EXPERIMENTAL VALIDATION OF COMBINED TRIP ESTIMATOR FOR SMALL POWER ELECTRIC TRACTOR
/
VALIDAREA EXPERIMENTALĂ A ESTIMATORULUI DE PARCURS COMBINAT LA TRACTORUL ELECTRIC DE PUTERE MICĂ

Tudor Emil$^{1)}$; Matache Mihai Gabriel*$^{2)}$; Sburlan Ion Cătălin$^{1)}$; Vasile Ionuț$^{1)}$; Cristea Mario$^{2)}$ [1]
$^{1)}$ INCDIE ICPE-CA / Romania;
$^{2)}$ INMA Bucharest / Romania;
Tel: +40722235842 E-mail: gabimatache@yahoo.com
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ABSTRACT

The combined use of the electric tractor in high-speed travel and high-torque towing must involve a trip range estimation and an optimal driving behavior of the vehicle. The paper proposes an estimation method based on the measured usable energy reserve and on prediction of the power consumption for the two selected operating modes: rolling and towing. As driver's interface will be used an interactive graphical display which can be used for the initial settings and further adjustments of some of the working parameters. The demonstrations are sustained by trip recordings used for calibration process and for error mitigation.

REZUMAT

Folosirea combinată a tractorului electric în regim de deplasare cu viteză ridicată și în regim de tractare cu cuplu mare trebuie să implice o estimare a parcursului rămas și recomandări pentru modul de conducere al vehiculului. Lucrarea propune o metodă de estimare a autonomiei bazată pe măsurarea rezervei de energie disponibile și pe predicții ale consumului în cele două moduri de funcționare specifice: deplasare și tractare. Pentru interfața cu utilizatorul se folosește un afișor grafic care permite setările inițiale și ajustările ulterioare ale unor parametri. Demonstrațiile sunt susținute de înregistrările utilizate în timpul procesului de calibrare și pentru atenuarea erorilor.

INTRODUCTION

Users of the new vehicles, by now, are struggling to deal with the range anxiety which is involved by the new energy storage used for powering the electric vehicles (EV). Range anxiety is a driver's fear of being stranded by a depleted EV battery. For now, the classical indication regarding the remaining range of the Internal Combustion Engine vehicles (ICE) was the remaining volume of the gas tank (the "fuel" gauge on the dashboard instrument) and some range estimator located in the Board Computer (CB) based on recorded mileage and recorded gas consumption over a trip counter which can be restarted by the driver. Due to their relative estimation, some methods to avoid excessive usage of this estimators and to mitigate the trust of the driver in the trip estimator, both the trip estimation and the remaining tank gas reserve are not valid for the last 5 liters of gas in the tank, being replaced by a yellow warning which asks for immediate refueling.

Meanwhile, the traction battery of the electric vehicle is dealing with similar information, as the State of Charge (SOC) of the battery, expressed in kWh.

By analyzing the traction power requested by a vehicle, in (*Kuew and Leong*, *2014*)

$$P = mav + mgv\sin\propto + C_{RR}mgv\cos\propto + \frac{1}{2}\rho C_D A v^3 \qquad (1)$$

the authors consider the mass *m*, the acceleration *a*, the slope of the road *α*, the aerodynamic coefficients and the air viscosity.

The formula is complex and cannot be used for online calculation of the range of a special vehicle, being more usable when we need to estimate the energy requirements over an imposed trip (like a bus line) in order to decide the energy level needed to be available in the battery when starting a new trip, especially if the vehicle is located in an isolated area with special precautions about the available energy *(Maican et al., 2019)*.

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[1] *Tudor E., Ph.D. Eng.; Matache M. G., Ph.D. Eng.; Sburlan I. C, Mst. Eng.; Vasile I., Mst. Eng.; Cristea M., Ph.D. Stud. Eng.*

MATERIALS AND METHODS

Methods for state of charge measurement

As a fact, the trip estimation is based on measured SOC value and an energy consumption prediction. The methods for measuring the SOC are described widely in the literature, are subject of continuously improving and the SOC methods are becoming more and more accurate. The SOC estimator is well described in the literature *(Yong Tian et al., 2016)* describing four popular model-based SOC estimation algorithms, namely extended Kalman filter, unscented Kalman filter (UKF), sliding mode observer and nonlinear observer (NLO), which are compared in terms of prediction accuracy, tracking ability to initial SOC error, and computation complexity.

As the Li-Ion batteries have different topologies, the battery builder is providing the electronic Battery Management System (BMS) which performs various tasks as:

- Cell voltage balancing (active or passive);
- Temperature monitoring, including fan control for ventilation and for overtemperature protection;
- Voltage monitoring, including over-voltage or under-voltage monitoring, charger voltage request, max pack voltage;
- Current monitoring, including over-current protection and charging current protection;
- State of charge estimation, using pack voltage, pack current and pack temperature;
- State of Health estimation, using pack voltage and pack current;
- Charger limits for voltage and current, provided by CAN communication and by analog output signal;
- DC contactor control for protection of the battery;
- The protection system contains a DC fuse for overcurrent and short circuit protection.

One of the most popular methods used by BMS systems *(P. A. Topan et al., 2016; ORION, 2020; D. Xu et al., 2010)* to calculate a battery pack's state of charge (SOC) is coulomb counting (keeping track of the amount of current that has entered or left the battery pack). This method requires the use of a current sensor and generally tracks the state of charge of the battery pack quite well provided that the capacity of the battery is known, and the current sensor is accurate. Also, the BMS uses a secondary SOC correction algorithm using the measured open circuit voltage of the highest and lowest cells (the voltage as if the cell were at rest) and compares them to a table of known voltages. If the BMS has previously been calculating the state of charge at a lower value, it can correct the state of charge calculation based on this information. The BMS will always use the highest open circuit cell voltage (to drift up) and lowest open circuit cell voltage (to drift down) for these calculations so that the pack is properly protected. This helps improving the accuracy of the calculated state of charge.

In addition to the correction drift points that are programmed in, the BMS can also correct the calculated state of charge when a charge cycle completes.

The SOC measurements are more accurate as the battery is in new-condition, and when the battery is worn, the cells will have different open-circuit voltage and less capacity, thus making the full-charge status reached in lesser time, with less energy stored. A new parameter is then used when the energy availability of the traction battery has to be measured: the State of Health (SOH), which is 100% at the new battery and below for the worn one. This parameter must be considered when computing the available range of the whole vehicle, and the SOH parameter has to be verified for range estimation.

Trip estimator based on electric power consumption

Some authors are imposing the trip, including road conditions, by willing to estimate the remaining SOC at the arrival at the end of the trip (*K. Sarrafan et al., 2017; V. R. Tannahill et al., 2016*). Those methods are mainly an estimator regarding consumption.

We are using the SOC estimator described below to obtain the on-line SOC status. This is determined by subtracting the electric energy consumption and by adding the electric energy regeneration (coulomb tracking).

For trip estimator we can use the following data:

- SOC_0 at starting point (provided by BMS);
- SOC at actual point (provided by BMS);
- Energy loss (by integration of the energy consumption);
- x_0 Initial trip (km) (provided by Bord Computer (CB));
- x Actual trip (km) (provided by CB);
- Initial time (from both BMS and CB)
- Actual time (from both BMS and CB);
- x_{max} Maximum trip (from CB).

The estimation of the remaining trip is to be made by the bord computer CB and must be presented to the driver. One method is to calculate the remaining range, in *km*, using the formula:

$$x_{max} = x + (SOC - SOC_{min}) \cdot \frac{x - x_0}{SOC_0 - SOC} \tag{2}$$

Where the SOC_{min} is the minimum discharge state of the battery (usually 20%).

This method is close to the ICE range estimator, considering the reset of the counter at the beginning of each trip, as being equivalent to full recharge of the electric vehicle. However, this method lacks in accuracy due to the pour resolution of the km counter and offers less information about the driving mode, being effective only for constant load and constant trip.

Electric tractor presentation

Our trip estimator must solve the range anxiety of an electric tractor prototype driver, tractor showed in Fig. 1, which must operate a small demonstrator with the following characteristics:

- Mass	1210 kg;
- Traction (AC motor)	PS2 = 32 kW;
- Transmission	8+1 speeds;
- Maximum speed	26 km/h;
- Traction battery voltage	Vbatt = 141 Vdc;
- Traction battery energy	Ebatt = 17.28 kWh;
- Maximum current	Ibatt < 121 Adc.

Fig. 1 - Electric tractor prototype

The main functions of the electric tractor are:

- Road transfer from the charging point / workshop to the operation area, using the high-speed gear, by using up-to 10% of the stored energy;
- Ploughing or towing loads as requested, using the high-torque gear;
- Returning to charging point with high-speed gear.

The main components of the electric drivetrain *(Cristea et. Al, 2020)* are connected as provided in Fig. 2. The tractor has an AC traction motor TM driven by a traction power converter TPC powered from a traction battery BAT2 connected though DC contactors contained in connection box CONB. Charging of the battery is controlled by the On-board charger OBCC which is supplied from the 220Vac network through Mode 2 connector MOD2.

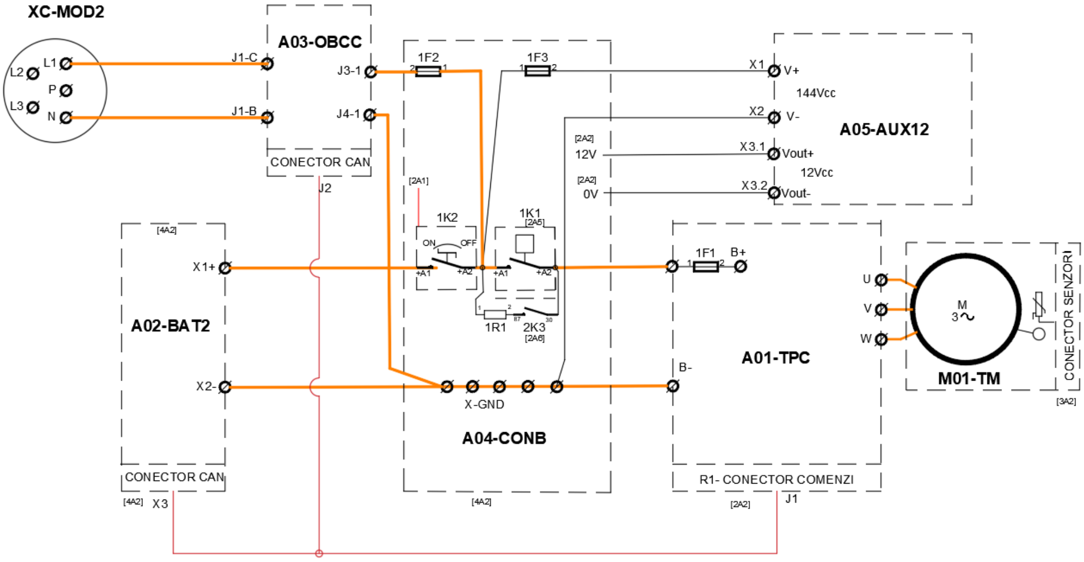
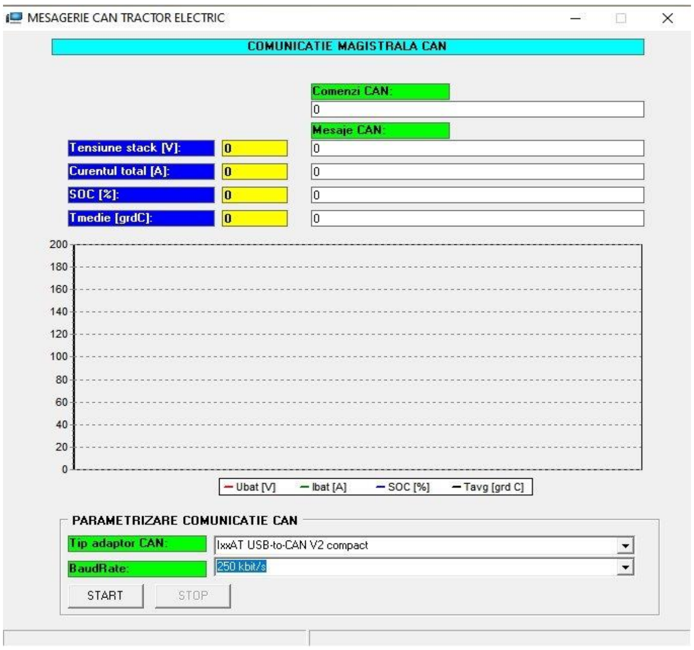


Fig. 2 - Main electric diagram of the electric tractor

Control electronics are supplied from traction battery using a DC-DC galvanic-insulated converter AUX12, thus making obsolete the 12Vdc primary battery of the tractor.

Measuring the State of Charge from Battery Management System

The BMS electronic unit is designed with the aim to provide enough information via serial CAN communication in order to organize multiple battery units connected in series or in parallel on the EV for range extension. The data is provided on-line and is designated to be used by a master-BMS unit or, directly, by the external connected electronic units as the battery charger and the traction converter. A special software was developed in order to extract the most important data exchanged on the CAN communication line between the battery, charger and traction converter. A caption of the Romanian interface of the software is presented in Fig. 3.


MESAGERIE CAN TRACTOR ELECTRIC

COMUNICATIE MAGISTRALA CAN

Comenzi CAN: 0

Mesaje CAN: 0

Tensiune stack [V]: 0 0

Curentul total [A]: 0 0

SOC [%]: 0 0

Tmedie [grdC]: 0 0

PARAMETRIZARE COMUNICATIE CAN

Tip adaptor CAN: IxxAT USB-to-CAN V2 compact

BaudRate: 250 kbit/s

Fig. 3 - Communication software for data recording

In the figure below is presented a charging log-file recorded from a 1 ½ hour charging from SOC 51% up to SOC 89%, using a 6.6 kWh charger. The maximum charging current was set up at 32 A using a regular 240 Vac power supply.

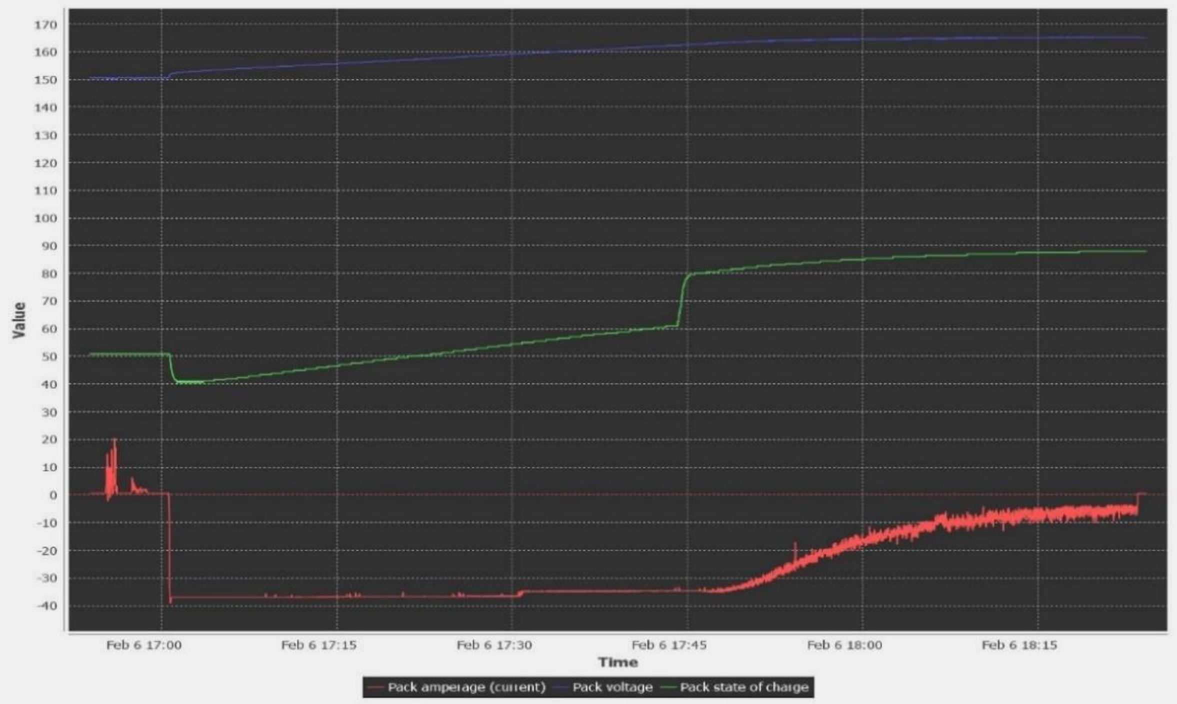


Fig. 4 - Charging battery in time - Current, Voltage and SOC using 15 min grid

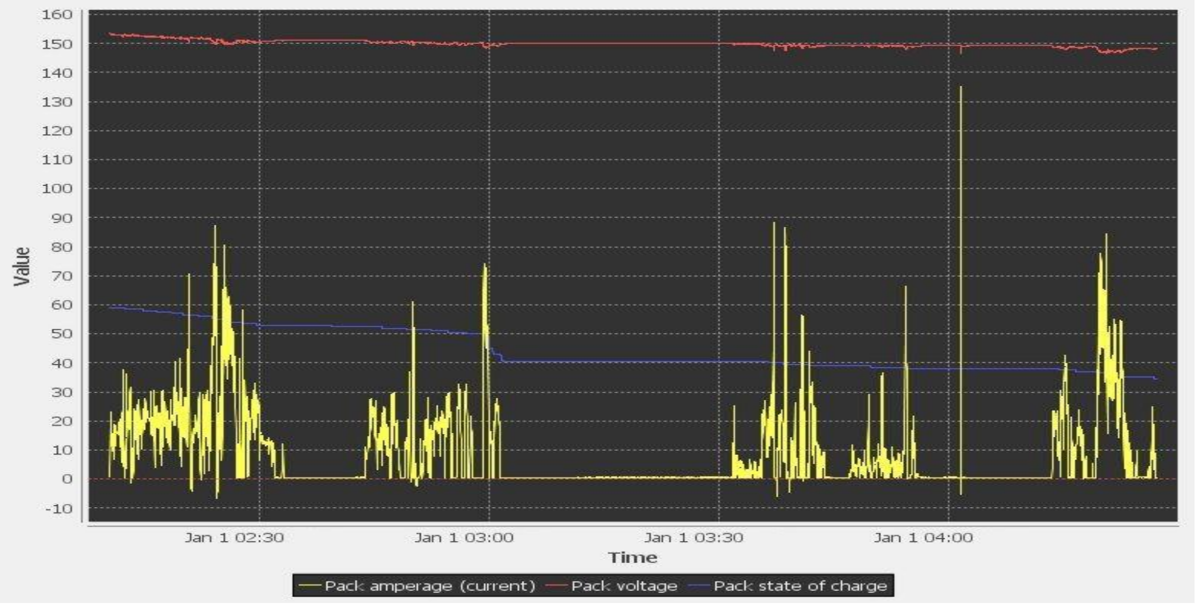


Fig. 5 - Discharging battery in time - Current, Voltage and SOC using 15 min grid

In Fig. 5 is presented a working current diagram, where we can see the SOC depletion from 59% down to 35% in only one hour of ploughing. There could be observed peaks of up to 90 A drawn from the battery with a drop of 6 Volts from the total pack voltage. Also there are periods with very low current consumption which are corresponding to the process of taking out the plough from the soil and reversing the ploughing direction by turning the tractor.

RESULTS

As observed in Table 1 and in Table 2, our tractor does not have a reliable trip counter expressed in km. The main trip counter resides in the traction controller, and is based on computation related to the number of revolutions performed by the rotor of the traction motor. As our tractor has to maintain a classical gearbox and a differential redactor in order to provide both high torque and high-speed service, then the trip becomes more difficult to be estimated. Furthermore, the tractor is a vehicle which operates often in sliding mode (Table 1, column 4) as it must operate on soil. Then, the actual trip is much lesser than the real one because of the sliding of the tractive wheels.

Table 1

Electric tractor autonomy for ploughing works

Experiment no.	Electric power input Pe, W	Tractor autonomy, h	Ploughing productivity, ha/h	Total ploughed surface, ha
0	***1***	***2***	***3***	***4***
1	3454	5.00	0.09	0.46
2	4594	3.76	0.09	0.33
3	7354	2.35	0.08	0.20
4	7940	2.18	0.18	0.39
5	9702	1.78	0.17	0.31
6	12602	1.37	0.17	0.23
7	11487	1.50	0.25	0.38
8	14435	1.20	0.24	0.29
9	19147	0.90	0.22	0.20

Table 1

Experimental results obtained for draft force

Experiment no.	Working depth, m	Actual working speed, m/s	Mean draft force, N	Travel reduction ratio TRR, %
0	***1***	***2***	***3***	***4***
1	0.10	0.50545	3822	8.1
2	0.15	0.48895	5728	11.1
3	0.2	0.4719	7527	14.2
4	0.10	0.9988	3884	9.2
5	0.15	0.9526	5801	13.4
6	0.2	0.8954	7644	16.6
7	0.10	1.4032	3926	12.3
8	0.15	1.3392	5844	16.3
9	0.2	1.2608	7789	23.2

One can notice that the reference for tractors autonomy is the operation time (in hours) (*G. A. Golub et al.*, *2019*). Also, from Table 1 is possible to compare and discover that the power consumption is proportional with the operational speed (compare data from column 1, records 1, 4 and 7 corresponding to the same working depths at different speeds). Regarding the SOC measurements, some aspects must be interpreted. In Fig. 4, there are two specific areas to be analyzed: The SOC drop is determined by a minimum cell voltage and the 10% is missing from the reported value, but is re-displayed when the cell voltages restored to normal values due to active cell balancing; When the SOC is more than 80%, the charging current is gradually reduced by the charger, as instructed via the CAN bus by the battery.

Combined dynamic measurements Method 1 – trip estimator based on recorded consumption

We transferred the data imported from CAN communication (Fig. 5) into spreadsheet software and some data analysis was performed.

The goal is to provide accurate trip estimator for the driver, regarding the actual (recorded) consumption of the tractor which was related to the load characteristics. The diagram below presents the current provided by the battery in time – expressed in seconds. For a correct evaluation we provide an integrated value of the current over the last 60 seconds, using the Moving Average Method (*Ilmiawan et al., 2014)*.

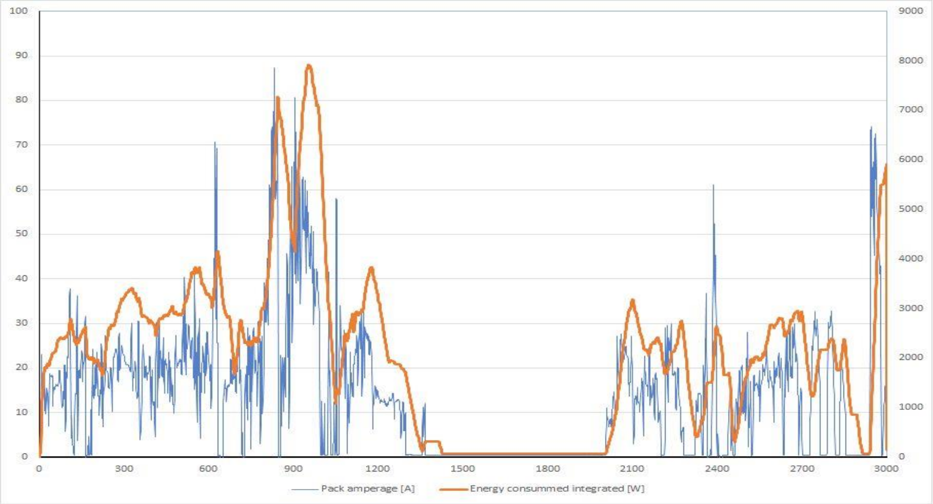


Fig. 6 - DC current [A] and Power measurement [W] with 60s moving average in time [s]

As the diagrams show a high variation in the output function, we cannot use the values presented in Fig. 6, for the estimation of the remaining trip. Current [A] multiplied by the pack voltage [W] is filtered and integrated over a 600s time interval. The moving average value is presented in the following diagram.

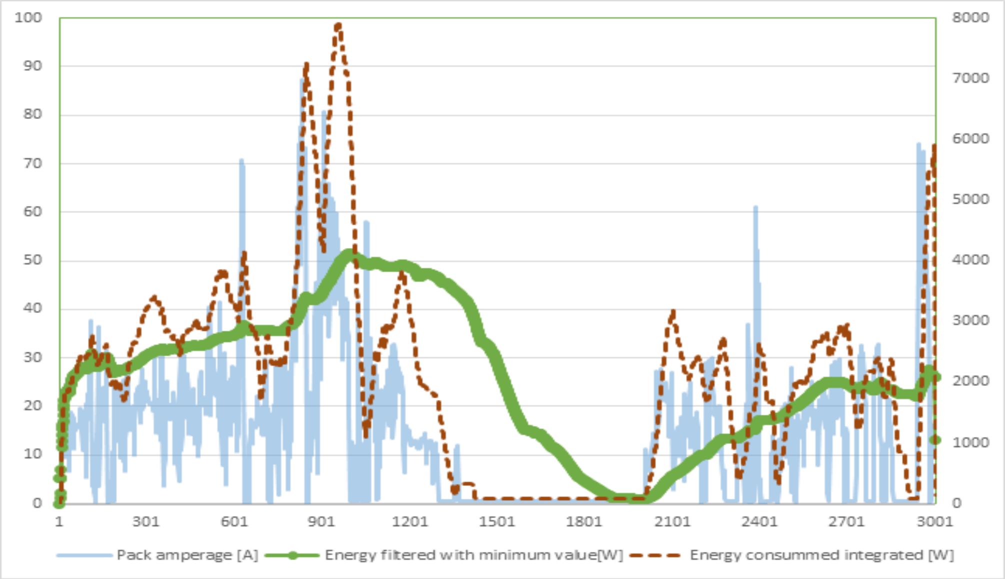


Fig. 7 - DC current [A] and Power measurement [W] with 600s moving average in time [s]

One can see that, if we intent to predict the remaining energy for the remaining trip estimation at moment *n*, the equation (4) has to be used, and, since the value of the integrator factor k_n is a divider, we must consider a minimum value for this factor. In this case we shall consider a value of 1054W that we chose as the smallest value of instantaneous power when the tractor marches with no load.

$$t_n = Ptot\frac{SOC - SOC_0}{k_n} \tag{3}$$

Where:

- Ptot is the total power, in this case Ptot=120Ah*144V=17280Wh;
- SOC is the actual value reported;
- SOC_0 is the final energy reserve provided by the battery manufacturer (usual value is 20%);
- k_n is the integrated power representing the medium power consumption for the last *m* records of Δt.

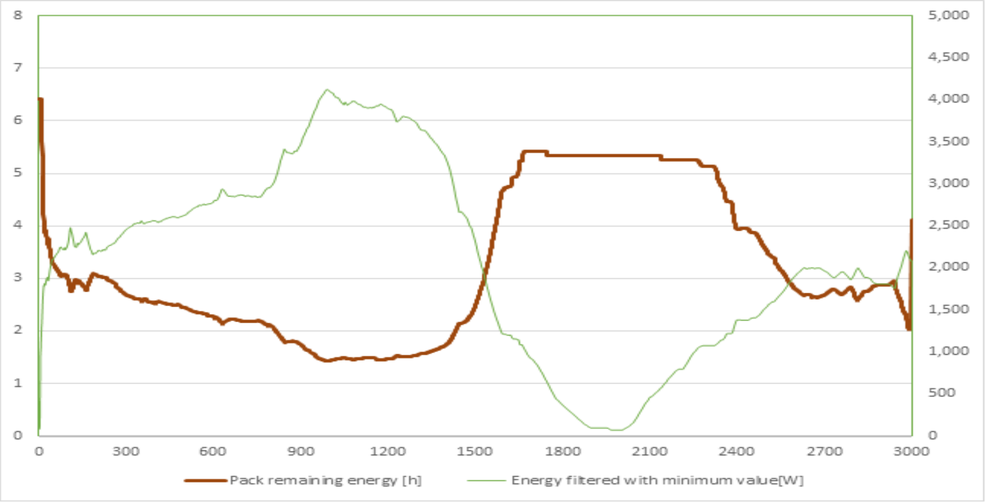


Fig. 8 - Estimating remaining trip [h] according to the average 600s load [W]

$$k_n = \frac{1}{m * \Delta t} \sum_{i=n-m}^{n} Pi \tag{4}$$

Applying the relation (3) and (4) on the example presented in Fig. 6 and Fig. 7, we will have the following predictions regarding the remaining operational time, Fig. 8.

Method 2 – trip estimator based on energy reserve with predefined and recorded measurements

The method consists in using the equation 3 and needs setting one energy consumption factor for minimum load k_{min} and other for maximum load k_{max}. There are two trip expectations, the minimum t_{load} and the maximum t_{free}.

$$t_{free} = Ptot \frac{SOC - SOC_0}{k_{min}} \tag{5}$$

$$t_{load} = Ptot \frac{SOC - SOC_0}{k_{max}} \tag{6}$$

Fig. 9 presents the evolution of the remaining time evaluation starting with the values of the SOC, with a 20% reserve, and with an average consumption of 1052 W/s measured during the tests while the tractor runs free and a maximum consumption of 4208 W/s while ploughing.

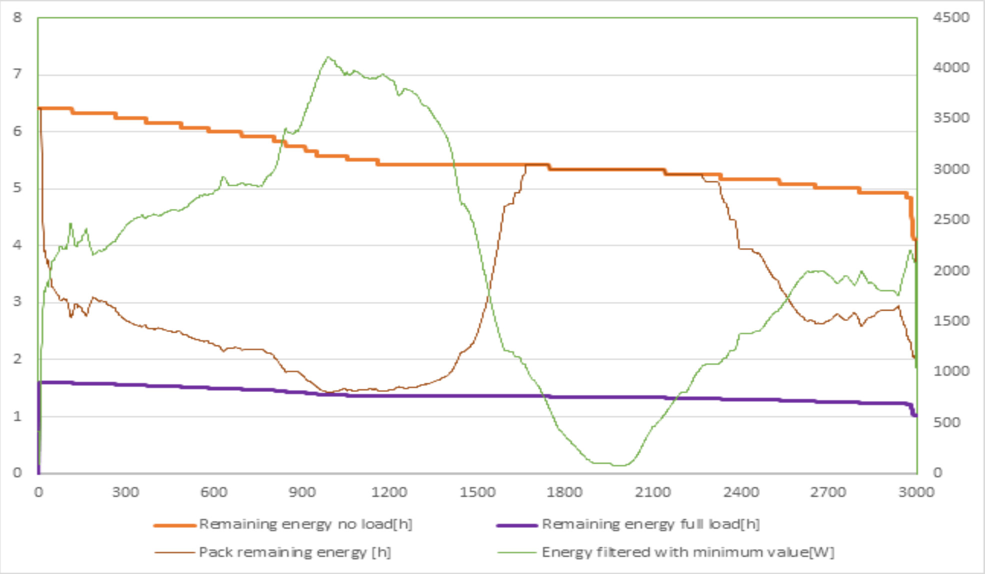


Fig. 9 - Preset consumption from load/no-load characteristics - trip estimation (s)

Method 3 – combined trip estimator based on predefined and recorded measurements and energy reserve introduction

The third method is proposed and tested on the track with mixed loads.

The trip estimator is very important for the ploughing activity, where a correlation between the SOC and the ploughing effort must be made. No lesser is the trip estimator for the return home energy reserve needed to avoid stalling the tractor on the field, Fig. 10.

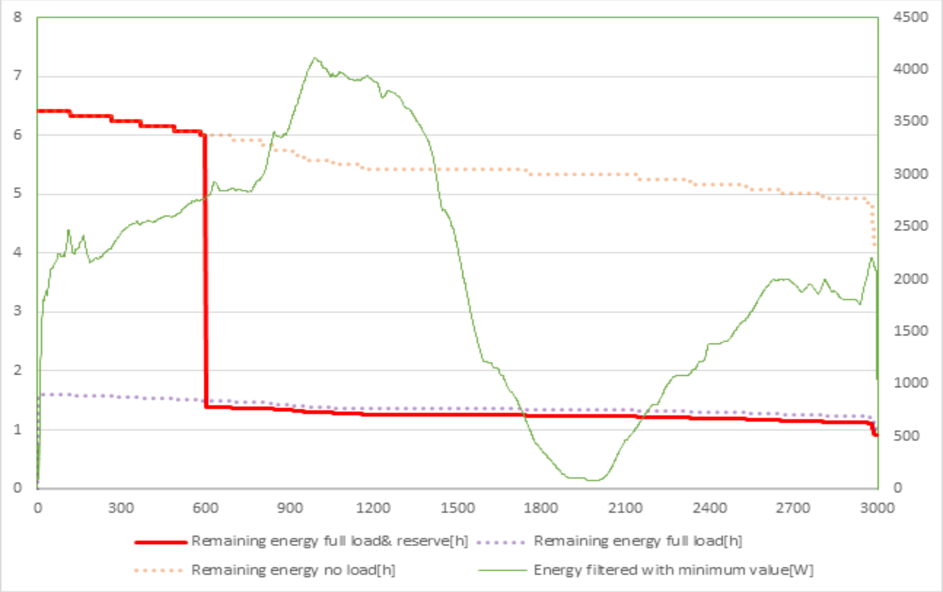


Fig. 10 - Trip estimation with return home reserve set before starting ploughing

Our proposal was to set an energy reserve for return home, via the human interface. Then, the estimation with method 1 or method 2 could be shown on screen as the “remaining working time”. We selected the first 600s for the trip, and the rest for the ploughing (higher currents). The energy reserve was about 2.5% of SOC, because the test was performed near the garage.

CONCLUSIONS

- The goal of the trip estimator is to provide the remaining working time until depletion of the battery. Also, saving the information about the energy consumption recorded over the road trip from the garage to the working area is useful for retaining same amount of energy for the returning path.
- The experiments performed with the tractor prototype were recorded and analyzed. The moving average method must be used for on-line energy consumption measurements, by using the energy integrated over 1 minute or 10 minutes.
- The maximum consumption and the minimum consumption rates are a fair enough instrument for trip estimator. For convenience, the display can also show the value of the remaining time, and the driver can use the one which is close to the operation performed. The average value from full charge can be used, but only for operations at constant load.
- The trip estimator for a wide type of working tasks, like the tractor has, can be instructed to provide also range in km, but the usage in the agricultural works operates with remaining working hours, and so do our methods proposed and tested with the tractor prototype.

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