Remaining Range Indicator System for Electric Vehicle

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Abstract— **This paper presents a Breadth-First Search-based Indicator System for remaining range estimation and representation in battery electric vehicle driving range indicators. The representation enables detailed illustration of electric vehicle's "distance to empty". To build up a remaining range graph the Breadth-First Search (BFS) algorithm is coupled with a simple electric energy consumption model taking into account the driver-desired speed, road data in a near horizon (route network topology, legal speed, grade and grip), ambient temperature, headwind speed and state of charge of electric battery. The presented study focuses on investigation of the effect of the ambient temperature variations on the vehicle remaining range. Simulation results clearly show an increased energy requirement at low temperature resulting in a reduction of the vehicle range.**

Keywords: advanced driver assistance systems, navigation, remaining range estimation, electric vehicle, energy consumption, breadth-first search.

I. INTRODUCTION

Since its creation in 2010 the Laboratory of Engineering of Surface Transportation networks and Advanced Computing (GRETTIA) of the French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) contributes to transport networks and systems development taking into consideration integration, intermodality, reliability and system analysis issues. The areas of research include road sector, collective, and particularly guided transport. In this framework, GRETTIA together with the Taganrog Polytechnic Institute of Don State Technical University participate in development of new approaches for remaining range estimation and representation in battery electric vehicle (BEV) driving range indicators.

Range estimation remains complicated by the fact that:

- Future driving behavior is often unknown [1,2].
- Road data as well as weather, traffic conditions (often uncertain) have to be taken into account [1], [3,4,5], [8].
- Batteries are subject to external influences and aging [4].

Several studies have been performed for conventional and electric vehicles to estimate/predict the remaining range or extend it by providing (for a given road segment) the optimal speed profile aiming at reducing the electric energy consumption. Rodgers et al. [1] investigated conventional and novel methods for estimating an electric vehicle's "Distance to Empty" (D_{TE}), the actual distance the vehicle can be driven before recharging is required. They proposed a Novel Regression-based D_{TE} algorithm that reduces the error in D_{TE} estimation if the future changes in driving conditions are detected beforehand by obtaining route information from the user.

Yuhe et al. [3] introduced an estimation method, in which to save time and computing resources, range estimation is classified into rough range estimation and precise range estimation according to remaining battery energy.

Besselink et al. [4] analyzed the energy usage and range of a battery electric ECE VW Golf, using over 20000 km of real life data. The study showed the impact of ambient temperature: in cold weather conditions additional energy was needed to heat the interior resulting in a higher specific energy usage.

To the authors' knowledge, modern indicators use two different ways to represent the remaining range estimation results on the road map (Fig. 1):

- By simply drawing a circle containing all the achievable road network nodes (in red).
- Detailed graph-based representation (in green).

To plan a ride we use two different on-board devices:

- A range indicator computing the vehicle's DTE.
- A GPS-navigator providing us with the optimal path/distance to the destination point.

Having that information in mind we then take a decision on whether to schedule a stop for refueling/recharging or not. **And why not to couple those two devices?**

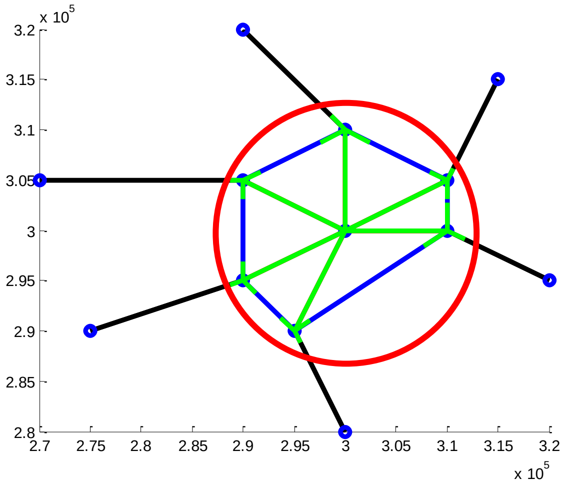

Figure 1. Circle- and graph-based representations.

For the purposes of the BFS-based Indicator System we have chosen the detailed representation of the output graph of road segments all starting from the initial EV position and ending at the farthest achievable road nodes (Fig. 2). The chosen graph-based representation allows defining more accurately the achievable road network zones. This makes it possible to easily couple the BFSIS with modern on-board GPS navigators.

This paper extends the study presented in [5] by investigating the effect of the ambient temperature variations on the EV remaining range. The remaining of this paper is organized as follows. Section 2 introduces the architecture of the BFS-based Indicator System and the consumption model used. Section 3 shows and discusses some simulation results. The conclusion of the paper and future work are given in section 4.

II. BFS-BASED INDICATOR SYSTEM

The BFS-based Indicator System (BFSIS) uses the extension of the BFS [6] coupled with a simple electric energy consumption model to build up the BEV remaining range graph (in green, Fig. 2) taking into account the driver-desired speed, road data in a near horizon (route network topology, legal speed, grade, grip), ambient temperature and state of charge (SoC) of the battery.

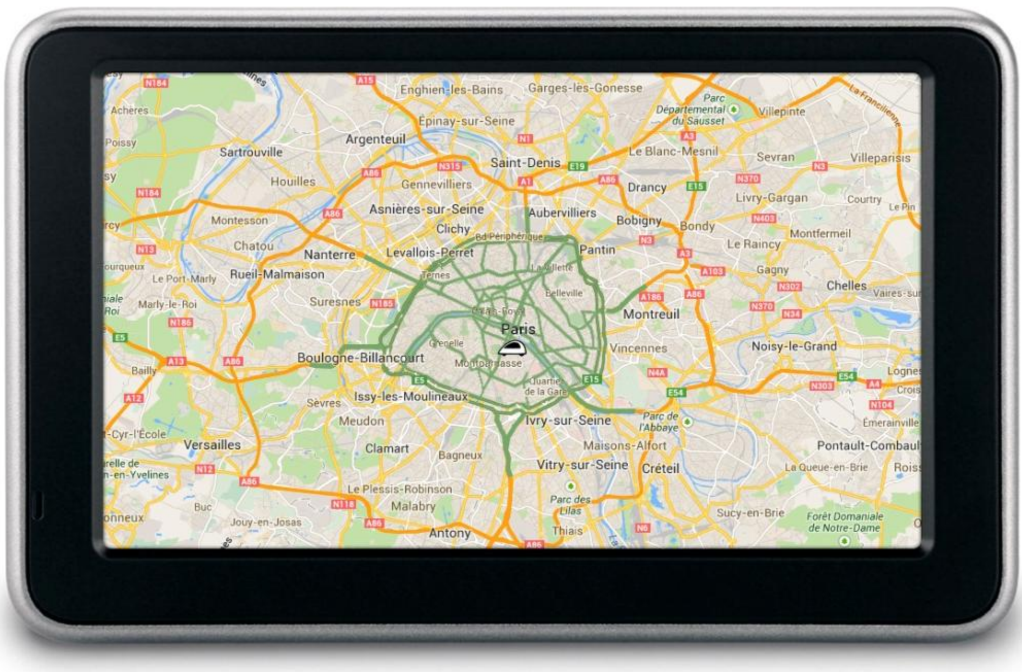

Figure 2. BFSIS illustration: remaining range graph (in green) on Google Maps.

TABLE I. NOMENCLATURE

Variable	Description	Units
V	Average vehicle speed (within a road segment)	m/s
V_{driver}	Driver-desired speed	m/s
eHorizon	Data structure of predefined size containing the road data and weather forecast	-
Route graph	Road network graph (has to be known ahead of time)	-
Av. Vleg	Average road segment legal speed	m/s
Av. Grade	Average road segment grade (slope)	-
Av. Grip	Average road segment grip (road slipperiness or road friction)	-
Amb. Temperature	Outdoor air temperature	°C

Av. Vhw	Average headwind speed	m/s
SoC	Battery state of charge	-
Rem. Range Graph	EV remaining range graph	-
E_k	Kinetic energy	J
η_g	Transmission efficiency	-
T_e	Engine torque	N*m
w_e	Engine speed	rad/s
E_{elec}	Electric energy	J
E_{aux}	Energy requirement for heating/cooling	J
η_b	Battery efficiency	-
η	Electric motor efficiency	-
r	Wheel radius	m
M	Vehicle mass	kg
rho	Air volumetric mass	kg/m^3
SCx	Vehicle drag area	m^2
g	Gravitational acceleration	m/s^2
Crr	Rolling resistance coefficient	-

Low-level description

Fig. 3 below presents the low-level description of the BFSIS. The eH block converts the data of eHorizon into an appropriate format that can be read by the BFSIS. eH provides the following data for each road segment (input road graph arc):

- Road network topology.
- Average road grade.
- Average road grip.
- Average legal speed.
- Average outdoor air temperature.
- Average headwind speed.

We assume the driver always prefers to keep the maximum speed allowed within a given road segment:

$V = \min(Av.Vleg, Vdriver)$.

Based on the provided data the output remaining range graph is constructed by the BFSIS as described below.

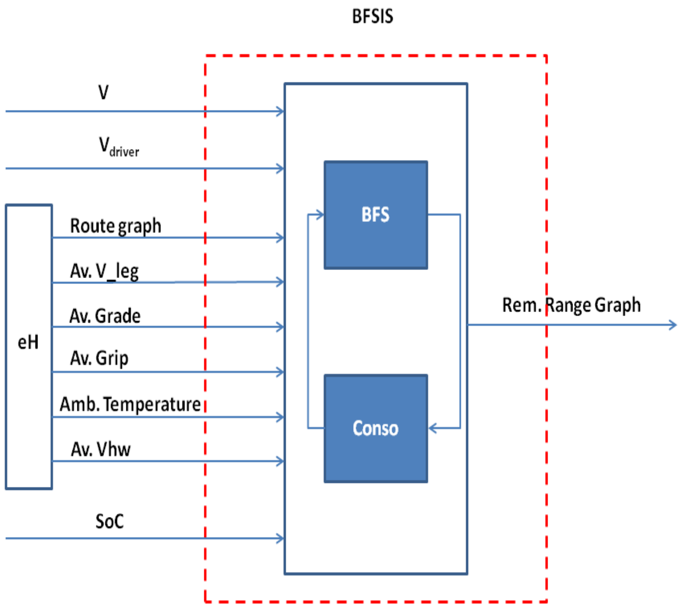

Figure 3. Block diagram of the BFS-based Indicator System.

Consumption model

The kinetic and the electric energies (consumed during a time slice *t*) are evaluated based on the following equations:

$$E_k = \frac{1}{\eta_g} T_e w_e.$$

$$E_{elec} = \frac{\eta_b}{\eta(T_e, w_e)} E_k + E_{aux}(Amb.Temperature).$$

The engine speed computation is performed based on the absence of gearbox:

$$w_e = V/r.$$

The torque T_e is computed as follows:

$$T_e = r * (0.5 * rho * SCx * (V + Vhw)^2 +$$

$$+M * g * Crr + M * a)/2.$$

BFS approach for remaining range estimation and representation

The proposed extension of the BFS approach for remaining range representation is depicted below. It consists of two phases. The first phase calculates the path cost for each road segment by means of the consumption model described in the previous sub-section and returns the *RoadSegmentEnergyCost* array. Then the phase 2 performs the BFS algorithm which uses a queue data structure to store intermediate results as it traverses the graph, as follows:

Input: *NNodes* – number of nodes of the road network graph, *DCs* – set of direct children of a node, *Eelec* – *NNodes***NNodes* matrix of electric energy needs to traverse a road segment, *RemRange* – 1**NNodes* array of nodes' remaining range values, *Examined* – 1**NNodes* Boolean array of examined nodes.

Initialize: *RemRange*(initial vehicle location) = *SoC*, *Examined* [1..*NNodes*] = 0.

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Enqueue the root node (initial vehicle location).
While the queue is not empty
    Dequeue a node, v = node, IndInVertices = index of v in Vertices set, v is labeled as examined, Examined(v) = 1
    for each i ∈ DCs(v)
        RayToDraw = min(Eelec(i,IndInVertices), RemRange(IndInVertices));
        Plot the remaining range ray
        if !Examined(i)
            Enqueue i
            RemRange(i) = RemRange(IndInVertices) – RayToDraw, i is labeled as examined, Examined(i) = 1
        endif
    endfor
endwhile
```

III. SIMULATION RESULTS

The system is implemented in Matlab/Simulink. Table 2 and Table 3 summarize the vehicle and simulation parameters based on which the simulation has been performed. The efficiency profile of YASA-400 Advanced Axial Flux Electric motor [7] has been used for the simulations.

TABLE II. VEHICLE PARAMETERS

Variable	Value/Range
r	0.30
M	1700
SCx	0.7
η_g	0.9
η	[0.01, 0.95]
η_b	0.7

TABLE III. SIMULATION PARAMETERS

Variable	Value
Crr	0.012
V (initial)	16
Vdriver	30
SoC	From 0.35 to 0.2
eHorizon	100 km

Test scenarios

To simulate D_{TE} we have generated a route network graph depicted in Fig. 4. The graph contains 20 nodes, including the root node ($X = Y = 3.00$) where the EV is initially located.

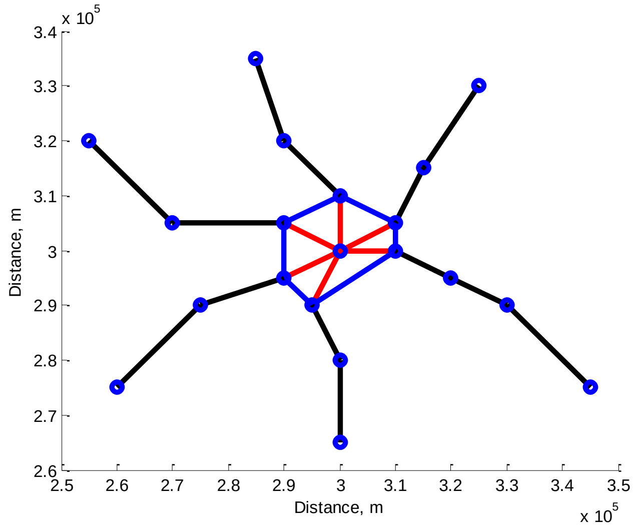


Figure 4. Road network topology.

Table 4 summarizes the *Av. Vleg* values used for all four test scenarios described below.

TABLE IV. AVERAGE ROAD SEGMENT LEGAL SPEED VALUES

Road segment color in Fig. 4	Value
Red	16
Blue	22
Black	30

Scenarios 1 to 4

All four scenarios are temperature-oriented. They investigate the effect of the ambient temperature variations on the EV remaining range. Table 5 lists the simulation parameters for each of them. All the parameters are applied to the entire road network. The scenarios differ from each other by the air density *rho* and the *Amb. Temperature* values.

TABLE V. SCENARIO 1 TO 4 SIMULATION PARAMETERS

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Av. Grade	0	0	0	0
Crr	0.012	0.012	0.012	0.012
Vhw	0	0	0	0
Amb. Temperature	-15	0	20	30
rho	1.37	1.29	1.20	1.16

The auxiliary power (heating/cooling) measurements (executed on a distance of 100 km) for different values of the ambient temperature have been performed by Tober [8] and presented in Fig. 5 below.

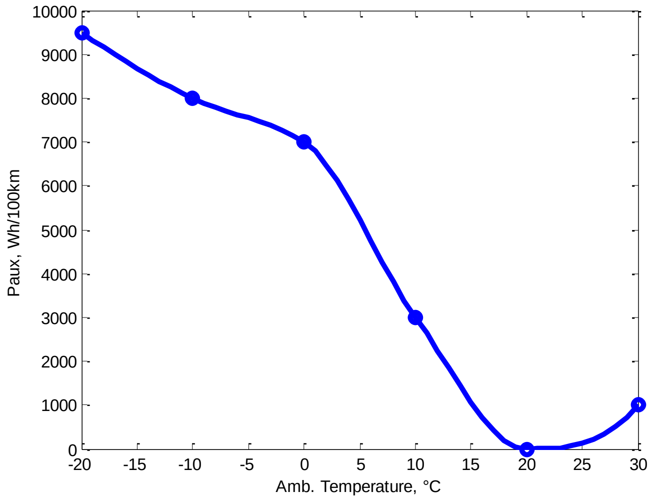
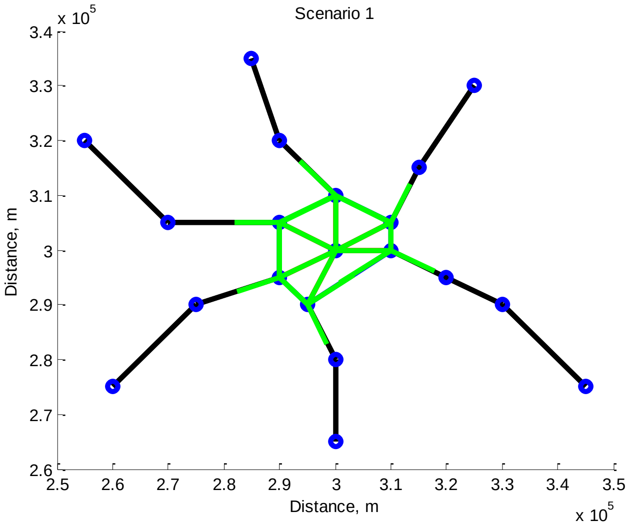
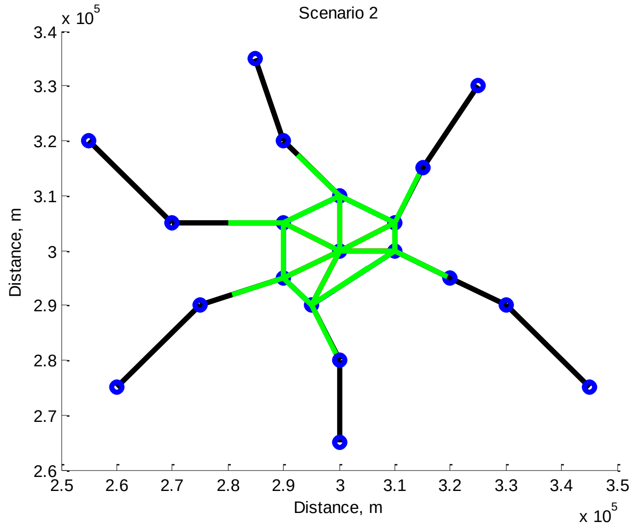


Figure 5. Energy requirement for heating/cooling as a function of the ambient temperature for Nissan Leaf electric car [8].

In Fig. 6 and 7 the proposed BFS Indicator System is used to output the remaining range graph for four different scenarios defined in Table 5.

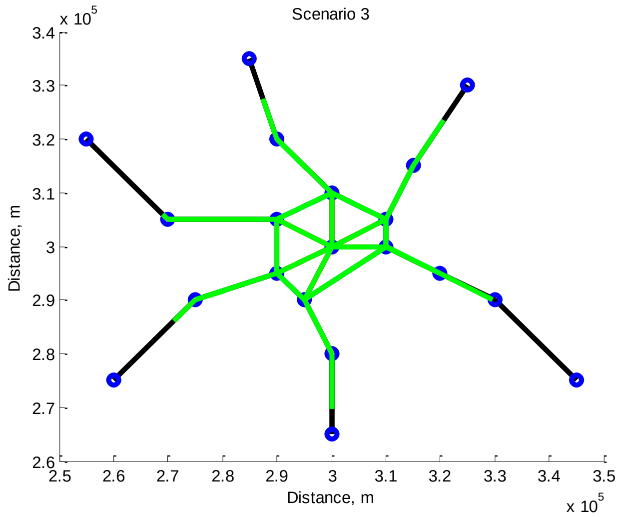


a) DTE ((3.0, 3.0) to (2.9, 3.2) via (3.0, 3.1)) = 18.8 km

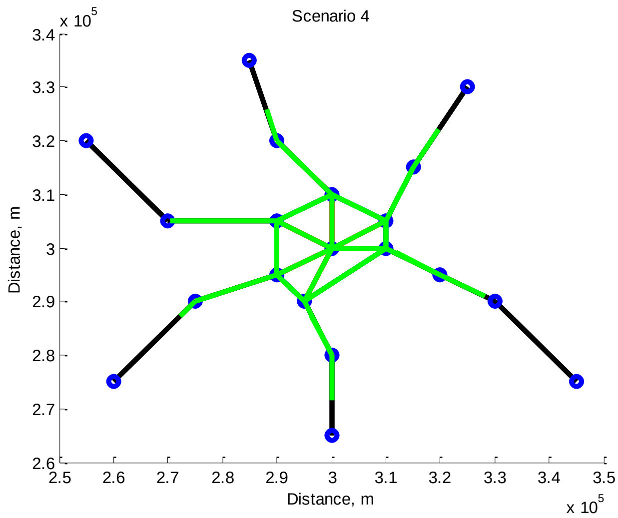


b) DTE ((3.0, 3.0) to (2.9, 3.2) via (3.0, 3.1)) = 21.5 km

Figure 6. Scenario 1 (a) and 2 (b) simulation results.



a) DTE ((3.0, 3.0) to (2.85, 3.35) via (3.0, 3.1) and (2.9, 3.2)) = 32 km



b) DTE ((3.0, 3.0) to (2.85, 3.35) via (3.0, 3.1) and (2.9, 3.2)) = 30.3 km

Figure 7. Scenario 3 (a) and 4 (b).

Results discussion

The Breadth-First Search-based Indicator System has been tested on the four previously described scenarios. The simulation results show that the simplified consumption model used for the purpose of the system reacts properly to the ambient temperature changes. The tests report an increased energy usage at low temperatures, resulting in a major reduction of the vehicle range. Scenario 1 is the 'coldest' scenario with its critical *Amb. Temperature* = -15°C and D_{TE} = 18.8 km. In the Scenario 2 the vehicle range slightly increases until D_{TE} = 21.5 km at *Amb. Temperature* = 0°C. In the Sceario 3 the weather conditions are optimal and there is no need to heat/cool the interior of the vehicle, thus resulting with the maximum D_{TE} = 32 km. Then in the last Scenario 4 the size of the remaining range graph (the number of green edges and their length) is affected by the energy requirements for cooling at 30°C, D_{TE} = 30.3 km.

To extend the vehicle range we propose to:

1) "Eco-drive", keeping, for example, the constant speed of 80 km/h (22 m/s) all over the road network.
2) Couple the BFS Indicator System with the Smart and Green ACC driver assistance system developed in [9].

IV. Conclusions and Future Work

In this paper, the Breadth-First Search-based Indicator System for electric vehicle has been tested on several temperature-oriented scenarios. The tests have reported an increased energy usage at low temperatures, resulting in a major reduction of the vehicle range. The BFS-based remaining range representation we have chosen for the purposes of the BFSIS allows detailed illustration of electric vehicle's "distance to empty".

Future developments will be oriented at using of a map-based service (Google Maps, OpenStreetMap or others) to show the output road graph overprinted in real time. Different traffic conditions will be taken into account when calculating the average vehicle speed and road segments' energy costs.

To validate the proposed system we build a moke-up, which will represent a road network drawn at a rectangular piece(s) of wood. The road segments will be built in such a way to represent uphill, downhill and slippery roads. Different average legal speed as well as different traffic density values will be assigned to all the segments of the road network.
The cars will be car-like robots moving from their initial locations to their destinations. All of them will have a small LCD direct user interaction and information display visualizing the road network and the RR graph overprinted in real time. The spectators will be invited to choose the initial location of a robot(s) and its destination point. Then the BFSIS will compute the time-optimal (or the most efficient in terms of fuel/energy consumption) path taking into account the road data in a near horizon (route network topology, legal speed, grade and grip), traffic conditions as well as ambient temperature. If the destination point is not achievable, the BFSIS will propose the optimal path via the nearest refueling/recharging station.

V. References

[1] Rodgers, L., Wilhelm, E., Frey, D.: Conventional and Novel Methods for Estimating and Electric Vehicle's 'Distance to Empty'. In: ASME IDETC/ATV, Portland, Oregon, USA (2013).

[2] Smart, J., Powell, W., and Schey, S.: Extended Range Electric Vehicle Driving and Charging Behavior Observed Early in the EV Project. SAE Technical Paper 2013-01-1441, 2013, doi:10.4271/2013-01-1441.

[3] Yuhe, Z., Wenjia, W., Kobayashi, Y., Shirai, K.: Remaining driving range estimation of electric vehicle. In: IEEE Electric Vehicle Conference, Greenville (2012), doi:10.1109/IEVC.2012.6183172.

[4] I.J.M. Besselink, J.A.J. Hereijgers, P.F. van Oorschot, H. Nijmeijer.: Evaluation of 20000 km driven with a battery electric vehicle. In: European Electric Vehicle Congress, Brussels (2011).

[5] Potarusov, R. Lebacque, J.-P.: Breadth-First Search-Based Remaining Range Estimation for Electric Vehicle. SAE Technical Paper 2014-01-0273, 2014, doi: 10.4271/2014-01-0273.

[6] Knuth, Donald E. (1997), "The Art Of Computer Programming Vol 1. 3rd ed.", Boston: Addison-Wesley, ISBN 0-201-89683-4.

[7] YASA-400 Advanced Axial Flux Electric Motor, http://www.yasamotors.com/products/yasa-400/

[8] W. Tober.: The energy requirement of battery electric vehicles under different conditions. In: 4th EVE Meeting, Geneva (2013).

[9] Potarusov, R., Nouveliere, L., Orfila, O., Glaser, S.: Smart and Green Adaptive Cruise Control for an Electric Vehicle: First Results. In: 7th IFAC Conference on Manufacturing Modelling, Management, and Control, Saint-Petersburg (2013), doi:10.3182/20130619-3-RU-3018.00190.