2015 Models and Technologies for Intelligent Transportation Systems (MT-ITS)
3-5. June 2015. Budapest, Hungary

The Elevation Factor: Digital Elevation Model Quality and Sampling Impacts on Electric Vehicle Energy Estimation Errors

Anita Graser, Johannes Asamer and Wolfgang Ponweiser
Mobility Department
Austrian Institute of Technology
1210 Vienna, Austria
Email: anita.graser@ait.ac.at

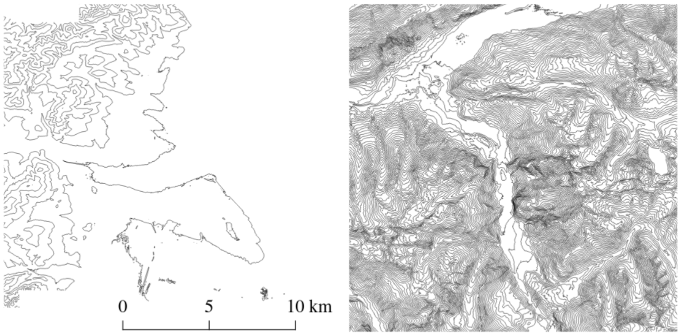
***Abstract*—Energy used to overcome elevation is a significant factor in estimating energy consumption of moving objects and (electric) vehicles in particular. A common source of elevation data for electric vehicle energy estimations are digital elevation models (DEMs). These DEMs are available from multiple providers and with varying quality as free or paid data. This paper presents an evaluation of the impacts of DEM quality and methods used to sample DEM values for elevation profiles on energy estimations for electric vehicle routes. The evaluation is carried out for two different study areas: an urban mostly flat area, and a rural alpine area. An overview of the error obtained with different DEMs and sampling methods in these two areas is provided. These results can serve as a reference for estimating the magnitude of the energy estimation error in case high resolution elevation data is not available in a study area.**

***Keywords*—electric vehicle; e-mobility; energy estimation; digital elevation model**

I. INTRODUCTION

Due to their limited battery capacity and longer recharging times, it is necessary to have tools to reliably estimate electric vehicle (EV) energy consumption in order to leverage the full potential of e-mobility. Range anxiety is an issue for both potential commercial an private users. To address this issue, it is crucial to provide users with adequate information about the current energy status and to reliably predict the energy required to complete planned trips. It is therefore necessary to develop solid methods to estimate energy consumption for trip and tour planning purposes. Energy consumption modeling for EVs is a complex topic which requires a thorough understanding of various technical and human factors such as motor and recuperation efficiency rates as well as individual driver behavior. One significant factor in estimating energy consumption is the energy used to overcome elevation changes.

A common source of elevation data for electric vehicle energy estimations are digital elevation models (DEMs). DEMs are available from multiple data providers as free or paid data with varying quality, for example, with respect to spatial resolution, up-to-dateness, coverage, and applied data correction. This paper shows how DEM quality and methods used to sample DEM values for route elevation profiles impact energy estimations for EV routes. There currently exists no guideline for an informed decision about which DEM quality and sampling methods (nearest neighbor, bilinear or bicubic sampling) should be employed to compute accurate energy estimates for EVs or what errors to expect when no high resolution DEM is available for a study region. Most papers in the mobility research context so far do not specify which sampling method was used to derive elevation information from the DEM [1]–[4] – most commonly NASA Shuttle Radar Topography Mission (SRTM) – with the exception of [5] who use nearest neighbor sampling and [6] who perform bicubic sampling but do not go into detail on how these methods compare to the alternative methods.



(a) (b)

Fig. 1. Elevation contours at 50 meter intervals in Vienna (a) and Imst (b) based on 10m DEMs

The evaluation presented in this study was carried out for two different study areas with different topography: the city of Vienna and the district of Imst in Tirol, Austria. While the city of Vienna is mostly dominated by flat terrain (with the exception of some western city districts which are dominated by the north-eastern foothills of the Alps, as depicted in Figure 1(a), the district of Imst is located in the Tyrolean Alps and represents a mountainous study area, illustrated in Figure 1(b). We present an overview of the error obtained with different DEMs and sampling methods in the two areas. These results can serve as a reference for how large the error will be when

ISBN 978-963-313-142-8 @ 2015 BME

high resolution elevation data is not available in a study area.

Section II introduces the energy consumption model and raster sampling methods used in this study. Section III describes the different DEMs. Section IV presents the results which are discussed in Section V. The conclusions are summarized in Section VI.

II. METHODOLOGY

To estimate energy consumption on a route, we use a vehicle longitudinal dynamics model based on [7]. For accelerating a vehicle against external resistances (air drag, rolling and grade resistance), the electric motor has to provide a tractive effort. The relationship between acceleration a, tractive and resistance forces can be written as

$$F_T = a \cdot f \cdot m + F_R, \tag{1}$$

where F_T is the traction force, provided by the electric motor and F_R are resistances acting on the vehicle. m is the total mass of the vehicle and factor f represents mass factor of all rotating parts. The composition of resistances is defined as

$$F_R = \underbrace{m \cdot g \cdot sin(\alpha)}_{Grade} + \underbrace{m \cdot g \cdot cos(\alpha) \cdot c_{rr}}_{Rolling} + \underbrace{\frac{\rho \cdot A \cdot cw}{2} \cdot v^2}_{Air}, \tag{2}$$

with g as the gravitational acceleration, α the grade angle of the road and c_{rr} the rolling friction coefficient. Air drag is influenced by velocity v, air density ρ, vehicle front surface area A and air drag coefficient cw.

The tractive power for moving the vehicle is provided by the motor, connected to the battery. The electrical power drawn from the battery is denoted as

$$P_{el,out} = \frac{F_T \cdot v}{\eta_M} + P_0. \tag{3}$$

where η_M is the energy efficiency of transmission, motor and power conversion. Auxiliary components of the car cause an additional demand for electric power (P_0), also known as basic consumption.

During decelerating or downhill driving, traction force F_T may be negative. In this case energy is transmitted back to the battery described by

$$P_{el,in} = F_T \cdot v \cdot \eta_G + P_0, \tag{4}$$

with η_G as the efficiency of transmission, generator and in-vehicle charger.

For estimating the total energy demand of a trip, the electrical power P_{el}, flowing either into or out of the battery is integrated over trip time T

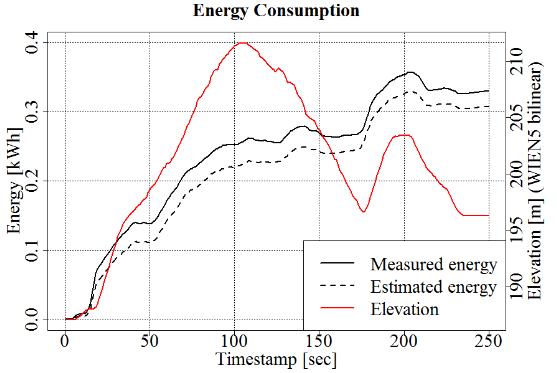


Fig. 2. Model predictions and actual energy consumption measurements for a sample trip in Vienna

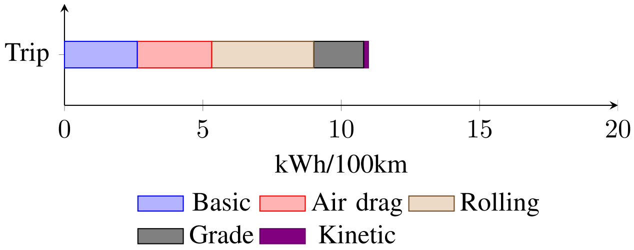


Fig. 3. Energy estimate composition for the sample trip depicted in Fig. 2

TABLE I. PROPERTIES OF THE SAMPLE TRIP DEPICTED IN FIG. 2

Description	Value
Distance [m]	2807
Travel time [sec]	251
Avg. speed [km/h]	40
Avg. running speed (speed $>$ 0) [km/h]	46
95th **percentile speed** [km/h]	61
Number of stops	1
Sum of elevation down [m]	23
Sum of elevation up [m]	32
Avg. grade up [%]	3.3
Avg. grade down [%]	3.8
Estimated energy consumption [kWh/100km]	11
Measured energy consumption [kWh/100km]	11.8

$$E_{el} = \int_0^T P_{el} dt. \tag{5}$$

Figure 2 shows energy consumption estimates based on this model (5) compared to actual measurements for a section of a trip in Vienna. The properties of the whole trip are summarized in Table I. Moreover this table contains estimated and measure energy consumption for the whole trip. The test vehicle was a Mitsubishi iMiEV and parameters have been chosen according to Table II, except for the basic energy demand which was estimated ($P_0 = 964W$) directly from the trip measurements, by analyzing electric power during halts. The figure shows a good correspondence between estimated and measured energy consumption.

For each of the two study regions, the energy consumption model (5) has been applied to 500 randomly generated routes.

TABLE II. VEHICLE PARAMETERS

Parameter	iMiEV	E-Cell	eNV200
Empty weight (m) [kg]	1120	1594	1480
Power [kW]	49	50	80
Front surface area (A) [m^2]	2.14	2.81	3.26
Air drag coeff. (cw)	0.33	0.29	0.31
Battery Size [kWh]	16	36	24
Rolling friction coeff. (c_{rr})	0.01		
Air density (ρ) [$\frac{Kg}{m^3}$]	1.24		
Efficiency drive (η_M)	0.95		
Efficiency recuperation (η_G)	0.6		
Basic energy demand (P_0) [kW]	0.5		
Mass factor (f)	1.05		

The routes were generated by routing on an OpenStreetMap [9] street graph between randomly generated start and end locations. Given a route

$$R =< x_k, y_k > \qquad with \qquad k = 1...K, \tag{6}$$

the elevation values must be determined from the DEM for every route geometry node (x_k, y_k).

We define a DEM as

$$H(x_i, y_i) \qquad with \qquad \begin{aligned} x_{i+1} &= x_i + \triangle x \\ y_{i+1} &= y_i + \triangle y, \end{aligned} \tag{7}$$

where $\triangle x$ and $\triangle y$ are the DEM resolution in x and y direction, respectively.

Raster sampling at route geometry nodes is determined as

$$H(x_k, y_k) = I(x_k, y_k), \tag{8}$$

where I is the interpolation method applied to the route geometry node. Raster sampling was implemented using the open source geographic information system QGIS [10] Processing framework. The three commonly used raster sampling methods [11] which were compared in this study are: Nearest Neighbor which determines the value at the sampling location by the nearest cell center on the input grid, bilinear interpolation which uses the nearest four cell centers, and bicubic interpolation using cubic splines based on [8] which uses the 16 nearest cell centers.

For the energy estimation, the speed was kept constant on the whole route to keep the non-elevation-dependent parameters fixed, since this evaluation focuses exclusively on the impact of elevation on energy estimates. The vehicle parameters used for the computations are based on a Mercedes A Klasse E-Cell. Table II lists all parameters necessary for applying the energy estimation model (5) for different vehicles. This table thus provides an overview of common vehicle parameter values for small private EVs such as the Mitsubishi iMiEV and bigger ones such as the Mercedes E-Cell and Nissan eNV200 – an EV used, for example, as taxi in London. The second group of parameters listed bellow the horizontal braces are not available for individual vehicles and therefore general values have been assumed.

TABLE III. DEM PROPERTIES

Name	Resolution [m]	Elevation value data type
SRTM	90	Integer
EU-DEM	25	Float
Wien 10 & Imst 10	10	Float
Wien 5	5	Float

Note that energy estimation results vary for different vehicle types (e.g. mass or size of vehicle) but this does not affect the general conclusion since grade remains a relevant factor for energy consumption.

III. DIGITAL ELEVATION MODELS

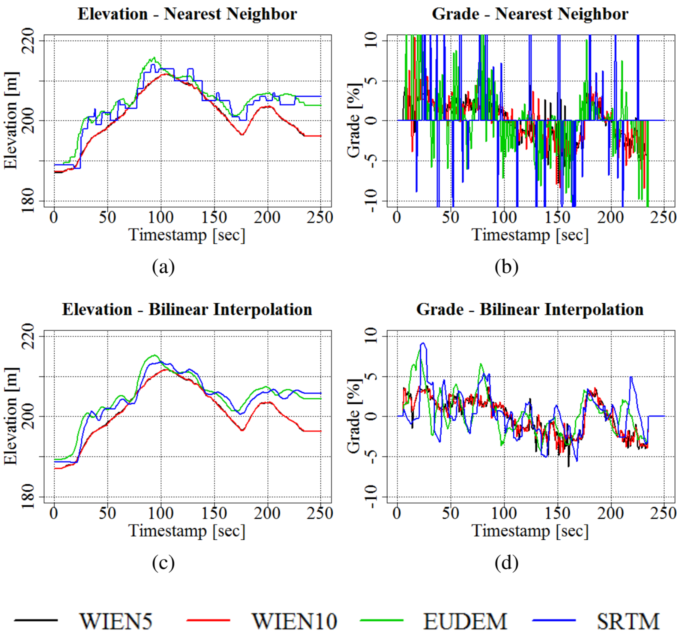
We compare four DEMs for the city of Vienna and three DEMs for the district of Imst in Tirol, Austria (as listed in Table III): NASA Shuttle Radar Topography Mission (SRTM) Version 3.0, EU-DEM, a 10 meter DEM of Vienna, a 10 meter DEM of Imst, and a 5 meter DEM of Vienna.

NASA SRTM V3.0 (from now on referred to as SRTM) was released on November 20th, 2013. SRTM V3.0 has eliminated voids found in previous versions with fill from ASTER Global Digital Elevation Model Version 2, and USGS GMTED2010 or USGS National Elevation Dataset. SRTM v3.0 data for areas outside the U.S. is provided with a resolution of approximately 90 meters (three-arc-second postings) [12] with elevation values stored as integers.

EU-DEM is a digital surface model covering Europe, created in the course of the Copernicus programme funded by the European Union. The data was released in November 2013 [13] and is provided at a resolution of 25 meters with elevation values stored as floats. EU-DEM is based on SRTM and ASTER GDEM data [17].

The 5 and 10 meter elevation models for Vienna and the 10 meter elevation model of Imst have been published as open government data (OGD) by the city of Vienna and the state of Tirol respectively under a Creative Commons license [14], [15]. The 5 and 10 meter DEMs of Vienna (from now on referred to as Wien 5 and Wien 10 respectively) are based on surveying data such as surface points, break lines (slope edges, shoreline), and airborne laser scanning data. Wien 5 was provided as a regular vector point grid with elevation values stored as floats via a Web Feature Service (WFS). In 2014, Wien 5 was removed from the OGD servers and replaced with a 10 meter GeoTIFF raster version [14]. A rasterized version of the Wien 5 data is still available from the open data website opendataportal.at [16]. The 10 meter DEM of Imst is provided in the same GeoTIFF format [15].

To illustrate the differences between these DEMs and the effect of different raster sampling methods, Figure 4 shows elevation and grade profiles based on the four Viennese DEMs for the sample trip depicted in Figure 2 which was tracked with a sampling interval of 1 second. For each position, elevation was sampled from the DEMs using Nearest Neighbor (Figure 4(a)) and bilinear interpolation (Figure 4(c)). The sudden elevation changes exhibited particularly by the elevation profile based on SRTM in Figure 4(a) are due to the Nearest Neighbor



(a) (b) (c) (d)

Fig. 4. Elevation (a),(c) and grade (b),(d) profiles for the sample trip depicted in Fig. 2

sampling of the integer raster values in SRTM. These sudden elevation changes translate into erratic changes in grade values as illustrated in Figure 4(b). In contrast, bilinear interpolation leads to a better alignment of grade profiles derived from high and low-resolution DEMs, as shown in Figures 4(c)-(d).

IV. RESULTS

Based on the vehicle longitudinal dynamics model [7], the overall energy consumption is composed of: basic energy consumption, kinetic energy to accelerate and energy to overcome air drag, rolling resistance, and elevation difference (grade). Figure 5 shows the average energy composition for routes in Vienna and Imst for a constant vehicle speed of 50 km/h based on Wien 10 and Imst 10 DEMs. As can be seen from the figure, energy consumption estimates are considerably higher for routes in Imst with the main difference being the higher energy necessary to overcome elevation differences in this Alpine region. Note that the kinetic energy is always zero in this study due to constant vehicle speeds which were assumed since we are focusing exclusively on the effect of elevation data and sampling.

Tables IV and V show the energy estimation results in kWh per 100 km for 500 EV routes in Vienna and 500 EV routes in the district of Imst. Energy estimates were computed for constant speeds of 20, 30, 40, 50, 60, and 70 km/h. In addition to the above-mentioned DEMs, energy estimates were also computed for completely flat terrain representing missing/omitted elevation data.

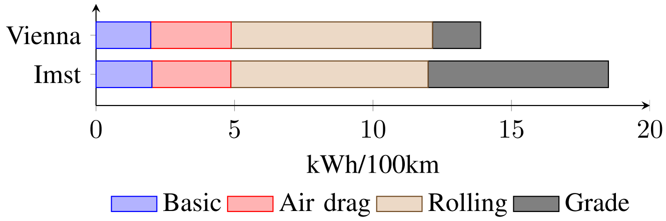


Fig. 5. Energy estimate composition in Vienna and Imst for speeds of 50km/h using Wien 10 and Imst 10 DEMs

V. DISCUSSION

Naturally, energy estimates are lowest if elevation data is omitted. When elevation data is included in the computations, high-resolution DEMs (i.e. 10 meter or 5 meter DEMs) lead to lower energy estimates while lower-resolution DEMs (i.e. SRTM or EU-DEM) lead to higher energy estimates. An omission of elevation information in Vienna leads to an underestimation of 8% (at 50 km/h) while we observe an underestimation of 30% in Imst due to the Alpine topology of this region.

Considering raster sampling methods, results show that the impact of the chosen sampling method increases with decreasing DEM resolution. This effect can be observed in both regions but while nearest neighbor sampling only causes an over-estimation of 17% (at 50 km/h) when SRTM is used in Vienna, the same approach results in an over-estimation of 116% if applied in the Alpine setting of Imst. Using bilinear interpolation instead of nearest neighbor sampling reduces the errors to 1% and 23% respectively.

When EU-DEM or SRTM are used to compute energy estimates, t-tests show a significant difference between the results based on nearest neighbor sampling and the more advanced raster sampling methods (bilinear and bicubic). When 5 or 10 meter DEMs are used, no statistically significant differences are found between the energy estimation results of any of the three raster sampling methods. In all cases, t-tests show that differences in energy estimation results between bilinear and bicubic interpolation are not statistically significant.

The relative influence of elevation changes on the overall energy consumption will be smaller for real-world trips where kinetic energy used for acceleration and recuperation during deceleration play a role as well but, as shown in Figure 3, kinetic energy accounts only for a small share of the total energy consumption of EVs.

VI. CONCLUSION

This study shows that the quality of elevation information is an important factor in estimating EV energy consumption. Even in less mountainous regions such as the city of Vienna, an omission of elevation information would cause underestimations of up to 8% compared to high-resolution DEM results and in alpine regions the error grows up to 30%.

TABLE IV. ENERGY ESTIMATES [KWH/100KM] FOR ROUTES IN VIENNA

		speed [km/h]											
		20		**30**		**40**		**50**		**60**		**70**	
flat		13.3	-7%	12.2	-8%	12.2	-8%	12.8	-8%	13.9	-7%	15.2	-6%
Wien 5	**Near. N.**	14.4	1%	13.4	1%	13.5	1%	14.1	1%	15.0	1%	16.3	1%
	Bilinear	14.3	0%	13.3	0%	13.3	0%	13.9	0%	14.9	0%	16.2	0%
	Bicubic	14.3	0%	13.3	0%	13.4	0%	13.9	0%	14.9	0%	16.2	0%
Wien 10	**Near. N.**	14.4	0%	13.3	1%	13.4	0%	14.0	1 %	15.0	0%	16.2	0%
	Bilinear	**14.3**		**13.3**		**13.3**		**13.9**		**14.9**		**16.2**	
	Bicubic	14.3	0%	13.3	0%	13.3	0%	13.9	0%	14.9	0%	16.2	0%
EU-DEM	**Near. N.**	14.8	4%	13.8	4%	13.8	4%	14.3	3%	15.3	3%	16.5	2%
	Bilinear	14.4	1%	13.4	1%	13.4	1%	14.0	1%	15.0	1%	16.3	0%
	Bicubic	14.5	1%	13.4	1%	13.5	1%	14.1	1%	15.0	1%	16.3	1%
SRTM	**Near. N.**	16.4	15%	15.5	17%	15.7	18%	16.3	17%	17.2	15%	18.4	14%
	Bilinear	14.5	2%	13.5	2%	13.5	2%	14.1	1%	15.0	1	16.3	1%
	Bicubic	14.7	3%	13.7	3%	13.7	3%	14.3	3%	15.2	2%	16.5	2%

TABLE V. ENERGY ESTIMATES [KWH/100KM] FOR ROUTES IN IMST

		speed [km/h]											
		20		**30**		**40**		**50**		**60**		**70**	
flat		13.3	-24%	12.2	-28%	12.3	-30%	12.9	-30%	13.9	-29%	15.3	-26%
Imst 10	**Near. N.**	17.9	2%	17.4	2%	17.9	2%	18.8	2%	19.8	1%	21.0	1%
	Bilinear	**17.5**		**17.0**		**17.6**		**18.5**		**19.5**		**20.8**	
	Bicubic	17.5	0%	17.1	0%	17.6	0%	18.5	0%	19.6	0%	20.9	0%
EU-DEM	**Near. N.**	25.7	47%	25.8	51%	26.3	50%	27.0	46%	27.9	43%	28.9	39%
	Bilinear	20.9	20%	21.0	23%	21.7	24%	22.7	23%	23.7	22%	25.1	21%
	Bicubic	21.0	20%	21.1	24%	21.8	24%	22.8	23%	23.8	22%	25.2	21%
SRTM	**Near. N.**	38.3	120%	38.6	127%	39.0	122%	39.8	116%	40.3	107%	41.3	99%
	Bilinear	21.0	20%	21.1	24%	21.7	24%	22.6	23%	23.7	21%	25.0	20%
	Bicubic	20.8	19%	20.9	23%	21.5	23%	22.5	22%	23.5	21%	24.9	20%

Furthermore it is essential to use bilinear or bicubic raster sampling methods instead of simple nearest neighbor sampling especially when using lower resolution DEMs such as NASA Shuttle Radar Topography Mission (SRTM) or EU-DEM to avoid gross over-estimations (up to 127% in the alpine test region). Concerning the choice between bilinear and bicubic sampling, statistical tests showed no significant difference between the energy estimation results based on these two methods.

The results for Vienna show that a 25 meter DEM such as EU-DEM with bilinear or bicubic sampling is sufficient to reach errors of only 1% and even with SRTM data errors stay at a maximum of only 3%. In contrast, errors of 20 to 25% have to be expected in mountainous regions such as Imst if no high resolution 10 meter DEM is used.

These results can be used to make informed decisions about which DEM quality is necessary in a certain area. Potential applications include, for example, the optimization of disk space requirements for applications on mobile devices by using high resolution DEMs only for selected mountainous areas while using lower resolution DEMs in the remaining areas.

The analysis has been performed for a medium size passenger car. For significantly larger vehicles (e.g. trucks), the interdependency of alternative vehicle parameters (especially mass and efficiency) and different DEMs has to be investigated and is a topic for future research activities. Moreover, for assessing the impact of driving behavior, real-world energy consumption measurements of both regions have to be compared to the model results.

ACKNOWLEDGMENT

This work was partially funded by the Austrian Federal Ministry for Transport, Innovation and Technology (BMVIT) within the strategic program JPI Urban Europe under grant 847350 (project e4-share) as well as the KLIEN initiative of the Austrian BMVIT (project no. 839478 Crossing Borders) and was produced using Copernicus data and information funded by the European Union – EU-DEM layers.

REFERENCES

[1] F. Bachofer, “Einfluss der vertikalen Genauigkeit von DGM auf das EcoRouting von Elektrofahrzeugen” (Impact of the vertical accuracy of DEM on eco-routing of electric vehicles), Wichmann Fachmedien, Angewandte Geoinformatik 2011, 2011.

[2] M. Baum, J. Dibbelt, T. Pajor, and D. Wagner, “Energy-optimal routes for electric vehicles,” Proceedings of the 21st ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems, pp. 54-63, 2013.

[3] T. Kono, T. Fushiki, K. Asada, and K. Nakano “Fuel consumption analysis and prediction model for eco route search,” 15th World Congress on Intelligent Transport Systems and ITS Americas 2008 Annual Meeting, 2008.

[4] R. Prins, R. Hurlbrink, and L. Winslow, “Electric vehicle energy usage modelling and measurement,” International Journal of Modern Engineering, 13 (1), pp. 5-12, 2013.

[5] A. Graser, J. Asamer, M. Dragaschnig, “How to Reduce Range Anxiety? The Impact of Digital Elevation Model Quality on Energy Estimates for Electric Vehicles,” GI_Forum 2014, pp. 165-174, 2014.

[6] T. Jurik, A. Cela, R. Hamouche, A. Reama, R. Natowicz, S.I. Niculescu, CH. Villedieu, D. Pachetau, “Energy optimal real-time navigation system: application to a hybrid electrical vehicle,” Proceedings of the 16th International IEEE Annual Conference on Intelligent Transportation Systems (ITSC 2013), The Hague, The Netherlands, 2013.

[7] M. Ehsani, Y. Gao, S.E. Gay, and A. Emadi, "Modern Electric, Hybrid Electric, and Fuel Cell Vehicles Fundamentals, Theory, and Design," CRC Press, 2004.

[8] P. Dierckx, "Curve and surface fitting with splines," Oxford University Press, Inc., 1993.

[9] OpenStreetMap Project, Visited: 10.10.2014. URL: http://www.openstreetmap.org, 2014.

[10] QGIS Development Team, "QGIS Geographic Information System. Open Source Geospatial Foundation Project," Visited: 10.10.2014. URL: http://qgis.osgeo.org, 2014.

[11] M. Neteler, and H. Mitasova, "Open Source GIS: A GRASS GIS Approach," Springer, 2007.

[12] NASA, "NASA Shuttle Radar Topography Mission (SRTM) Version 3.0 (SRTM Plus) Product Release," Visited: 10.10.2014. URL: https://lpdaac.usgs.gov/nasa_shuttle_radar_topography_mission_srtm_version_30_srtm_plus_product_release, 2013.

[13] Inspire, "EU-DEM and hydrographic network Version1 for Europe released," Visited: 10.10.2014. URL: http://inspire-forum.jrc.ec.europa.eu/pg/news/admin/read/238988/eudem-and-hydrographic-network-version1-for-europe-released, 2013.

[14] Stadtvermessung Wien, "Gelädemodell," Visited: 10.10.2014. URL: https://open.wien.at/site/datensatz/?id=82764cdb-a0e0-4e64-ba8f-31cc9a303c5a, 2014.

[15] Tiroler Landesregierung Abteilung Geoinformation, "Digitales Geländemodell Tirol," Visited: 10.10.2014. URL: https://www.tirol.gv.at/data/datenkatalog/geographie-und-planung/digitales-gelaendemodell-tirol/, 2014.

[16] A. Graser, "Digitales Geländemodell Wien 5m-Raster," Visited: 10.10.2014. URL: http://data.opendataportal.at/dataset/digitales-gelandemodell-wien-5m-raster, 2014.

[17] EEA, "EU-DEM - Metadata," Visited: 20.01.2015. Permalink: http://www.eea.europa.eu/data-and-maps/data/ds_resolveuid/ca503256de1b4231b029e4145d0a8b7b, 2015.