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MODELING THE DRIVING RANGE OF ELECTRIC VEHICLES: A TECHNICAL CONTRIBUTION

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Abstract

Modern development of electric vehicles imposes an extremely important requirement related to their driving range. In addition to traction force and acceleration, driving range is one of the most important performance indicators that contributes to the assessment of the functional quality of a vehicle.Driving range is a measure of energy autonomy, and low autonomy is one of the biggest limitations to the wider adoption of electric vehicles.The main issue behind the limited autonomy lies in the capacity (and design concept) of the embedded energy storage system. The design of such a storage system should enable high operational efficiency with the smallest possible volume and mass of the propulsion battery. Another challenge related to vehicle range concerns the management of available energy, which involves controlling electricity consumption. This means identifying all vehicle usage options that affect energy (and power) consumption, keeping in mind that the battery is the only energy source in fully electric vehicles.

***Keywords**: electric vehicle, driving range,speed profile, acceleration and deceleration modes, battery power.*

1 INTRODUCTION

The driving range of an electric vehicle refers to the maximum distance, measured in units of length (e.g., kilometers or miles), that the vehicle can travel on a single charge of its traction battery. The range of an electric vehicle (hereinafter: EV) depends on several factors: battery capacity, vehicle mass, road conditions, driving style, and the use of auxiliary systems in the vehicle.

The capacity of the traction battery is inherently linked to its size. However, increasing the battery dimensions also increases the vehicle's mass, which negatively affects energy consumption – raising it. This issue can be partially mitigated by using battery materials with higher specific energy (amount of energy per unit of mass). Contemporary research in the automotive industry [1–4] addresses challenges related to improving the energy capabilities of EVs, among which the choice of battery materials is one of the most prominent. The design of rechargeable batteries for EVs considers key characteristics such as: dimensions, shape, volume, mass, capacity and charging efficiency, energy density (how much energy can be stored in a unit of volume), specific power (how much power can be obtained per unit of mass), self-discharge rate, operating temperature, external temperature influence, number of charge-discharge cycles (lifespan), aging rate, and resistance to self-ignition.

Variations in vehicle mass lead to significant changes in the duration of energy availability from a single battery charge. In other words, adding passengers in addition to the driver increases energy consumption and thus reduces the vehicle's range on a single battery charge.

Road conditions refer to the loads imposed on the vehicle due to road influences, such as road design, inclines, curves, etc., as well as weather-related effects on both the road and the vehicle (wet and slippery surfaces, snow and ice, high and low ambient temperatures), and traffic conditions (which are especially relevant when analyzing loads in urban environments). These loads, in addition to the basic load caused by resistance to movement due to acceleration and inertia of the vehicle's mass with the cargo, reduce the EV's driving range.Additional vehicle loads can also occur due to the method of use, i.e., driving style.

Modern vehicles are increasingly equipped with systems aimed at enhancing passenger comfort and safety. The use of various auxiliary systems, such as the air conditioning system, significantly increases stored energy consumption and thereby reduces EV range.

The distances achievable on a single battery charge in today's EVs typically range from 250 to 400 km. Vehicles in the highest market segments already offer ranges exceeding 600 km per charge. Table 1 presents a list of EVs with the longest ranges in 2024, based on tests of current models [5], which involved highway driving at a speed of 120 km/h on a single traction battery charge.

Table 1 Electric cars with the longest range (2024)

	Vehicle model	Rangein km	Price in dollars
1.	Lucid Air	660	78.900
2-3.	Mercedes-Benz EQS	645	74.800
	Chevrolet Silverado EV	645	105.550
4.	Tesla Model S	515	76.630
5.	BMW i7	500	106.695
6.	Hyundai Ioniq 6	485	38.650
7-9.	BMW iX	465	88,095
	GMC Hummer EV Pickup	465	98,845
	Mercedes-Benz EQS SUV	465	105.550
10-12.	Genesis Electrified G80	450	75 625
	Porsche Taycan	450	92.550
	Rivian R1T	450	71.700

Table 1 shows that price is not necessarily the determining factor for the range of an EV achieved on a single battery charge. The price of an EV is influenced by numerous economic factors as well as technical components installed in the vehicle, such as batteries of varying capacities and materials, electric motors of different power ratings, etc. It does not follow that EVs with the longest range must also be the most expensive; on the contrary, the price is often more influenced by components that contribute to other performance categories. The three leading current EV models in terms of driving range are shown in Fig. 1.

Fig. 1*Three current models with the longest range >600 km per battery charge, [5]*

2 ELECTRIC VEHICLE POWER MODELING

The driving range of an EV (in kilometers per single battery charge) is generally shorter than the range of an internal combustion engine (hereinafter: ICE) vehicle per full fuel tank. This difference in favor of ICE engines was more pronounced in the past, but today it is significantly smaller.It should be kept in mind that the fuel tank of a gasoline or diesel vehicle can be refilled very quickly while driving, unlike the battery storage of an EV.Gas stations (for gasoline, diesel, LPG, CNG) are widespread, while battery charging stations for EV are still relatively rare. Therefore, energy management in EVs must be highly efficient, relying on an Energy Management System (EMS).The EMS should be equipped with data on external and internal air temperature, battery current and voltage during charging and discharging, electric motor current and voltage, vehicle speed and acceleration, and other relevant parameters.

Modeling EV driving range can be approached as modeling the amount of energy (power) required for the vehicle to overcome all loads during a defined period of movement (and idling), using only a single battery charge down to a specified discharge threshold. The issue of EV range will remain relevant until a widespread network of battery charging stations is established – comparableto today's network of gas stations for ICE vehicles.

Solving the EV range problem can be supported by analyzing the power consumption required by the vehicle in each minimal time increment (persecond, eg.) toovercome all forces opposing motion. The observed operating time is described by a model that includes driving cycles with corresponding speed variations. Simultaneously, it is necessary to calculate the energy consumption efficiency under given driving conditions. These calculations are performed iteratively, starting with the observed time point reduced to the i-th second, and then repeated for each subsequent second until the battery is fully discharged.

The traction power,P_T, required to propel the vehicle is calculated using the following expression:

$$P_{\mathrm{T}} = F_{\mathrm{T}}\, v \qquad (1)$$

Where: $F_T$is the traction force, and v is the vehicle speed, taken from the driving profile.

To evaluate the energy efficiency at each iteration point, we use the calculated traction force,F_T, and the corresponding speed,v, from the driving profile.

Transmission efficiency in EVs is generally very high, as torque is usually transmitted through a single-stage gear system. The efficiency of the electric motor (EM) in an EV – whichmust generate the required traction force $F_T$using energy from the traction battery – dependson several parameters, including:the mass of the motor and its components,the angular velocity of the motor, andthe motor torque.The motor efficiency is calculated using the following expression:

$$\eta_{\mathrm{EM}} = \frac{E_{\mathrm{e}}}{E_{\mathrm{tot}}} = \frac{M_{\mathrm{EM}}\,\omega}{M_{\mathrm{EM}}\omega + k_{Cu}M_{\mathrm{EM}}^2 + k_{Fe}\,\omega + k_{\mathrm{w}}\omega^3 + C} \qquad (2)$$

Where: $E_e$is the effective or useful energy, $E_{tot}$is the total energy which includes all losses, $M_{EM}$is the motor torque, $\omega$is the angular velocity of the motor, $k_{Cu}$is the loss coefficient related to copper components of the motor, $k_{Fe}$is the loss coefficient related to metal components of the motor, $k_w$is the wind resistance loss coefficient, C=const. represents constant losses that occur under any speed regime (Table 2).

Table 2 Loss coefficients for certain EM types, [6]

Coefficient	motor type: PM P=(2-5)kW	motor type: IM P=100kW
k_{Cu}	1,5	0,3
k_{Fe}	0,1	0,01
k_w	0,00001	0,000005
C	20	600

In addition to PM or PMSM (Permanent Magnet Synchronous Motors) and IM (Induction Motors), SRM (Switched Reluctance Motors) and DC (Direct Current) electric motors are also in use, [7-9].From an energy consumption perspective, it is important to distinguish between the following two vehicle operating modes:

- Acceleration mode, and
- Deceleration mode.

The calculation of the required power and power losses for acceleration and deceleration modes is performed on as follows.The electric motor must provide an output power greater than the traction power, P_T, due to the efficiency of the gear transmission system, η_G, which is always less than 1:

$$P_{EM(out)} = \frac{P_T}{\eta_G} \quad (3)$$

Consequently, the input power of the electric motor, drawn from the vehicle's battery, must be greater than the output power,$P_{EM(out)}$, because it includes the efficiency of the electric motor drive system consisting of the motor, inverter, and controller, [6], denoted η_{EM}:

$$P_{EM(in)} = \frac{P_{EM(out)}}{\eta_{EM}} \quad (4)$$

The total power losses (i.e., inefficiencies of the EM system) during traction consist of the intrinsic losses of the motor, controller, and gear transmission, and can be expressed as:

$$\Delta P = P_{EM(in)} - P_T = \frac{P_T}{\eta_G \eta_{EM}} - P_T = \frac{1-\eta_G \eta_{EM}}{\eta_G \eta_{EM}} P_T \quad (5)$$

The traction battery (or main battery) must supply power, P_B, not only for the primary propulsion function but also for various support and auxiliary functions, P_{af}, of the EV:

$$P_B = P_{EM(in)} + P_{af} \quad (6)$$

In the case of deceleration mode, the vehicle uses its mass and the effect of all resistive forces to reduce its speed. In this mode, the output power of the electric motor is less than the traction power:

$$P_{EM(out)(d)} = P_T \eta_G \quad (7)$$

Accordingly, the input power of the electric motor becomes:

$$P_{EM(in)(d)} = P_{EM(out)(d)} \eta_{EM} \quad (8)$$

3 SPEED PROFILE MODELING

The driving range of an EV can be evaluated using simulation methods, which require the definition of appropriate speed models, i.e., speed profiles. Two types of these models can be applied to simulate the driving range:

- Constant speed model, and
- Variable speed model.

The constant speed model assumes "steady" driving without disruptive influences until the complete depletion of the energy resource – battery. Models based on constant driving speed provide results that can be useful for general assessment, but not for precise determination of vehicle range.In contrast, variable-speed models enable calculations that yield results closer to real driving patterns and traffic conditions. The simulation of a variable speed model involves cyclic changes between different speed regimes (or profiles) similar to those that occur in real practice. Such models are significantly more complex and require longer processing time.

Among the models developed for urban conditions of use, the ECE-15 model (Fig. 2) should be mentioned. It is particularly suitable for evaluating the performance of small electric vehicles and is often used in the EU, [6]. The simulation time for this model is T=200s and it is characterized by trapezoidal speed change cycles. The shape of the cycle implies linear changes in driving speed, except during intervals when the speed remains constant (periods of maximum constant test speed).

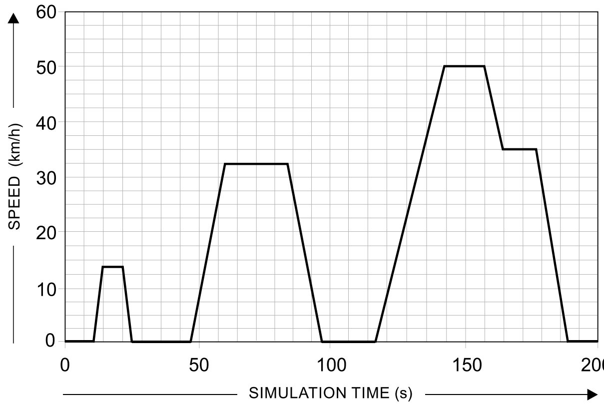

Fig. 2*Simplified urban driving model ECE-15*

A slightly more complex model, also intended for testing under urban driving conditions, is shown in Fig. 3. The simulation time is T=360s, and each second represents a data point at which the vehicle's performance parameters (energy, power) are observed. These parameters vary depending on load changes, such as driving speed and road conditions.

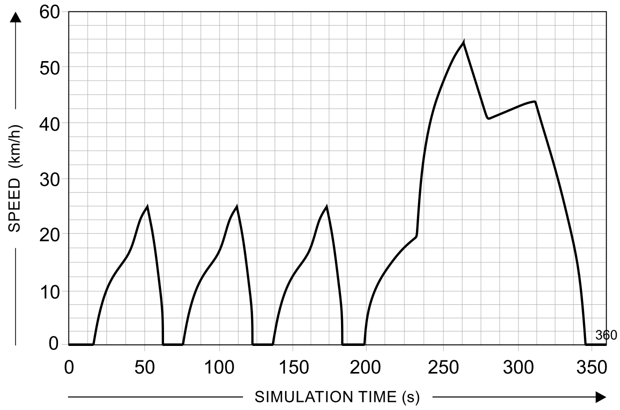

Fig. 3*Urban driving model with nonlinear speed variation(FUDS[1])*

The low-speed driving cycle involves non-linear speed variations typical of movement through a city center with dense public transportation and pedestrian traffic, resulting in urban "traffic jams" and so-called stop-and-go driving. The maximum speed in this phase reaches 25 km/h for a brief moment (approximately 1 s). The low-speed phases are followed by a significantly longer interval of 145 s, characterized by a wider range of speed variations.This segment includes a peak speed of 55 km/h, reached under nonlinear conditions.This is followed by two linear speed changes - decreasing and increasing, and then a non-linear decrease in the speed of movement until the state of rest. The higher-speed interval simulates driving along multi-lane boulevards, offering more space for uninterrupted movement without forced deceleration. The model also accounts for

[1] Federal Urban Driving Schedule, U.S.A.

uniform inter-cycle pauses, represented by periods of zero speed (idling), as well as pauses at the beginning and end of the simulation time.
Fig. 4 presents the FHDS (USA) speed variation model used for highway driving simulation.Although this model assumes a maximum speed of only 100 km/h, it faithfully reflects the actual behavior of vehicle on highways.This model is still used to simulate vehicle range even though highway speeds have been significantly increased. Due to the high traffic saturation on highways in large metropolitan areas (megacities with dense infrastructure), the maximum permitted speed is often unattainable during most of the journey.Therefore, this model remains highly reliable.By applying specific standards, the model can be easily adjusted to reflect different speed limits.

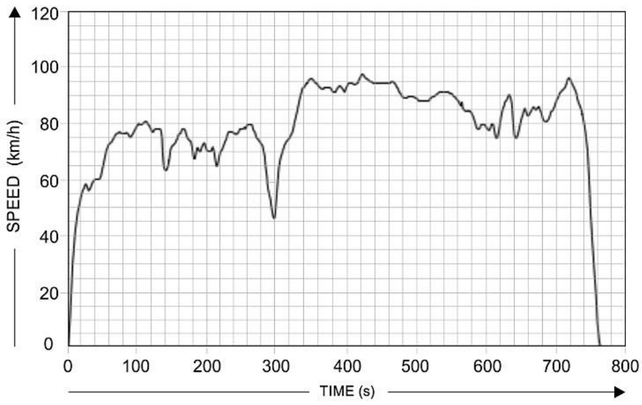

Fig. 4*Driving model in highway conditions (FHDS[2])*

The widely used SAE J227a standard has proven to be very good for defining the general speed profile, [10]. According to this standard, speed variations in the general case are divided into five phases:

1. Acceleration phase: This involves acceleration from v=0 to the maximum speed $v=v_{max}$, which occurs duringthe interval T_a.
2. Constant speed phase: Characterized by a steady speed $v=v_{max}=v_{const}$; this phase takes place during the interval T_c.
3. Unpredictable dynamics phase: Also called the "pop-out effect" or disturbance phase, which represents unpredictable speed fluctuations not influenced by the vehicle's tractive force; this happens during the interval Td.
4. Braking phase: In this phase, the speed decreases linearly to v=0, during the interval T_b.
5. Resting phase: The cycle ends with the vehicle stopping (v=0) in the time interval T_r.

The standard defines four speed categories, which correspond to vehicles capable of reaching different specified maximum speeds.
Table 2 contains the time intervals for all cycle phases in these four characteristic speed categories. Cycle D from Table 2 is rarely used, considering that it does not include the maximum speeds that are significantly increased in the operation of modern vehicles.

[2] Federal Highway DrivingSchedule, U.S.A.

The remaining cycles – i.e., the motion simulation models shown in Fig. 5 – are highly relevant for evaluating the performance of electric scooters and small electric vehicles.

Table 2 Test cycle parameters according to SAE J227a

Cycle	v_{max} (km/h)	Cycle phase duration (s)					T(s)
		T_a	T_c	T_u	T_b	T_r	
A	16	4	0	2	3	30	39
B	32	19	19	4	5	25	72
C	48	18	20	8	9	25	80
D	72	28	50	10	9	25	122

Legend: T_a is the acceleration phase; T_c is the constant maximum velocity phase; T_u is the unpredictable dynamics phase; T_b is the braking phase; T_r is the resting phase; T is the total simulation time.

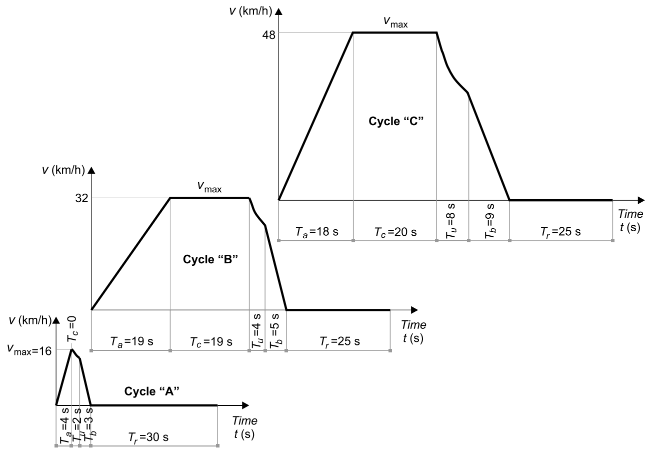

Fig. 5*Diagrams of speed profiles A, B and C (SAE J227a)*

Similar variable speed profiles are also used to check the exhaust gas emissions of ICE vehicles.

4 ESTIMATING THE DRIVING RANGE OF MODERN ELECTRIC VEHICLES

Range calculators are used to estimate the driving range of modern electric vehicles. These are expert-level digital tools that enable quick and approximate the range calculations based on given operating conditions and predefined speed profiles tailored to specific vehicle classes. Companies in the automotive industry are engaged in creating accurate range calculators.In addition to range calculators, other similar professional tools are being developed, such as energy consumption calculators, cost estimators, etc.Professional calculators incorporate an increasing number of parameters in the analysis, including input variables and output performance metrics.
They serve as instruments for evaluating specific operational and technical characteristics of various types of EV, intended not only for consumers but also for experts in the field of vehicle operation and maintenance. The range assessment tools contain a database of vehicle operating parameters that influence the final range, from which appropriate calculation options must be selected.
Commonly included parameters in EV calculators are: battery capacity, battery voltage, vehicle mass including driver mass, speed profile, external conditions (road incline, ambient temperature, etc.), interior temperature, wheel size,

stopping frequency, and other factors that may affect the final range, [11].

The most commonly used speed profiles (models) in expert range estimation methods are:

- Urban driving profile,
- Highway driving profile, and
- Mixed driving profile.

The urban driving model assumes that most individual trips take place within city limits and nearby areas, at an average speed of 27 km/h (17 mph). The highway speed profile should be selected when most of the driving takes place on highways, at an average speed of 92 km/h (57 mph). The mixed profile includes both urban and highway segments, with an overall average speed of 47 km/h (29 mph).

Urban driving gives the longest vehicle range, followed by mixed and highway driving, as shown in Figures6 and 7. Highway driving is the most energy-intensive and depletes the battery fastest. Comfort conditions include cooling and heating of the vehicle interior during operation. The use of air conditioning significantly reduces the energy autonomy, or driving range, of an EV.

The ambient temperature is considered to be the minimum characteristic temperature of the environment in which the vehicle predominantly moves. For example, if winter temperatures vary from -10°C to 0°C, the lower limit value tmin=-10°C is chosen. If low temperatures are less relevant, and summer temperatures often reach 40°C, the calculation should be directed accordingly.The temperature is selected from a predefined range, depending on the expert tool and the vehicle type/manufacturer.

Certain numerical driving simulators, depending on the desired level of analysis accuracy, may include more or fewer influencing factors as input variables in the calculation process. Figure 6 shows the range results in kilometers for the Volvo EX40 vehicle for given speed profiles (urban, highway, and mixed) and ambient temperature conditions. The calculation was performed using an expert tool that, in addition to temperature and speed models, includes options for selecting motor operating modes and heat pump operation (as influential factors on energy consumption), [12].

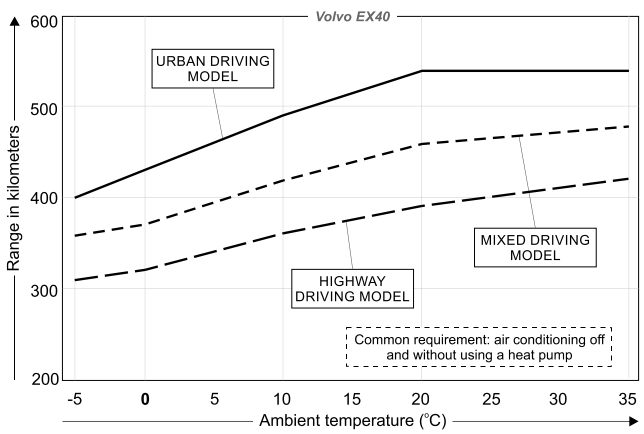

Fig. 6 *An example of calculating the range of the Volvo EX40 vehicle for different speed models under the influence of different ambient temperatures*

The temperature range in Fig.6 spans from -5°C to +35°C, with discrete range values explicitly provided at temperature points {-5, 0, 10, 20, 35}.Approximate driving range values for temperatures between characteristic points can be read from the diagram using linear interpolation.

The highest ranges are achieved within the +20°C to +35°C interval across all three driving profiles. The urban profile provides the greatest energy autonomy, while driving at high speed (on the highway) consumes the battery the fastest due to the increased aerodynamic resistance of the EV.Volvo recommends installing a heat pump, which is used to heat the cabin and regulate the battery temperature, thereby contributing to increasing the vehicle's range.

The expert models for EV range calculation allow, in addition to the ambient temperature, the selection of other different parameters, for example the dimensions of the wheels from the offered assortment, etc. Figure 7 shows diagrams of the range variation of the Jaguar I-Pace[3]EV per single battery charge, as a function of the specified ambient temperature. The diagrams compare three driving profiles: urban (U), highway (H), and mixed (M), depending on the selected wheel size: 18" and 22".

The range models, connected to the required power to overcome the characteristic resistances, i.e. the loads to which the EV is exposed during operation, represent in a specific example the consequence of the application of the specified speed profiles and wheel sizes.The models are labeled as follows: U-18, H-18, M-18, U-22, H-22, and M-22, and are represented by linearized functions. In this model, the air conditioning factor is considered constant (vehicle air conditioning is turned off).

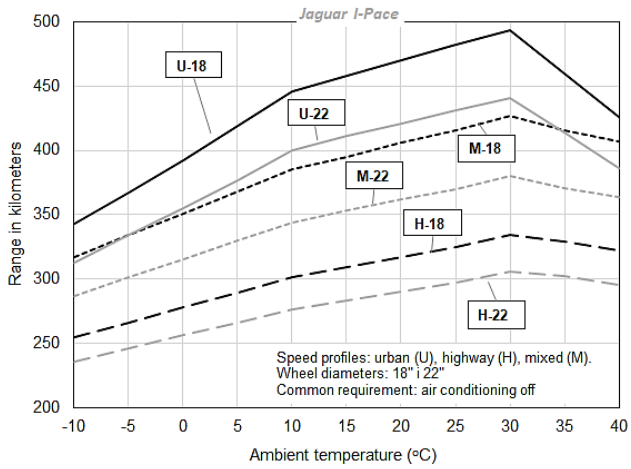

Fig. 7*An example of calculating the range of the Jaguar I-Pace vehicle for different speed models at different ambient temperatures and wheel sizes*

The urban driving speed profile U-18, shown in Fig. 7, is characterized by lower accelerations and the lowest speeds. It represents the most energy-efficient regime among all considered profiles, and therefore yields the greatest range. It is followed by the less favorable mixed driving profile, and the least favorable – highwaydriving.

Increasing the diameter (size) of EV wheels generally leads to higher energy consumption, resulting in reduced range across all three speed profiles and for all ambient temperatures.If we compare the curves at points corresponding to the same temperature, for example 30°C –

[3]Na osnovu kalkulatora sa sajta [19].

specificallyU-18 vs. U-22, M-18 vs. M-22, and H-18 vs. H-22 – wecan observe clear evidence supporting this claim.
Moreover, the differences between individual driving modes are evident: at the same temperature (e.g., 30°C), the largest range drop occurs in urban driving when larger 22-inch wheels are used instead of smaller 18-inch wheels.

5 CONCLUSIONS

- The range of an EV is modeled as the amount of energy required by the vehicle to overcome all resistance forces, or loads, during movement and idling, using a single battery charge until a defined discharge threshold is reached.
- The calculation of energy consumption takes into account the current speed and tractive effort of the EV, and is performed iteratively for each subsequent second of operation (i.e., simulation time).
- Models for simulating the load of EVs in constant speed operation are simple but imprecise for real conditions.
- Variable speed models are more reliable because they better reflect real driving conditions, but they are more demanding to process.
- Simplified models have trapezoidal speed cycles and are suitable for small EVs.
- Complex urban models with nonlinear speed variations include stop-and-go behavior and more closely reflect real-world usage.
- Highway speed profiles simulate significantly higher speeds and speed changes; older models with lower maximum speeds are still used alongside newer ones that take higher speeds in account.
- The SAE model (with five phases: acceleration, cruising, disturbance, braking, idling) serves as a standard for simulating vehicle movement across different classes based on their maximum speeds.
- Typical driving profiles affect EV range differently: urban profiles yield the longest range due to lower speeds and reduced aerodynamic drag, while highway driving depletes the battery fastest due to high speeds and increased air resistance.
- Multicriteria EV range modeling must consider speed, terrain, external conditions (temperature, humidity, snow, ice, wind), vehicle dimensions, and auxiliary systems such as air conditioning.
- Expert tools (usually in the form of interactive calculators) enable flexible analysis and assessment of EV performance in real-world conditions.
- Urban driving remains the most suitable regime for maximizing EV range (or the greatest energy autonomy), but is sensitive to factors such as ambient temperature, use of the air conditioning system, wheel size, etc.

REFERENCES

1. Hassini, M., Redondo-Iglesias, E., Venet, P., 2023, *Lithium–ion battery data: From production to prediction*, Batteries, 9(7):385.
2. Saxena, S., Hendricks, C., Pecht, M., 2016, *Cycle life testing and modeling of graphite/$LiCoO_2$ cells under different state of charge ranges*, J. Power Sources, 327, pp. 394-400.
3. Garche, J. et al, 2013, *Encyclopedia of electrochemical power sources*, Newnes, p. 407.
4. Moseley, P.T., Garche, J., 2014, *Electrochemical energy storage for renewable sources and grid balancing*, Newnes, p. 440.
5. https://www.caranddriver.com, June 2024.
6. Larminie, J., Lowry, J., 2012, *Electric vehicle technology explained*, 2nd ed., John Wiley & Sons Ltd, Chichester, West Sussex, U.K.
7. Chan, C.C., 2002, *The state of the art of electric and hybrid vehicles*, IEEE, 90(2).
8. Zeraoulia, M., El Hachemi, B.M., Diallo, D., 2006, *Electric motor drive selection issues for HEV propulsion systems: A comparative study*, IEEE Transactions on Vehicular Technology, 55(6), pp.1756-1764.
9. Xue, X.D., Cheng, K.W.E., Cheung, N.C., 2008, *Selection of electric motor drives for electric vehicles*, Proc. Australasian Universities Power Eng. Conf. – AUPEC'08, P.170.
10. Dhand, A., 2015, *Design of electric vehicle propulsion system incorporating flywheel energy storage*, PhD Thesis, DOI:10.13140/RG.2.1.3220.0406
11. https://srbija.jaguar.com/, dec. 2024
12. https://www.volvocars.com/ba/cars/electrification/range/, December 2024.

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