Ground Vehicle Mobility Requirements.
Meeting the Challenge with Electric Drives

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1. Abstract

Military ground vehicle requirements are defined by the terrains they traverse and the performance specifications defined by the users. While terrains have not changed much throughout the history of ground vehicles, the performance specifications have always evolved with the ever-changing technologies and the threats associated with them.

This paper contains a summary of current and future vehicle requirements, and the enabling technologies necessary for meeting them, including prime power sources which range from conventional engines to fuel cells.

Among the various technologies under consideration for future vehicle needs, electric drive stands out as a leading candidate. Therefore, a good portion of the paper is dedicated to electric drive systems and their impact on vehicle missions; particularly mobility.

2. Introduction

Military vehicles must have the capacity to operate anywhere in the world, under extreme environmental conditions, from the frigid temperatures of the arctic to the intense heat of the deserts, and from hard rocky and paved roads to hilly and soft soil. They must withstand the vibrations, shocks and violent twisting experienced during cross-country travel over rough terrain, and they must be able to operate for long periods of time with very little or no maintenance.

The above description was extracted from a handbook published by AMC in 1965. All of the conditions mentioned above are still valid today. However, there are additional requirements, which are changing the whole philosophy of vehicle design. The vehicles of the future must be lighter, faster, and more deployable but at the same time more lethal and more survivable. These constraints impose a departure from the traditional methods of making tanks. Therefore, new enabling

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technologies have to be developed and implemented to meet the technical challenges of future vehicles. For survivability, electromagnetic armor must be developed to replace the thick armored plates. For lethality, higher speed projectiles with very high penetration capability must be introduced. For mobility, Active and semi active suspension systems must be considered to achieve greater cross-country speeds.

The above mentioned future vehicle needs require electric power that could be generated, stored and delivered to the different users in the vehicle within one integrated power management and distribution system. Thus an All Electric Combat Vehicle (AECV) is a concept whose time has arrived.

3.0Mobility requirements

3.1 Mobility levels

There are three levels of mobility: Strategic, operational and tactical. Strategic mobility is the ability of the vehicle to move or be moved into the operational theatre. This implies that lighter and smaller vehicles have greater strategic mobility. Operational mobility is the ability of the vehicles to move by their own power at various speeds. Tactical mobility or battlefield mobility is the ability of the vehicle to move over various terrains and obstacles such as ditches, trenches and streams.

The operational and tactical mobilitity requirements are extreme but necessary because the vehicle must be able to operate in various military environments. The most critical mobility requirements are:

- Vehicle top speed
- Vehicle top cross country speed
- Gradeability (60% max)
- Steering
- Acceleration
- Braking
-

3.2 **Tractive forces**

Some of the mobility requirements (steering, gradeability) are specified in terms of tractive effort to weight ratio (te/wt). Tractive effort being the tractive force needed to cause vehicle movement. For further clarification, the torque at the wheel or sprocket is the product of the tractive effort and the sprocket or tire radius.

Coincidentally, the te/wt for 60% grade and for pivot steer is approximately the same and is equal to 0.6, and a tracked vehicle traveling at 15 mph while turning on a 50 foot radius subjects its tracks to stresses comparable to climbing a 40% grade. The cooling point is 0.7 te/wt ratio. That means the vehicle cooling system must be designed so that the drivetrain components can be continuously subjected to loads equivalent to 0.7 te/wt without exceeding their thermal limits. The maximum transient te/wt requirement for the total vehicle is 1.2, which is needed under certain severe operating conditions such as pulling out of deep and frozen mud. The most critical te/wt ratio is required for regenerative steering and it is 0.9 per side only, with 1.0 te/wt differential between the two sides. The rational for the last requirement was specified for certain rare operating conditions where the vehicle's weight would be supported by one track only. Such conditions arise when one track is in a ditch or totally stuck in frozen mud or ice. Another situation is when one track is in a ditch to the extent that substantial earth movement is required. Under both of these situations the te/wt was calculated and found to be about 0.9 which must be achieved by the track that carries the weight of the vehicle. Fig 1. illustrates the different levels of te/wt ratio for the various conditions described above.

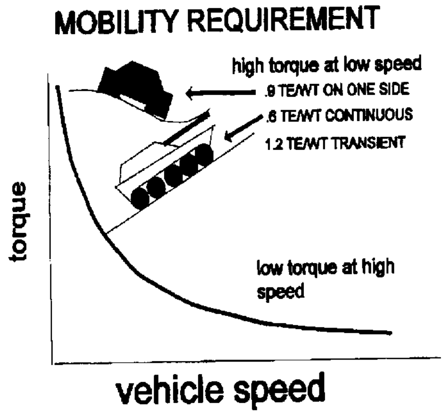


Fig 1

It should be noted that the te/wt values for the cooling point and the gradeability requirements are continuous. Whereas the maximum vehicle te/wt of 1.2 and the regenerative steering of 0.9 per side are transient values ranging from 0 to 60 seconds.

The governing equations for mobility are:

$$TE = RRF + GRF + WRF$$

$$DBP = TE - (RRF + GRF + WRF)$$

$$GRF = GVW * SIN((ARCTAN(.01 * \%GRADE))$$

$$WRF = \frac{CD * FA * V^2}{418.5}$$

Where:

RRF Rolling resistance i.e. force resisting vehicle's motion due to tire or track and road surface deflection and is also a function of the amount of sinkage of the track or tire in soft soil. Values range from 2% to 10% of the total vehicle weight.

GRF Slope resistance

WRF	Wind resistance
CD	Coefficient of drag
FA	Vehicle frontal area
V	Vehicle ground speed

3.2 Horsepower requirements

Requirements such as acceleration, top vehicle speed, steering at large radii and cross-country speed depend on the available horsepower originating from the prime mover and getting to the sprockets or wheels when needed for the various vehicle mobility conditions.

For all vehicles the power is transmitted from the prime mover to the wheels or sprockets through some type of transmission (mechanical, hydraulic or electrical) at different speeds and torques. The relationship of these parameters is defined by an operating envelope such as the one shown in Fig.2.

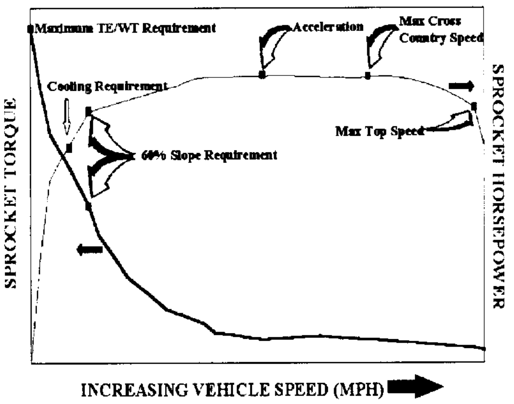


Fig.2 Operating envelope

For a combat vehicle each point shown on the operating envelope is a critical requirement. The top speed is required to enable the vehicle to move quickly into the operation zone. The top cross-country speed allows the vehicle to move at the highest possible speed in a battlefield environment, thus minimizing its exposure as a moving target. The 60% slope requirement, which requires about 0.6 te/wt at a speed of 10 kph, is needed for following the most strategic routes despite unfavorable terrain. Other transient conditions higher than 0.7 te/wt exist under some rare conditions as described in paragraph 3.2 (Tractive forces). Acceleration requirement is directly tied to survivability as it provides the vehicle the maximum dash capability and limits its exposure time from cover to cover.

State-of-the-art hydromechanical and hydrokinetic transmissions can meet all vehicle requirements described above; provided that an adequate power is delivered to the transmission from an engine. Electric transmissions in a hybrid electric drive system offers two advantages over their mechanical counterparts vis-à-vis the mobility requirements: Faster acceleration, and Burst power capability. The greater acceleration results from the peak torque at zero speed, which is a characteristic of all electric motors. The burst power is provided from the energy storage system.

One important mobility operation; not shown on the operating envelope is steering. Some steering conditions for tracked vehicles require power at the outer track that exceed the engine horsepower by a factor of two.

The outer sprocket must be able to handle about 220% of the power delivered from the engine and the power absorbed at the inner sprocket may amount to 165% of the engine power, which can be regenerated to the outer track with a suitably designed transmission.

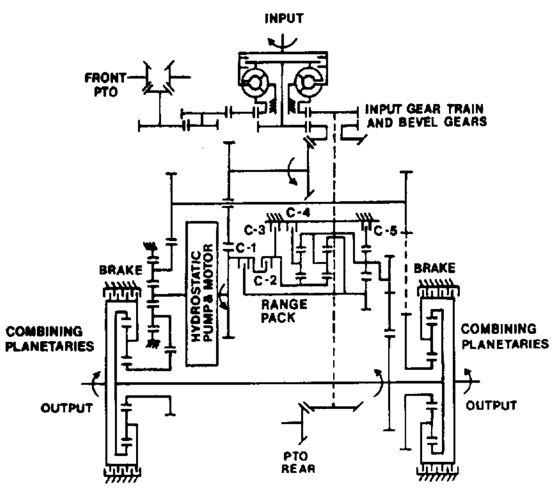


Fig.3 Hydrokinetic Transmission

Power regeneration can be achieved through clutch and gearing arrangement in the case of mechanical and hydraulic transmissions as shown in Fig 3. and electrically in the case of electric drives.

The hp equation for the power needed at the vehicle sprocket is given by:

$$HP_{SP} = \frac{TE*V}{375}$$

Typically about 75% of the net power from the prime mover

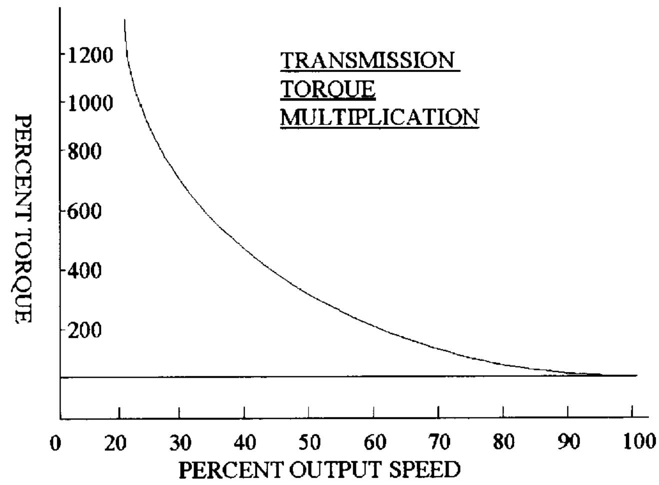


Fig. 4

reaches the sprocket over 10% to 100% of vehicle speed and The rest 15-20% of the engine power is wasted into frictional, spinning and heat losses. Fig 4 shows the speed and torque of a tracked vehicle over the speed range

4.0 Vehicle performance calculations

4.1 Mechanical drives

For a typical tracked vehicle with a hydraulic transmission (i.e either hydrokinetic, hydromechanical), as represented in Fig 5.

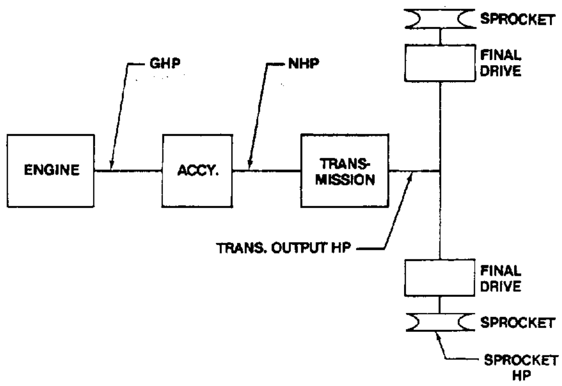


Fig.5

The approximate Losses can be broken down as follows:

Accessories 85% efficiency	15%
Transmission 85% efficiency	15%
Final Drive 97% efficiency	3%

Thus the total driveline efficiency:

$$Eff_{driveline} = .85*.85*.97=70\%$$

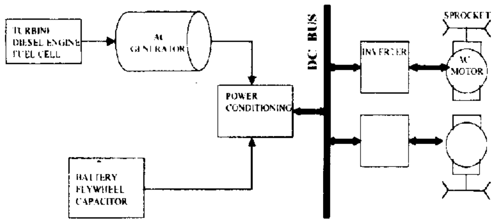
The required engine gross horsepower is therefore the sprocket horsepower divided by the total driveline efficiency, or:

$$\text{Engine GHP} = \frac{\text{Sprocket hp}}{.70}$$

5.0 Electric Drives

There have been several attempts since the beginning of this century to power the automobile and heavy vehicles both industrial and military with electric drive. However, each attempt finished by identifying technical shortfalls that forced the electric drive to remain a concept in the minds of engineers and scientists while allowing the conventional powertrains of IC engines and mechanical or hydraulic transmissions to advance. Two of the main shortfalls of the electric drive systems have been the battery range and the inefficient controls. Despite their shortfalls however, electric drives have been very successful where high power was needed, as is the case with locomotives, ships and mining equipment

It should be indicated that most of the reasons for considering electric drives have remained the same for the last sixty years. For commercial applications, the compelling reasons are fuel economy, reduced emissions, modular components and better performance. Similarly, the same reasons are driving electric drives for military applications; plus some very important benefits that are critical for military missions, such as silent watch, silent mobility, more electric power on-board the vehicle, better utilization of the under armor space claim and the design flexibility for either front drive or rear drive systems.



HYBRID ELECTRIC

Fig.6 Electric drive schematic

Fig (6) shows a typical configuration of electric drives for military applications.

The schematic which is very generic shows a hybrid system having two sources of power, an engine (Turbine or diesel) driving a generator and an energy storage device (Flywheel or batteries). All the power generated from either or both sources are put into a DC bus and then transferred to the traction motors and other auxiliaries as needed to match the continuous and transient loads. The hybrid system has the advantages of using a small engine that can satisfy some of the continuous mobility requirements with less fuel and less emission levels than the bigger engine that would otherwise be required. All the transient requirements in a hybrid system are met from the stored energy. This also allows the vehicle integrator to size the components for burst power requirements such as accelerating or hill climbing. The Hybrid system provides also the added capability of silent watch and silent mobility while operating on the battery power alone.

5.1 Performance calculations

Thus far the performance characteristics of the electric drives have been primarily based on projections and limited test data of prototypes. Therefore, all performance predictions in terms of total system efficiency over the speed range of the vehicle need to be verified through field testing and evaluation. However, the data obtained from component lab tests show that electric drive total losses are equivalent to those of the mechanical systems. A typical electric transmission shown in fig.6 consists of a generator/alternator, a rectifier, a DC bus, two traction motors and their inverters. For such a system, the losses are estimated to be:

Generator	4%
96% efficiency	
Rectifier	4%
96% efficiency	
Motors	5%
95% efficiency	
Inverter	5%
95% efficiency	

The accessory losses are similar to those of the mechanical drive system I.e. 15% and the final gear losses are 3%.

The total system efficiency:

$EFF_{driveline}$= .96*.96*.95*.95*.85*.97=.69%

The Prime power source(s) will have to deliver an output of :

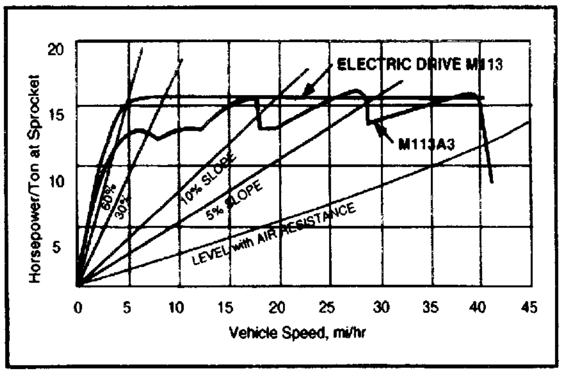
$$GHP = \frac{\text{Sprocket hp}}{.69}$$

5.2 Advantages

Some of the advantages of electric drives are listed in the previous paragraph. In order to understand the benefits of electric drives for military vehicles; we should evaluate their impact on the mobility criteria described in section 3.1.

5.2.1 Effect on vehicle speed and acceleration

Electric drives provide better agility than the mechanical system because of the inherent torque speed characteristic of all electric motors. Unlike mechanical and hydraulic transmissions, electric motors reach their peak torque at zero speed, which provides more power for acceleration at the low end of the power speed curve as shown in fig.7. In addition, since there is no gear shifting, electric drive act as continuously variable transmission where torque and speed are delivered to the traction motor to match its mobility needs on a continuous basis.



Comparison of available horsepower for the M113A3 and the Electric Drive M113 at same engine rating

Fig. 7

For cross country speed, electric drive systems provide sufficient power to incorporate active suspension which is needed to maintain stability of the platform on cross country terrain at high speeds

5.2.2 Effects on Gradeability

Electric drives have been successfully proven to meet the 60% grade with speeds equal to or higher than those achieved with mechanical drivetrains. In the case of a hybrid system, the energy storage on-board the vehicle can provide the burst power needed for hill climbing while keeping the engine at its constant speed.

5.2.3 Effects on steering

For wheeled vehicle, there is no difference between the steering systems used other than the fact that electric powered steering system is more readily integrable in electric drives. For tracklaying vehicles however, steering with electric drives offers precise control by making one motor act as a generator to slow the inner track and speed the outer one. Although, it is the same principle for mechanical systems, the mechanism to achieve speed differential between the tracks is much simpler with electric drives.

5.2.4 Effects on braking

In the case of braking both traction motors are turned into generators to slow the vehicle and cause it to stop. A significant advantage in the electric braking is the capability of the system to capture the braking energy and store it back into the energy storage of the vehicle. Thus energy is regenerated and redirected into either a battery system or to other auxiliary users on the vehicle.

6. Challenges and enabling technologies

The most critical technical barrier for electric drive is the limiting operating temperature of the power semiconductors used in the motor and generator controllers. The power handling capability and reliability of state-of-the art silicon devices is limited by thermal performance. The operating temperature of Silicon devices is limited to approximately 150^0C. Other parameters such as reliability, frequency, and power handling capability of power semiconductors are also limited by the thermal characteristics of silicon.

The key challenge for electric drive is to develop power semiconductor switches that will provide system-level performance needed to meet vehicle requirements. However, the strategy should not strictly focus on the power switch. Advances in power converter circuit topology and control, thermal management, and improvements in other components, such as capacitors, bus bars, or inductors, may also yield significant system improvements.

Important system-level benefits for military applications are:

Higher reliability, longer life, high efficiency, improved fuel economy, lower cost, lower losses, smaller and lighter components, and reduced signature. At the switch level, the specific technical challenges for power semiconductors are: lower losses, higher reliability, higher operating temperature, lower thermal resistance, higher surge capability, and higher frequency operation at higher power levels.

The use of wide-bandgap semiconductors can have significant impact on electric drive application in a number of ways. Wide bandgap materials offer high temperature operation and much

higher electric fields. This leads to significant improvements in efficiency, cooling, and power density. Thus far, silicon carbide (SiC) is the most advanced of the wide band gap materials. The higher junction temperature possible with SiC allows effective cooling with higher temperature coolant, better surge capability, and higher power density. Silicon carbide thyristors have already demonstrated reliable operation at temperatures up to 500^0C, much higher than what is possible with silicon devices.
Estimates suggest that SiC devices, probably diodes, may be commercially available as early as 2003. There are, however, significant problems to be addressed before the potential of the material is fully realized. Material defects, particularly killer defects called "micropipes", must be reduced. High quality, uniformly doped, low-defect epitaxial layers must be consistently produced. Processing and device fabrication techniques must be advanced.

Considerable effort is underway worldwide to produce useable SiC wafers for switching devices.

6. Prime Power

The prime power used so far for electric and hybrid electric drives have been conventional engines. High speed diesel engines are currently being developed for hybrid electric cars and trucks. Fuel cells are being developed in the United States, Canada and Europe as an alternate prime power but they are not expected to replace the conventional engines any time soon.

6.1 Diesel engines

Most of the electric drive demonstrators to-date are powered with diesel engines. The main reasons for the diesel selection are its availability, and its high efficiency compared to other power plants. The diesel engine however has some disadvantages that need to be considered if it is to be used successfully in a hybrid electric system. First, the diesel is heavy, the hp/ton property of a diesel may be difficult to meet the desired metric of (20-25 hp/ton) due to its weight and the large cooling system it requires. Second the diesel engine has high levels of noise and smoke signatures. For a hybrid system there is an opportunity to reduce the weight and cooling burdens of the diesel by reducing the size of the engine which is made possible through the proper design and selection of the energy storage system.

6.2 Turbines

The turbine is ideally suited for electric and hybrid electric drives.

Its output speed matches that of the alternator it drives without the need of a gearbox. It is light with very low signature compared to a diesel engine and it runs cooler, therefore its cooling system is small and does not pose a design or integration problem. However, the turbine does have some disadvantages. The initial cost of the turbine is relatively high, it requires large amounts of intake air, which imposes air filtration burden, and it is not as efficient as diesel engines. Typically the specific fuel consumption (SFC) of a turbine is 0.45-.50 lbs./hp-hr as compared to 0.35 lbs/hp-hr for a diesel engine.

In a hybrid application, the efficiency of the turbine could be maintained at a comfortable level by running at a quasi steady state; which is possible with a hybrid electric since the ground speed is not dependent on the speed of the engine. This will prevent the turbine from cycling during varying vehicle speed, which is a primary cause for high fuel consumption.

Other desirable application of turbine engine in electric drives is the electrical turbo-compounding currently under investigation. This concept redirects the energy from the diesel exhaust to drive the turbine wheel of a small turbine and convert some of the wastegated exhaust heat into electrical energy.

6.3 Fuel Cells

The fuel cells are still in their development stage. Their advantages are the claimed high efficiency associated with them. Efficiency numbers as high as 60% or more have been quoted for fuel cells by virtue of the direct conversion of chemical energy into electrical energy. Fuel cells have been demonstrated on a small scale for stationary power plant and for busses. However, for small commercial vehicles and for military vehicles, fuel cells have some disadvantages that require extensive development, which put them in the category of long term technologies. For commercial applications, fuel cells seem bulky and occupy large spaces, their configuration is not simple because of the complicated plumbing associated with them.

For military applications, fuel cells could not be considered unless they use the same fuels used for military vehicles. That implies that fuel cells would require reformers to extract the hydrogen from hydrocarbons before they could be accepted for military use. Adding a reformer would significantly reduce the efficiency of the fuel cell to make it almost the same as that of the diesel engine.

7. Summary

Military vehicle requirements are defined by mission scenarios over various terrains and environments anywhere in the world. These requirements dictate the design philosophy of the vehicles, which has evolved in the last eighty years according to the technological evolutions.

Future vehicles have new requirements, which could not be met with conventional methods. Therefore, new technologies have to be developed and applied to meet future vehicle needs. Electric drive is a prime candidate that is being considered worldwide for the XXI century. Its application will cover both the military and commercial markets even though the motives and benefits are not the same. Although electric and hybrid electric cars and trucks could be introduced for highway driving today, they are not yet applicable for the military due to the shortfalls of power electronics. Current development of wide band gap materials such as Silicon Carbide seem very promising for fielding electric vehicles in the next ten to fifteen years from now.

8. References

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Khalil & Hitchcock
(presenter: G. Khalil)

Question 1: R.L. Evans, University of British Columbia, Canada

You mentioned several prime movers, such as fuel cells and diesels. What do you see as the role of the gas turbine?

Answer:

The gas turbine is not popular in this application because of its poor fuel ecomony. However, a potentially good application for the gas turbine would be in a hybrid system. With a hybrid system the speed of the engine is not coupled to the speed of the drive-wheels or the sprockets. Therefore, the turbine does not have to be cycled during transients. It can be run steady-state at constant speed in its best operating mode. This would probably eliminate the fuel consumption penalty. Then, the gas turbine advantages could be capitalized upon, such as better matching with the generator, low noise, high power density, etc.