A Hybrid-Electric Drive Concept For High Speed Tracked Vehicles

Živko Ilijevski
Brodarski Institut, d.o.o. Zagreb, Croatia
zivko@hrbi.hr

Abstract. Huge, ineffective and inefficient drive systems in the high-speed tracked vehicles are the most accountable for the contemporary behemoths of Main Battle Tanks (MBT). However, the main problem presently existing in the transmission system resides in the role of the high speed tracked vehicles. To ensure vehicle operations, such a vehicle requires a continuously variable output on both sides of the drive train in a very large range of speed and torque. Applying the most inefficient hydraulic power transmission units for that purpose, such a transmission system not only devours enormous quantity of energy, it also needs a powerful cooling system consuming 14 to 15% of the engine maximum power to dissipate the generated heat. New technology development in the field of electric motors and power electronics opens a new area for vehicle drive system development. However, a high speed tracked vehicle, due to a huge amount of circulating power throughout the transmission, needs components of great power density. Although achievements of new electric motors are impressive, their power density is not good enough to serve as a transmission on their own in a high speed tracked vehicle. A completely mechanical transmission concept for high speed tracked vehicles known as Transmission with Independent Turning Radii (TITR), applied for repowering of the Croatian tank M84, has shown exceptional effectiveness and efficiency in steering, and enabled to achieve an incomparable power density of the drive train. Its modular architecture enables various combination with electric machines in order to get a hybrid-electric drive train which can maximizes the synergistic effect of a mechanical and an electric drive. The paper reports on the compatibility of the TITR transmission concept with the specific needs of a high speed tracked vehicle proved on field testing. For further development, a hybrid-electric drive concept is shown in the bases of which are modules of TITR transmission concept. The overall characteristics and advantages of such a drive concept are pointed out.

Keywords. Hybrid-Electric Drive, Tracked Vehicle.

1 Introduction

New achievements in the development of electric machines, power electronics and electric energy storage devices boosted the development of alternative drives for ground vehicles. Hybrid-electric passenger vehicles and city buses are already bringing benefits in substantial fuel economy and better environmental protection, both of these issues being the prime ‘mover of the alternative drives development.

High speed tracked vehicles, used as combat vehicle, are very sensitive to the transmission system. Development of new technology in the form of power hydraulic at the beginning of 70’s, made us believe that numerous advantages may be taken by implementing them in the transmission system. The result was enormous size, weight and power losses of the power train, which eventually penalized the vehicle as a whole (Jenkins, C.1985; Fletcher, R. 1997; Ilijevski, Ž., Stojković, V., Bobanac, N. 2002). The question is whether nowadays enthusiasm concerning application of electric drive technology will bring back the *déjà vu* vicious circle of more power- more weight and size – more power?

Remarkable results concerning performances and vehicle characteristics as a whole were achieved with mechanical solutions of the transmission system. A new transmission concept named transmission with independent turning radii (TITR) was applied for modernisation of the Russian tank T72, produced in Croatia as model M84.

What kind of alternative drive will be used in a military vehicle in the future will finally depend on numerous requirements like: availability of the fuel, autonomy of the vehicle, performances requirements, cost, etc. This list, of course, goes on and on. In the end, the technology that dominates will be a compromise between economy and practicality.

Although fossil fuels are facing dead treats, their energy density is irreplaceable and military, especially combat vehicles, will probably be the last to replace it. But given the possibility of fuel economy and other advantages of hybrid-electric drives, there is a high probability that those drive systems will very soon penetrate the military sector. However, there are still many challenges that hybrid-electric drives face: component technology (energy storage, motor/generators, power electronics), costs, reliability, user acceptance, etc.

The paper discusses the expectations and challenges of heavy hybrids for tracked military vehicles. A solution of hybrid-electric drive, based on the TITR transmission system, which ma be characterised as a light or mild hybrid, is shown. Light or mild hybrids which marry electric technology to mechanical solutions seem to be a more realistic model for application on high speed tracked vehicles in the near future.

2 Hybrid-Electric Drives for Military Vehicles - Expectations and Challenges

Military vehicles may also take benefits of the development of alternative drives, even much more than a passenger or a commercial vehicle:

- **fuel economy improvement** by breaking the link between the internal combustion engine and the drive wheels or eventually by getting rid of the internal combustion engine, which generally operates at very low efficiency;
- **reduced emission levels of pollutants** which goes with the decrease of fuel consumption;
- **electric energy on board –** electric energy in abundance can be useful for auxiliary systems, electric weapons, EM armour, and even for external use;

- **reduced thermal, acoustic and exhaust signatures -** stealth operation for extended periods can be of crucial importance for military operations;
- **design flexibility and better space utilization** – smaller engine combined with electric machines and flexible component arrangement;
- etc.

As to technology, the energy storage system is certainly the weakest link of a hybrid electric drive system. The problem concerns mostly energy density and burst power, as the most visible characteristics. But the efficiency of energy transformation, given that the energy passing through the energy storage system is transformed twice, has an important influence on the overall efficiency of a hybrid-electric structure.

As to tracked vehicles, there are much more problems to worry about when thinking of hybrid-electric drive application, than in a wheeled vehicle.

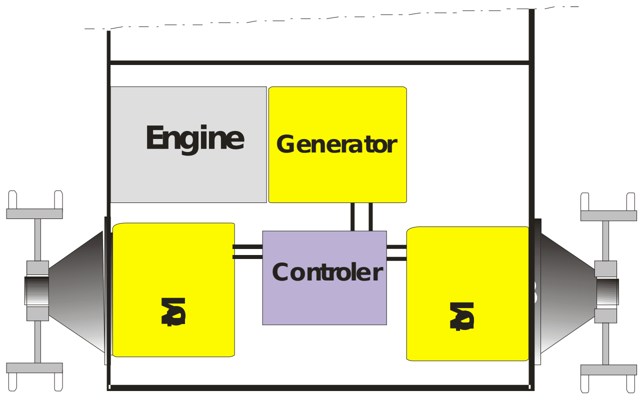

Figure 1: Series Hybrid-Electric Drive for a tracked vehicle

A heavy hybrid, i.e. a series hybrid-electric drive for a tracked vehicle, is shown in Figure 1. A combat vehicle must be able to deliver its maximum performances when deployed on the battlefield. The series hybrid system components: engine, generator and traction motor must be sized to maintain vehicle performance requirements at gross combat weight. This results in a high continuous power requirements of all the components: engine, generator and two traction motors. Since the inner track when the vehicle is in steering generate energy in the most operating off-road conditions, each of the electric machines has to transmit two to tree times the power needed in straight forward motion. The generator and traction motors continuous ratings are also inflated due to the requirement of transporting all the vehicle energy requirements through the generator, traction motor and battery storage with their associated. This results in an engine and generator power rating increase by 15% to 20% to make up for the inefficiencies in the generator and traction motors over a mechanical link from the engine to the sprockets. High continuous power requirements for traction motors and generator result in extreme size, weight and cost penalties.

There are some more problems to think about:

- an electric motor hardly can satisfy the speed range of such a vehicle – an additional mechanical gearing is needed on both sides,
- efficient, effective and powerful braking system is needed in addition – taking a huge amount of energy in several seconds,
- a huge amount of energy is transformed into heat which need a powerful cooling system

The question is whether the electric motors can efficiently and effectively take the role of a power transmission of a high performances tracked vehicle and what kind of benefits is really possible to take of it?

3 Mechanical Transmission System Assisted by an Electric Motor

3.1 Background of the Transmission System

A new drive system of 900 kW (1200 HP) was developed for repowering of the Croatian tank M84, which production started under licence of the Russian T72 tank.

shows the architecture of the drive train, which is the same as in the original vehicle. Everything is put in a volume of 3,4 m^3. The power density of the drive train is 265 kW/m^3 (350 HP/m^3) which is the best achievements so far. The new transmissions consist of two complex gear boxes of special kinematics (Ilijevski, Ž., Koroman, V. 1997). They enters the same housings of the original transmission and take no more than 0,23 m^3 of the drive train installation box.

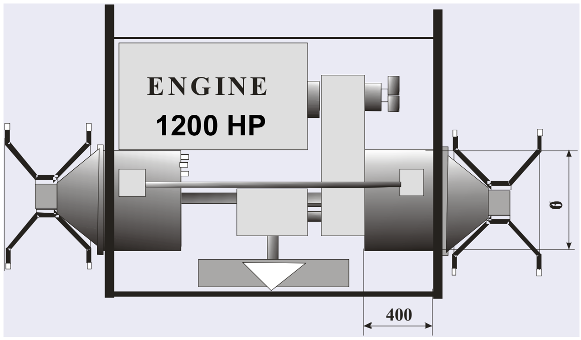

Figure 2: The TITR transmission system applied for repowering of the Croatian tank M84

Each gearbox of this transmission is able to transmit an amount of power of 1200 kW (1600 HP), which is a power density of about 10 kW/dm^3 (14 HP/dm^3). It is difficult to imagine on other kind of power transmission unit, except a mechanical one, which could transmit continuous power at such a power density.

The technology of the complex gearboxes is the same as the gearboxes of the original transmission, Figure 3. It consists of planetary gearing activated by a set of hydraulically controlled wet clutches and brakes.

This transmission has the role of overall control of the vehicle: starting, speed shifting, steering, braking.

A special kinematical arrangement of the gearboxes makes a progressive and independent arrangement of the kinematical (fixed) radii - one steering radius for each speed range.

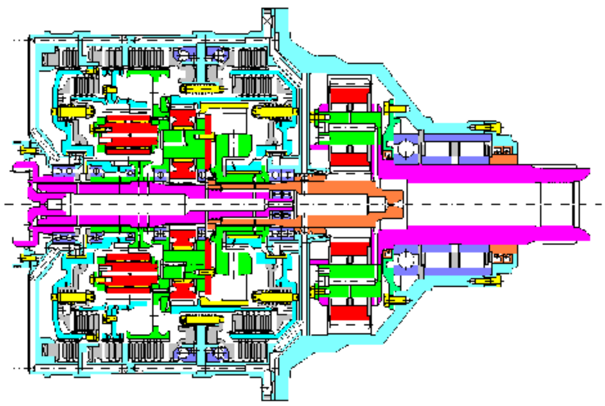

Figure 3: Technology of the gearboxes

The new transmission had been submit to severe lab and field trials with remarkable results. Special field test had been performed by guiding the vehicle over circled paths, Figure 4, in order to investigate power losses in steering. At speed above 25 km/h and radii above 25m, no additional power losses in steering, measured by taking the temperature on the surface of the friction components, where registered (Ilijevski, Ž., Behavy L., Koroman, V. 1999).

Although steering on path of great radii turn is much more sensitive (Ilijevski, Ž., Stojković, V., Abrashi, A. 2003) on the difference of the tracks speed, the experimental vehicle with TITR transmission system has followed any path precisely and steadily due to the appropriate arrangement of the fixed radius for each vehicle speed range.

The video taken during the field tests when steering on a path of 40m radius at 32 km/h average speed, Figure 4, compared to an ideal computer simulation steering, shows little difference of the precision in following the path and no difference in speed and steadiness.

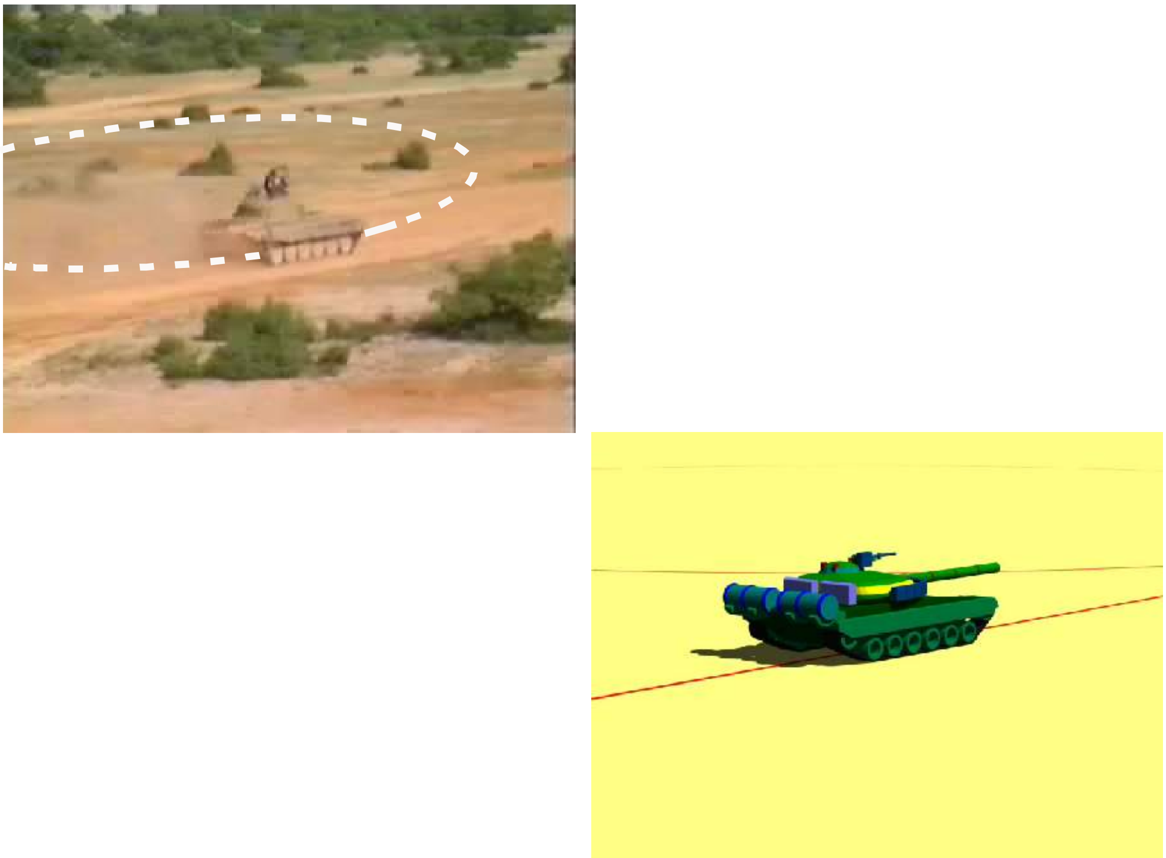

Figure 4: Field test on a circled path of 40m radius of the M84 tank chasses with a 1200 HP engine and TITR transmission system compared to a computer simulation

3.2 Essence of the TITR transmission System

3.2.1 Operating Efficiency in Steering of a non-kinematical steering system

Steering by a non-kinematical steering system is performed by acting on friction components at the inner side of the vehicle (Ilijevski, Ž., Stojković, V., Abrashi, A. 2003). Figure 5 shows en example of such a steering system. In straight forward motion the clutch C is engaged and the brake B is released. When the clutch is released the speed at the inner side decreases due to the resistance and the vehicle turns at the free steering radius (no driving force). If the brake B is engaged the steering radius decreases depending on the braking force.

The kinematical parameters are defined by the planetary gear characteristic k . During the sliding of the clutch, the efficiency of the clutch is:

$$\eta = \frac{\omega_3}{\omega_2} \qquad (1)$$

While braking, the efficiency will be:

$$\eta = \frac{k+1}{k}\frac{\omega_3}{\omega_2} \qquad (2)$$

~~W~~where:
k – is the characteristic of the planetary gear;- ω_2 and ω_3 – are the speeds of the input shaft and the sprocket respectively.

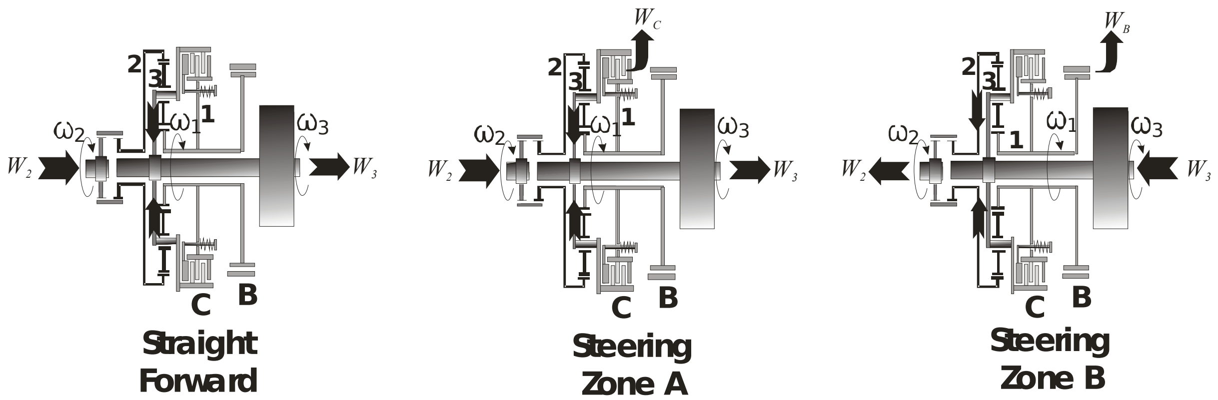

Figure 5: Steering process in steering by a non-kinematical steering system
C – Clutch; B – Brake; 1,2,3 – components of the planetary gearing; W_2 - power at the input shaft of the gear box; W_3 - power at the sprockets; Zone A – positive driving force; Zone B – negative driving force (braking)

~~So~~Thus, at the very beginning of the braking process, i.e. for $\omega_3=\omega_2$,- the efficiency will be equal to -*k/(k+1)* and at the end of the process, i.e. for $\omega_3=(k/(k+1))\omega_2$,- it will be equal to 1, Figure 6. In fact the braking of the inner track starts after releasing the clutch, while the output speed will loose ~~a~~ certain value caused by the resistance. From that moment down to the fixed radius the vehicle sweeps the steering zone B, Figure 6. The total change of the inner track speed (δv_1) would correspond to the change of the speed of the inner side and it represents the total steering zone.

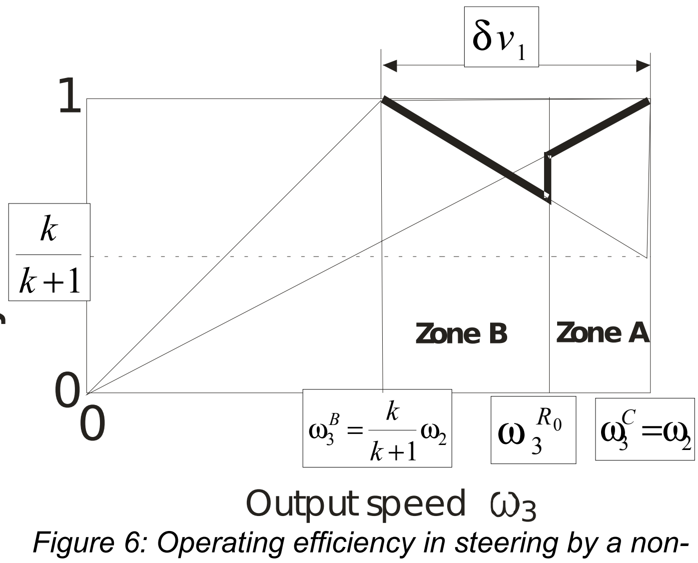

Figure 6: Operating efficiency in steering by a non-kinematical steering system

If a ~~a~~ steering ratio is defined as:

$$q_k = \frac{v_1}{v_{1k}} \qquad (3)$$

~~W~~where v_1 is the inner track speed in straight forward motion and v_{1k} is the inner track speed at the fixed radius, with regards to the kinematics, Figure 5, it will be:

$$q_k = \frac{\omega_3^C}{\omega_3^B} = \frac{k+1}{k} \qquad (4)$$

From that follows that the efficiency at the beginning of steering by braking the inner track is:

$$\eta_b = \frac{1}{q_k} \quad (5)$$

The operating efficiency in steering of a non-kinematical steering system depends on the steering ratio, i.e. on the difference the inner track in straight forward and at the fixed radius.

3.2.2 Operating Efficiency in Steering of the TITR Transmission System

The TITR transmission system is characterised by its special kinematics, i.e. each speed gear has its own steering gear which defines the fixed radius. The progression factor, which can be called steering factor q_s between the speed gear and the steering gear is the same as the steering ratio. Thus the operating efficiency while braking, i.e. engaging the steering gear, at the beginning of the steering zone, will be:

$$\eta_b = \frac{1}{q_k} = \frac{1}{q_s} \quad (6)$$

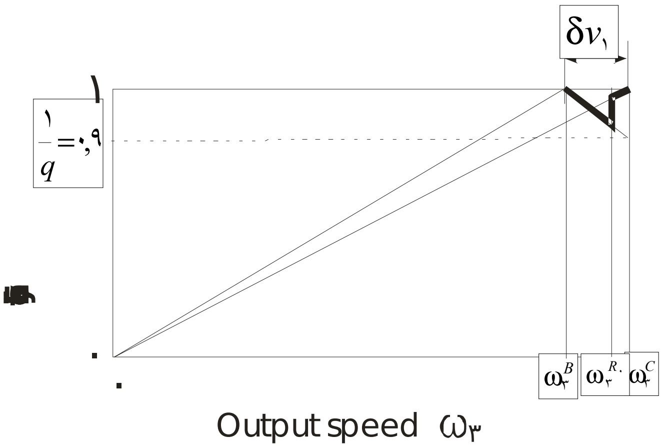

Figure 7: Operating efficiency of the TITR transmission system in steering above 25 km/h

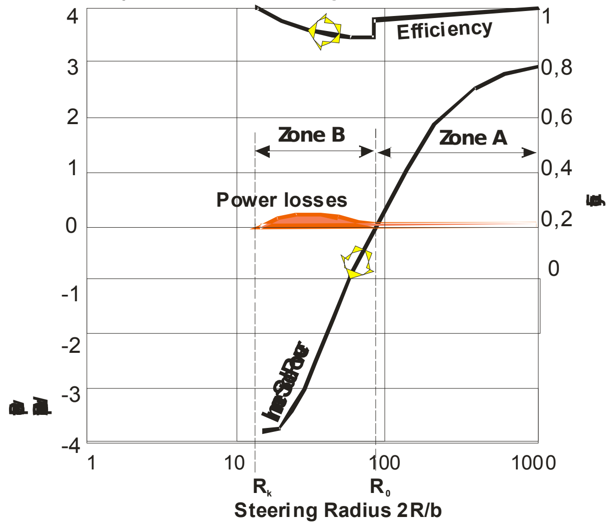

Figure 8: Power losses in steering of the TITR transmission for speed range 25 to 45 km/h

With the decrease of the steering factor the operating efficiency increases. Small difference of the inner track speed makes an important effect in steering and small difference between the inner track speeds in straight forward motion and at the fixed radius, * v_1 Figure 7, means great fixed radius and high operating efficiency. That is the philosophy of the TITR transmission system kinematics. A tracked vehicle for steering above 25m radius needs about 10% speed change. So everything happens between 0 and 10% speed change. A frication component can handle this speed change at much better efficiency than any other power transmission device. For instance since the steering factor for the speed range 25 to 45 km/h of the TITR transmission is q_s*=1,115* the operating efficiency in steering is always greater than 0,9, Figure 7.

As to the power losses, the diagram in shows theoretically calculated specific power (presented as power to weight ratio) at the inner side sprocket in steering at speed of 30 km/h (Ilijevski, Ž., Koroman, V., Behavy, L. 1998). The steering radius is given as dimensionless value, i.e. the steering radius R divided by the half of the track distance. The operating efficiency is also presented depending on the steering radius. As the power at the inner side increases, the operating efficiency increases so that the power losses has a maximum between the free steering radius R_0 and the fixed radius R_k.

Field test of the TITR transmission shown in Figure 4 were performed at average speed of 32 km/h on a circled path of a radius of 40m which corresponds to the max power losses, . However the tests did not show significant power losses due to the their small amount.

3.3 TITR Transmission System Assisted by an Electric Motor

The TITR transmission kinematics excels in use of friction components and solve perfectly the steering problem of high speed tracked vehicles. It enables also effective braking, starting and power speed shifting.

An electric motor could bring additional improvement of the drive train. Figure 9 shows a configuration of a hybrid-electric drive system based on a TITR transmission system. An electric motor/ generator assists the engine and the power needed may be split between the engine and the motor. An electric motor even of a small power can enhance significantly the driving power, Figure 10. Together with the TITR transmission modules (complex gearboxes), everything could put in one line and avoid additional transfer cases. The electric motor may be alimented from an electric power plant which can be installed anywhere on the vehicle.

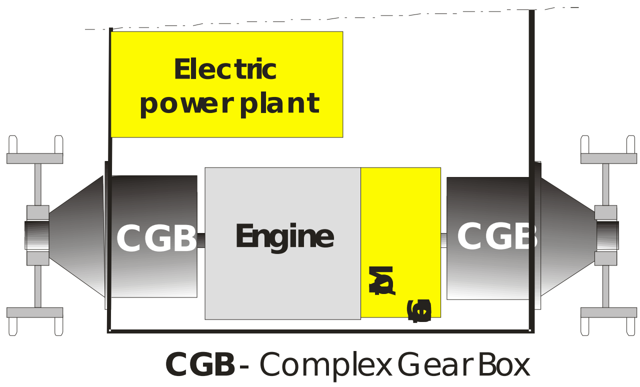

Figure 9: Hybrid-electric drive based on a TITR transmission system

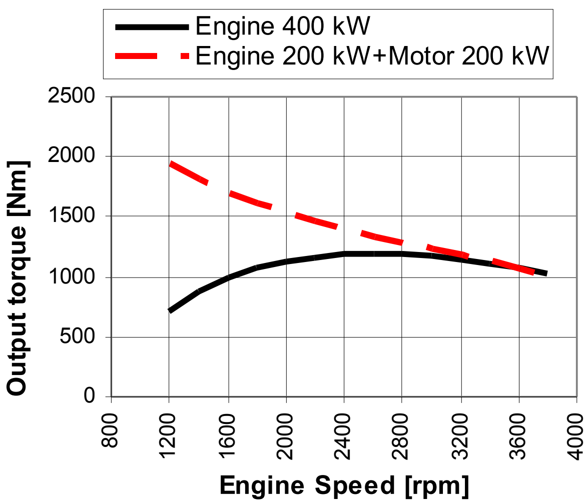

Figure 10: Driving torque of an engine assisted by an electric motor

The overall characteristics of such a drive system are:

- Small size – power density may achieve the rate of over 400 HP/m^3 – due to: the transmission modules which integrates many roles (starting, speed shifting, steering, braking) in one mechanism; capability of the transmission modules to transmit an important amount of power, the power density rating about 14 HP/dm^3, which is of a paramount importance for tracked vehicles where the circulating power trough the transmission system in steering may triple the power in the straight forward motion; integration of all the drive components into one driving line; small capacity of the cooling system due to a high efficiency of the overall drive system.
- The efficiency of the overall drive system is high due to: combination of engine(s)-electric motor for powering the vehicle which enables use of smaller engine(s) which operate in more efficient regimes; there is no need of high capacity energy storage; the kinematics of the transmission modules excels in use of wet friction clutches and

enables continuously variable output operating with steering efficiency exceeding 95% in the most frequent operating conditions.

- Offer high performances due to: high output torque and power as a result of the combination of an engine and electric motor; high torque and power on the sprockets as a result of an appropriate transmission kinematics and increased efficiency.
- The drive system enables low operating costs due to: fuel economy; the system design consists of small and easy exchangeable modules – the transmission consists of two almost identical modules; share the source of electric energy for the entire vehicle and enables use of electricity for all the accessories and other vehicle systems. It can also supply electric energy for needs outside the vehicle.
- The drive system consist of components of mature technology. The transmission modules are proven technology, simple but robust, enabling cost/effective design of the drive system.
- The drive system will be an open system for future improvement and application of immerging technologies like alternative fuels and new energy transformers.

4 Conclusion

Alternative drive is the ultimate solution for propulsion of any kind of vehicle. Hybrid-electric drives as bridge towards a more radical future will certainly spread rapidly on vehicles like cars, buses, light utility vehicles, etc. Military, especially combat vehicles will probably be the last to replace fossil fuels by an alternative, given its energy density. Heavy hybrids have still to much drawbacks and it is hard to believe their mass application on combat, especially tracked vehicles.

Light and mild hybrids seem a more realistic model for the near future which may marry conventional with new technologies to get substantial improvements not only in fuel economy and performances but also in many other aspects concerning combat vehicles.

References

Fletcher, R. 1997. *Dooming the behemoths – European Nations Consider Innovative Approaches To Reduce Tank Size And Weight*, Armed Forces Journal International, May 1997.

Ilijevski, Ž., Koroman, V. 1997. *Transmission with Independent Turning Radii (TITR) for Tracked Vehicles,* Proceedings of the 7th European ISTVS Conference - Ferrara, Italy.

Ilijevski, Ž., Koroman, V., Behavy, L. 1998. *The Impact of Transmission Kinematics on the Operating Efficiency in Tracked Vehicles Steering*, Tracks and Wheels Symposium, Royal Military College of Science, Cranfield University, UK.

Ilijevski, Ž., Behavy L., Koroman, V. 1999. *An Approach To The Transmission With Independent Turning Radii For Tracked Vehicles",* Proceedings of the 13th International ISTVS Conference - Munich, Germany.

Ilijevski, Ž., Stojković, V., Bobanac, N. 2002. *What Is A Good Tank From The Mobility Point Of View?,* Proceedings of the First Symposium for Explosive Materials, Weapons and Military Technology – Ohrid, Macedonia.

Ilijevski, Ž., Stojković, V., Abrashi, A. 2003. *Some Specific Aspects of Transmissions with Non-kinematical Steering System for High Speed Tracked Vehicles,* ISTVS Conference, Harper Adams University College, Newport, UK.

Jenkins, C.1985. *The Old, the New and the Future,* BATTLE TANKS – Supplement to International Defence Review 9/85.