APME — Actualităţi şi Perspective în Domeniul Maşinilor Electrice
Electric Machines, Materials and Drives - Present and Trends
19, *1*, pp. 74-83, 2023

ELECTRIC VEHICLE PERFORMANCE ANALYSIS USING MULTI-MOTOR PROPULSION SYSTEM

Liviu POPESCU[1], Alexandru STĂNESCU[2] and Ştefan VASILIU[3]
[1, 2, 3] National University of Science and Technology POLITEHNICA Bucharest, RO-060042, Bucharest, Romania
liviu_p@yahoo.com[1], alexandrus.elth@gmail.com[2], stefanvasiliu@yahoo.com[3]

Abstract. Developing powertrains for Electric Vehicles requires first to evaluate the target vehicle. From vehicle data, the resistant forces appearing during vehicle movement can be determined. The required power and torque for the propulsion system depend on vehicle speed and road slope angle. To reduce the losses on mechanical transmissions in-wheel motors are used. The motors are limited by the torque, power, and speed capabilities. In the present paper, the vehicle performance is analyzed from this perspective including nominal and maximum supported values by the powertrain motors.

1. INTRODUCTION

Vehicles performance represents a studied topic from the very beginning of motor vehicles and continues to be an important one [1-2]. The reintroduction of Electric Vehicles (EV) at the beginning of 21st century [3], stimulates even more the study of vehicles performance. The electric motors present improved capabilities than thermal predecessors, but in parallel, there are less capabilities to produce onboard energy from chemical reactions than from the usage of traditional fuels. As the vehicle shape influences the aerodynamic drag, the EV design [4] helps to improve vehicle performance, as the maximum speed on flat road.

The author's precedent works analyzed EV powertrain solutions using multiple motors. A first example is given in [5]. The present study will continue with similar powertrain solutions analyzing the impact of the powertrain performance on the vehicle one. The simulation continues to be utilized to obtain first results [6-7] before going to a physical application [8]. The question of controlling multiple motors [9-12] in the same powertrain will continue to be investigated once the vehicle and the powertrain are designed for reducing the electric energy consumption maximum speed improvement [9-10], [12-13] and improving the maximum speed [11]. Also related to the conversion efficiency of electric energy in mechanical one, the methods for building efficiency maps and usage for multi-motor powertrain constitution are previously investigated [14-15]. Additional example of powertrain sizing is given in [16]. The main goal of the analysis is to continue the activity for realizing the didactical platform in [17] by a physical implementation of an electric powertrain on a real vehicle. Also, precedent works performed investigations related to torque transfer between powertrain motors [18] and steering wheel influence on motors torque and speed [19] with the possibilities to be conducted on physical vehicle.

In this context, starting from vehicle data, the present paper analyses the needs for torque and power to be covered by an electric multi-motor powertrain. There is a direct dependence on vehicle speed. Also, the grading resistance is integrated in the study to determine the slope of the road that the vehicle will be able to climb. The vehicle configuration integrates powertrain possibilities for rear axle, but also rear and front axle driving. In the analysis the advantages of electric motors are included and studied for nominal values, and, for limited time, for maximum accepted values. A final analysis is performed into the obtained results.

ISSN / ISSN-L: 1843-5912
DOI: 10.36801/apme.2023.1.10

2. **VEHICLE INVESTIGATION**

2.1 Vehicle data

The present investigation is conducted on a classic vehicle having the characteristics presented in Table 1.

Table 1. Characteristics of the vehicle

Characteristic	Value	Measurement Unit
Vehicle mass	1536	kg
Wheel radius	0.31	m
Aerodynamic drag coefficient	0.39	-
Frontal area	2.39	m^2

In Table 2 are shown the complementary elements needed to calculate the resistant forces and the maximum tractive effort supported by the vehicle.

Table 2. Data for resistant forces calculation

Characteristic	Value	Measurement Unit
Rolling resistance coefficient	0.013	-
Maximum tractive effort coefficient	0.8	-
Air density	1.225	kg/m^3
Gravitational acceleration	9.8	m^2

2.2 Resistant forces calculation model

The vehicle mass, M, generates the gravitational force acting on the vehicle

$$G = M\,g. \tag{1}$$

The forces acting on the vehicle are explained in [5] and shown in Fig. 1.

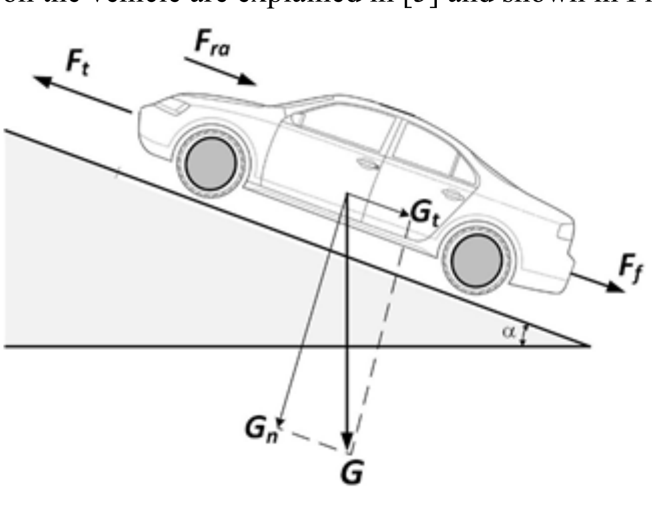

Figure 1. Forces acting on a vehicle during straight road movement [5]

When the road has an inclination to the vertical, given by a slope angle, α, the normal component on the road is.

$$G_n = M \cdot g \cdot \cos(\alpha). \tag{2}$$

This component generates the rolling resistant force, depending on the rolling resistance coefficient, C_r,

$$F_f = C_r \cdot M \cdot g \cdot \cos(\alpha). \quad (3)$$

The gravitational force component parallel to the road gives the grading resistance,

$$G_t = M \cdot g \cdot \sin(\alpha). \quad (4)$$

For the powertrain calculation, is important to know the maximum force that can occur between the tires and the ground without losing the adherence, the maximum tractive effort,

$$F_e = C_e \cdot M \cdot g \cdot \cos(\alpha). \quad (5)$$

It is important to observe that when climbing a road, the maximum tractive effort diminishes.

The air pressure creates a force resisting the vehicle motion, depending linearly on the air density, ρ, the vehicle frontal area, S, the shape of the vehicle characterized by the aerodynamic drag coefficient C_x and the square of the speed [5]:

$$F_{ra} = (1/2) \cdot \rho \cdot S \cdot C_x \cdot (V - V_w)^2, \quad (6)$$

where, ρ is the air density, S is the frontal area of the vehicle, C_x is the aerodynamic drag coefficient, V is the vehicle speed, and V_w, the wind speed on the vehicle moving direction.

To move the vehicle with an acceleration a, the tractive effort to be developed by the powertrain is.

$$F_t = F_f + G_t + F_{ra} + M \cdot a. \quad (7)$$

The condition to move the vehicle, and not lose the tire adherence, is.

$$F_t < F_e. \quad (8)$$

2.3 Vehicle main requirements for the powertrain

To move the vehicle at very low speed, the powertrain must cover the rolling resistant force, which decreases slowly when increasing the slope, and the grading resistance force which increases fast with the slope, as shown in Fig. 2.

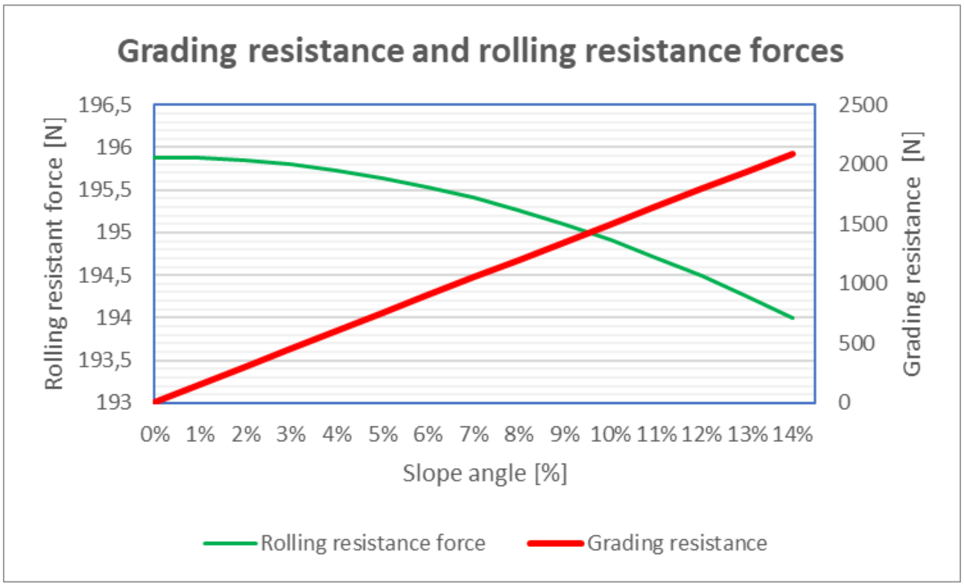

Fig. 2. Dependence of grading resistance and rolling resistance forces on slope

Based on precedent data and resistant forces calculation, to move the vehicle at very low speed on a flat road, the propulsion system must provide a minimum of 60.7 Nm, and on a slope of 14%, a minimum of 707.8 Nm (Fig. 3).

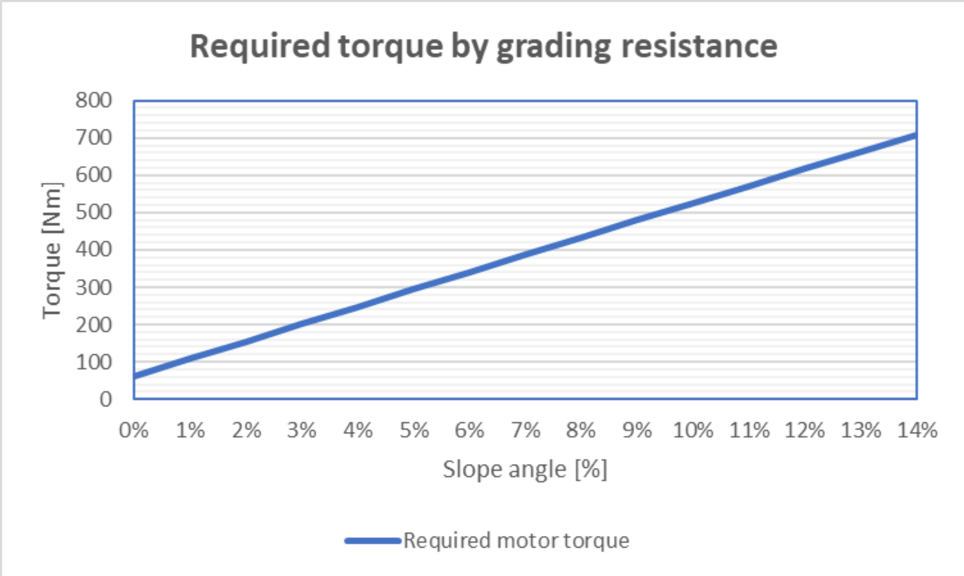

Fig. 3. powertrain torque requirement dependence on slope

On a flat road, an additional force to the rolling resistance is generated by the movement of the vehicle in the air, as a fluid, Increasing the speed, the aerodynamic force increases and the torque request to the propulsion system, as presented in Fig. 4. For 220 km/h, the torque to be covered by the powertrain is 721.7 Nm.

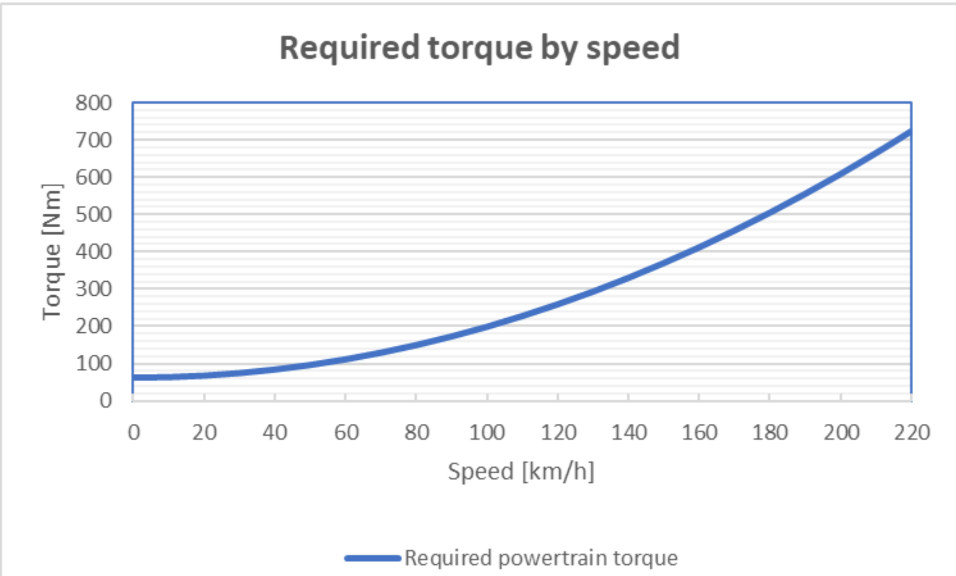

Fig. 4. Powertrain torque requirement dependence on speed

Precedent figures have given first information related to the torque production by the powertrain. Considering the needed mechanical power as the product between the force developed by the powertrain (at the contact between tires and ground) and the vehicle speed, Fig. 5 presents this requirement.

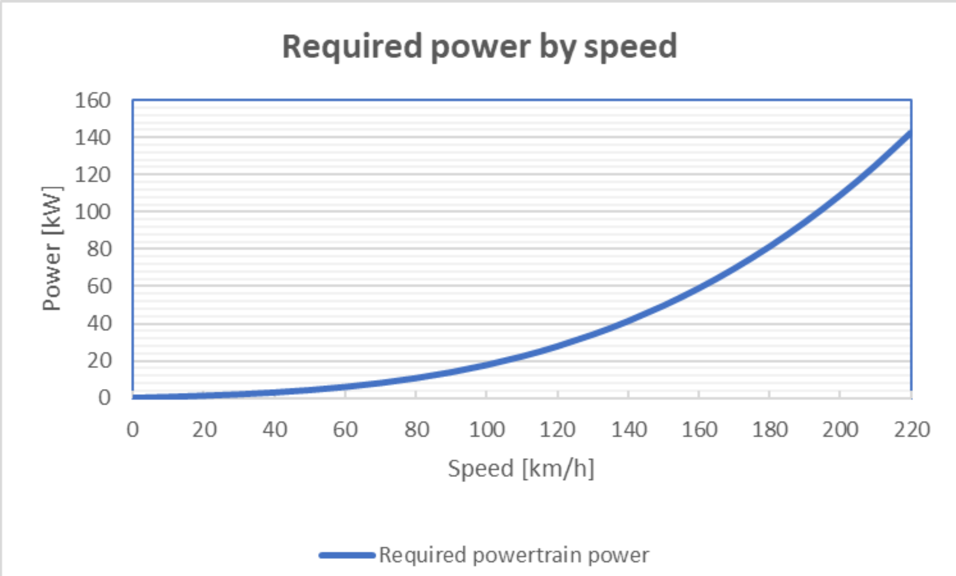

Figure 5. Power requirement dependence on speed

For the in-wheel motors configuration, or transmission ratio between motors shaft and wheels equal to one, the motors of the powertrain must covers the speed area shown in Fig. 6.

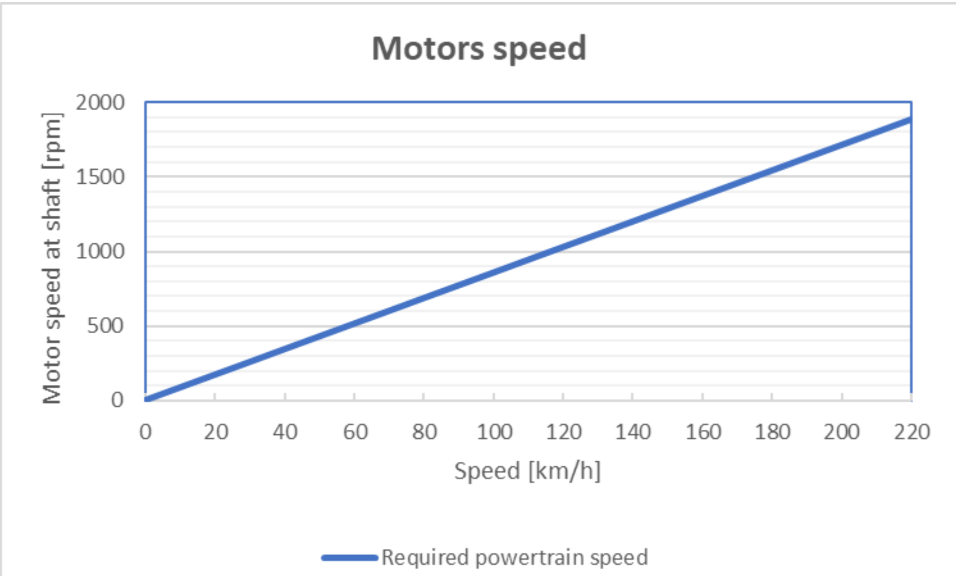

Fig. 6. Speed area of the powertrain motors

3. POWERTRAIN DATA

3.1 Motors data

From the precedent analysis regarding the power and torque requirements, a powertrain providing more than 707. 8 Nm and 34 kW would be able to move the vehicle at maximum 130 km/h on a flat road and climb a slope of maximum 14% at very low speed.

For the investigation, the powertrain with the characteristics in Table 3 and Table 4 is considered.

Table 3. Powertrain data – initial version

Characteristics	Values	Measurement Unit
Nominal power	30	kW
Peak power (20 sec)	40	kW
Nominal torque	740	Nm
Peak torque (20 sec)	1000	Nm

Table 4. Powertrain data – improved version

Characteristics	Values	Measurement Unit
Nominal power	34	kW
Peak power (20 sec)	50	kW
Nominal torque	900	Nm
Peak torque (20 sec)	1400	Nm

3.2 Powertrain integration

For a rear axle integration of the electric powertrain, the schematic representation from Fig. 7 is proposed.

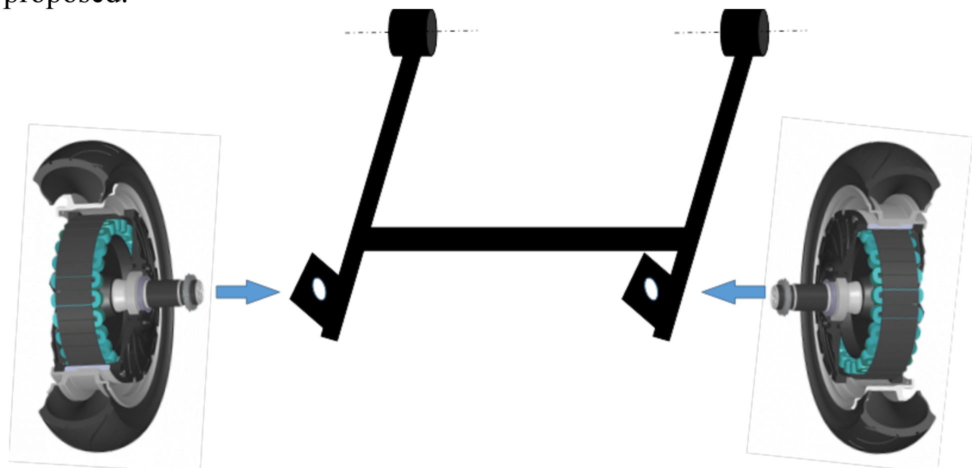

Fig. 7. Rear axle integration of the powertrain

4. RESULTS OF THE INVESTIGATION

For the initial version of the powertrain, Table 3, the vehicle is considered accelerating from zero to the maximum speed at nominal torque of the powertrain. At the vehicle speed of 45.3 km/h the nominal power of the propulsion system is attempted. Starting from this point the acceleration of the vehicle will decrease more rapidly. The dependence between vehicle acceleration and speed is presented in Fig. 8.

From 0 to 100 km/h the vehicle can accelerate during 38 s. The maximum acceleration is 1.43 m/s^2 obtained when starting from 0 km/h.

The maximum speed of the vehicle is 124 km/h. The condition of 130 km/h as maximum vehicle speed is not respected.

In Fig. 9 the same representation as in Fig. 8 is realized with the improved version of the powertrain.

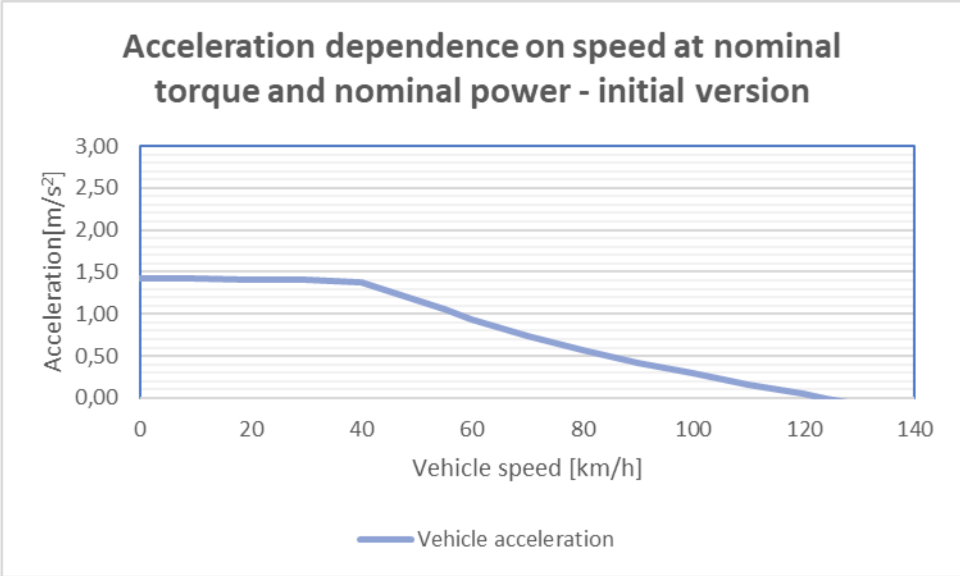

Fig. 8 Vehicle acceleration respecting nominal conditions -initial version of the powertrain.

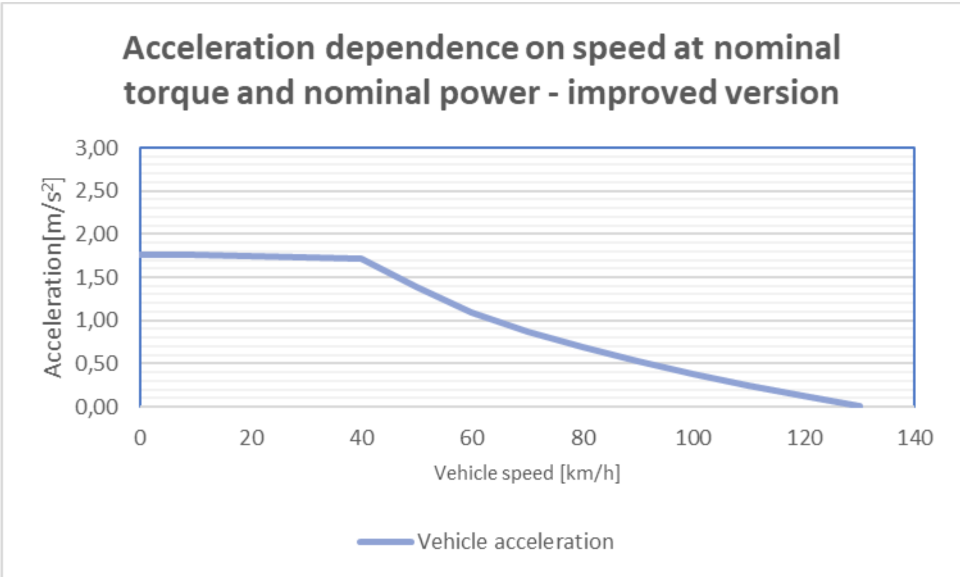

Fig. 9 Vehicle acceleration respecting nominal conditions -improved version of the powertrain.

At the vehicle speed of 42.2 km/h the nominal power of the improved propulsion system is attempted. Starting from this point, the acceleration of the vehicle will decrease more rapidly (Fig. 9). From 0 to 100 km/h the vehicle can accelerate during 30.6 s. The maximum acceleration is 1.76 m/s^2 obtained when starting from 0 km/h. The maximum speed of the vehicle is 130 km/h (maximum speed condition respected).

As the motors of the powertrain accept to exceed the nominal values for a limited period, in Fig. 10 is presented the acceleration dependance on speed, using maximum accepted values.

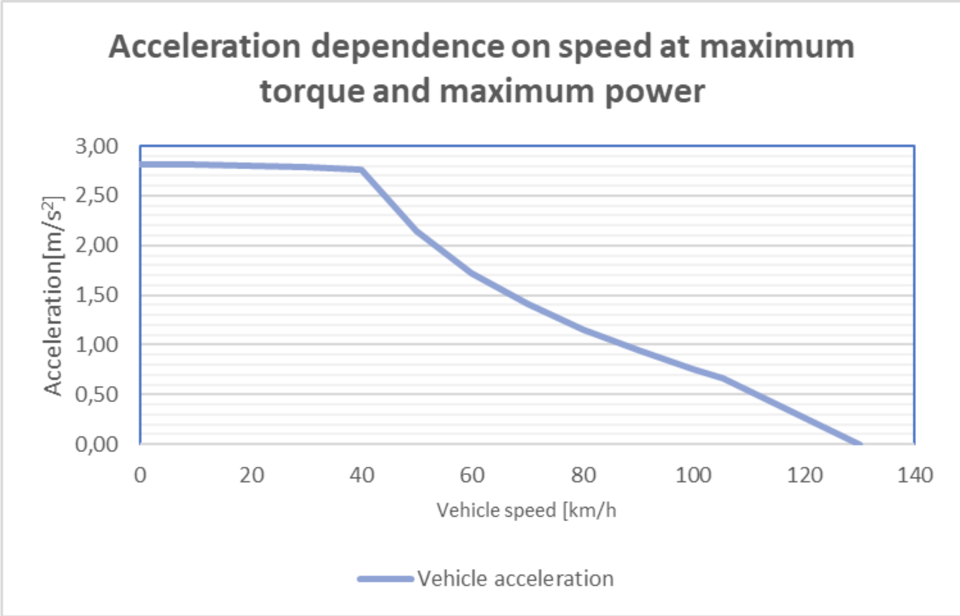

Fig. 10. Vehicle acceleration respecting nominal and maximum values - improved version of the powertrain.

At the vehicle speed of 39.9 km/h the maximum power of the improved propulsion system is attempted. Starting from this point, the acceleration of the vehicle will decrease more rapidly (Fig. 10). From 0 to 100 km/h the vehicle can accelerate during 17.9 s. The maximum acceleration is 2.81 m/s^2 obtained when starting from 0 km/h. At 105.3 km/h the period of 20 s for running at maximum values is attempted, and the powertrain will continue running at nominal ones. The maximum speed of the vehicle is 130 km/h, at nominal values of the powertrain and 150.5 km/h at maximum ones (possibly not more than 20 s).

Also, For the improved version of the powertrain at nominal conditions the maximum speed dependance on slope has been investigated. The same for the required torque at maximum speed. The results are shown in Fig. 11 and Fig. 12.

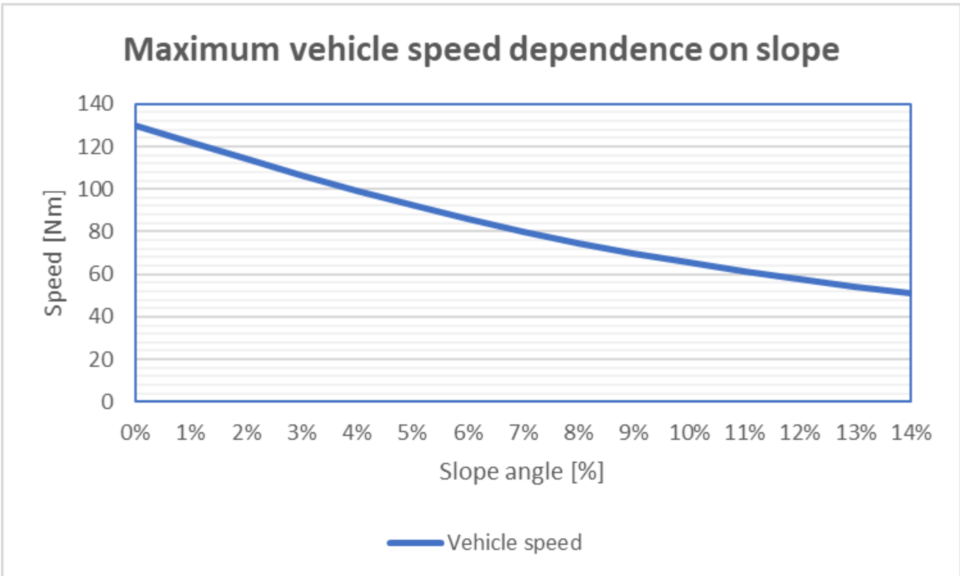

Fig. 11. Maximum vehicle speed at nominal conditions using the improved powertrain.

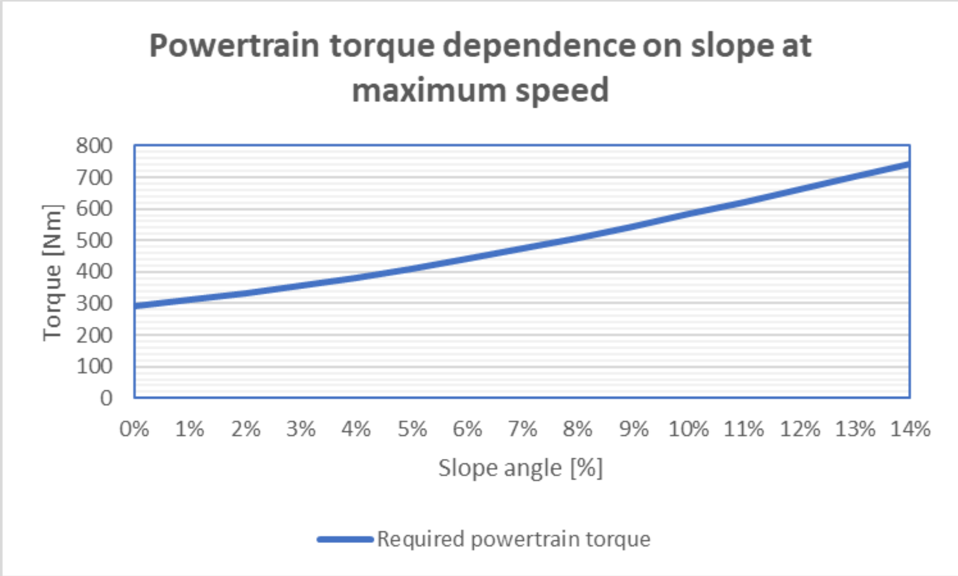

Fig. 12. Powertrain torque at maximum vehicle speed for different accepted slopes

4. CONCLUSION

A classic vehicle has been investigated from perspective of an electric powertrain integration. In-wheel solutions have been proposed for the rear axle of the vehicle.

First, from vehicle data a general request for the powertrain has been determined. Two powertrain versions have been investigated. The improved version has been kept for deeper analysis using the motors of the powertrain at maximum accepted values.

For a peek power of 50 kW and a peak torque of 1400 Nm, the vehicle performances are improved offering a maximum acceleration of 2.81 m/s2, a maximum speed of 150.5 km/h, and an acceleration from 0 to 100 km/h in 17.9 s. The maximum speed in nominal conditions for the powertrain is 130 km/h.

CONFIRMATION

The paper was presented at the Symposium on Electric Machines SME'23, the XIX edition.

REFERENCES

1. Junshu Han, Zhenhai Gao, Shulin Tan and Xiangdong Cui, "An approach of modeling on dynamic performance evaluation for offroad vehicle," *2010 8th World Congress on Intelligent Control and Automation*, pp. 5592-5597, Jinan, 2010.
2. A. Fotouhi, D. J. Auger, K. Propp and S. Longo, "Simulation for prediction of vehicle efficiency, performance, range and lifetime: a review of current techniques and their applicability to current and future testing standards," *5th IET Hybrid and Electric Vehicles Conference (HEVC 2014)*, pp. 1-8, London, UK, 2014.
3. L. Popescu, "Electromobility topics entering a new decade", in *Electrical Machines, Materials and Drives Present and Trends*, **17**, *1, pp. 131-140,* 2021:
4. F. Bao, B. Huang, X. Zou and C. Lai, "Analysis and Matching of Electric Vehicle Dynamic Performance Based on CRUISE," *2020 IEEE 18th International Conference on Industrial Informatics (INDIN)*, pp. 129-133, Warwick, United Kingdom, 2020.
5. L. Popescu, L. Dumitran and A. Stanescu, "Multi-motor solutions for electric vehicles," *2021 International Conference on Applied and Theoretical Electricity (ICATE)*, pp. 1-6, 2021.
6. J. G. Yadav, Y. K. Yadav and N. Kumar, "Motor Power Calculation for Power-Train of Electric Vehicles and Estimation of its Performance Parameters Using MATLAB/Simulink," *2021 IEEE 2nd International Conference on Electrical Power and Energy Systems (ICEPES)*, pp. 1-6, Bhopal, India, 2021.
7. C.L. Popescu, L.M. Dumitran, A. Stănescu " Simulation of Multi-Motor Propulsion System for Energy Efficiency in Electric Vehicles" in *Annals of the University of Craiova, Electrical Engineering series,* **45**, *1*, ; pp 75-82, 2022.
8. N. Sharma, B. Jiang, A. Rodionov, Y. Liu, "A Mechanical-Hardware-in-the-Loop Test Bench for Verification of Multi-Motor Drivetrain Systems," in *IEEE Transactions on Transportation Electrification*, 2022.

9. L. Popescu, L. Melcescu, L. Dumitran, A. Crăciunescu and A. Stanescu, "Control analysis of a bi-motor electric traction system for energy and performance optimization", *International Scientific Conference on Communications, Information, Electronic and Energy Systems (CIEES)*, 2021.
10. W. Hao, D. You, W. Guangjie, Y. Cheng and J. Hong, "Energy-efficient control of dual-motor electric vehicles considering slope information," *2021 China Automation Congress (CAC)*, pp. 7838-7843, Beijing, China, 2021.
11. L. Popescu, L. Melcescu, O. Craiu, A. Craciunescu and V. Bostan, "Phase Advance and Dwell Control Applied to a PM BLDC Motor for Increasing the Maximum Speed of an Electric Vehicle," *2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, pp. 850-855, 2022.
12. L. Popescu, L. Melcescu and O. Craiu, "Energy Efficiency Improvement for an Electric Vehicle PM BLDC Propulsion System Using Phase Advance and Dwell Control," *2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*, pp. 1-6, 2022.
13. J. D. Valladolid, D. Patino, G. Gruosso and F. Espinoza, "Study on the Torque-Speed Allocation on PMSM to Improve Energy Efficiency in Electric Vehicles Using Metaheuristic Optimization," *2021 IEEE Vehicle Power and Propulsion Conference (VPPC)*, pp. 1-5, Gijon, Spain, 2021.
14. L. Popescu, A. Stănescu, "Efficiency maps for an EV BLDC motor using analytic calculation and simulation", *in Electric machines, materials and drives present and trends* (SME 2022), **18**, *1*, pp. 89-99, March. 2023.
15. L. Popescu, O. Craiu, "Energy Consumption Analysis for an EV Powertrain using Three BLDC Identical Motors", Rev. Roum. Sci. Techn. – Électrotechn. et Énerg. **68**, *2*, pp. 152–157, Bucarest, 2023,
16. H. Nagar *et al*., "Powertrain Sizing and Performance Evaluation for Battery Electric Vehicle Using Model Based Design," *2021 Innovations in Power and Advanced Computing Technologies (i-PACT)*, Kuala Lumpur, Malaysia, pp. 1-6, 2021.
17. L. Popescu, A. Stănescu, Șt. Vasiliu, "Didactical platform for multi-motor solutions," in *Electrical Machines, Materials and Drives Present and Trends*, *17*(1), 172–180, **17**, *1*,2022.
18. L. Popescu, O. Craiu and L. Melcescu, "Analyzing the Torque Transfer between Two In-Wheel Motors of an Electric Vehicle," *2023 13th International Symposium on Advanced Topics in Electrical Engineering (ATEE)*, pp. 1-6, Bucharest, Romania, 2023.
19. L. Popescu, A. Crăciunescu, O. Craiu, " Analysis of the Wheel Steering Influence on Energy Consumption of an EV PMSM In-wheel Propulsion System", in *Interdisciplinarity in Engineering (INTER-ENG 2023, the 16th edition)*, Tg. Mureş, 5-6 October 2023.