TRANSPORT PROBLEMS 2025 Volume 20 Issue 3
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2025.20.3.17

Keywords: electromechanical transmission; power consumption; heavy tracked military vehicles

Arkadiusz MĘŻYK[1]*, Stanisław WAWAK[2], Sławomir KCIUK[3]

ANALYSIS OF POWER DEMAND IN A HYBRID DRIVE SYSTEM OF A HEAVY TRACKED VEHICLE

Summary. This article reviews selected current solutions and analyzes the possibilities of using a hybrid, diesel-electric drive system in heavy military vehicles. The criterion adopted was the effective use of the power of the drive engine, and the power demand of individual subsystems of the power transmission system was estimated. The present research aims to determine the possibilities of reducing the unit fuel consumption while increasing the tactical mobility of the vehicle.

1. INTRODUCTION

The concept of using diesel-electric drives to propel heavy vehicles has a long history, with many successful civilian applications such as diesel locomotives, the largest dump trucks used in open-pit mines, and even the propulsion systems of modern ocean-going cruise ships. Internal combustion engine (ICE)-electric drives have been used for many years in conventional submarines. In all these cases, the system used is an ICE with an electric generator that powers the electric motors or charges the battery banks. Similar propulsion systems have been tested and implemented for tank propulsion since their introduction on the fronts of World War I. Despite the clear advantages of such a propulsion system, except for the French St. Chamond tank of World War I or the German Ferdinand/Elefant self-propelled gun of World War II, vehicles with ICE-electric systems were not produced in larger series, and combat experience with them showed that the technology was not yet adequate [1]. The development of hybrid drive technology in passenger cars and the emergence of permanent magnet (PM) electric motors led to renewed interest in hybrid drives for heavy military vehicles in the early 1990s [6].

In tracked vehicles, the drivetrain is integrated with the steering mechanisms, which creates additional requirements, especially if the vehicle's center of mass during turning is to move at the corner entry speed. The turn is implemented by varying the speed of the tracks, so the outer track must move at a higher speed than the vehicle's center of mass, and the inner track at a proportionally lower speed [1, 2]. The power transmission mechanism must therefore allow the power flux to each track to vary, preferably in a stepless manner. Such possibilities are provided by, for example, dual power-feed drive systems and electric or electromechanical drives (Fig. 1).

A crucial aspect of utilizing diesel-electric hybrid propulsion systems in heavy military vehicles is the reduction of CO_2 emissions and fuel costs. It is estimated that the world's combined armed forces produce about 5% of the world's total annual carbon dioxide emissions. The U.S. military consumes 59 million tons of fuel per year and has a larger emissions footprint than Sweden [7]. Many governments have called for a reduction in military vehicle emissions, and leading Western armies have already

[1] Silesian University of Technology, Faculty of Mechanical Engineering; Konarskiego 18A, 44-100 Gliwice, Poland; e-mail: amezyk@polsl.pl; orcid.org/0000-0001-9746-2030
[2] Research and Development Centre for Mechanical Equipment OBRUM Ltd.; Toszecka 102, 44-100 Gliwice, Poland; e-mail: swawak@obrum.pl; orcid.org/0009-0004-2108-6939
[3] Research and Development Centre for Mechanical Equipment OBRUM Ltd.; Toszecka 102, 44-100 Gliwice, Poland; e-mail: skciuk@obrum.pl; orcid.org/0000-0003-1022-5652
* Corresponding author. E-mail: v.zhikhareva@gmail.com

developed environmental strategies to reduce fossil fuel consumption in the years to come. Improving fuel efficiency is not only a strategic priority but also a budgetary issue.

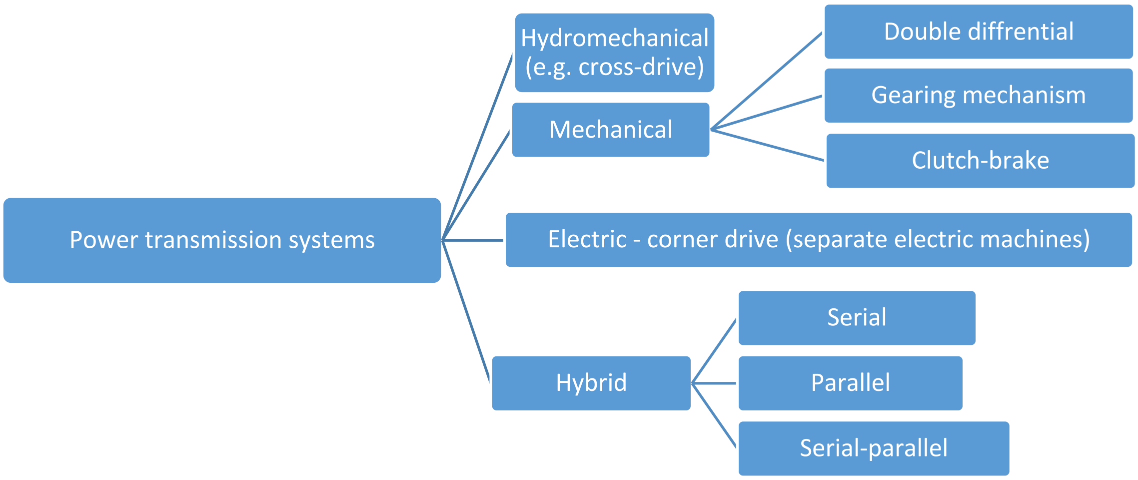

Fig. 1. Classification of selected power transmission systems with steering mechanisms for heavy tracked military vehicles

In 2014, only 17% of the U.S. Department of Defense was classified as personnel performing combat tasks. During World War II, nearly a dozen trucks were needed to transport fuel, ammunition, and spare parts to operate a tank. As weapons systems were modernized and became more complex, the demands on logisticians increased. The M1 Abrams tank consumes three times more fuel than its predecessor, the M60 Patton. According to U.S. military sources, the cost of a gallon of gasoline could rise to $1,000 if transportation and fuel conservation costs are included [7].

2. HEAVY COMBAT VEHICLE ARCHITECTURE

Heavy combat vehicles, despite their increasing weight and dimensions, face problems concerning the power-to-weight ratio of the vehicle and the volume and weight of the propulsion system in relation to its power (Fig. 4). At the beginning of this century, MTU and RENK companies intensively researched the possibilities of using hybrid drive systems in military vehicles [6]. However, despite the development of electric drive technology and high-power electronics, hybrid drives in these applications still have significant weight and volume.

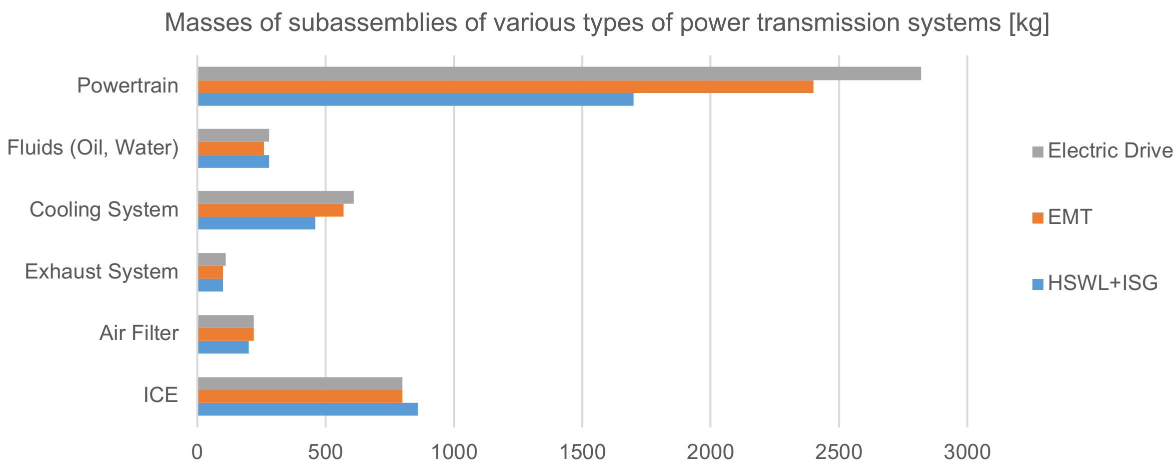

Fig. 2. Masses of the components of the drivetrain of a military tracked vehicle weighing about 41 tons with different power transmission system configurations [4]

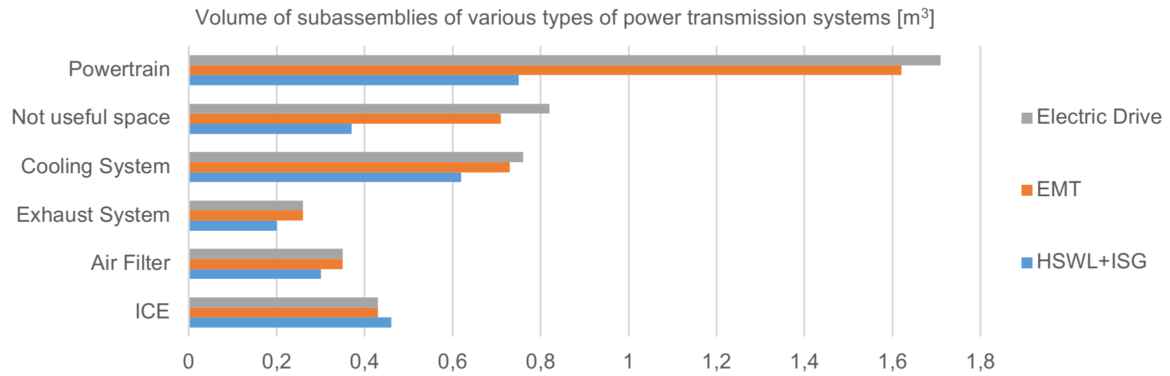

Fig. 3. Volumes of components of the drivetrain of a military tracked vehicle weighing about 41 tons with different power transmission system configurations [4]

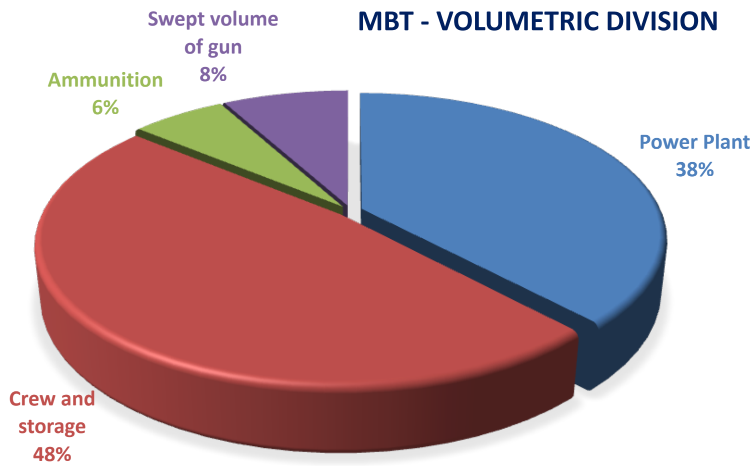

Fig. 4. Estimated share of major components in the volume of a third-generation tank [2]

Figs. 2 and 3 show the mass and volume parameters of the drivetrain, comparing variants of the power transmission system consisting of a diesel engine and:

- a hydromechanical transmission HSWL 256 with an integrated starter generator ISG
- an electromechanical two-speed transmission EMT and a mechanical coupling between the right and left tracks
- a high-power generator with an electric drive of the double corner drive type with two motors independently driving each of the tracks.

In particular, an electric drive is often characterized by a significant volume of the power transmission system and cooling system. Electric PM machines and control systems operate at a much lower temperature (below 80°C) than the classical solution. Similarly, there is a need to cool the battery bank as well. Moreover, the motors and electronics of the double-corner electric drive must be oversized compared to the ICE drive due to the electric way of energy recovery during turning and braking. Mixed propulsion systems involving mechanical transmissions still have an advantage in this regard [5].

Modern requirements for military vehicles emphasize high vehicle mobility and precise control, with the option for unmanned operation, which has led to a resurgence of hybrid propulsion technology in recent years for military tracked vehicles.

Modern electromechanical drive systems use the already proven and compact cross-drive transmission [1, 2], in which a hydrodynamic torque converter and a hydraulic steering motor are replaced by electric machines (operating in motor/generator mode) providing high efficiency, precise drive-by-wire control, and energy recovery (Fig. 5).

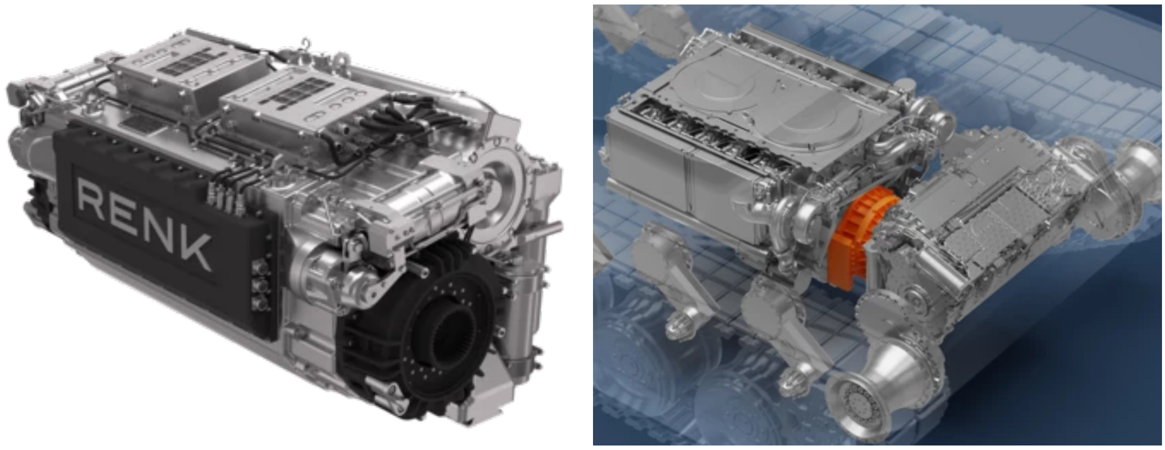

Fig. 5. ATREX electromechanical transmission from RENK for driving tracked vehicles weighing up to 70t and with a power of 1400–1500 kW with an integrated 150-kW electric steering motor [8]

However, electric batteries and energy storage remain a challenge, as they do not provide adequate fast-charging performance and logistical autonomy in combat conditions, nor the necessary level of safety required for military equipment. In this regard, the implementation of solid-state battery technology with higher power density, lower weight, and smaller volume is expected in the near future [9].

3. PROJECTS UNDERWAY IN POLAND

The Polish defense industry and research centers have joined the research and development on the application of hybrid drives to heavy tracked vehicles. The Autonomous Universal Combat Platform - APG project was carried out by a scientific-industrial consortium: Silesian University of Technology SUT, HSW SA, AGH University of Science and Technology in Krakow and Wasko SA. It uses a serial-parallel propulsion system designed by the Silesian University of Technology and implemented with an internal combustion engine, mechanical transmission and two electric motors acting simultaneously as steering mechanisms, as well as an additional parallel power stream and energy recovery system.

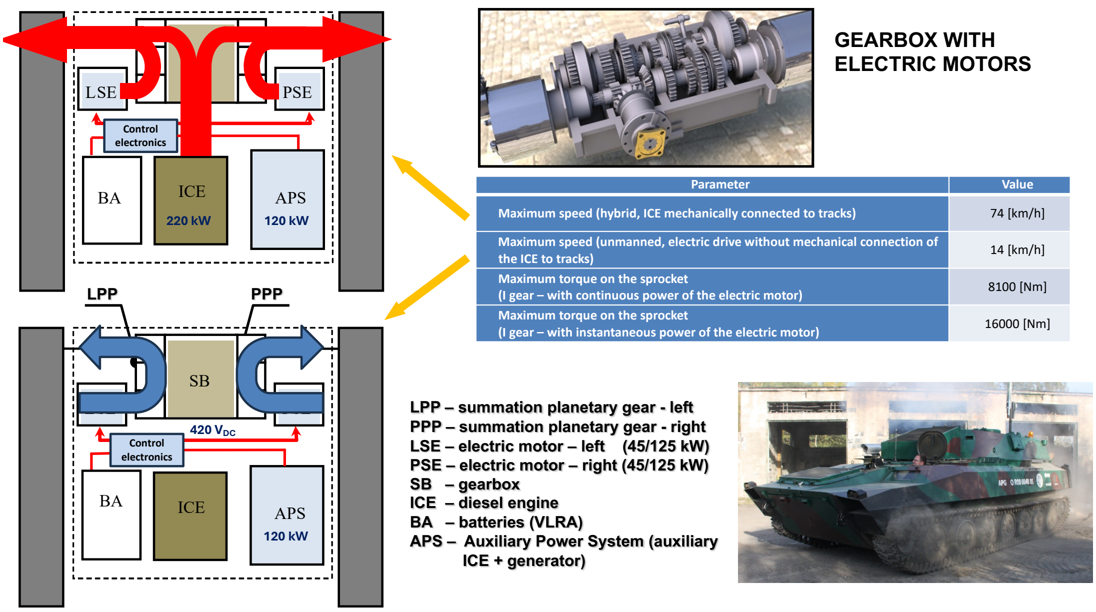

Fig. 6. Electromechanical serial-parallel hybrid propulsion system of the Autonomous Universal Tracked Platform built on the S-70 chassis (SUT's own materials)

The research was conducted using the S-70 tracked platform, with the goal of developing a new 16-ton multi-purpose floating armored personnel carrier equipped with a hybrid propulsion system, capable of carrying out unmanned missions.

The drivetrain did not use a typical cross-shaft system, resulting in the possibility of fully independent propulsion of each track and unprecedented maneuverability of the vehicle (Fig. 6). The results of the tests of this demonstrator confirmed the very high maneuverability of the vehicle and the ability to precisely steer in unmanned, silent mode. However, the weight and volume of the entire drive system, in particular the battery bank, posed a problem.

Nevertheless, the propulsion system of the Polish Light Tank with a total weight of 36 t (known under its own name ANDERS), represents a unique solution of the mild-hybrid type in applications for the propulsion of tracked vehicles (Fig. 7). The project was realized by the scientific-industrial consortium consisting of OBRUM sp. z o.o., WAT Military Technical Academy in Warsaw, WZM Siemianowice. The vehicle's unique architecture and full electrification of auxiliary propulsion systems made it possible to implement a hybrid propulsion system with drive-by-wire control capabilities and carry out unmanned missions in a unified swarm of vehicles (Figs. 7 and 8). The platform is modular, allowing for the creation of a family of vehicles with a wide range of applications and varying weights.

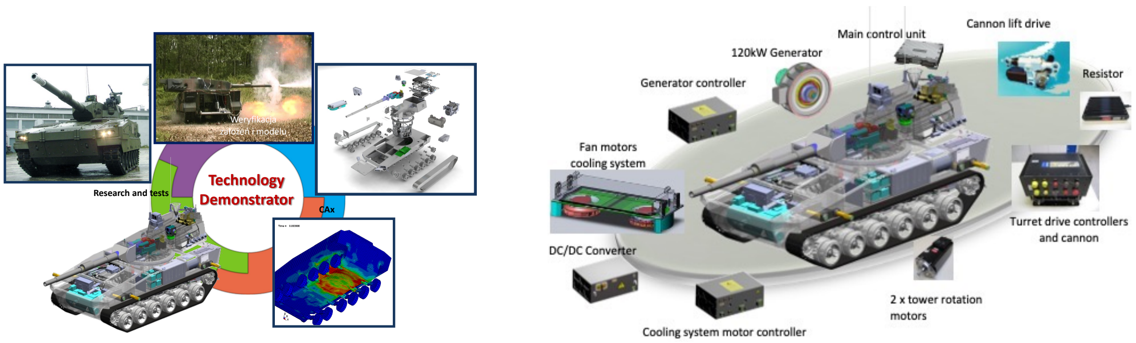

Fig. 7. Electrical components of the Polish Light Tank platform (OBRUM's own materials)

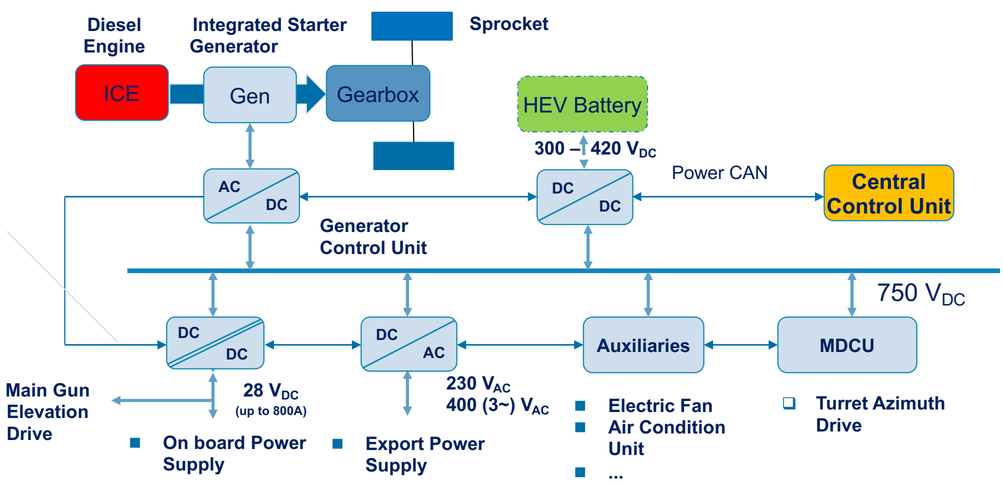

Fig. 8. Schematic of the power flow system of the Polish Light Tank platform (OBRUM's own materials)

The presented vehicle demonstrators were used for test trials, which provided a substantial amount of valuable data on the advantages and disadvantages of individual variants of hybrid-powered military tracked vehicle architectures. Additionally, they enabled the assessment of existing technological gaps that still hinder their full implementation in the armed forces.

4. PROPULSION SYSTEM CONCEPT OF THE HEAVY MILITARY VEHICLE

The parameters adopted for further research were obtained from the literature [6] and a comparison of numerous design solutions of modern MBT basic tanks of both post-Soviet production and NATO countries. In addition, the war in Ukraine and the geographical conditions of Central and Eastern Europe were considered. A propulsion system consisting of a diesel engine, a generator, and an electromechanical power transmission system was considered. Research conducted by RENK has shown that the use of two separate electric motors to drive the tracks is uneconomical due to the need to significantly oversize the electric motors. It was estimated that two 1900 kW electric motors are needed in order to fully utilize the power of the vehicle's 1100 kW internal combustion propulsion engine to provide full-speed driving and turning, as well as regenerative braking [6]. With the increase in power, the weight and volume of these motors and the cost of the control system increase significantly.

For further analysis, we selected the propulsion system shown in Fig. 9, which consists of a main electric propulsion motor, a double differential steering mechanism, a two-speed integrated planetary powershift transmission, and an auxiliary electric motor used to change direction. When driving straight ahead, the propulsion motor drives the steering differentials' internal gear wheels. The main power flow is transmitted equally to both sprockets.

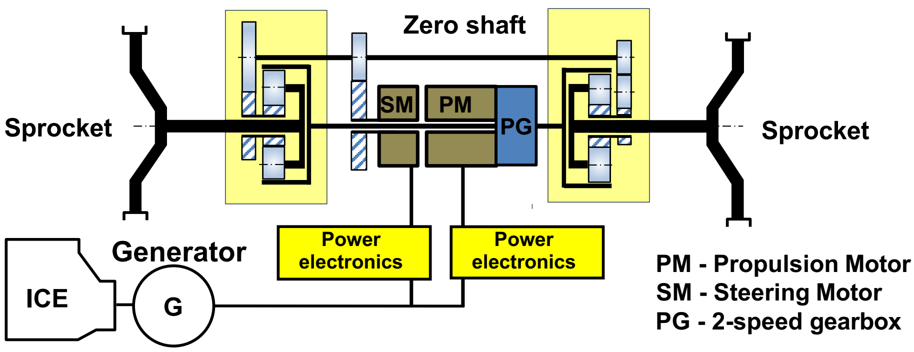

Fig. 9. Diagram of the electromechanical drive system with a two-speed planetary gearbox corresponding to the EMT 1100 [6]

Table 1

Assumed parameters for the concept of a heavy military vehicle (HMV)

Parameter	Unit	HMV	K2 Black Panther [10]
Max. road speed	km/h	70	70
Max. off-road speed	km/h	50	50
Engine power [kW]	kW	1100	1100
Transmission	n/a	Electromechanical	Hydromechanical
Forward gears	n/a	2	5
Power/mass ratio [kW/t]	kW/t	20	20
Combat mass	t	55	55
Gradient	%	60	60
Side slope	%	30	30

The zero shaft remains stationary during straight travel. While turning, to accelerate the outer track and simultaneously slow down the inner track, a steering motor is activated to drive the previously stationary zero shaft meshed with an additional intermediate gear on one side. The additional gear changes the direction of rotation of one of the sun wheels to the opposite, which in turn increases the speed of the outer track and decreases the speed of the track on the opposite side. In this way, when turning, the power from the slow side is mechanically recuperated to the faster side via the zero shaft. The speed of the vehicle's center of mass movement remains the same as before the turn began.

The concept of electromechanical propulsion (Table 1) refers to the use of an 1100-kW electric motor for vehicle propulsion, the characteristics of which are shown in Fig. 13. This engine power, assuming a vehicle weight of 55 tons (e.g., MBT K2 Black Panther), ensures a power-to-weight ratio of 20 kW/ton, which is expected due to the high mobility of tracked combat vehicles. A drivetrain with an MTU873 diesel engine and a mechanical transmission with five gears was chosen as a reference (Figs. 10 and 11).

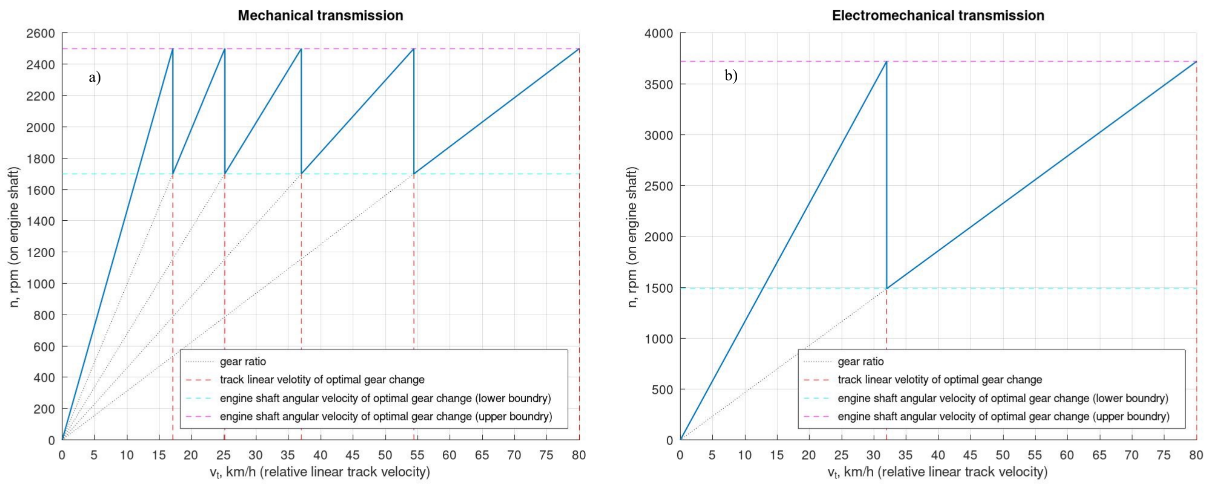

Fig. 10. Characteristics of the five-speed gearbox and the two-speed electromechanical transmission, adapted to (a) the MTU873 engine and (b) the electric motor

For reliable analysis, it is crucial to estimate effective power on sprockets based on gross engine power. Calculations for the combustion engine are performed in the following way (presented in Fig. 11):

$$\Delta N = \left(c_{Pf} + c_{Ps} + c_{Pv}\right) \cdot N_{max} \cdot \left(\frac{n_{eng}}{n_N}\right)^3 \tag{1}$$

$$N_{sh} = N_{eng} - \Delta N \tag{2}$$

$$N_{se} = N_{sh} \cdot \eta_g \tag{3}$$

η_g – transmission efficiency coefficient
c_{Pf} – power loss coefficient on air filters
c_{Ps} – power loss coefficient on the silencer
c_{Pv} – power loss coefficient on the ventilator
n_{eng} – engine shaft revolutions [rpm]
n_N – engine shaft revolutions at N_{max} [rpm]
ΔN – power loss in engine room [kW]
N_{eng} – gross engine power [kW]
N_{max} – max. engine gross power [kW]
N_{sh} – power on engine shaft [kW]
N_{se} – power on sprocket (outgoing from engine shaft) [kW]

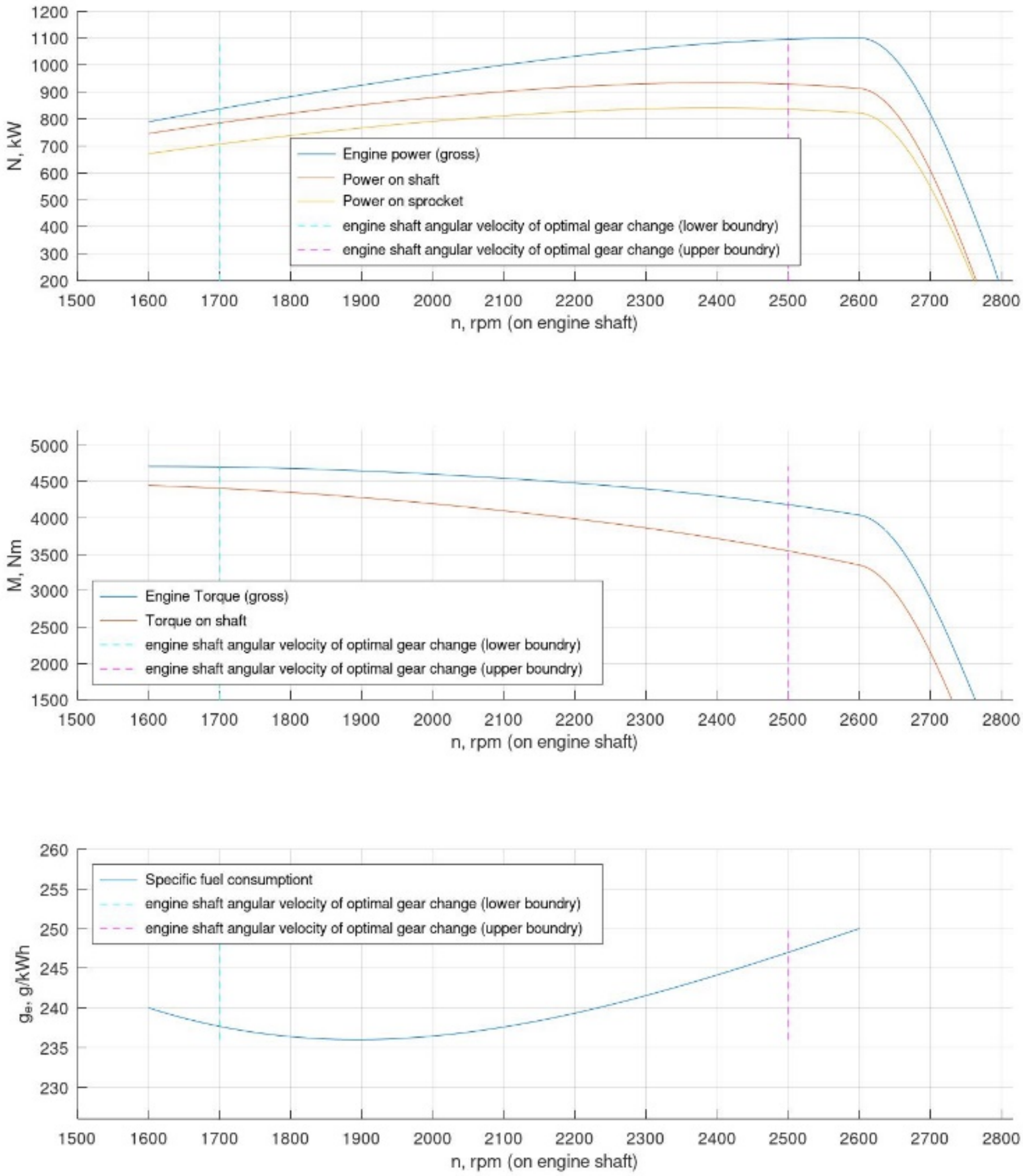

Fig. 11. Power, torque, and fuel consumption characteristics of the MTU873 engine, including power losses [1, 3]

For comparison, calculations for the electric engine are performed as follows (presented in Fig. 13):

$$N_{se} = N_{eng} \cdot \eta_e \tag{4}$$

η_e − electric engine efficiency coefficient

Data were used to determine the following characteristics:

η_e = 0.85

η_g = 0.9

c_{Pf} = 0.04

c_{Ps} = 0.03
c_{Pv} = 0.10
n_{eng} – data from engine characteristics (see Fig. 11)
n_N = 2600 [rpm]
N_{eng} – data from engine characteristics (see Fig. 11)
N_{max} = 1100 [kW]
η_t – track efficiency coefficient
s – slip coefficient
N_d – MBT drive power [kW]
N_{dt} – drive power on track [kW]

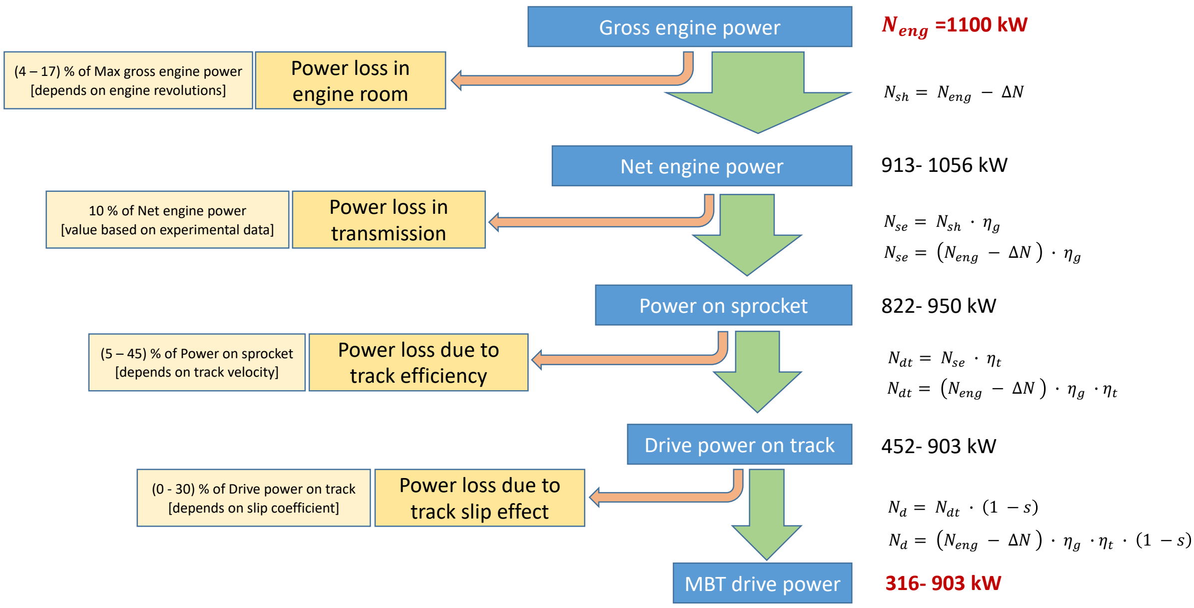

Fig. 12. Estimated power losses in the drivetrain of a heavy, high-speed tracked vehicle with MTU 873 engine and mechanical transmission

Table 2

Ground type classification, with coherent coefficients

	Ground type	**coefficients range**			
		f (min)	**f (max)**	**μ_{max} (min)**	**μ_{max}**
R1	asphalt, paved road	0.03	0.07	0.75	0.8
R2	dirt road (dry)	0.06	0.08	0.8	1
R3	grassland (dry, wet), ploughed field	0.08	0.12	0.7	1.04
R4	mud	0.12	0.15	0.35	0.4
R5	sand (wet), cropped field	0.07	0.1	0.5	0.7
R6	sand (dry)	0.15	0.2	0.4	0.5
R7	snow (high density), ice - without track spurs snow (low density) - low temperatures	0.03	0.05	0.17	0.2
R8	snow (high density), ice - with track spurs	0.03	0.05	0.47	0.5

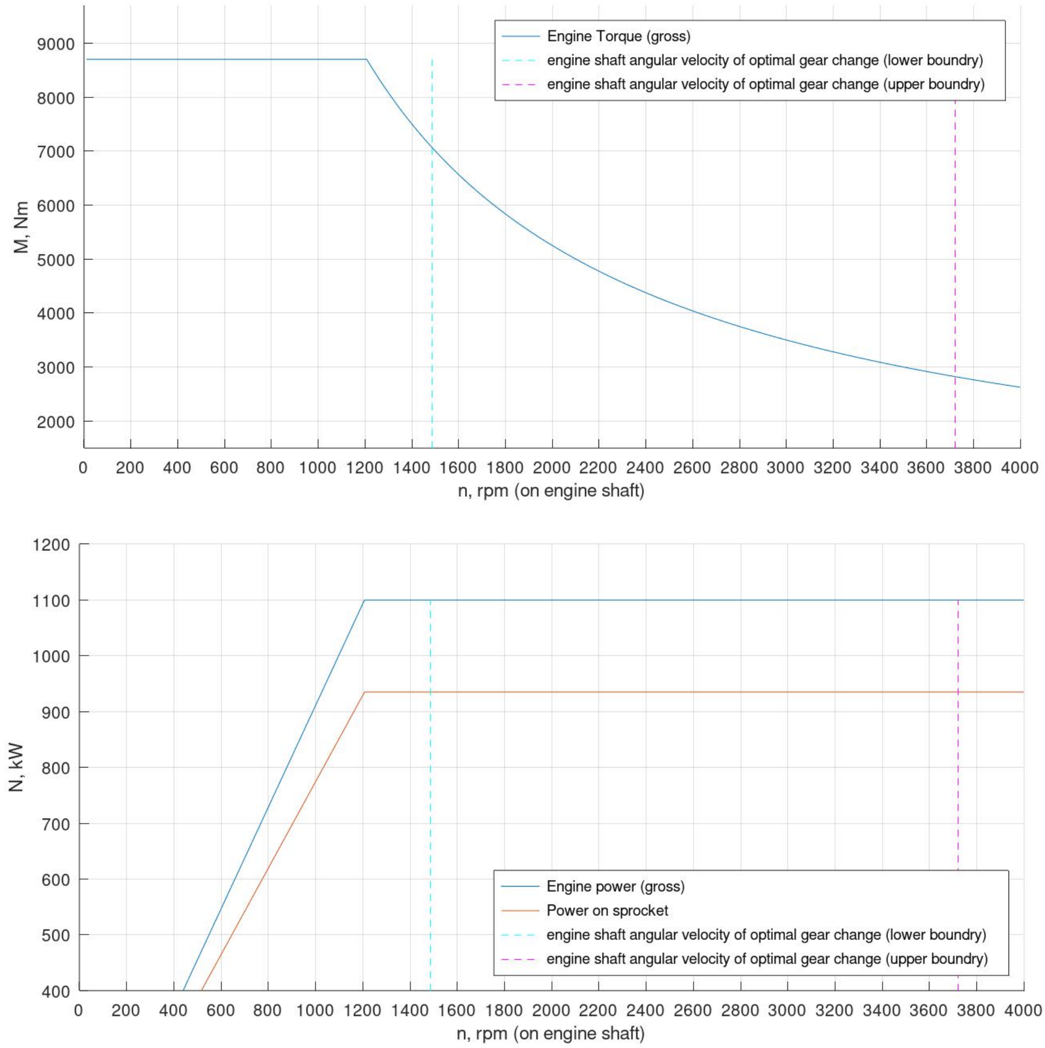

Fig. 13. Characteristics of the 1100-kW main electric propulsion motor

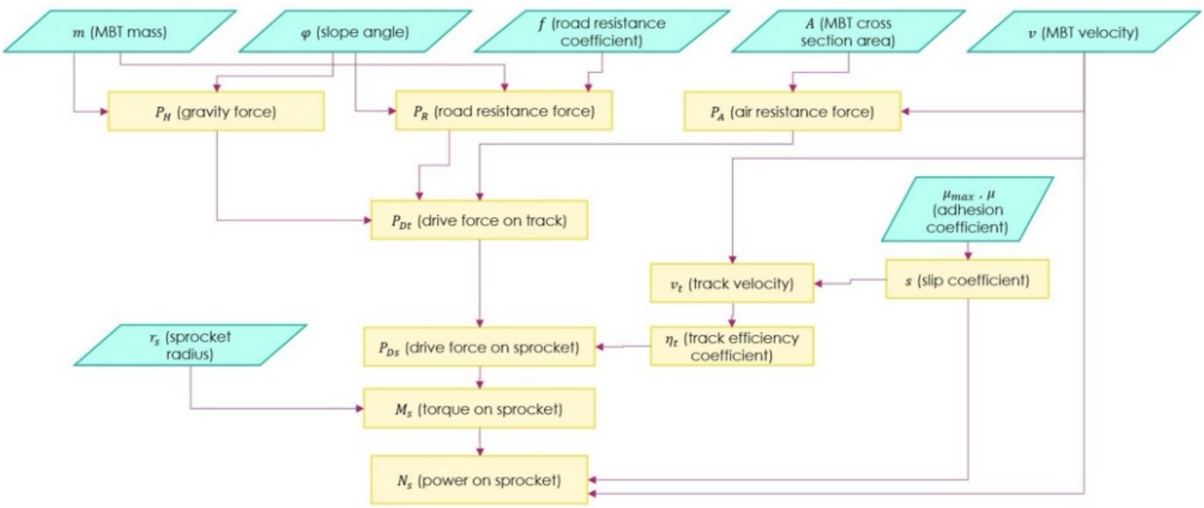

Fig. 14. Resistance calculations algorithm

As the results in Fig. 12 show, the loss of the power transmission system required to drive the vehicle, considering the slippage of the tracks, ranges from approximately 197 kW to 784 kW in the case under consideration.

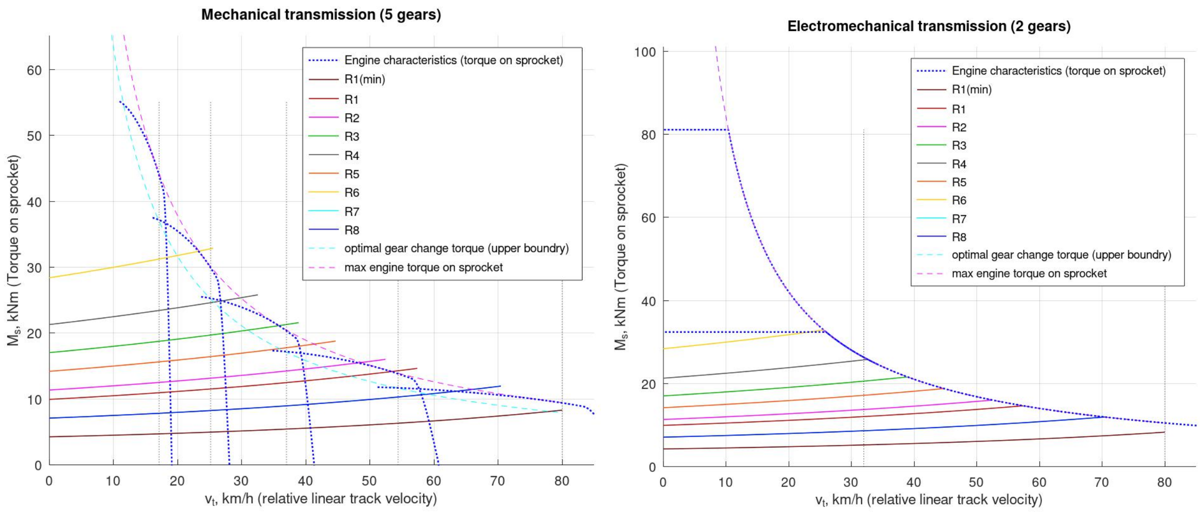

Fig. 15. Torque characteristics of individual gears of mechanical and electromechanical transmission in relation to different resistance to motion

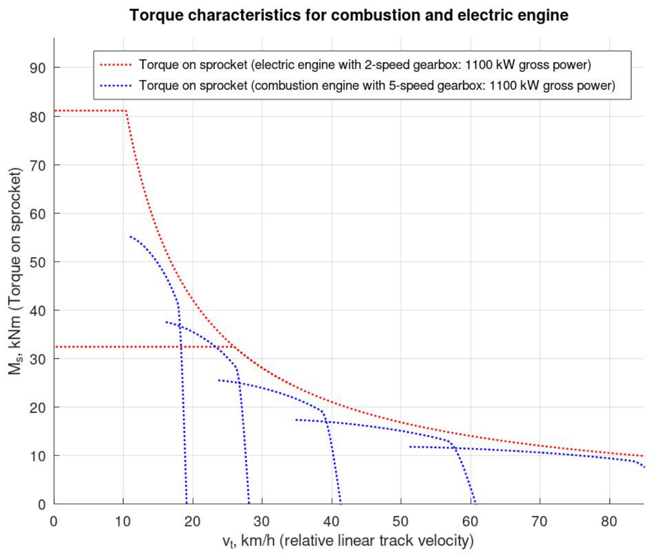

Fig. 16. Comparison of maximum available torque for combustion and electric engines

Subsequently, for the vehicle under consideration, calculations of traffic resistance were carried out according to the scheme in Fig. 14. Calculated resistance characteristics (torque on sprockets as a function of track velocity) are presented in Fig. 15. The calculations included different types of ground, which were characterized by the resistance and maximum adhesion coefficients listed in Table 2. The graphs in Figs. 15 and 16 indicate that the two-speed transmission coupled to the electric motor provides better traction characteristics and optimal use of motor power over the entire range of vehicle speeds.

The most relevant parameters characterizing the efficiency of electric propulsion are energy consumption and battery volume requirement per operating range unit as a function of the vehicle's velocity, especially when the vehicle is to perform the mission in autonomous mode (i.e., using only electric propulsion). Energy consumption and battery volume requirement for an electric engine are calculated as follows (presented in Fig. 17):

$$N_{ec} = \frac{N_s}{\eta_e} \tag{5}$$

$$C_d = \frac{d_e \cdot N_{ec}}{v} \tag{6}$$

$$E_{ed} = \frac{N_{ec}}{v} \tag{7}$$

N_{ec} – gross power consumption for electric engine [kW]
N_s – resistance power on sprocket [kW]
C_d – estimated space occupied by the battery pack in m³ required to travel 1 km powered solely by the battery [m^3/km]
E_{ed} – energy consumption per distance unit for electric engine [kWh/km]
d_e – estimated volume of the battery pack, in m³, providing 1 kWh of energy [m^3/kWh]

For comparison, fuel and energy consumption for combustion engines are calculated as follows (presented in Fig. 18):

$$N_c = \frac{N_s}{\eta_g} + \left(c_{Pf} + c_{Ps} + c_{Pv}\right) \cdot N_{max} \cdot \left(\frac{n_{mean}}{n_N}\right)^3 \tag{8}$$

$$G_d = \frac{g_e \cdot N_c}{v} \tag{9}$$

$$E_d = \frac{N_c}{v} \tag{10}$$

N_c – gross engine power consumption for combustion engine [kW]
E_d – energy consumption per distance unit for combustion engine [kWh/km]
G_d – fuel consumption per distance unit [kg/km]
g_e – specific fuel consumption [kg/kWh]
n_{mean} – engine mean revolutions [rpm]
v – MBT velocity [km/h]

The results in Fig. 17 show that in manned mode, due to volume and weight, the use of electric battery power alone during the execution of long-distance silent missions of a 55-ton vehicle is practically impossible under combat conditions. At speeds of 6–8 km/h and an operational range of approximately 6 km in difficult mud terrain, the battery volume would be about 0.9 m^3 (see Fig. 17), as calculated using Equation (12). An intermediate solution could be to use a modular structure with interchangeable power sources. For example, an auxiliary power supply (APS) consisting of a smaller combustion engine and a generator, housed in a soundproof chamber (see Fig. 6).

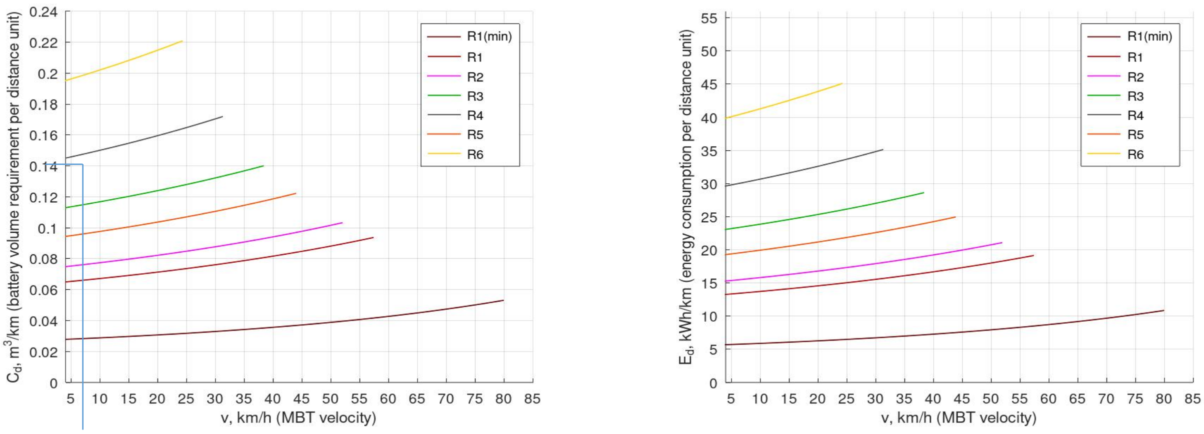

Fig. 17. Battery volume and energy consumption per operating range unit as a function of the vehicle's velocity in the autonomous mode of the vehicle using electric drive only

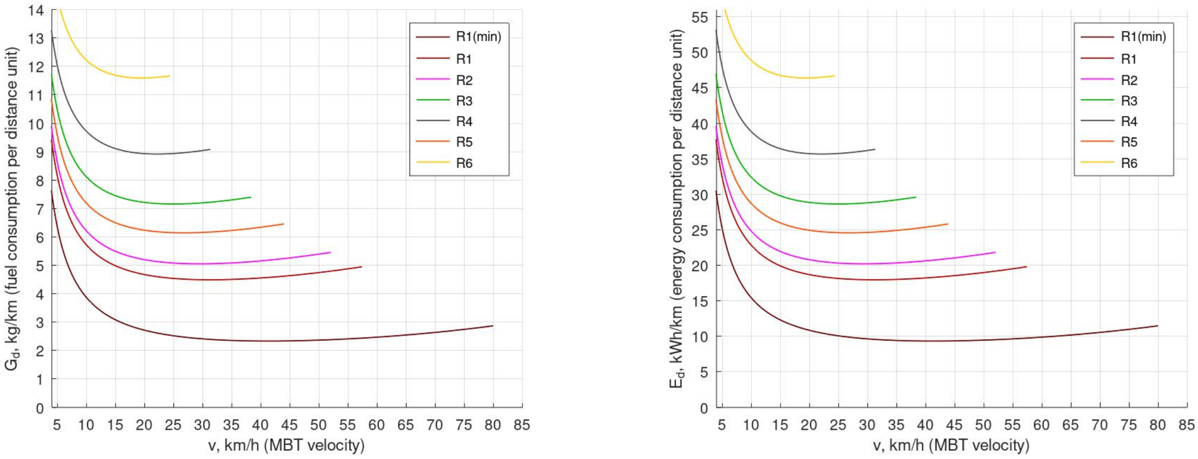

Fig. 18. Fuel and energy consumption per operating range unit as a function of a vehicle's velocity using diesel drive only

Data were used to determine the following characteristics:
d_e = 4.9·10^{-3} [m^3/kWh] – data based on estimated Tesla Model S performance
g_e = 0.25 [kg/kWh] – data from MTU873 engine characteristics
n_{mean} = 2100 [rpm]
v – function argument
N_s – data from resistance characteristics (see Fig. 15)
other data inputs - the same values as in Equations (1)–(4).

The graphs in Figs. 17 and 18 enable the quick and easy estimation of fuel or battery demand for combustion and electric engines, respectively. This demand can be calculated using the following equations:

$$G_t(v) = G_d(v) \cdot l \tag{11}$$

$$C_t(v) = C_d(v) \cdot l \tag{12}$$

C_t − total battery volume requirement [m^3]
G_t − total fuel consumption [kg]
l − driving distance [km]

Table 3

Selected specific data values from Figs. 17 and 18

		MBT velocity, km/h	**4**	**10**	**20**	**30**	**50**	**70**
Energy consumption, kWh/km	**R1(min)**	*Combustion engine*	29.98	15.41	10.85	9.64	9.47	10.55
		Electric engine	5.69	5.89	6.27	6.73	7.93	9.68
	R2	*Combustion engine*	39.24	24.78	20.78	20.21	21.58	
		Electric engine	15.29	15.82	16.80	17.93	20.76	
	R3	*Combustion engine*	46.26	32.37	28.86	28.80		
		Electric engine	23.08	23.87	25.33	27.02		
	R6	*Combustion engine*	62.49	48.85	46.38			
		Electric engine	39.86	41.27	43.88			

Due to different characteristics of power drops, as shown in Equations (5)–(10), in an electric and diesel drive, there is a substantial difference in energy consumption demand at low velocities (see Figs. 17 and 18 and Table 3). For example, at a constant velocity of 4 km/h on easy terrain (asphalt, paved road), the energy consumption for a diesel drive is approximately. 5.3 times greater than for an electric one. These results show the opportunity for a significant energy usage reduction while implementing hybrid technologies.

5. CONCLUSIONS

The growing demand for liquid fuels generated by armed forces worldwide, combined with the increasing number of military vehicles, is driving the search for new solutions for drive systems with lower CO_2 emissions and reduced fuel consumption. The use of electric propulsion systems in heavy tracked vehicles offers such possibilities, but technical challenges remain concerning energy storage and the significant weight and dimensions of the electric propulsion system. Logistical autonomy and the ability to refuel or recharge batteries quickly and easily, regardless of weather and terrain conditions, are also important.

Analyses show that a hybrid drive system with a diesel and electric motor provides greater power transmission efficiency (see Fig. 16), better vehicle traction, and lower fuel consumption (see Figs. 17 and 18 and Table 3). On the other hand, technical problems increase rapidly with increasing engine power and vehicle weight. However, the introduction of hybrid drives in heavy tracked vehicles seems inevitable, and it is only a matter of time before key solutions in the field of control and power systems reach the required level of technological readiness. In addition, the use of hybrid drives, which have no mechanical connection between the ICE and the sprockets, allows for better vehicle configuration and more efficient use of interior space. The future vehicle architecture should be modular to enable the vehicle to be adapted to the current needs of users.

Given the rapid technological progress and growing market for civilian electric vehicles, a new generation of battery technology can be expected in the near future, representing a breakthrough in the optimization of the weight and volume of the electric powertrain. However, the problems of mobile charging stations on the battlefield and the time needed to recharge the battery remain unresolved. Therefore, the current work of the design teams focused on the implementation of mild, series, or mixed hybrid drives, which allow driving without the need for external battery charging.

References

1. Ogorkiewicz R.M. *Technology of tanks.* Jane's Information Group Limited. Sentinel House. 1991. 422 p.
2. Terry, T.W. & Jackson, S.R. & Ryley, C.E.S. et al. *Fighting Vehicles.* Vol. 7. Brassey's Ltd. 1991. 315 p.
3. Burdzinski, Z. *Teoria ruchu pojazdu gąsienicowego.* Warszawa: Wydawnictwo Komunikacji i Łączności. 1972. 347 p. [In Polish: *Theory of movement of a tracked vehicle.* Warsaw: Communications and Contacts Publishing House].
4. Kiefer, G. HPD engines for hybrid electrical drives. In: *International Symposium Hybrid Technologies for Military Tracked Vehicles*. Augsburg. 2006.
5. Bhatia, V. Hybrid tracked combat vehicle. In: *IEEE International Transportation Electrification Conference (ITEC)*. Chennai, India. 2015.
6. Naunheimer, H. Electric drive technology for tracked vehicles. *Journal of Battelfield Technology*. July, 1998. Vol. 1. No. 2.
7. *Modern Mobility Solutions. Optimizing fuel efficiency: A strategic imperative for military vehicles*. Available at: https://www.renk.com/en/newsroom/news/vms/optimizing-fuel-efficiency-a-strategic-imperative-for-military-vehicles. 2025.
8. *ATREX – integrated hybrid propulsion and Drive-by-Wire for increased mission capability*. Available at: https://www.renk.com/en/products/vehicles/transmissions/atrex. 2025.
9. Joshi, A. & Mishra, D.K. & Singh, R. et al. A comprehensive review of solid-state batteries. *Applied Energy.* 2025. Vol. 386. DOI: 10.1016/j.apenergy.2025.125546.
10. *K2 Black Panther.* 2025. Available at: https://en.wikipedia.org/wiki/K2_Black_Panther.

Received 01.06.2024; accepted in revised form 27.08.2025