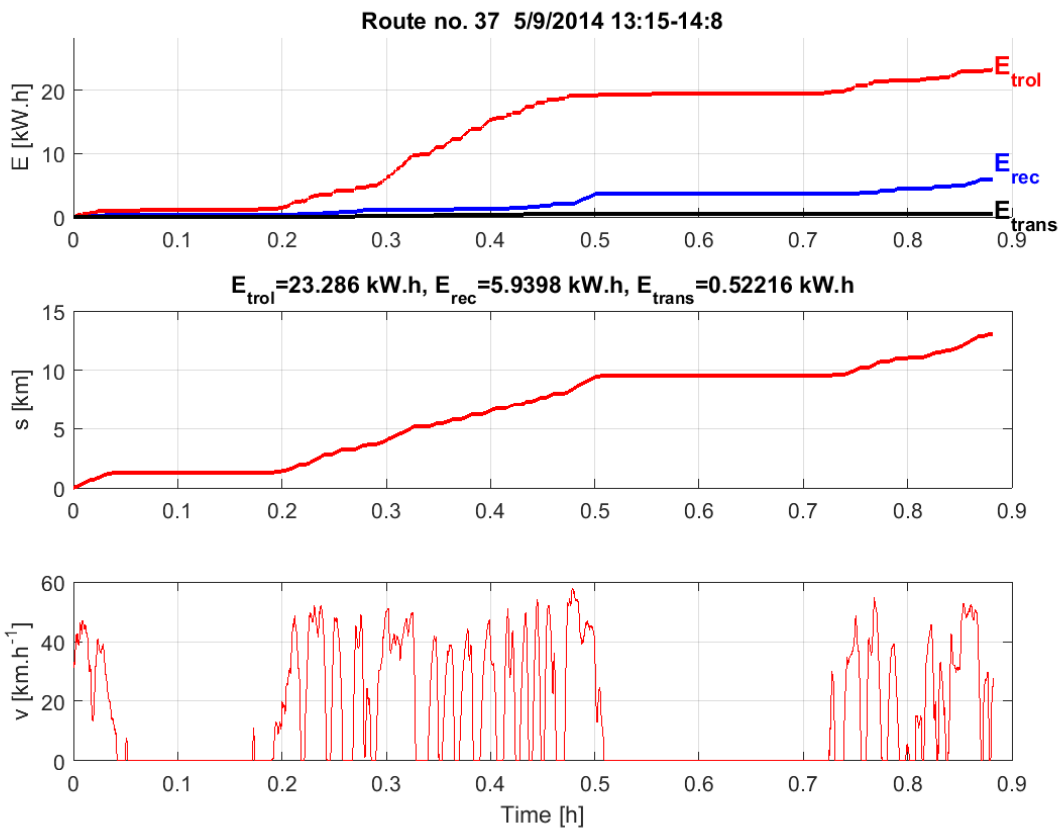

Route no. 36 20/9/2014 14:35-15:30
E [kW.h]
E_trol
E_rec
E_trans
E_trol=16.9669 kW.h, E_rec=3.6606 kW.h, E_trans=0.41288 kW.h
s [km]
v [km.h^-1]
Time [h]

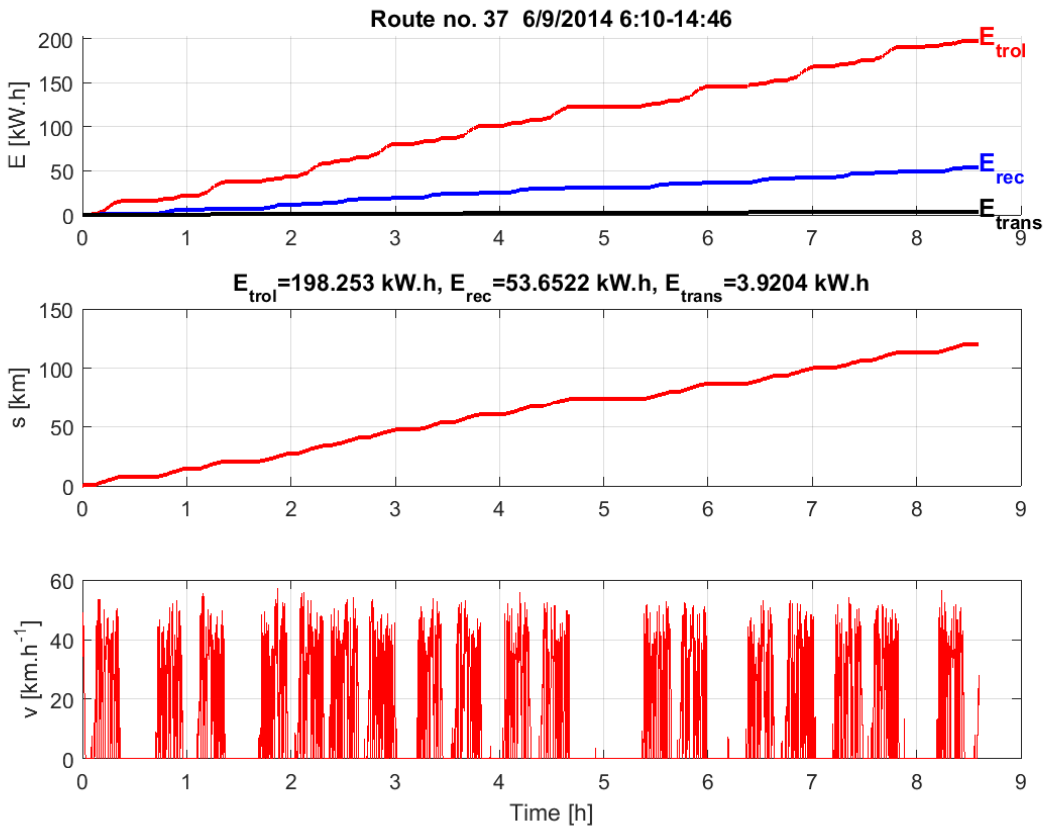

Route no. 36 20/9/2014 16:20-17:30
E [kW.h]
E_trol
E_rec
E_trans
E_trol=26.0266 kW.h, E_rec=5.9772 kW.h, E_trans=0.69057 kW.h
s [km]
v [km.h^-1]
Time [h]

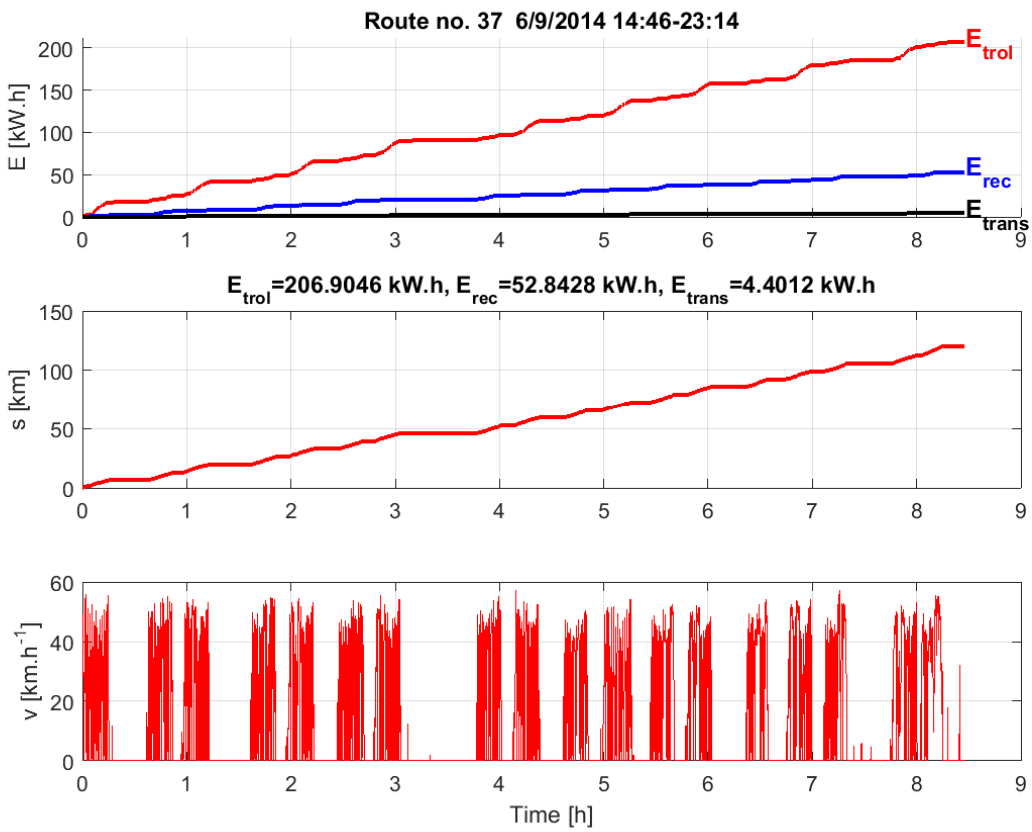

Route no. 36 20/9/2014 18:20-19:30
E [kW.h]
E_trol
E_rec
E_trans
E_trol=24.822 kW.h, E_rec=5.7142 kW.h, E_trans=0.66399 kW.h
s [km]
v [km.h^-1]
Time [h]

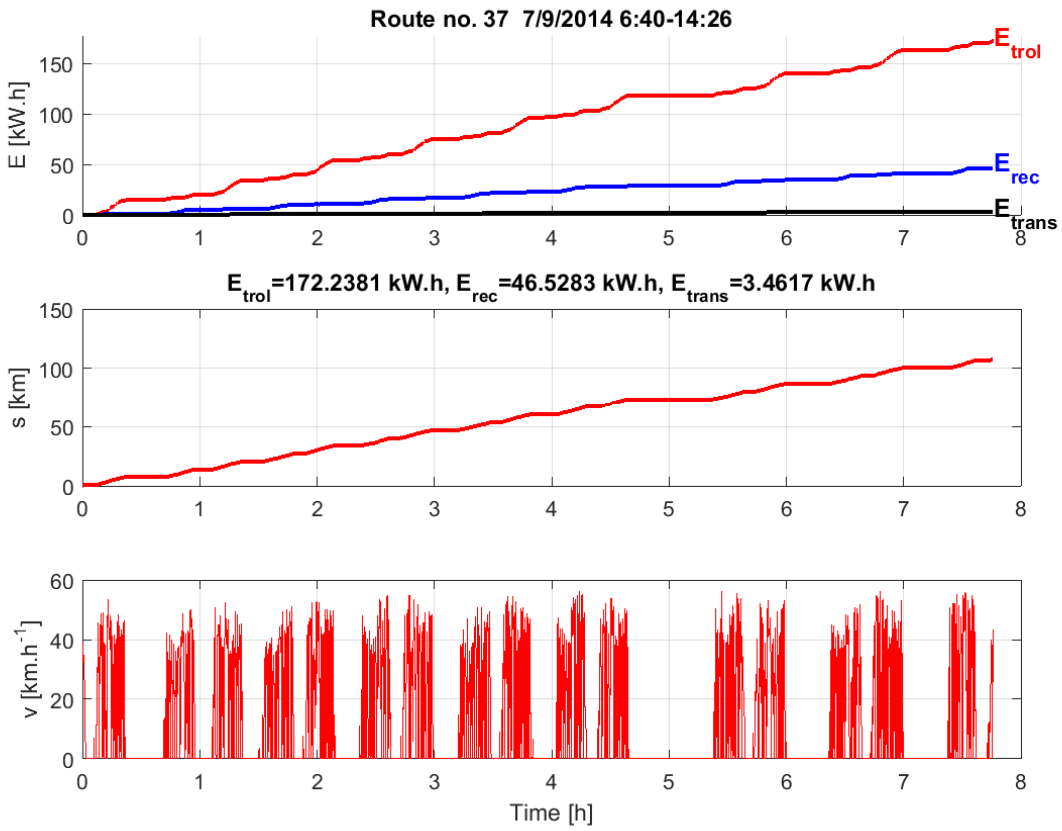

Route no. 36 20/9/2014 20:0-22:41
E [kW.h]
E_trol
E_rec
E_trans
E_trol=60.3426 kW.h, E_rec=14.6557 kW.h, E_trans=1.6018 kW.h
s [km]
v [km.h^-1]
Time [h]

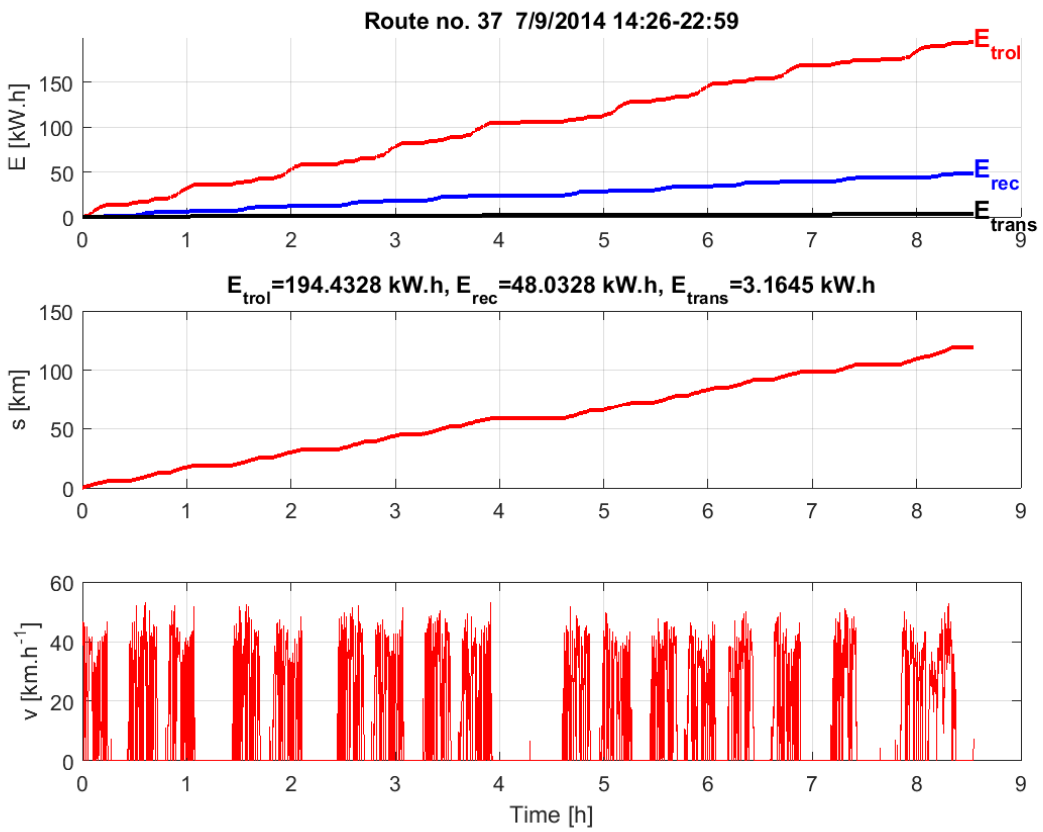

Route no. 37 5/9/2014 9:9-9:47
E [kW.h]
E_trol
E_rec
E_trans
E_trol=10.121 kW.h, E_rec=2.5944 kW.h, E_trans=0.15424 kW.h
s [km]
v [km.h^-1]
Time [h]

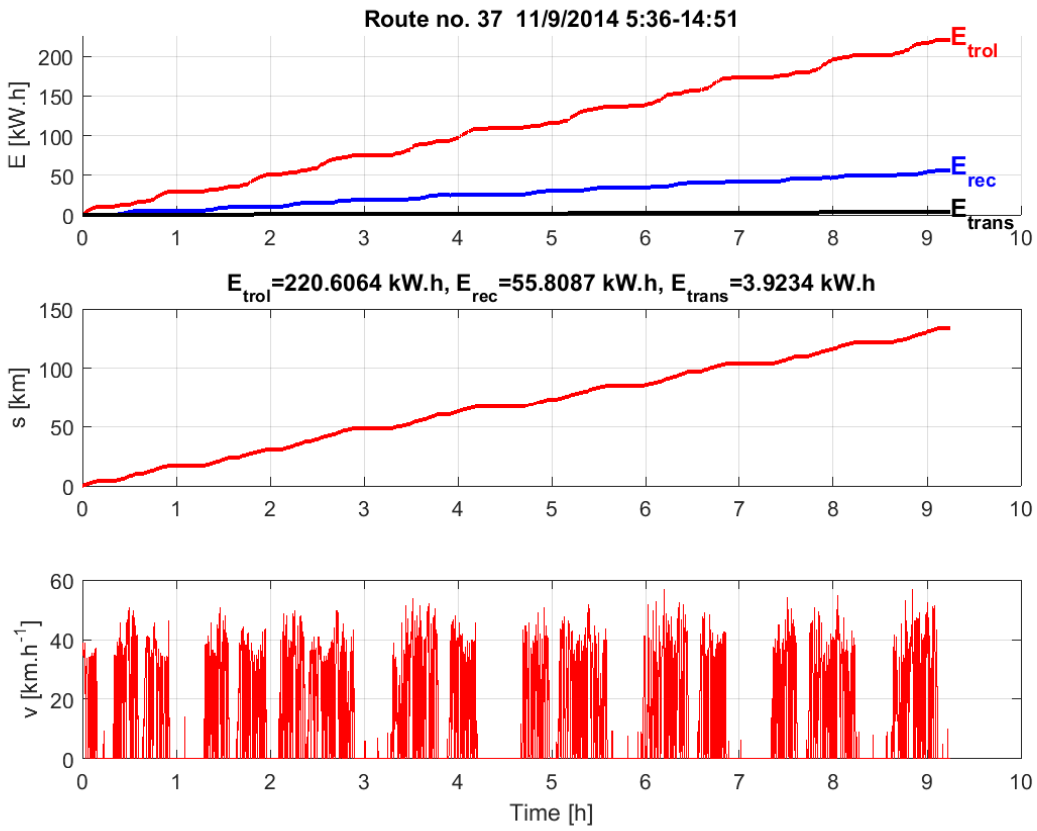

Route no. 37 5/9/2014 13:15-14:8
E [kW.h]
E_trol
E_rec
E_trans
E_trol=23.286 kW.h, E_rec=5.9398 kW.h, E_trans=0.52216 kW.h
s [km]
v [km.h^-1]
Time [h]

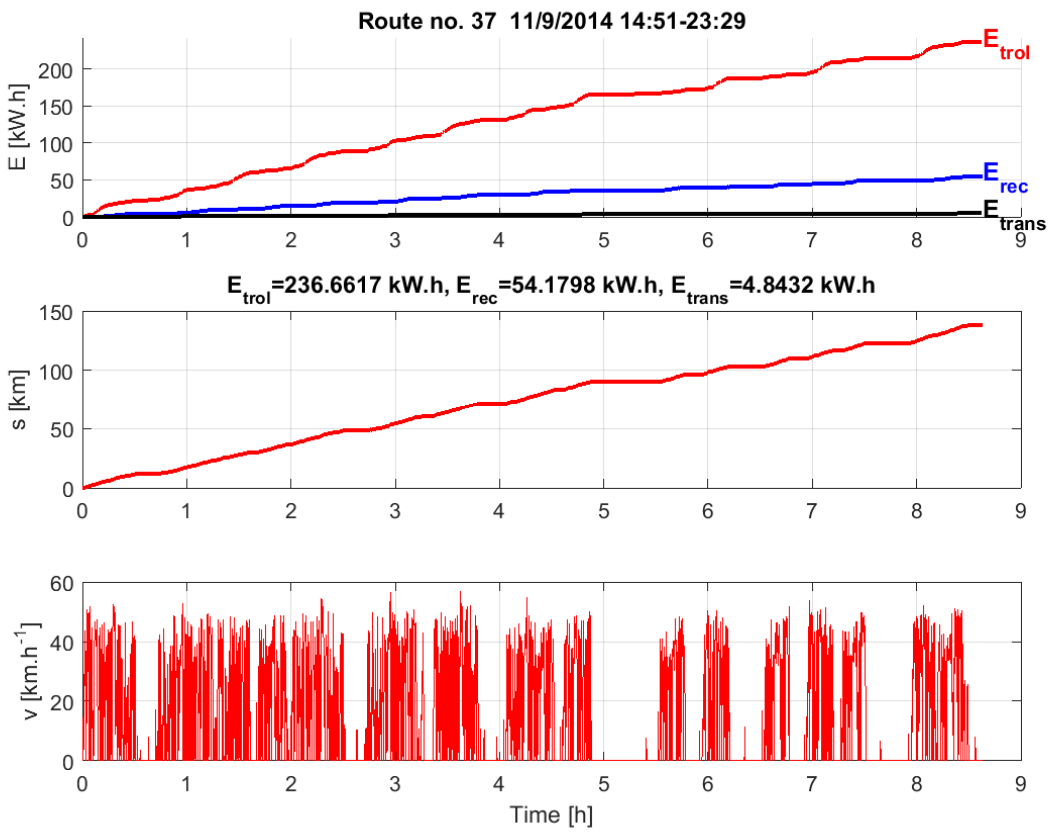

Route no. 37 6/9/2014 6:10-14:46
E [kW.h]
E_trol
E_rec
E_trans
E_trol=198.253 kW.h, E_rec=53.6522 kW.h, E_trans=3.9204 kW.h
s [km]
v [km.h^-1]
Time [h]

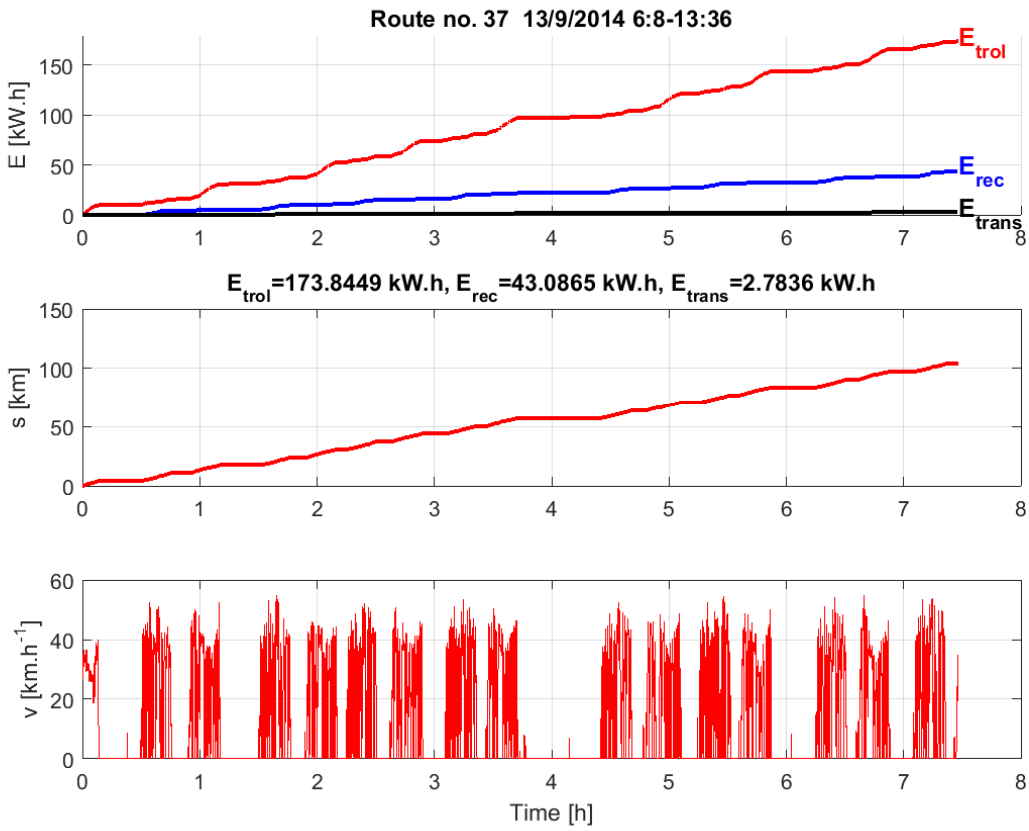

Route no. 37 6/9/2014 14:46-23:14
E [kW.h]
E_trol
E_rec
E_trans
E_trol=206.9046 kW.h, E_rec=52.8428 kW.h, E_trans=4.4012 kW.h
s [km]
v [km.h^-1]
Time [h]

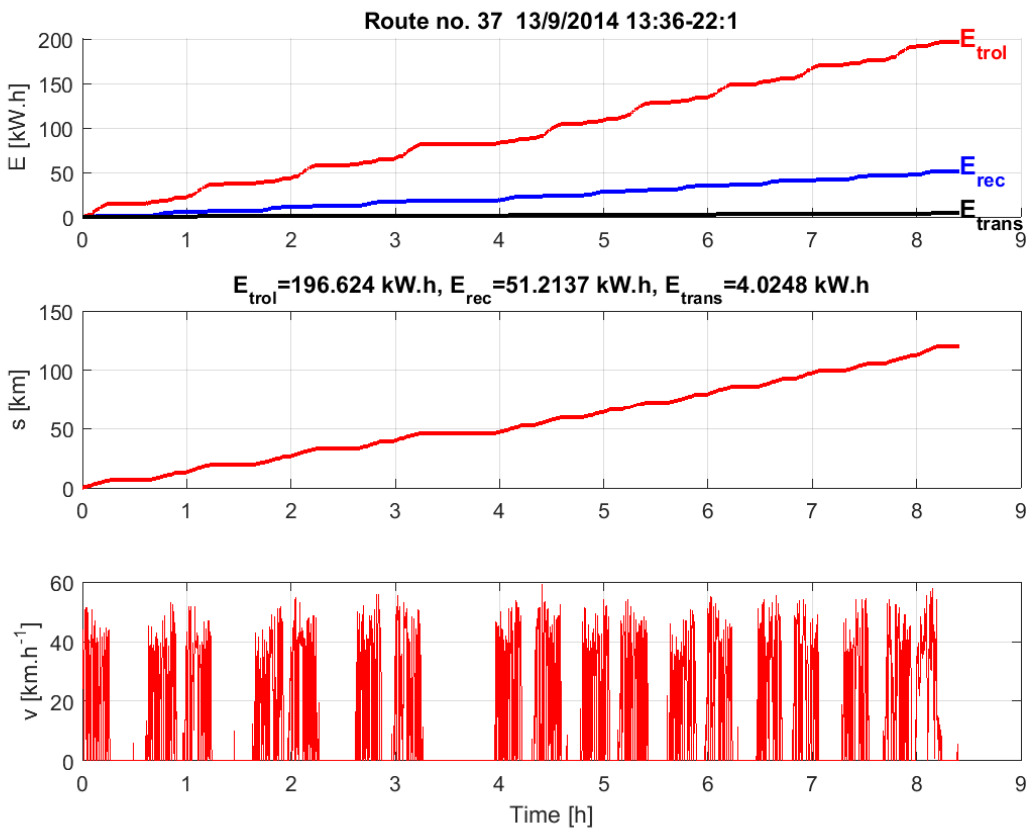

Route no. 37 7/9/2014 6:40-14:26
E [kW.h]
E_trol
E_rec
E_trans
E_trol=172.2381 kW.h, E_rec=46.5283 kW.h, E_trans=3.4617 kW.h
s [km]
v [km.h^-1]
Time [h]

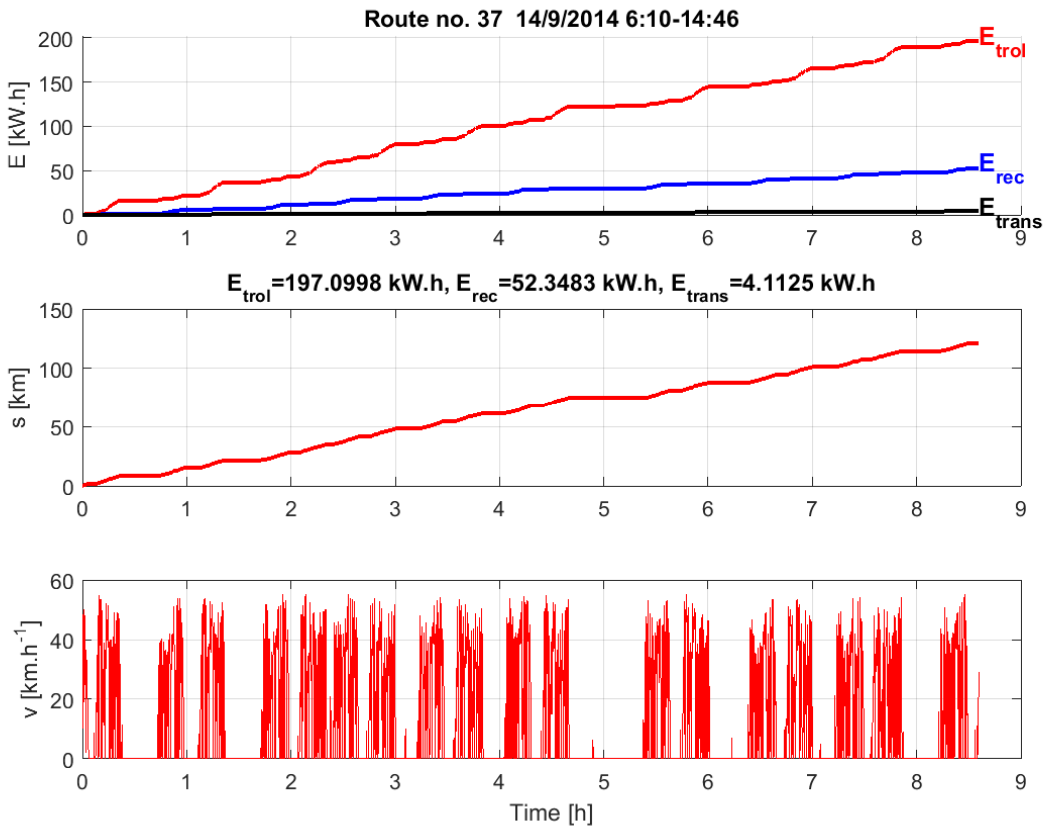

Route no. 37 7/9/2014 14:26-22:59
E [kW.h]
E_trol
E_rec
E_trans
E_trol=194.4328 kW.h, E_rec=48.0328 kW.h, E_trans=3.1645 kW.h
s [km]
v [km.h^-1]
Time [h]

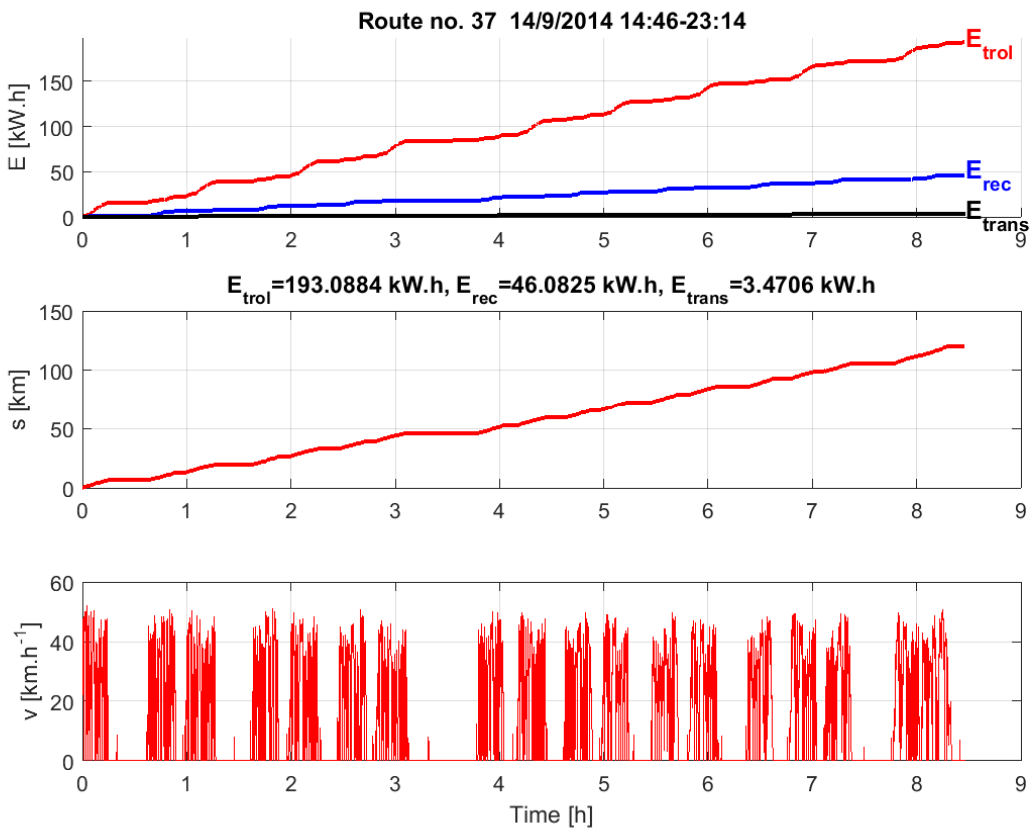

Route no. 37 11/9/2014 5:36-14:51
E [kW.h]
E_trol
E_rec
E_trans
E_trol=220.6064 kW.h, E_rec=55.8087 kW.h, E_trans=3.9234 kW.h
s [km]
v [km.h^-1]
Time [h]

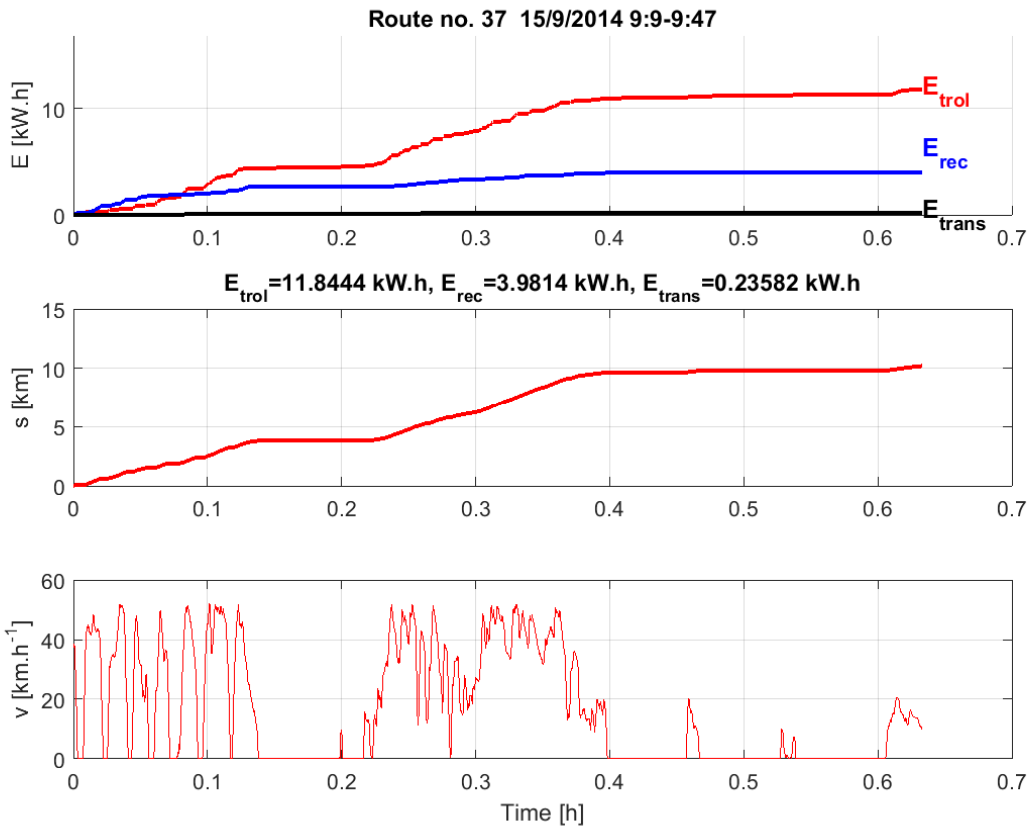

Route no. 37 11/9/2014 14:51-23:29
E [kW.h]
E_trol
E_rec
E_trans
E_trol=236.6617 kW.h, E_rec=54.1798 kW.h, E_trans=4.8432 kW.h
s [km]
v [km.h^-1]
Time [h]

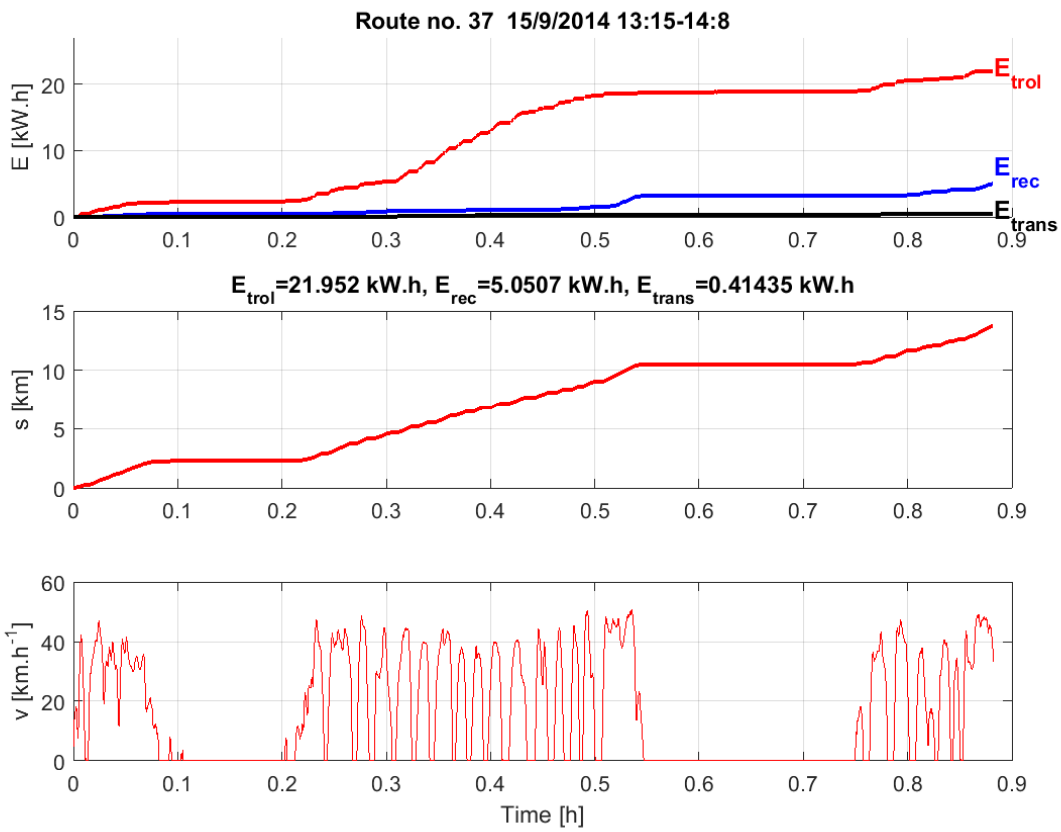

Route no. 37 13/9/2014 6:8-13:36
E [kW.h]
E_trol
E_rec
E_trans
E_trol=173.8449 kW.h, E_rec=43.0865 kW.h, E_trans=2.7836 kW.h
s [km]
v [km.h^-1]
Time [h]

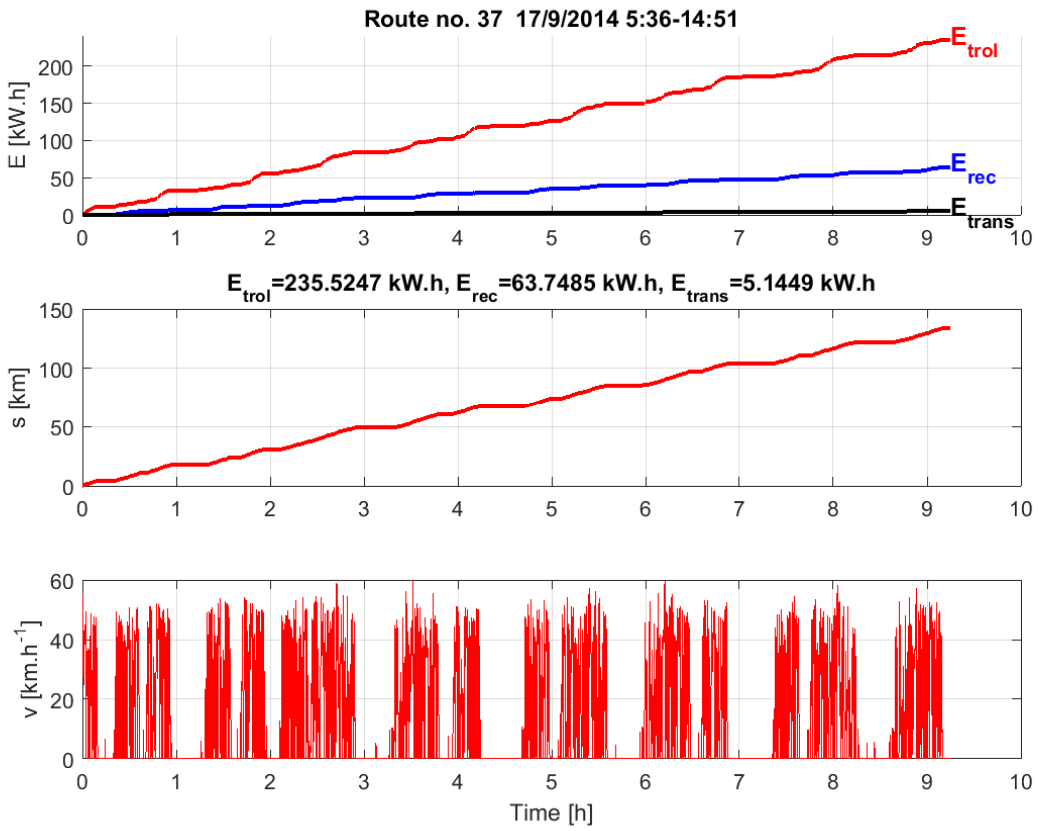

Route no. 37 13/9/2014 13:36-22:1
E [kW.h]
E_trol
E_rec
E_trans
E_trol=196.624 kW.h, E_rec=51.2137 kW.h, E_trans=4.0248 kW.h
s [km]
v [km.h^-1]
Time [h]

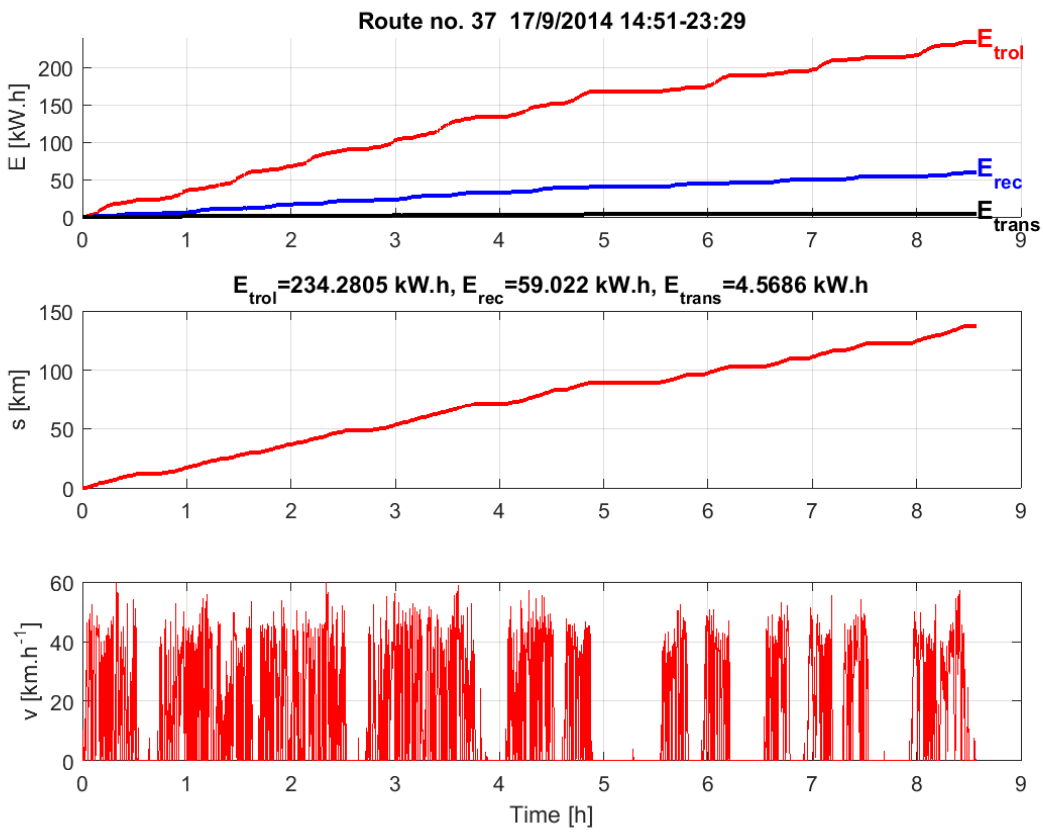

Route no. 37 14/9/2014 6:10-14:46
E [kW.h]
E trol
E rec
E trans
E trol=197.0998 kW.h, E rec=52.3483 kW.h, E trans=4.1125 kW.h
s [km]
v [km.h-1]
Time [h]


Route no. 37 14/9/2014 14:46-23:14
E [kW.h]
E trol
E rec
E trans
E trol=193.0884 kW.h, E rec=46.0825 kW.h, E trans=3.4706 kW.h
s [km]
v [km.h-1]
Time [h]


Route no. 37 15/9/2014 9:9-9:47
E [kW.h]
E_trol
E_rec
E_trans
E_trol=11.8444 kW.h, E_rec=3.9814 kW.h, E_trans=0.23582 kW.h
s [km]
v [km.h^-1]
Time [h]


Route no. 37 15/9/2014 13:15-14:8
E [kW.h]
E_trol
E_rec
E_trans
E_trol=21.952 kW.h, E_rec=5.0507 kW.h, E_trans=0.41435 kW.h
s [km]
v [km.h^-1]
Time [h]


Route no. 37 17/9/2014 5:36-14:51
E [kW.h]
E trol
E rec
E trans
E trol=235.5247 kW.h, E rec=63.7485 kW.h, E trans=5.1449 kW.h
s [km]
v [km.h-1]
Time [h]


Route no. 37 17/9/2014 14:51-23:29
E [kW.h]
E trol
E rec
E trans
E trol=234.2805 kW.h, E rec=59.022 kW.h, E trans=4.5686 kW.h
s [km]
v [km.h-1]
Time [h]