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ANALYSIS OF THE DRIVE OF ELECTRIC VEHICLES WITH ITS DIFFERENT CONFIGURATIONS

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Abstract. In the process of car development, its drive is continuously improved. The properties of different types of driving with an internal combustion engine (ICE) are well-studied [1].

ICE's bleak future has forced major automotive manufacturers to turn to electric mobility. The motor, integrated with final drive and differential, is compact and takes up little axle space, making it easier to assemble the drive into one axle or all-wheel drive. Electric vehicles have many advantages over vehicles with ICE: no emissions, high efficiency, quiet and smooth operation, braking energy recovery, simplified maintenance, etc. The functional and fundamental principles of electric vehicles and vehicles with ICE are similar, but there are some features. The characteristic of the electric motor (hereinafter referred to as the motor) is ideal for the drive – it has a large zone of constant maximum power, and the maximum torque appears immediately during starting. The motor, integrated with final drive and differential, is compact and takes up little axle space, making it easier to assemble the drive into one axle or all-wheel drive. Possible drive designs without a differential with two motors and two final drives on the axle, or with low-speed motors without final drives. The heavy battery is placed in the floor, so the stability of the electric car is high.

The maximum possible recovery of braking energy is added to all the positive properties of all-wheel drive in the case of an electric car. To reduce the power consumption in the drive, two motors provide a drive mode with only one motor.

Among electric vehicles with one-axle drive, front-wheel drive prevails due to using multi-energetic front-wheel drive platforms, stable stability and handling performance and good traction properties in winter conditions.

The advantage of rear-wheel drive is the ability to realize greater traction forces during acceleration or movement on the rise due to the dynamic redistribution of the load on the rear axle. However, during braking, due to the dynamic redistribution of the load on the front axle, the possibility of recuperation of braking energy decreases.

For a more detailed analysis of the drive, typical electric vehicles are selected, the characteristics of their drive motors are given, traction characteristics are calculated and constructed in the traction force coordinates – speed of movement, the realized adhesion coefficients are determined, and appropriate conclusions have been drawn.

Keywords: electric vehicle configurations, electric motor characteristics, traction characteristics.

Introduction

All-wheel drive of cars exceeds the drive by one axle in terms of traction properties in any road condition. The torque distribution is ideal if the realized adhesion coefficients on the front and rear axle wheels are the same [2]. To do this, the distribution of torque must change with the change in acceleration or slope of the rise. This is easier to achieve in electric vehicles, where the wheels of the front and rear axles are driven by separate motors. In addition, the all-wheel drive provides the most possible recovery of braking energy.

A relatively small electric car engine does not take up much space and is easy to install at the front or rear, or both motors for all-wheel drive.

For an electric car, there is no good reason to put the engine in front and bring the front wheels, and thanks to rear-wheel drive, you can have better acceleration dynamics. With the same efficiency and costs in both cases of the drive, the dynamics of acceleration will prevail [3]. On the other hand, the battery is the most expensive component, not the motor. The addition of a second engine at the front will make all-wheel drive electric vehicles more affordable than all-wheel drive cars with ICE.

Problem Statement

In drive configurations per axle of modern electric vehicles, at least one axle motor is used, integrated with single-speed final drive and differential. In all-wheel drive electric vehicles, the same drive is used on two axles, or in the rear axle drive, instead of a single-speed one, there is an automatic two-speed transmission.

For comparative analysis, in addition to traction characteristics, it is important to determine the realized adhesion coefficients in different drive configurations.

Review of Modern Information Sources on the Subject of the Paper

Analysis of the drive of electric vehicles is to determine its traction-speed properties: speeds, accelerations, and road boundary conditions in which it is possible to move it with specified design parameters. Indicators of traction and speed properties (maximum speed on a horizontal road, acceleration time to a certain speed, acceleration during acceleration, realized adhesion coefficients, etc.) are determined experimentally and by calculation and analytical means. Methods for assessing the traction and speed properties of electric vehicles are described in [4].

Objectives and Problems of Research

The aim of the work is to analyze the drivers of electric vehicles with their different configurations and evaluate their effectiveness through traction characteristics and the realized adhesion coefficients.

Main Material Presentation

Electric vehicles were selected for analyzing various drive configurations: Opel Mokka-e (2021) with front-wheel drive, Honda e (2023) with rear-wheel drive and all-wheel drive – Hyundai Ionic 5 225 kW AWD (2022), Audi e-tron GT Quattro (2023).

According to technical data [5–9] selected electric vehicles on Figs. 1–4, the characteristics of their traction motors are built.

Motor characteristics (Figs. 1–4) – the dependence of the maximum possible torque $T_{m\,i}$, N·m and power $N_{m\,i}$, W on the angular velocity ω_m – are expressed as:

– in the low-velocity zone (0; ω_{basa}):

$$T_{m\,i}=T_{m\,i\,\max};\ i=\overline{1;2}, \tag{1}$$

$$N_{m\,i}=T_{m\,i\,max}\cdot\omega_m;\ i=\overline{1;2}; \tag{2}$$

– in the high-velocity zone (ω_{basa}; ω_{max}):

$$T_{m\,i}=N_{m\,i\,\max}/\omega_m\,;\ i=\overline{1;2}, \tag{3}$$

$$N_{m\,i}=N_{m\,i\,max};\ i=\overline{1;2}, \tag{4}$$

where ω_{basa} – basa angular velocity ($\omega_{\text{basa}}=N_{m\,\max}/T_{m\,max}$); i – the index of the axle (1 – front axle; 2 – rear axle).

The tractive effort $F_{w\,i}$, N on driven wheels and the vehicle speed v_i, km/h are expressed as:

$$F_{w\,i}=\eta_t\cdot T_{m\,i}\cdot u_0/R\,;\ i=\overline{1;2}, \tag{5}$$

$$v_i=3{,}6\cdot\omega_i\cdot R/u_0;\ i=\overline{1;2}, \tag{6}$$

where η_t – the efficiency of the whole driveline from the motor to the driven wheels; u_0 – the gear ratio of final drive; R – the radius of the drive wheels.

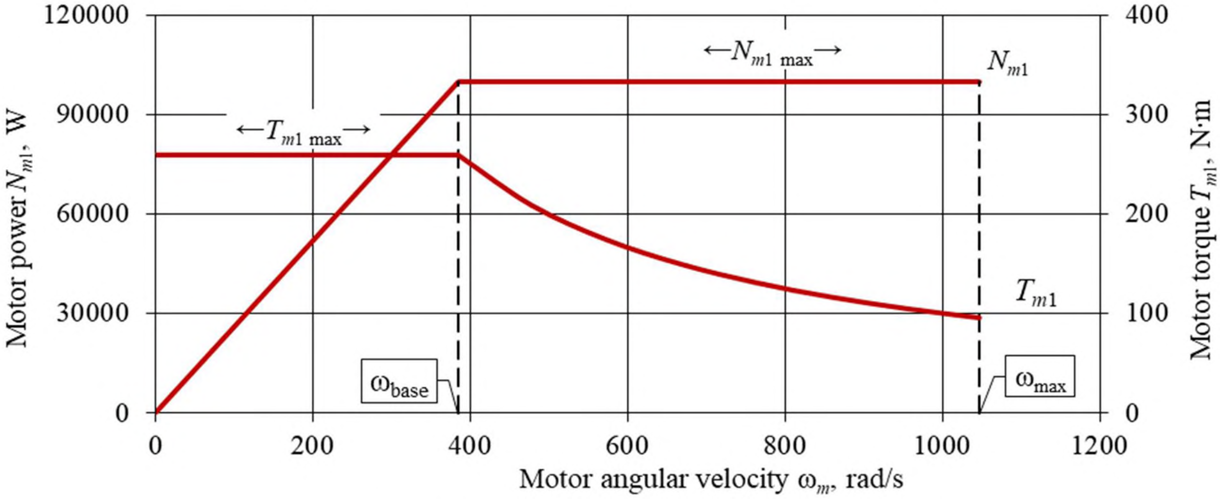

Fig. 1. Characteristics of the traction motor Opel Mokka-e (2021)

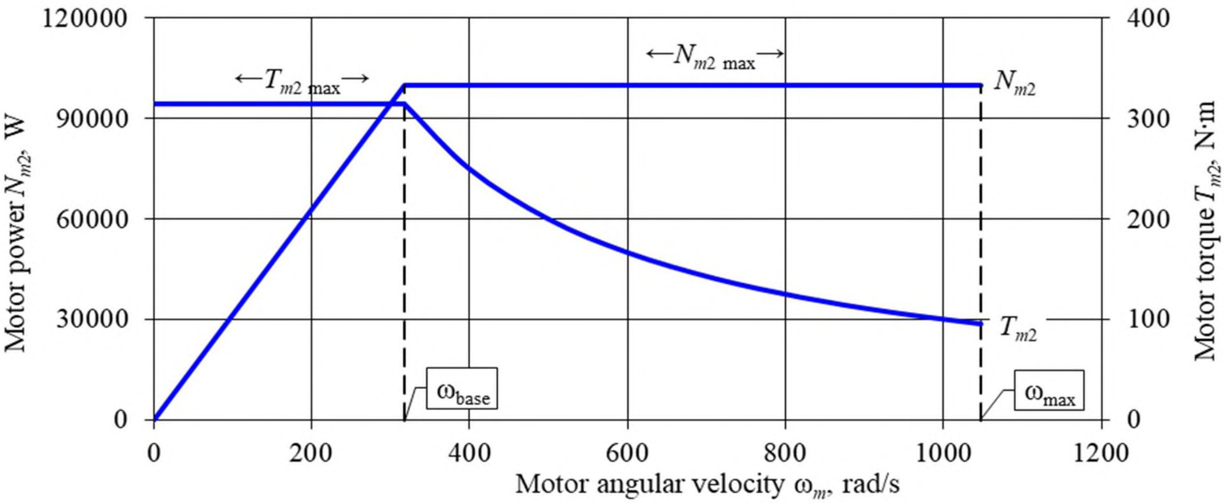

Fig. 2. Characteristics of the traction motor Honda e (2023)

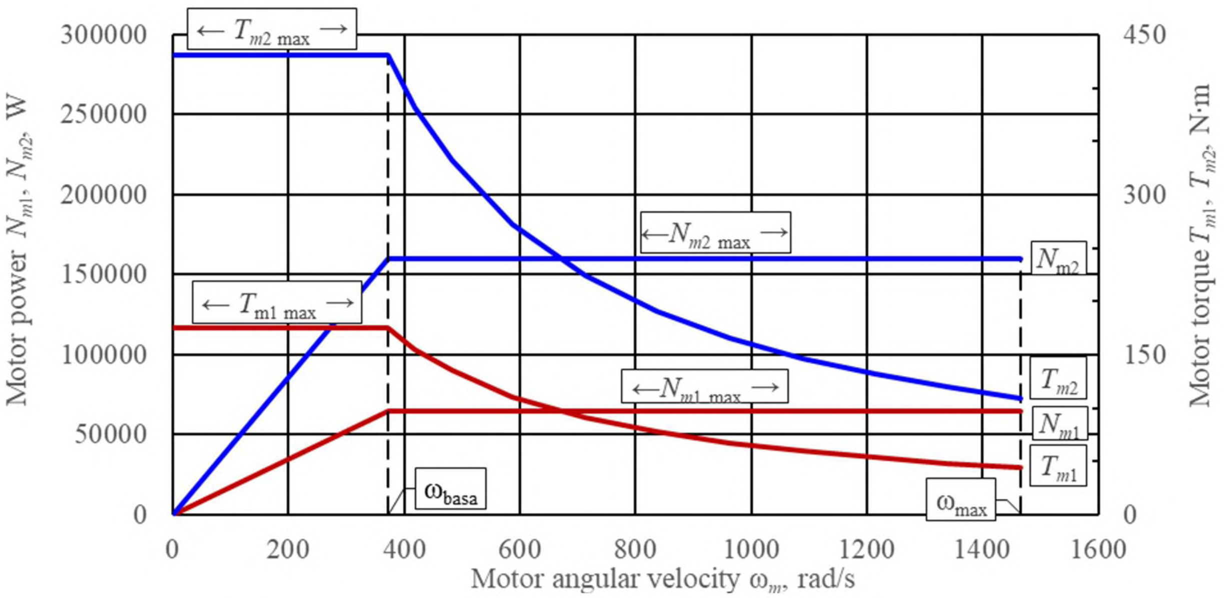

Fig. 3. Characteristics of the Hyundai Ionic 5 225 kW AWD (2022) traction motors

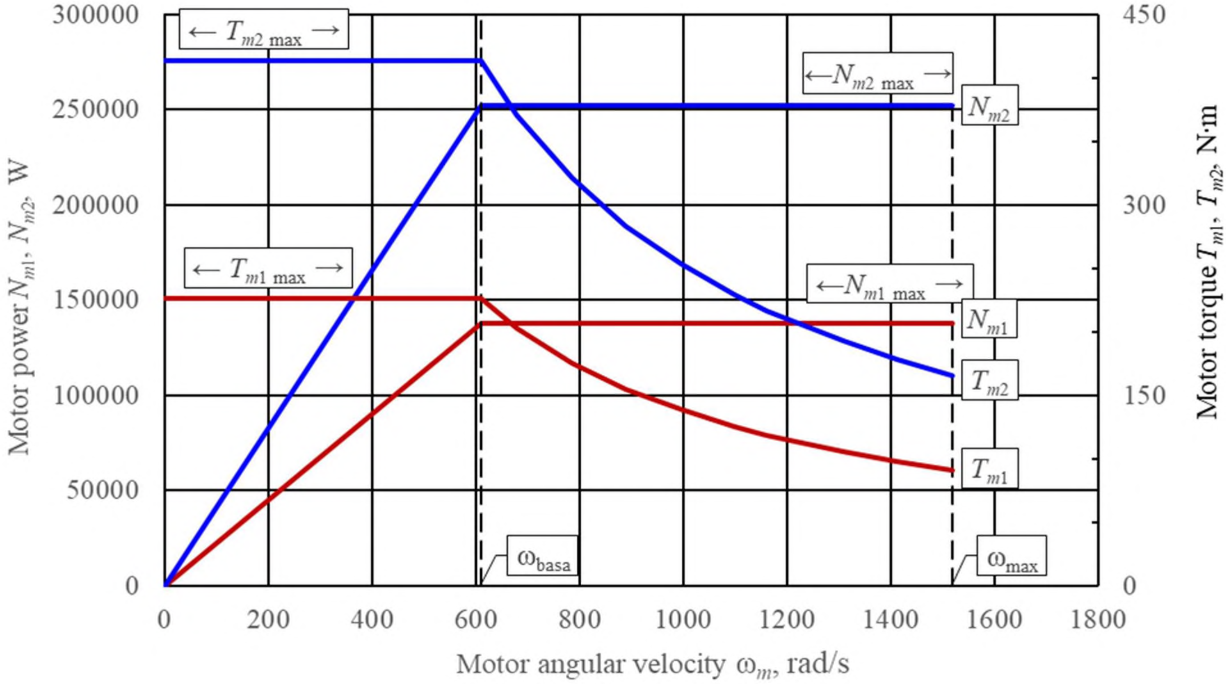

Fig. 4. Characteristics of Audi e-tron GT Quattro (2023) traction motors

The Audi e-tron GT Quattro (2023) rear axle wheel drive has a two-speed gear with gear ratios $u_{2.1}$, $u_{2.2}$. In this case, the tractive effort $F_{w\,2.1}$, $F_{w\,2.2}$, N on driven wheels and the vehicle speed $v_{2.1}$, $v_{2.2}$, km/h are determined as:

$$F_{w\,2.1} = \eta_t \cdot T_{m\,2} \cdot u_{2.1}/R, \tag{7}$$

$$F_{w\,2.2} = \eta_t \cdot T_{m\,2} \cdot u_{2.2}/R, \tag{8}$$

$$v_{2.1} = 3{,}6 \cdot \omega_2 \cdot R/u_{2.1}, \tag{9}$$

$$v_{2.2} = 3{,}6 \cdot \omega_2 \cdot R/u_{2.2}. \tag{10}$$

Rear axle wheel drive of the Porsche Taykan Turbo S (2023) is the same [10].

Based on (1)–(10), traction characteristics are calculated and constructed in the coordinates tractive effort on wheels – vehicle speed for selected vehicles (Figs. 5–8).

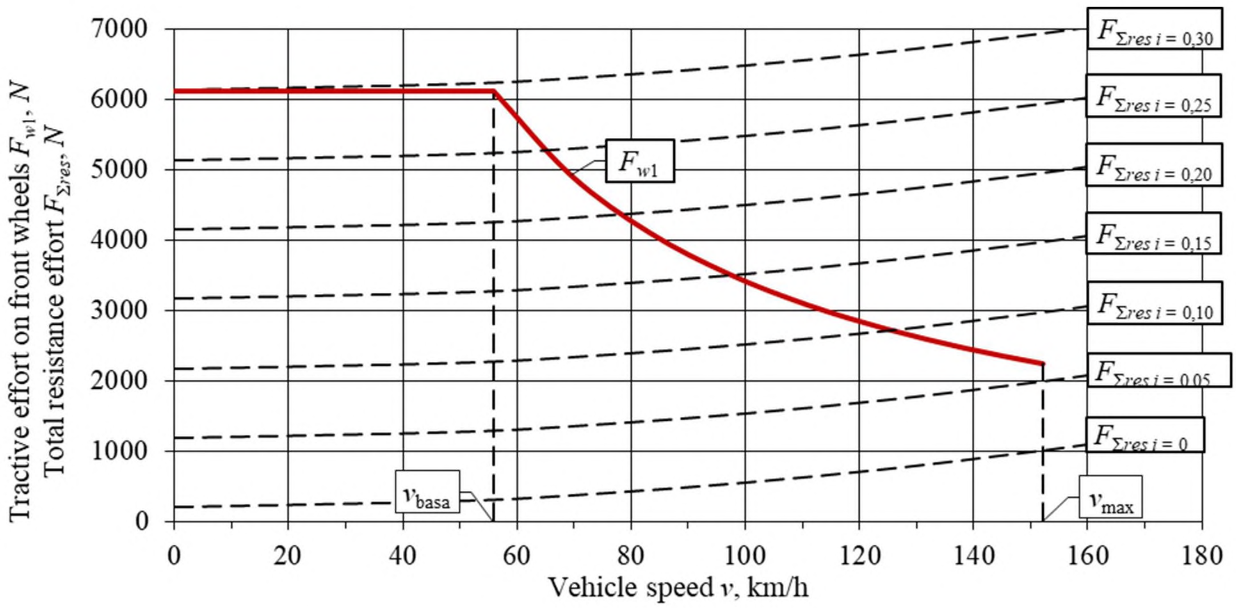

Fig. 5. Traction characteristic of the Opel Mokka-e (2021) in coordinates tractive effort on wheels – vehicle speed

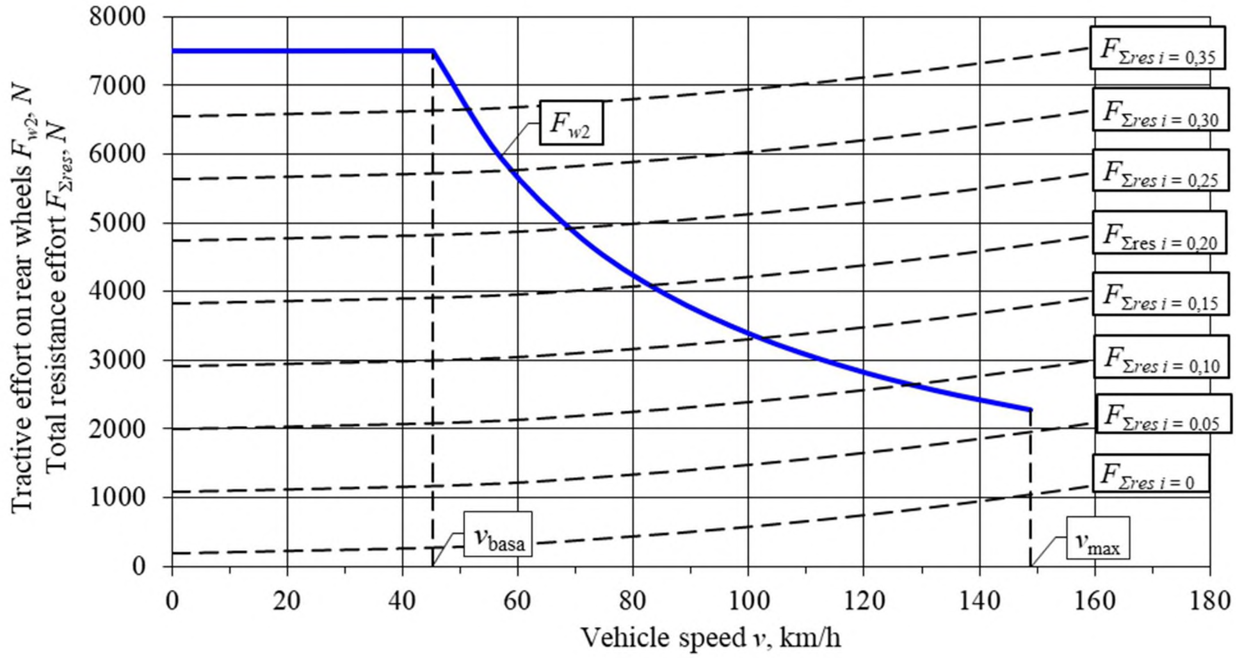

Fig. 6. Traction characteristic of the Honda e (2023) in coordinates tractive effort on wheels – vehicle speed

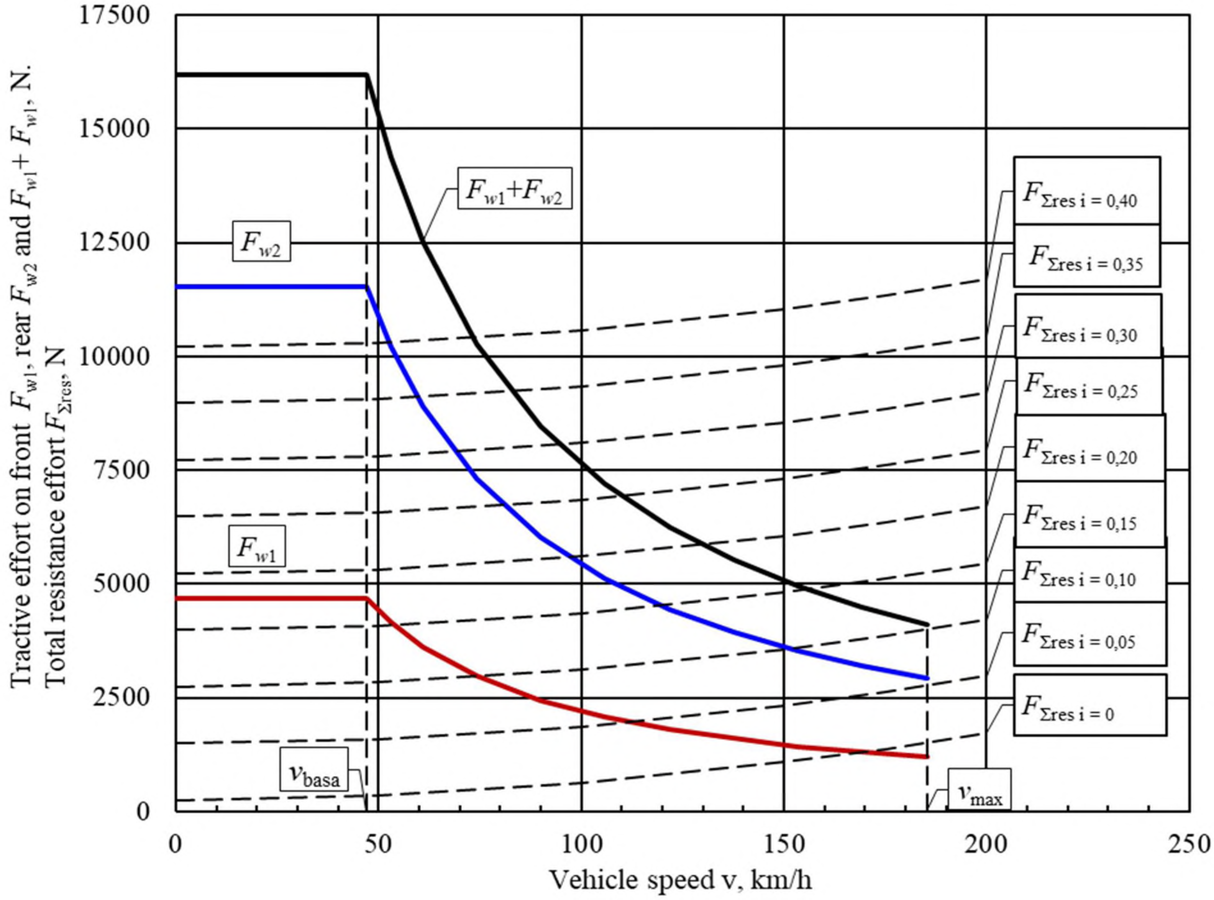

Fig. 7. Traction characteristic of the Hyundai Ionic 5 225 kW AWD (2022)
in coordinates tractive effort on wheels – vehicle speed

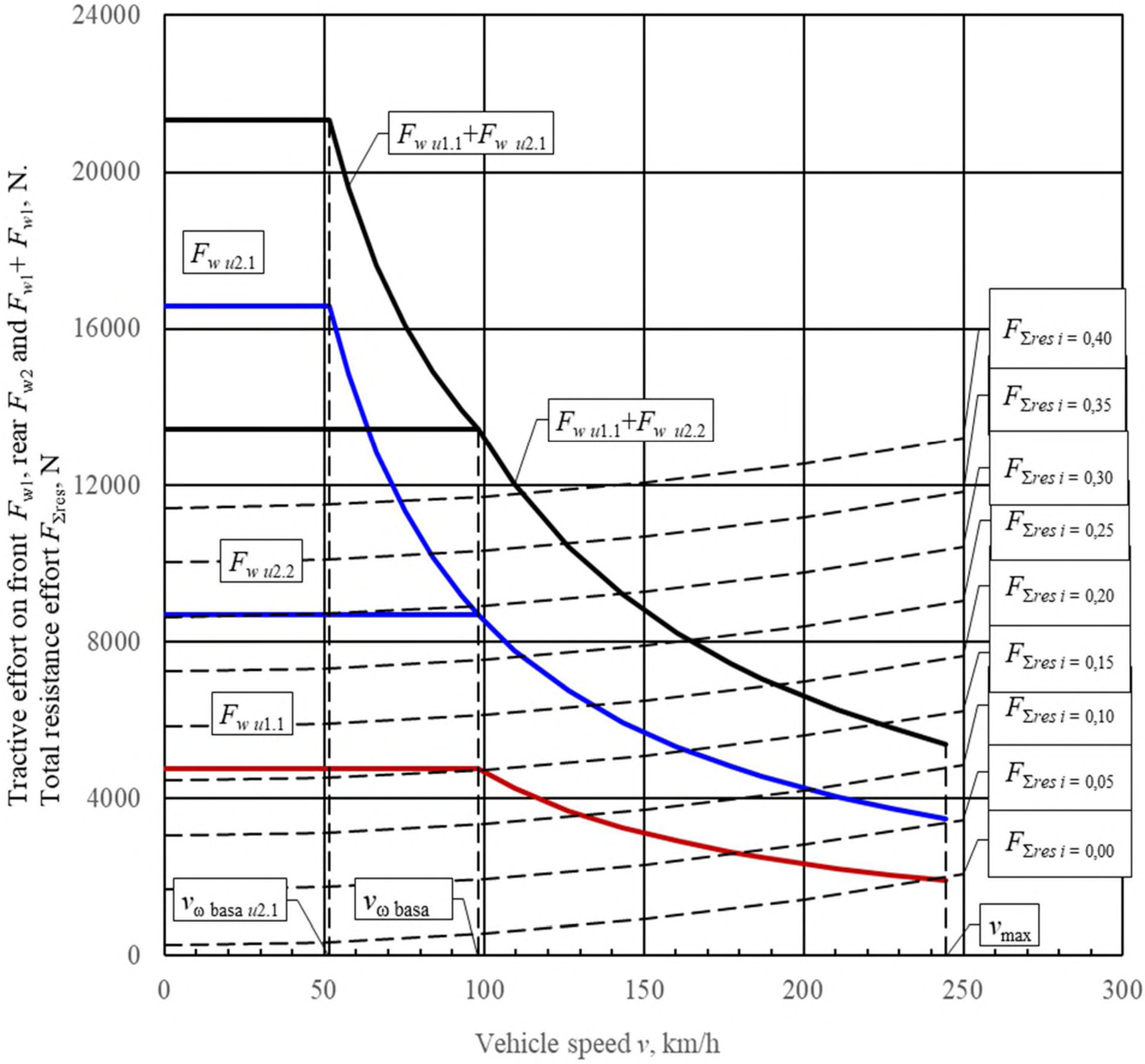

Fig. 8. Traction characteristic of the Audi e-tron GT Quattro (2023) in coordinates tractive effort on wheels – vehicle speed

Vehicle resistance opposing its movement includes: rolling resistance of the tires, aerodynamic drag and grading resistance. The total resistance force $F_{\Sigma res}$, N can be expressed as:

$$F_{\Sigma res} = m_v \cdot g \cdot (f_r \cdot \cos\alpha + \sin\alpha) + C_D \cdot A \cdot \frac{\rho}{2} \cdot (v/3{,}6)^2, \quad (11)$$

where m_v – total mass of the vehicle; g – gravitational acceleration; f_r – rolling resistance coefficient; α – road angle; C_D – aerodynamic drag coefficient; A – vehicle frontal area; ρ – air density; v – vehicle speed.

Then the road angle is small, cosα ≈ 0, sinα ≈ tanα = i and equation (11) can be simplified as:

$$F_{\Sigma res} = m_v \cdot g \cdot (f_r + i) + C_D \cdot A \cdot \frac{\rho}{2} \cdot (v/3{,}6)^2, \quad (12)$$

where i – grade.

The total resistance forces FΣres, N depending on speed and grade, are applied on the traction characteristics. They are calculated by the formula (12).

The maximum speed of a vehicle can be easily found by the intersection point of the tractive effort curve F_{w1} (see Fig. 5), F_{w2} (see Fig. 6), $F_{w1} + F_{w2}$ (see Fig. 7) or $F_{wu1.1} + F_{wu2.2}$ (see Fig. 8) with the resistance curve $F_{\Sigma res\, i=0}$.

It should be noted that such an intersection point does not exist in those designs, which usually use a larger traction motor or a large gear ratio. In this case, the maximum vehicle speed is determined by the maximum angular velocity of the traction motor.

In electric vehicle operation, the maximum tractive effort $F_{w\,i\,\max}$ on the drive wheels (see Figs. 5–8), transferred from the motor through transmission, are in the low-speed zone. They should not exceed the maximum values $F_{\mu\,i\,\max}$ that are limited by the tire-surface of the road adhesion. Otherwise, the drive wheels will spin on the ground, leading to vehicle instability.

The maximum tractive effort $F_{\mu\,i\,\max}$ that the tire–ground contact can support is usually described by the product of the normal load and coefficient of road adhesion μ or referred to as frictional coefficient in some literatures. To determine $F_{\mu\,i\,\max}$, the formulas [4] are used:

for a front wheel drive (FWD):

$$F_{\mu 1\,max}^{FWD} = \frac{\mu_p \cdot m_v \cdot g \cdot \cos\alpha \cdot [l_2 + f_r \cdot (h - r)]/l}{1 + \mu_p \cdot h/l}, \tag{12}$$

for a rear wheel drive (RWD):

$$F_{\mu 2\,max}^{RWD} = \frac{\mu_p \cdot m_v \cdot g \cdot \cos\alpha \cdot [l_1 - f_r \cdot (h - r)]/l}{1 - \mu_p \cdot h/l}, \tag{13}$$

for an all wheel drive (AWD) front wheels:

$$F_{\mu 1\,max}^{AWD} = \mu_p \cdot m_v \cdot g \cdot \cos\alpha \cdot \left[l_2 + f_r \cdot (h - r) - \mu_p \cdot h\right]/l, \tag{14}$$

for an all wheel drive (AWD) rear wheels:

$$F_{\mu 2\,max}^{AWD} = \mu_p \cdot m_v \cdot g \cdot \cos\alpha \cdot \left[l_1 - f_r \cdot (h - r) + \mu_p \cdot h\right]/l, \tag{15}$$

where μ_p – peak value of the coefficient of road adhesion (for dry asphalt and concrete $\mu_p = 0{,}9$); m_v – total mass of the vehicle; g – gravitational acceleration; α – road angle; l_1, l_2 – distance of front and rear axles; f_r – rolling resistance coefficient ($f_r = 0{,}01$); h – height mass center; r – height wheel center; l – wheel base.

The maximum tractive effort $F_{\mu 1\,\max}$, $F_{\mu 2\,\max}$ on the drive wheels of the front and rear axles depends on the longitudinal force that the adhesive capability between the tire and ground can supply, rather than the maximum torque that the motor can supply. When the tractive effort $F_{w\,i}$ of a vehicle exceeds the limitation of the maximum tractive effort $F_{\mu\,i\,\max}$ due to the adhesive capability between the tire and the ground, the drive wheels will spin on the ground. Actually, the adhesive capability between the tire and the ground is sometimes the main limitation of vehicle performance.

The degree of use of adhesion capabilities is characterized by realized adhesion coefficients μ_1, μ_2 on the drive wheels of the front and rear axles expressed as

$$\mu_1 = F_{w1\,\max}/Z_1;\ \mu_2 = F_{w2\,\max}/Z_2, \tag{16}$$

where Z_1, Z_2 – normal load on the drive wheels of the front and rear axles can be expressed as

$$Z_1 = m_v \cdot g \cdot [l_2 - h \cdot (F_{w1\,\max} + F_{w2\,\max})/m_v/g]/l, \tag{17}$$

$$Z_2 = m_v \cdot g \cdot [l_1 + h \cdot (F_{w1\,\max} + F_{w2\,\max})/m_v/g]/l. \tag{18}$$

Table 1 contains some technical data of electric vehicles selected for analyzing.

Table 2 shows values the maximum tractive efforts $F_{w1\,\max}$, $F_{w1\,\max}$ on the drive wheels of the front and rear axles (see Figs. 5–8), the maximum tractive effort $F_{\mu\,i\,\max}$ by (12)–(15) that the tire–ground contact can support and realized adhesion coefficient μ_i by (16).

Table 1

Some technical data of electric vehicles

No.	Electric vehicle models	m_v, kg	l, m	l_1, m	l_2, m	h, m	r, m	$N_{m1\ max}$, W	$T_{m1\ max}$, N·m	$N_{m2\ max}$, W	$T_{m2\ max}$, N·m
1	Opel Mokka-e (2021)	2015	2,561	1,26	1,301	0,511	0,315	100000	260	–	–
2	Honda e (2023)	1855	2,538	1,319	1,219	0,504	0,291	–	–	100000	315
3	Hyundai Ionic 5 225 kW AWD (2022)	2540	3,00	1,55	1,45	0,535	0,344	65000	175	160000	430
4	Audi e-tron GT Quattro (2023)	2840	2,90	1,45	1,45	0,491	0,336	138000	226	252000	414

Table 2

Determination of the realized adhesion coefficient μ_i (α = 0)

No.	Electric vehicle models	Traction	$F_{w1\ max}$, N	$F_{w2\ max}$, N	$F_{\mu1\ max}$, N	$F_{\mu2\ max}$, N	μ_1	μ_2
1	Opel Mokka-e (2021), u_0 = 8,5	FWD	6122	–	7673	–	0.82	0
2	Honda e (2023), u_0 = 8,0	RWD	–	7497	–	10347	0	0.68
3	Hyundai Ionic 5 225 kW AWD (2022), u_0 = 10,65	AWD	4681	11522	7254	15172	0.51	0.73
4	Audi e-tron GT Quattro (2023), $u_{1.1}$ = 8,16; $u_{2.1}$ = 15,56	AWD	4756	16574	8730	16345	0.46	0.94
	Audi e-tron GT Quattro (2023), $u_{1.1}$ = 8,16; $u_{2.2}$ = 8,16	AWD	4756	8692	8730	16345	0.41	0.54

Table 2 shows that the rear-wheel drive Honda e (202 3) (F w2 max = 7497 N, μ_2 = 0.68) is better than the front-wheel drive Opel Mokka-e (2023) ($F_{w1\ max}$ = 6122 N; μ_1 = 0.82), because even with a higher maximum traction force, the realized adhesion coefficient is smaller.

Electric vehicles with all-wheel drive Hyundai Ionic 5 225 kW AWD (2022), Audi e-tron GT Quattro (2023) and larger maximum traction forces have smaller adhesion coefficients realized.

The use of a two-speed transmission in the drive of the wheels of the rear axle Audi e-tron GT Quattro (2023) allows you to have in first gear F w 2 max = 16574 N; μ 2 = 0.94, and in second gear $F_{w2\ max}$ = 8692 N; μ_2 = 0,54. This allows the rear moose wheel drive to use a lower-power motor.

Conclusions

The drive of all wheels of electric vehicles, like ordinary cars with ICE, surpasses the wheel drive by one axle.

Only in electric vehicles with the drive of all wheels from two motors is the instant ideal distribution of torque between the drive wheels of the front and rear axles ensured, when the adhesion coefficients of all wheels are the same as those realized.

The use of automatic two-speed transmission in the rear axle wheel drive allows you to increase the traction forces of the rear wheels in the initial acceleration phase and have a lower-power rear motor.

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