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NEXT-GENERATION IN-WHEEL ELECTRIC HUB DRIVES

J. Mackey, S. Goldsack, S. Dick
QinetiQ Ltd.
Farnborough, UK

DISCLAIMER

ABSTRACT

The series Hybrid-Electric Drive (HED) architecture brings a significant range of potential benefits to military ground platforms. Electric-drive wheeled vehicles can feature electric traction motors in a conventional driveline, but also offer potential for motor incorporation into the axle or the wheel hub. The implementation of in-wheel hub drives presents challenges both in their design and to the overall vehicle system. However, by overcoming these challenges, the vehicle designer is rewarded with greatly increased freedom in vehicle hull and suspension design and numerous other benefits arising from the elimination of much of the mechanical driveline and the provision of individual wheel control.

Many hub drive development programs of the previous two decades that have produced demonstrator vehicles have been typified by a large wheel rim size in order to accommodate a traction motor of sufficient power to achieve both peak output torque requirements and peak rotational output speed through a single reduction ratio. In some cases, traction motor rating has also been driven by the need to provide full vehicle braking capability by absorbing energy in regeneration. The need for a large wheel rim limits the further development and adoption of hub drives, as it implies excessive un-sprung mass, reduced off-road tire performance, and limited off-the-shelf tire compatibility. Large motor size also implies proportionately large power electronics.

QinetiQ Limited are developing next-generation hub drives as part of DARPA's Ground-X Vehicle Technologies program, as well as under QinetiQ IRAD, with the aim of overcoming these obstacles by integration of a small, power-dense permanent magnet motor with a three-speed planetary reduction gearbox and liquid-cooled friction disk brake, packaged within the space-claim of the standard 20" wheel rim. The motor design has demonstrated capability to deliver power to exceed the power-to-weight ratio of present-day military platforms. Incorporation of a multi-ratio integrated gearbox allows the hub performance envelope to extend to both high-tractive torque at low speed for obstacle crossing/gradability, and to high vehicle speeds for on-road use. Using a cooled integrated friction brake allows for dissipation of braking energy far in excess of the rated power of the traction motor to ensure full braking capability. This system has been successfully demonstrated to TRL-5 within the space claim of a standard 20" military wheel rim. This effort takes the state of the art a significant step closer toward wide adoption of hub drives as a critical building block in the HED vehicle architecture.

INTRODUCTION

Hybrid-Electric Drive is the future

Hybrid-electric powertrains date back to the genesis of the automobile and have achieved thorough penetration into rail and industrial applications and continued growth in automotive, off-highway, and marine sectors. Despite prototype Hybrid-Electric Drive (HED) platforms as far back as WWII, HED has yet to enter full series production in a military ground vehicle.

The HED architecture (in various configurations, but most notably the familiar series-hybrid layout) offers a large set of significant system benefits to tracked and wheeled armored vehicles. These include increased automotive performance, considerable flexibility in powertrain packaging, electrical power take-off, and lifecycle cost reduction through growth capability, reliability, modularity, reduced maintenance and improved fuel efficiency.

HED is a decisive waypoint on the future technology path for military ground vehicles. The benefits that the associated architectures would bring to the warfighter will continue to pull HED towards the mainstream. Figure 1 shows the powertrain and running gear of BAE Systems' Ground Combat Vehicle (GCV) prototype, which incorporates the QinetiQ E-X-Drive® electro-mechanical transmission.

Figure 1: Tracked HED architecture. Photo courtesy BAE Systems

In-wheel electric hub drives

Further significant vehicle enhancements can be realized through optimization of the electro-mechanical driveline. In-wheel electric hub drives have long been recognized for the potentially disruptive advantages they offer to vehicle layout and capability. Hub drives have yet to enter service despite a number of promising research and development programs in the last two decades.

HUB DRIVE BENEFITS

Vehicle layout

Concentrating the electro-mechanical driveline into the width and diameter of the wheel hub confers a number of vehicle benefits in addition to those arising from the hybrid-electric architecture. A number of typical driveline elements are eliminated, including the launch device (clutch pack or torque converter), transmission, drive shafts, transfer case, differentials, half-shafts, and all associated mounts, bearings, interstitial joints and couplings (see Figure 2).

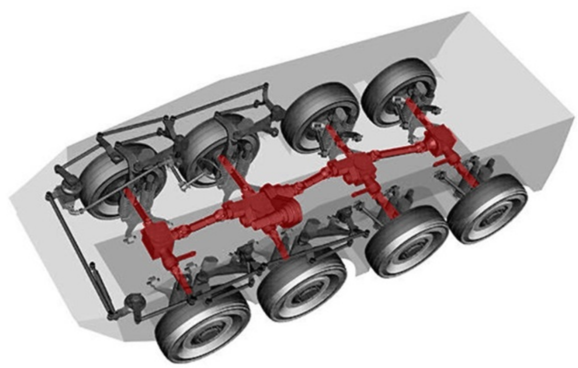

Figure 2: Boxer Multirole Armoured Vehicle (MRAV) (driveline highlighted in red). Photo courtesy UK Ministry of Defence (MOD).

Cutting down the number of driveline components improves vehicle volumetric efficiency, greatly reduces the total part count and the rotating mass, eliminates a number of wear items and single-point failures, and potentially allows hybrid powertrains to deliver total system weight savings. The UK MOD's HED Evaluation Program demonstrated an 8-percent lower total laden mass of a 6x6 hub-driven HED demonstrator over a like-for-like conventional reference vehicle. Decentralization of the powertrain can be employed to de-constrain interior space allocation, optimize vehicle weight distribution and to lower the center of gravity, particularly by comparison to conventional vehicles in which the engine position is elevated in order to clear the axles, as illustrated in Figure *3*.

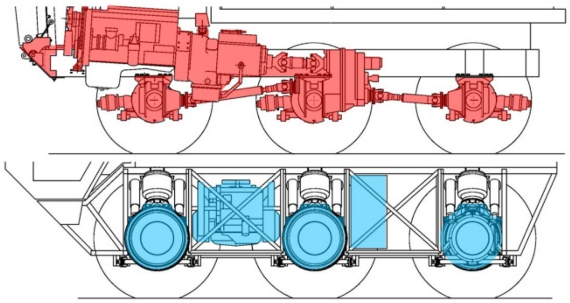

Figure 3: QinetiQ 6x6 powertrain comparison – conventional (red) vs. hybrid (blue).

Without the need for the driveline to pass from the vehicle interior out to the driven wheels, significant freedom is enabled in hull armor system design for increased blast survivability. This is a significant benefit because of the heavy influence of IED and mine threats on the design of current and next-generation armored vehicles.

Steering and suspension

Substantially increased design freedom is also afforded for the suspension and steering systems where articulation limits of the half-shaft conventionally imposes a strict boundary on the displacement envelope of driven wheels. Hub drives concurrently allow steering articulation with extended suspension travel. Implementation of more exotic capability such as diamond steer, crabbing and adjustable track-width is facilitated. Electric drive is ideal for integration with electrically actuated active suspension. Coordinated control of electric traction and ride offers significant performance enhancement in handling, off-road capability and obstacle climbing.

Individual wheel control

The use of in-wheel motors gives rise to the utilization of individual wheel control (IWC). Whereas in a conventional vehicle this can only be realized through the use of bulky torque-split devices or the control of individual brake actuators, hub drive wheel torques are directly and exclusively controlled by software which offers potential for enhanced vehicle performance. Improved traction control and direct yaw control can be used to aid cornering and also to reject lateral disturbances in straight line running. This improves vehicle stability, handling characteristics and acceleration performance, increases driver control and reduces driver cognitive burden. IWC can also be used to tactically break traction on selected wheels to enable pivot turns. This could provide vehicles with eight, six, or potentially even four wheels a greater ability to escape ambush situations in urban environments by pivoting on the spot, rather than having to perform challenging reversal maneuvers at speed.

Unlocking the current vehicle design paradigm

With the advantages described, future electric hub-driven vehicles will benefit both from incremental performance improvements over the state of the art and also from significant step-changes in capability. This will be critical to breaking the growing tension between the simultaneous demands for protection, mobility and more equipment on vehicle systems.

PRIOR WORK AND STATE OF THE ART

Previous development efforts

The incorporation of electric motors into vehicle wheel hubs is a concept nearly as old as the automobile (see Figure 4). Despite the ever-increasing level of electrification of vehicle powertrains, the approach of using in-wheel hubs has failed to achieve the packaging and dynamics requirements necessary to succeed in the commercial passenger automotive sector. A level of acceptance of in-wheel and near-wheel drive has been achieved in off-highway and industrial applications and increasingly in the Chinese bus market, where the packaging advantages have been recognized.

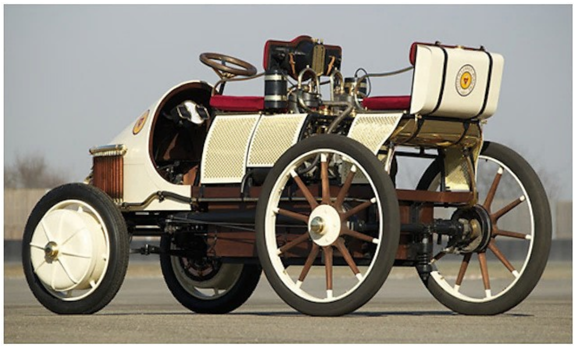

Figure 4: 1900 Lohner-Porsche Semper Vivus. Photo courtesy Porsche Cars North America, Inc.

A number of notable development programs in the 1990s and 2000s have demonstrated in-wheel hubs in platforms across the 5-30T weight range for both lighter protected vehicles and heavier combat platforms, such as RST-V (Figure 5) and the Swedish SEP-W (Figure 6).

Figure 5: GDLS RST-V Shadow. Photo courtesy US Marine Corps.

Figure 6: BAE Systems Hägglunds, SEP-W demonstrator. Photo courtesy BAE Systems.

Most in-wheel hub drive demonstrator programs have been unable to package the motor, gearing and brakes within a standard 20” rim. This is has been necessary in order to accommodate a traction motor of sufficient power to achieve both peak output torque and maximum rotational speed through a single reduction ratio. In some cases, traction motor rating (and hence volume) has also been driven by the need to provide vehicle braking capability solely with regenerative energy absorption. As typical peak braking powers are usually an order of magnitude greater than rated propulsion powers, this requirement dictates large electric machines.

The need for a large wheel rim limits the further development and adoption of hub drives, as it implies excessive un-sprung mass, reduced off-road tire performance, and limited off-the-shelf tire compatibility. Large motor size also implies proportionately large power electronics to handle the necessary current required to generate torque.

QinetiQ’s work and heritage

QinetiQ’s background in electric drives extends back to the late 1990s with the UK MOD HED evaluation and demonstration programs that culminated in the design and build of a HED 6x6 High-Mobility Load Carrier (HMLC) incorporating in-wheel hub drives, incorporating a multi-speed gearbox and mechanical foundation brake.

The purpose of the demonstrator was twofold, first to validate the QinetiQ HYSIM® driveline model and secondly to physically demonstrate the benefits of HED to UK MOD. Figure 7 shows the HED demonstrator in front of an earlier conventional driveline 6x6 HMLC designed and built by QinetiQ, as part of an earlier program.

Figure 7: QinetiQ HED & Conventional HMLC demonstrators.

QinetiQ is exploiting its expertise in in-wheel hub development and more recent experience developing electric drive to a high TRL for its E-X-Drive® tracked vehicle electro-mechanical transmission for the US DoD GCV program. Figure 8 shows E-X-Drive® installed in the BAE Systems L&A L.P. 'Hot-buck' dynamometer Systems Integration Lab (SIL).

Figure 8: QinetiQ E-X-Drive® installed the 'Hot-buck' SIL (Photo courtesy BAE Systems).

Knowledge and experience from nearly 20 years' activity in the HED domain has been brought to bear on the design and demonstration of the Next-Generation Hub Drive Unit (HDU) for the DARPA-managed GXV-T program and in-house IRAD-funded developments in this area.

QINETIQ'S DESIGN VISION

QinetiQ Limited are developing next-generation hub drives as part of DARPA's Ground-X Vehicle Technologies (GXV-T) program, seeking to overcome these obstacles by integration of a small, power-dense permanent magnet motor with a three-speed planetary reduction gearbox and liquid-cooled friction disk brake within the space-claim of the wheel hub.

High performance

QinetiQ's design vision is driven by:

- Providing an extreme performance HDU to meet DARPA's GXV-T vision for radically improved vehicle concepts
- Providing features and an architecture that would apply to both future and current vehicles, as new build or retro-fit proposition
- Establishing an architecture that can be scaled back or "de-tuned" from DARPA the extreme performance envelope to levels more in line with contemporary vehicles, which we call the Market-Attractive Hub (MAH)

Whether considering a radical new GXV-T type concept or a contemporary 8x8 Armored Fighting Vehicle (AFV) application, the starting point for the design specification is one of vehicle mobility; tire size and axle weight are the key parameters. All practical high mobility tires on current 8x8 vehicles have a diameter in the region of around 1.3 m, width of 0.4 m and a 20" wheel rim size. Other tires of these external dimensions are available on a 25" rim, which obviously provides more space for the hub drive, but these have a lower side wall height which does not provide such a good mobility footprint. These tires are really designed for quarry type applications, and for high mobility off-road vehicles hub drives must be designed to fit into a 20" rim. In terms of wheel load,
3.5 to 4 tonnes is a sensible maximum number; this ties to both weights typically found on contemporary vehicles and moreover represents the practical maximum that can be achieved in the high-mobility weight class, before ground pressure and mobility is compromised.

Suits any suspension

Given the diameter defined by the 20" wheel rim, and ensuring that the outer plane of the hub does not protrude outside the wheel where it could be damaged, nor allowing the inner plane to move inwards into the suspension volume, the design volume is fixed. A lot of credence is placed on ensuring the inner plane of the hub does not interrupt the idealized suspension geometry where one key objective for military ground vehicles is to minimize the ground offset.

Electro-mechanical system sizing

With the volume fixed, QinetiQ's design approach for DARPA has been to "pack as much power" into the volume as possible, whilst providing certain key performance levels and features:

- Sufficient continuous power to achieve 120 kph at 3.75 tonne-per-wheel on 0.06 rolling resistance soil

- 0.8 TE/GVW continuous
- 1.2 TE/GVW peak instantaneous
- Electrical regenerative braking
- Mechanical foundation and park brakes
- Central tire inflation

This has resulted in a design point for the DARPA GXV-T HDU of 90 kW mechanical output power at the wheel rim. Assuming 3.5-tonne wheel load and 0.86 overall driveline efficiency, this equates to 30 kW/tonne as measured at the engine. An assessment of 30 wheeled military vehicles from around the world shows an average power-to-weight ratio of 15 kW/tonne (installed); around half that of the GXV-T target design point. The highest power-to-weight ratios in existing vehicles are around the 20 kW/tonne mark. Figure 9 shows a plot of installed power against gross weights for a number of contemporary vehicles.

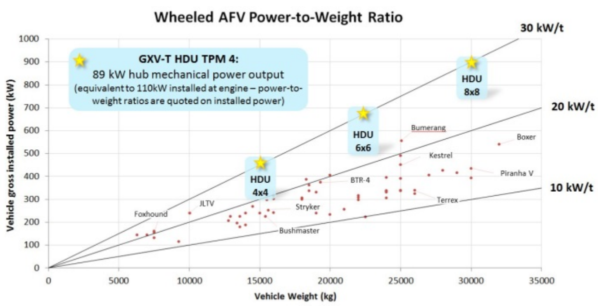

Figure 9: Chart of power-to-weight ratios with representative HDU installations indicated

As a part of QinetiQ's vision to take this technology to the market, a parallel design is in development with a target of 22 kW/tonne. The intent being that this is a 'Market-Attractive Hub' (MAH) that could be retro-fitted to existing platforms or incorporated in new platform designs.

In order to achieve these goals, QinetiQ's design philosophy has been to combine the electric drives with multi-ratio gear boxes. This has been an approach first deployed in QinetiQ's early hub drive work in the late 1990s and more recently successfully deployed in various iterations of the E-X-Drive® electro-mechanical tracked vehicle transmissions in the US Future Combat System (FCS) and Ground Combat Vehicle (GCV), working with BAE Systems L&A L.P.

This approach avoids having to size the power inverters and motors to deal with the extremes of the torque-speed map, and allows instead a motor that is balanced in terms of its torque and power and power generating capability. Figure 10 shows the HDU torque-speed map across three gear ratios, with comparison to a larger (hypothetical) direct-drive motor that would be required to achieve the same maximum speed and torque values. It should be understood that the in-hub gear changes would be initiated automatically by the in-hub wheel controller (i.e., no driver interaction required).

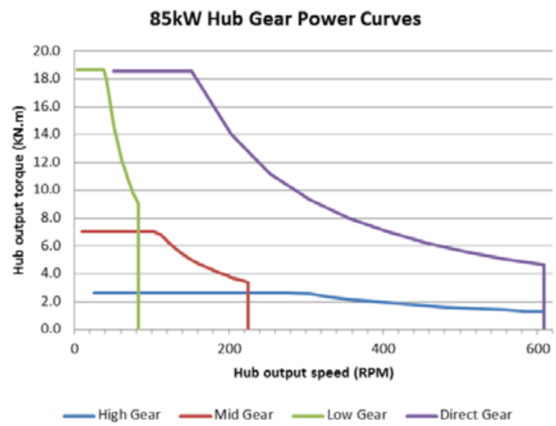

Figure 10: Hub drive torque-speed map (with hypothetical single-ratio direct-drive motor for comparison).

Cost effective

Also key to QinetiQ's vision is the need to establish a design that is cost competitive at system level (complete driveline) to a conventional system and work has still to be done quantifying this aspect. QinetiQ's approach in minimizing the size of the electrical system is seen as a key aspect of achieving a cost competitive solution.

Finally, QinetiQ sees electric hub drives, ultimately, as part of a "unit of mobility" – a wheel station that actively controls the suspension, wheel speed and drive torque to best suit the operating conditions of the vehicle. As suspension design and control is a balance between ride, handing and dynamic tire load (DTL) variation, the suspension can be controlled actively – for instance to minimize DTL in unison with the wheel drive torque and speed to maximize traction in a case where soft soil mobility is key (GO/NO-GO). QinetiQ also sees the use of a complementary long-travel suspension to open up the performance envelope of the electric drive vehicle with hub drives.

HDU DEVELOPMENT UNDER DARPA GXV-T

Radically enhanced tactical mobility

DARPA's GXV-T program seeks to disrupt current trends of increasing weight and compromised mobility in mechanized warfare by revolutionizing the speed, terrain access and survivability of future ground forces. Figure 11 shows the DARPA GXV-T concept vehicle.

Figure 11: DARPA artist's concept vehicle showcasing extreme agility and survivability

Extreme specifications

To further the program aims, the HDU was conceived to ambitious specifications, including high torque, power and speed as shown in Table A.

HDU initial specifications

HDU output power	85 - 100 kW
HDU output torque (max.)	16 kNm (24 kNm)
HDU max. output speed (vehicle speed)	600 rpm (120 kph)
Operating voltage	600 VDC
Inverter rating	300 Arms 8 kHz switching
Coolant flow	80°C PGW <18 LPM

Table A: HDU specifications determined at the program outset

Very high power-density and volumetric efficiency was sought at the outset in order to achieve these specifications within a 20" wheel rim profile. Figure 12 shows an early mock-up of the HDU. What is not shown is an applique thermal shield to minimize any contrasting thermal gradient, as unlike conventional hub ends, the HDU is actively cooled and, to a thermal imager, may actually show as cooler than the rest of the wheel.

Figure 12: Mock-up of an HDU constructed during the first year of technology development

Technical Performance Measures

Technical Performance Measures (TPMs) were set at the program outset to ensure that quantitative outputs were tracked and achieved. These are presented in Table B:

TPM	Value
1. Motorette	58 A sustained
2.Stand-Alone Motor power	100 kW continuous
3. HDU mass	225 kg
4. HDU power at the rim	89 kW continuous
5. Brake holding torque	13.5 kNm
6. Gear shift time	1.2 sec

Table B: Technical Performance Measures

Progress

The technology development program featured extensive trade studies to down-select a preferred HDU architecture and to optimize the design of the sub-systems. The motor design was initially developed and validated by construction and experimentation with a set of individual “motorette” test segments, and concluded in testing and characterization of a full Stand-Alone Motor SAM. Complete HDUs have been acceptance-tested independently (see Figure 13) and driven against each other in a back-to-back configuration to perform load testing.

As of the time of writing, the SAM has achieved 115 kW continuous power output, surpassing its target by 15 percent. The brake holding torque has been successfully met. However, the HDU mass target was exceeded by 4 percent (234 kg measured dry weight).

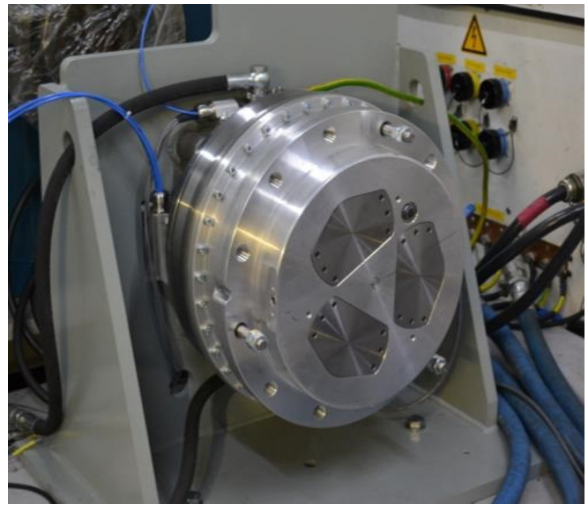

Figure 13: HDU on the test stand (April 2017)

Challenges

The high top speed, high drive torque and power levels of the HDU have been key design factors. HDU weight and cost have been directly driven by the high torque requirement. Packaging all gear stages, bearings, seals and cooling circuits around the motor has been particularly demanding.

The most significant identified technical risk of the development effort was the thermal aspects of the design. Substantial analysis and testing was applied to ensure the capacity of the splash lubrication system to remove heat to the liquid cooled outer casing while ensuring lubrication of moving contact surfaces. Full temperature instrumentation was integrated into the primary HDU in order to rigorously monitor thermal performance at all times during testing.

This effort takes the state of the art a significant step closer toward wide adoption of hub drives as a critical building block in the HED vehicle architecture.

QINETIQ IRAD

Revised specification

As part of QinetiQ’s continuing development of electric propulsion systems, an IRAD-funded program to a design & develop a HDU more aligned with current vehicle requirements has been initiated. As can be seen from Figure 9, the GXV-T targeted HDU design is significantly more capable in crude power/weight terms than existing wheeled vehicles in-service and this is the rationale behind the work to design a ‘Market-Attractive Hub’ (MAH). To support this development an outline performance specification has been prepared (Table C) to guide the design.

Outline MAH Specification

Unit mass	180 kg
HDU motor rated power (max.)	65 kW (100 kW)
HDU rated output torque (max.)	16 kNm (24 kNm)
HDU max. output speed (vehicle speed)	475 rpm (100 kph)
Axle load peak rating	4 tonne/wheel
Operating voltage	600 VDC
Inverter rating	200 Arms
HDU nominal efficiency	92%
Coolant flow	80°C PGW 16 LPM

Table C: Outline performance specification for MAH

System development

A functional and structural architecture for the MAH has been prepared and is simpler and significantly different to the GXV-T HDU design that is designed for extreme performance. The MAH design is currently at the late concept stage and is at the point of starting detailed design; Figure 14 illustrates the current concept.

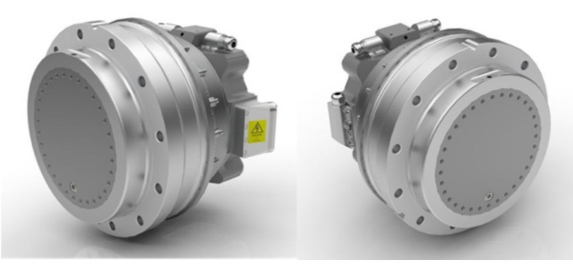

Figure 14: QinetiQ MAH concept

As part this IRAD activity a detailed 24 month program is being prepared that will address the development tasks necessary to take this design to the point where a full vehicle demonstration can be undertaken. Tasks include:

- Detailed design of MAH
- Sub-system development including matching inverter/integrating with the MAH and power and cooling interfaces/umbilicals
- Laboratory demonstration of MAH ‘Unit of Mobility’
- Preliminary environmental stress screening & EMC testing
- System demonstration on a representative vehicle

Figure 15: Immersion testing of earlier HDU

As a legacy of previous programs several existing facilities and test stands are available to undertake this work; for example immersion testing (Figure 15) at QinetiQ’s Haslar site in the south of England.

SUMMARY

Extreme performance achieved

HED aims to be a decisive waypoint on the future technology path for wheeled military ground vehicles. The adoption of in-wheel electric hub drives offers a potentially disruptive advantage to vehicle architecture and performance capability, such as improved mobility, agility and a fresh opportunity to simplify the hull structure to enable the implementation of a much-improved armor protection system.

QinetiQ’s GXV-T HDU is achieving the ambitious performance targets set by DARPA to provide ‘radically enhanced tactical mobility’. This program has already demonstrated that a hub drive motor can deliver the required power and torque. At the time of writing, hub drives are being load-tested and are on track to achieve the overall design requirement.

This would enable future vehicles with power-to-weight ratios considerably in excess of contemporary vehicles, whilst maintaining practical and realistic interfaces.

Path to produce Market Attractive Hub

Aligning hub drives with current perceived market need is the next step to wider adoption. This phase would allow improvement in weight and packaging of the hub drive unit to be achieved. It also includes: the development of the hub drive to chassis interfaces; environmental and durability testing; and production optimization.

Future visions – "unit of mobility"

Finally, QinetiQ's vision is the creation of the "unit of mobility", where an electric hub drive is integrated with a long travel active suspension, and controlled in unison to provide radically enhanced vehicle capability.

ABBREVIATIONS

DoD	US Department of Defense
FCS	Future Combat System
GCV	Ground Combat Vehicle
GXV-T	Ground-X Vehicle Technologies
HDU	Hub Drive Unit
HED	Hybrid Electric Drive
HMLC	High Mobility Load Carrier
IRAD	Internal Research and Development
IWC	Individual Wheel Control
MAH	Market-Attractive Hub
MOD	(UK) Ministry of Defence
PGW	Propylene Glycol Water
SEP	Splitterskyddad EnhetsPlattform
SIL	Systems Integration Lab
TPM	Technical Performance Measure
TRL	Technology Readiness Level