Article

A Standardised Mission Profile and Rapid Architecture Screening Methodology for Hybrid-Electric Tactical Wheeled Vehicles

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Abstract

The powertrain architecture of future tactical vehicles is driven by requirements for Silent Watch endurance, Silent Mobility and Export Power. Vehicle programme planning requires architectural decisions at an early stage, but conventional optimisation tools such as Autonomie are time consuming and resource intensive. This paper develops a standardised 24-hour mission profile and applies it to two British Army vehicles; the Boxer 8×8 wheeled platform and the Foxhound-class light patrol vehicle. The mission profile, which is equally applicable to US Army vehicles, is presented for open access, addressing the lack of standard cycles for tactical vehicles, and step-by-step instructions with supporting calculation workbooks are provided that do not need specialist modelling expertise. The cycle is implemented with ePOP Concept version 1.0, an optimisation tool from ZeBeyond Ltd., and parallel and series hybrid architectures are compared for each platform. Functional requirements for Silent Watch endurance, Silent Mobility range and continuous Export Power, are applied. Feasible design regions meeting all requirements are identified for both platforms, and the benefits of ICE-only (internal combustion engine), parallel-hybrid and series-hybrid architectures are compared. The combined mission profile and screening method provide a practical means of supporting architectural decisions quickly with reduced resources at the concept stage of military vehicle programmes.

Keywords: hybrid; Silent Watch; battery sizing; Export Power; tactical vehicle

1. Introduction

The U.S. Army's Rapid Capabilities and Critical Technologies Office has identified extended silent watch, silent mobility and exportable power as the principal operational benefits driving tactical vehicle hybridisation [27], requirements that are equally central to the modernisation of British Army platforms. Tactical vehicle electrification is a NATO strategic priority for enhanced capability, but fuel efficiency is also important. The cost of JP-8, the military diesel fuel standardized within NATO, can rise from a standard price of $1.21/L [1] to $4/L [2] in forward operational environments, and many times higher in combat theatres where fuel supply routes are compromised. Tactical vehicles spend over 75% of mission time at idle [3] including garrison time, maintenance periods, staging at forward operating bases, vehicle recovery, convoy marshalling, and long periods of stand-to. When idling with the engine running, a diesel drivetrain has both poor efficiency and detectable acoustic and thermal signatures, so engine-off operation is highly desirable. The onboard power demands of modern tactical vehicles are also growing, for computing and Directed Energy Weapons (DEW) in particular. Full battery electrification is impractical in remote locations. Hybridisation (the combination of ICE and battery-electric traction power) addresses these changes by making more electrical power available while also reducing fuel consumption.

The military performance requirements for light protected hybrid vehicles are different from those in civilian applications. Silent watch (SW, electrical operation with the engine off, reducing noise) requires onboard energy storage sufficient to power crew systems for operationally meaningful durations. For example, the US eJLTV demonstrator was designed to achieve 8.5 hours from a 30 kWh lithium-ion battery [4], and the GVSC Tactical Vehicle Electrification Kit targeted a 1:1 engine-charging to silent-operation ratio on the Joint Light Tactical Vehicle (JLTV) [5].

Exportable electrical power was a stated objective of the UK MoD’s Technology Demonstrator 6 (TD6) hybrid-drive programme [6], which tasked NP Aerospace, in collaboration with General Dynamics Land Systems–UK, Supacat, and Magtec, to demonstrate hybrid electric drive systems on Foxhound and Jackal vehicles. Hybrid systems were intended to increase onboard electrical generation capacity and enable support for off-board electrical loads in future tactical operations.

An exportable AC power system for tactical vehicles was demonstrated by GS Engineering under a US SBIR (Small Business Innovation Research) contract, achieving 29 kW continuous output (three-phase AC at 120/208 V) [7]. Export Power capability has also been demonstrated at significantly higher levels, with the Electric/Enhanced JLTV (eJLTV) providing up to 115 kW of exportable electrical power [4]. These examples indicate that exportable power levels on the order of ~30 kW represent a recognised capability class for tactical vehicles [4,8], while higher-power hybrid architectures are capable of substantially greater export output. The Leonardo DRS TITAN OBVP system [8] is a vehicle-mounted power generation solution meant to supply exportable electrical power directly from the vehicle’s drivetrain. For medium tactical and combat vehicles, the system can produce electrical power ranging from 30 kW up to 125 kW. The system is designed to support mission power both on the move and at halt, providing a scalable tactical power source.

Silent Mobility (SM, engine-off propulsion) is targeted at 3–6 km at 15 km/h for light tactical vehicles by the Ground Vehicle Systems Center (GVSC) [5]. All these metrics are of the more-is-better variety, i.e. there is no value beyond which the benefit ceases to increase (unlike noise reduction, for example), but these examples confirm the drive to achieve these benefits and provide guidance as to realistic targets.

Published simulations of military hybrid powertrains rely predominantly on high-fidelity tools, for example ADvanced VehIcle SimulatOR (ADVISOR), Powertrain System Analysis Toolkit (PSAT), Autonomie and AVL CRUISE, that require detailed input data such as BSFC maps and component efficiency tables. Several sources state that powertrain architecture selection requires complex analysis, large computation times, powertrain simulation expertise and laborious data-gathering.[9][16][17][28][29] By contrast, the method presented here requires only the vehicle parameters listed in Appendix A, which are typically available in open-source programme documents at the concept stage. No universally accepted military drive cycle exists for tactical wheeled vehicles; published studies have used the Munson, Churchville, Harford, UDDS (Urban Dynamometer Driving Schedule), and FTP-75 (Federal Test Procedure 75) cycles interchangeably, preventing comparison of results across studies [9], and confining each study to just one specific part of operational duty. Auxiliary electrical load, operationally critical for Silent Watch, has been shown to vary widely across multiple mission phases [9], [10][11].

The Foxhound LPPV (Light Protected Patrol Vehicle, 7,500 kg gross vehicle mass or GVM [12]), a blast- and ballistic-protected tactical wheeled vehicle similar to the JLTV in role and weight class, forms one of the two baseline vehicles for this study, and is the primary British Army platform in this category for electrification. The British Army’s TD6 programme [6], delivered by NP Aerospace with GDLS-UK, Supacat, and Magtec, demonstrated hybrid electric drive on Foxhound and Jackal [6] vehicles. The UK MoD’s Land Mobility Programme (LMP) is rationalising its armoured fleet around three successor families. Of these, the Light Protected Mobility (Lt PM) sub-programme, encompassing the Foxhound class at up to 10,000 kg GVM, is currently in early definition [13].

The Boxer 8×8 Wheeled Infantry Fighting Vehicle (38,500 kg GVM [14],[15]) forms the other baseline vehicle for this study. Procured under the British Army's Mechanised Infantry Vehicle (MIV) programme, Boxer is in service or on order with Germany, the Netherlands, Lithuania, Hungary, Australia, Slovakia, and Ukraine, making it one of the most widely adopted 8×8 platforms in NATO. Its Mission Module architecture separates the drive module from the mission-specific payload module, concentrating electrification investment in the drive module powertrain where it applies across the entire fleet. At 38,500 kg GVM, Boxer's power and energy demands differ substantially from those of the Foxhound class.

This paper applies ePOP Concept 1.0 (by ZeBeyond Ltd) [16-18], a rapid parametric powertrain screening tool, to the task of powertrain architecture selection and sizing across both platforms. An open-access mission profile applicable to both vehicle classes is developed from published military drive cycle data and operational requirements. Results are assessed against a multi-dimensional constraint envelope drawn from the US CHPS (Combat Hybrid Power System) programme [11], GVSC TVEK (Tactical Vehicle Electrification Kit) [5], NATO AECV (Advanced Energy Combat Vehicle) [19], and eJLTV demonstrator [4]. This paper is a methodology study, not a validation study. The CEMP-H cycle and the screening method are presented as a structured framework for concept-stage architectural decisions; the simulation outputs have not been validated against measured vehicle data, as no instrumented test data for these specific platforms is publicly available. The cycle parameters and component assumptions are calibratable (see Appendix A), and the method is intended to be applied with platform-specific data as it becomes available during a programme. The value demonstrated here is the speed and structure of the analytical process, not the absolute accuracy of the numerical outputs. It is not necessary to use ePOP Concept to use the Mission Profile, as it is software-agnostic, but instructions are provided in Appendix A for those who wish to see how ePOP Concept was used.

2. Materials and Methods

2.1. Absence of a Standard Military Drive Cycle

No standardised drive cycle exists for tactical wheeled vehicles of any weight class, as noted in Nedungadi et al. [20], where it is stated that the absence of a common duty cycle makes published fuel-economy and electrical-endurance results structurally incomparable. Kramer and Parker [9] list seven different cycle combinations used across published HMMWV (High Mobility Multipurpose Wheeled Vehicle) [21] and JLTV hybrid studies [9], but none of these is generally accepted as a standard, and there is no composite cycle covering all aspects of a mission.

2.2. *The Proposed 24-Hour Mission Cycle with Optional Directed-Energy Weapon Support*

A standard cycle is proposed to fill this gap, with the label "Central European Mission Profile for Hybrid-Electric Tactical Vehicles" (CEMP-H) and offered here for open access, by reference to this paper, which contains sufficient information to re-create the cycle elsewhere. The cycle is divided into nine phases covering a full 24-hour crew period. The schedule is shown in Table 1, and illustrated in Figures 1-3. It simulates a mission in a Central European scenario, where the vehicle departs from a base, drives to a conflict location via both on-road (at maximum speed) and off-road sections, and then performs a stationary Silent Watch for 5 hours during hours of darkness. This is followed by a Silent Mobility patrol for 2 hours, still under cover of darkness, at 20 km/h. Both "silent" phases are conducted on battery power alone, with the ICE switched off, to reduce thermal and acoustic signatures. The vehicle then returns towards base cross-country, and at the point where cross-country terrain switches to on-road terrain, it stops for one hour for weapons engagement. In this phase the engine is running for mobility preparedness, and auxiliary electrical load is at 100% for sensors, communications and weapons. After engagement, the vehicle returns to base on roads. At base, with the crew resting, the vehicle delivers 100% Export Power for 2 hours, and then fractional Export Power, with engine off, for the remainder of the rest period at base. The combined engine-off night block (Silent Watch plus Silent Mobility) totals seven hours, spanning the approximate hours of darkness in this theatre. This lies within the 6–10 hour envelope set by published programme requirements; the TARDEC CHPS (Tank Automotive Research, Development and Engineering Center, Combat Hybrid Power System) threshold [11], the GVSC Tactical Vehicle Electrification Kit (TVEK) programme electrification performance objectives for the JLTV class [5], and the practical darkness window at mid-European latitudes. The cycle is defined as charge-neutral over 24 hours; restoration of the initial state of charge must be demonstrated within the simulation rather than assumed. Whether the whole cycle can be completed with full restoration of charge is a result of the simulation, and particularly the battery sizing. The single maximum-speed segment is set to the target maximum speed for the vehicle. This enables ePOP Concept (or another simulation tool, if used) to determine the engine power required. The workbook for data preparation, as explained in Appendix A, also makes an estimate of the engine power in order to calculate the power used to increase speed between phases.

Table 1. 24-hour mission cycle.

Phase	Duration (h)	Speed (km/h)	Electrical Load (%)	Export Power (%)	Engine On/Off
Transit Departure — Road	2	Max [1]	100%		On
Transit Departure — Cross-Country	2	48	100%		On
Silent Watch	5	0	35%		Off
Silent Mobility Patrol	2	20	35%		Off
Transit Return — Cross-Country	2	48	100%		On
Engagement — Stationary, Engine Running	1	0	100%		On
Transit Return — Road	2	72	100%		On

Phase	Duration (h)	Speed (km/h)	Electrical Load (%)	Export Power (%)	Engine On/Off
Base Rest — Export Power, engine on	2	0	5%	100%	On
Base Rest — Export Power, engine off	6	0	5%	10%	Off

Electrical load % and Export Power % are expressed as a fraction of the vehicle-specific maximum for each, which is calibratable. Speed increases between fixed-speed phases are modelled as full-power acceleration events; transition duration is a simulation output dependent on powertrain architecture and vehicle mass.

Max [1] = maximum attainable speed with engine running; full engine power is applied throughout this segment, battery power is not used for traction, and speed attained is a simulation output.

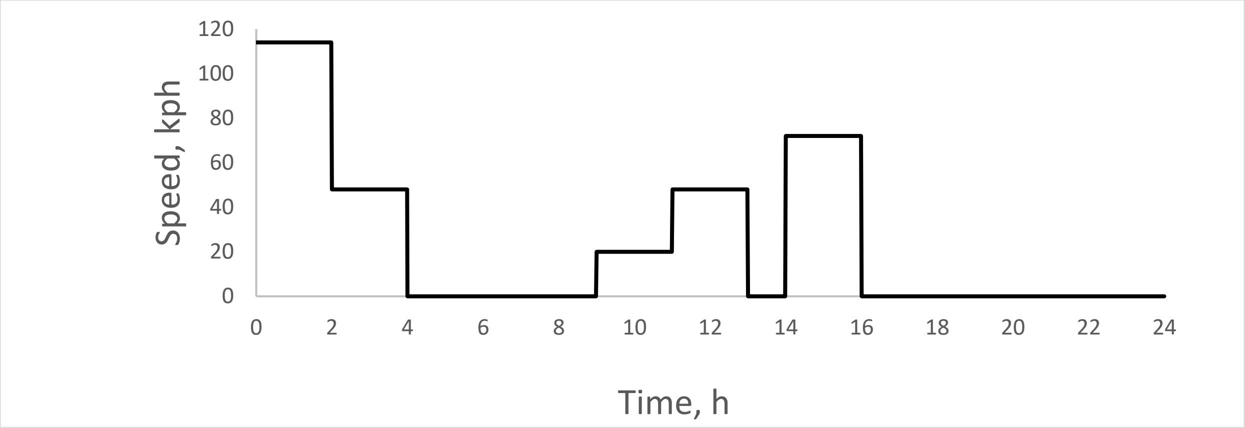

Figure 1. CEMP-H mission cycle: vehicle speed over 24 hours. Transit Departure Road phase operates at maximum engine-only speed (Max[1], simulation output); all other transit phases at fixed speeds.

Figure 2. CEMP-H mission cycle: electrical auxiliary load as percentage of vehicle-specific maximum.

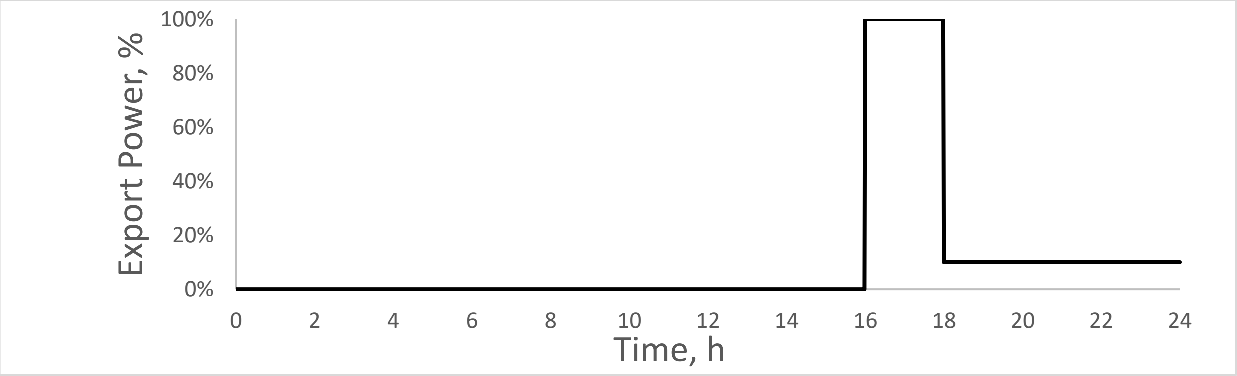

Figure 3. CEMP-H mission cycle: Export Power as percentage of vehicle-specific maximum.

2.3. Simplifications and Limitations of the Cycle

The cycle deliberately omits the following characteristics of a real-world scenario:

- increased rolling resistance for cross-country sections

- gradients
- frequent accelerations and decelerations within a phase
- testing the vehicle's range on a full tank of fuel.

These omissions allow the cycle to be applied to on-road physical vehicle tests as well as chassis roll tests and simulations, whereas if these characteristics were included, it would be difficult or impossible to match them in repeatable fashion across different road test facilities. (Practical physical testing would not be recommended for a full 24 hours, but would include shortened versions of each phase, with simulation support to extrapolate to the full cycle.) Similar simplifications are found in civilian fuel-economy cycles, for the same reasons. Range on a tankful of fuel is normally specified at a fixed cruising speed, so it is not appropriate to test it on a mixed-mode cycle of this type. Gradeability is usually specified as a percentage gradient that the vehicle must climb, but the speed of climb is not specified, so it can be met regardless of powertrain architecture by adjusting a gear ratio, which is not an early stage-gate architecture decision.

2.4. The Engagement Phase and Directed Energy Weapon Option

For vehicles equipped with a Directed Energy Weapon (DEW), the one-hour engagement phase is the appropriate phase for an additional pulsed electrical load on top of the continuous electrical load. The characteristics of this electrical load are very different from those of the other auxiliary electrical loads, and it is also an optional feature that does not apply to all vehicles. The method of adding DEW loads to the cycle will be developed in a future publication.

2.5. Vehicle-Specific Parameters

Table 2 shows vehicle-specific input parameters for two example platforms. The maximum continuous electrical load covers all electronics, communications, navigation, and HVAC (Heating, Ventilation and Air Conditioning) systems at simultaneous full draw. All other cycle inputs are standard vehicle parameters that are applied through simulation tools used to follow the cycle, and are not part of the cycle definition itself. They include vehicle mass, rolling resistance, aerodynamic drag, frontal area, drivetrain efficiency, and battery state of charge (SOC) limits.

2.6. Road Load Translation into Power Time Series

The mission cycle defined in Section 2 specifies vehicle speed as a function of time. To simulate the powertrain using ePOP Concept, this speed profile must be converted into a power demand at the driven wheels as a function of time. The ePOP Concept tool works in terms of wheel power rather than engine torque or shaft speed, so no gearbox ratio or engine speed model is required at this stage.

Table 2. Vehicle-specific cycle parameters for the two platforms studied.

Parameter	Light Protected Patrol Vehicle (Foxhound LPPV)	Wheeled Infantry Fighting Vehicle (Boxer MIV)
Maximum continuous electrical load including HVAC (kW)	10 †	20
Maximum Export Power (kW)	30	60

† P_max for the Foxhound LPPV is estimated from published data for comparable vehicles: the NATO AECV study [19] places basic watch-mode electronics at 1–3 kW; full operational draw including HVAC for a 5-seat light vehicle is estimated at 8–12 kW, giving a representative value of 10 kW. P_max for the Boxer MIV reflects the larger crew, mission module electronics, and C4ISTAR suite of an 8×8 infantry fighting vehicle.

2.7. Road Load Equation

The instantaneous wheel power demand is calculated from the standard longitudinal road load equation, which sums rolling resistance, aerodynamic drag, and inertial forces at each timestep [22]. Vehicle-specific parameters for both platforms are given in Table 3.

2.8. Vehicle Parameters

Table 3 gives the road load parameters assumed for each vehicle.

Table 3. Vehicle parameters for the two platforms studied.

Parameter	Foxhound LPPV (4×4)	Boxer MIV (8×8)	Notes / Basis
Gross vehicle mass, m (kg)	7,500	38,500	Foxhound production GVM [12]; Boxer MIV combat weight [14]
Rolling resistance coefficient, C_rr	0.015	0.015	Cross-country / unpaved road estimate for run-flat or cross-country tyres; standard value for off-road military vehicles [22]
Aerodynamic drag coefficient, C_d	0.70	0.75	Bluff-body estimate for armoured vehicles with flat-faced hull and external fittings; higher value for the larger 8×8 reflecting greater frontal complexity
Frontal area, A_f (m^2)	3.5	6.5	Estimated from published vehicle silhouette dimensions; Foxhound: ~2.2 m wide × ~1.9 m to hull roof; Boxer: ~3.0 m wide × ~2.4 m to hull roof with equipment

All aerodynamic and rolling resistance values are estimates based on published vehicle dimensions and typical military tyre data; exact values are not publicly available for these platforms.

2.9. Powertrain Architectures Evaluated

Two powertrain configurations are evaluated for each platform, with reference to a third as baseline. The baseline is an ICE-only platform, and this is shown in Figure 4. Figure 5 shows the series hybrid, in which the engine drives a generator exclusively, and all tractive effort is delivered electrically, decoupling engine operating point from vehicle speed. Figure 6 shows a parallel hybrid, in which both the internal combustion engine and an electric motor contribute to tractive effort through a shared driveline, and the electric motor can also be used as a generator driven by the engine, either connected to or disconnected from the wheels. These configurations span the practical design space available for conversion of an existing vehicle class, and represent the decision points most likely to face a programme office at the concept stage. Component efficiency values used in this study are drawn from the ePOP Concept internal parameter database, which aggregates efficiency characteristics from published sources across a range of drivetrain component classes. The database approach and its underlying assumptions are described in [17]. For this study, default values were refined using the custom parameters in Tables A3–A9, derived from published data for comparable military-grade components. This study is not a validation study; the methodology and its accuracy boundaries are assessed in [17].

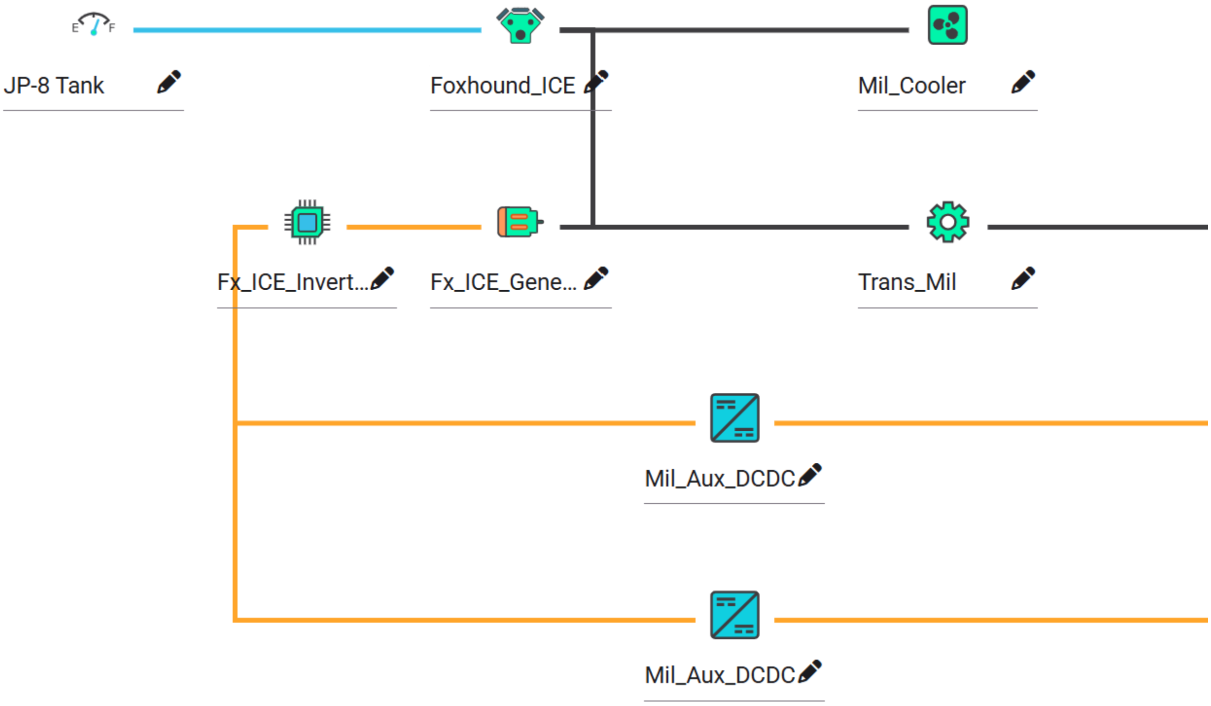

Figure 4. ePOP-generated architecture for an ICE-only powertrain, in which traction drive is supplied by the ICE only.

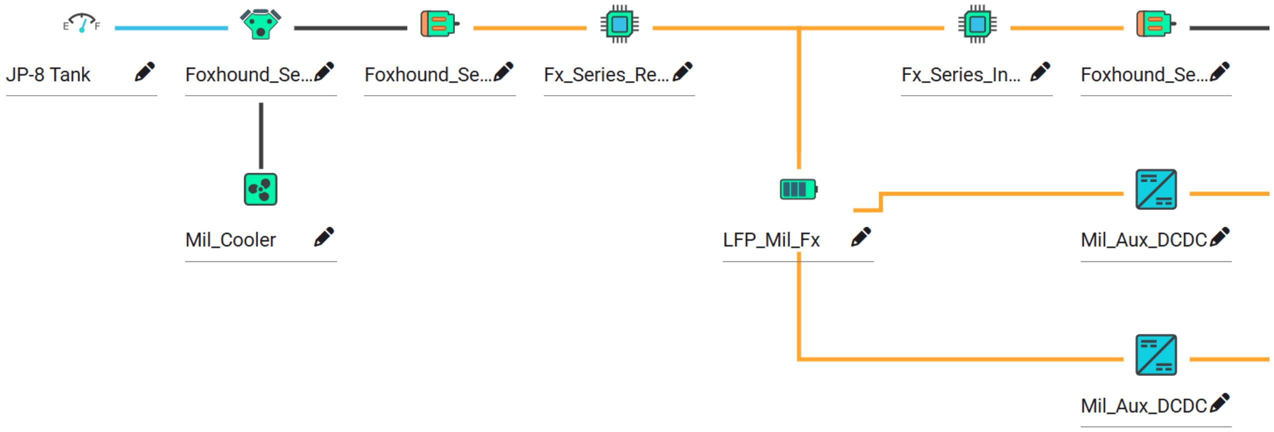

Figure 5. ePOP-generated architecture for a series hybrid powertrain, in which all the traction power passes through a generator, then an inverter, another inverter, and a motor, and then goes to the transmission (incorporated in the motor model). The battery is connected to the DC bus between the inverters and powers aux and Export Power via DCDC (direct current – direct current) converters.

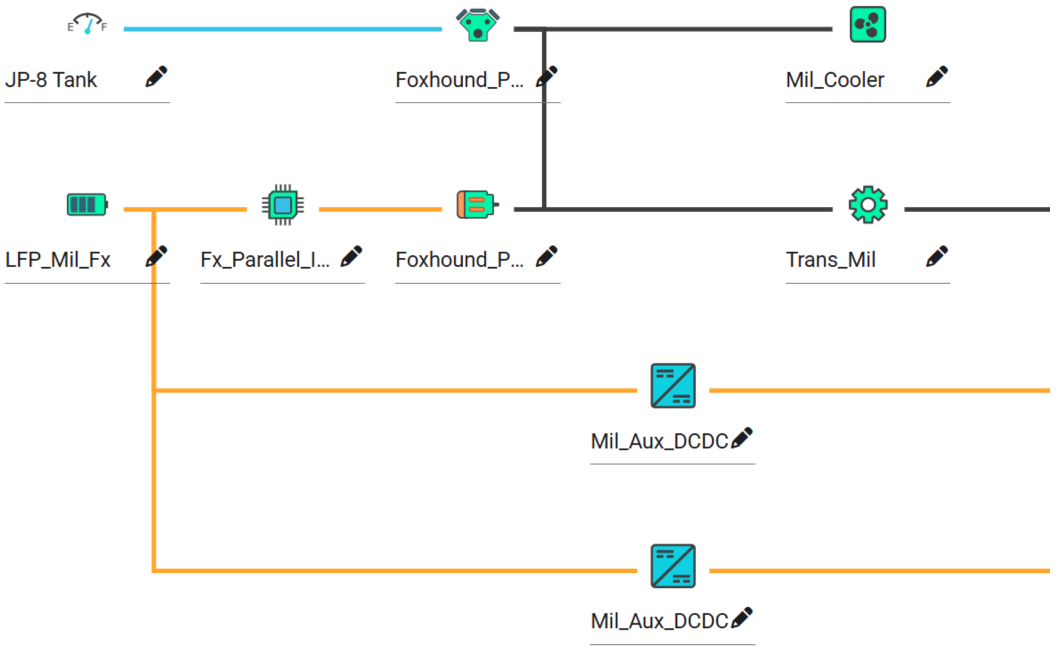

Figure 6. ePOP-generated architecture for a parallel hybrid powertrain, in which the traction power passes from the ICE to the transmission via mechanical linkage, as in a non-hybrid vehicle. The generator supplies aux and Export Power, but it also charges the battery and can act as a motor when the vehicle is operating in electric-only mode, for Silent Mobility.

2.10. Power-Time Trace Generation and Open-Access Implementation

The equations in Sections 2.7 are implemented in an open-access Microsoft Excel workbook, which is made available as a supplementary dataset accompanying this paper

[23]. The workbook generates second-resolution power-time traces for traction, auxiliary electrical load, Export Power, and (optionally) directed energy weapon load across all nine mission phases, and is formatted for direct import into ePOP Concept. Other researchers using alternative simulation tools may re-implement the equations directly from this paper, or use their own; the workbook is provided for those wishing to reproduce or extend the results reported here.

Speed transitions between phases are modelled as power-limited acceleration events rather than prescribed ramps. At each timestep, the speed increment is the lesser of the kinematic limit ($0.8g$ per second) and the increment achievable using the engine power required to reach the target speed for that phase, per equation 1:

$$\Delta v = \min(0.8g \cdot \Delta t,\ [(P\_eng{,}v\_target \cdot 1000 \,/\, v\_prev) - F\_road(v\_prev)] \cdot \Delta t \,/\, m]) \quad (1)$$

where $F\_road(v)$ is the sum of rolling resistance and aerodynamic drag forces at the current speed, and the formula is applied at each timestep until the target phase speed is reached. This produces a physically consistent acceleration profile without requiring a prescribed ramp duration. Deceleration between phases is modelled at $0.8g$ throughout, with no regenerative braking, consistent with Section 2.3. The acceleration phase may in theory prevent the speed from reaching the full speed target for that phase, but in practice the error is vanishingly small. The total power required for the cycle, summing the input power profiles, can be viewed in ePOP Concept and is shown in Figure 7. It is necessary to estimate the engine power before running the simulation, and the step by step instructions in Appendix A explain how this is implemented in the workbook provided.

Step by step instructions for replicating this work (assuming access to ePOP Concept) are provided in Appendix A.

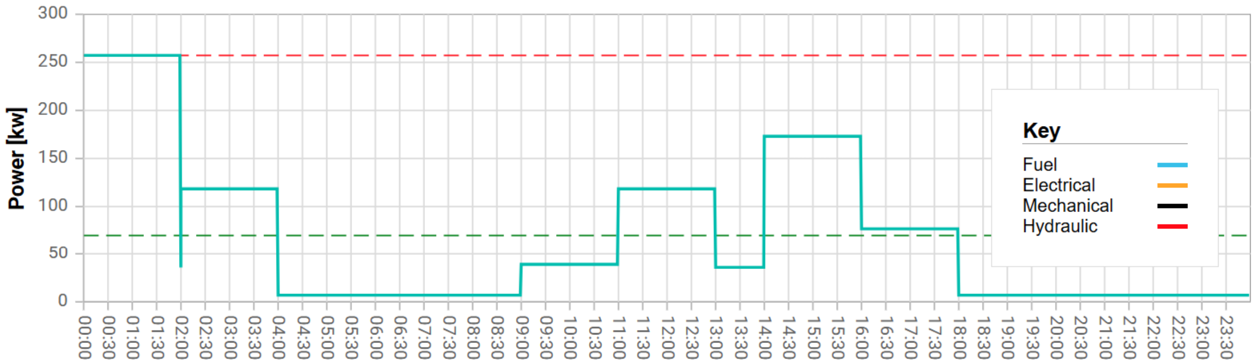

Figure 7. Total Power Requirement (kW) versus time (h) for the Boxer vehicle, including traction, auxiliary power and Export Power, showing mean power and peak power (dashed lines).

2.11. Fuel Consumption Estimation over Vehicle Lifetime

Fuel efficiency ranks below capability for military vehicles, but the added cost of hybridization can in some cases be repaid many times, over the lifetime of the vehicle. The lifetime fuel consumption of each hybrid powertrain architecture may be estimated given an assumed total mission cycle count over the platform service life.

The selection of an appropriate cycle count requires reference to published operational planning assumptions. U.S. Army program cost documentation provides the most comprehensive publicly available basis for this. The HMMWV Recapitalization program documentation states a design service life of 45,000 miles (72,420 km) at a programmed peacetime utilisation of 3,000 miles (4,828 km) per vehicle per year, yielding a 15-year useful life [21]. This figure is corroborated by DoD Selected Acquisition Report data for medium tactical vehicles: the Family of Medium Tactical Vehicles (FMTV) December 2010 SAR (Selected Acquisition Report) assumes 1,432–1,543 miles (2,305–2,484 km) per vehicle per year over a 20-year useful life for garrison and line-haul operations [24]. The CEMP-H mission cycle covers 603.5 km (375 miles) per 24-hour operational day. Dividing the HMMWV design service life of 45,000 miles (72,420 km) by that figure yields 120 mission cycles, which is adopted here as a common planning basis for both platforms. This figure is conservative relative to the programme service lives of both vehicles studied, and therefore understates rather than overstates the lifetime fuel cost differential between architectures.

3. Results

3.1. Battery Sizing

The state of charge (SOC) is shown in Figures 8 and 9. It is a condition of the Mission Profile that the SOC returns to its initial value at the end. The battery has been sized to ensure that the minimum SOC for the cycle is no less than the minimum SOC allowed (20%). The battery size is effectively determined by phases 3 and 4 (Silent Watch and Silent Mobility) because these phases begin with a fully charged battery, and use more energy than the other depletion event in Phase 9. The Boxer vehicle has more energy remaining at the end of the cycle than the Foxhound, which is an outcome of the calibratable value selected for Export Power. Table 4 shows the battery capacity determined for both vehicles. This sizing is based purely on energy requirements and addresses capacity, charging rate, cost and weight, but does not account for packaging volume, thermal management systems, structural integration or ballistic protection considerations, which would require platform-specific design studies.

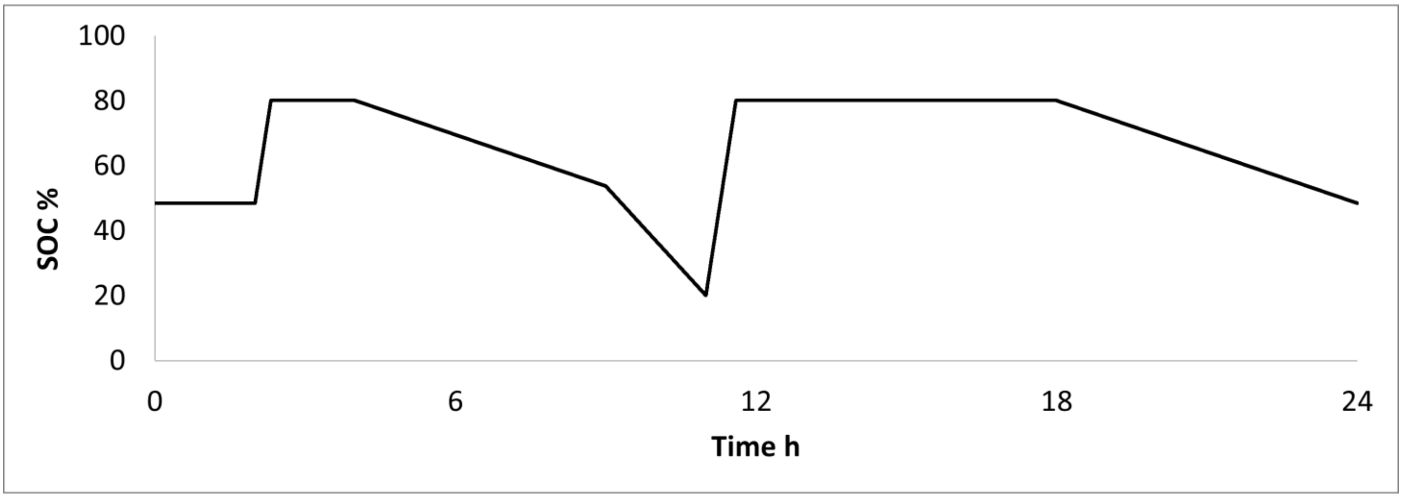

Figure 8. State of Charge (SOC %) versus time (h) for the Foxhound vehicle.

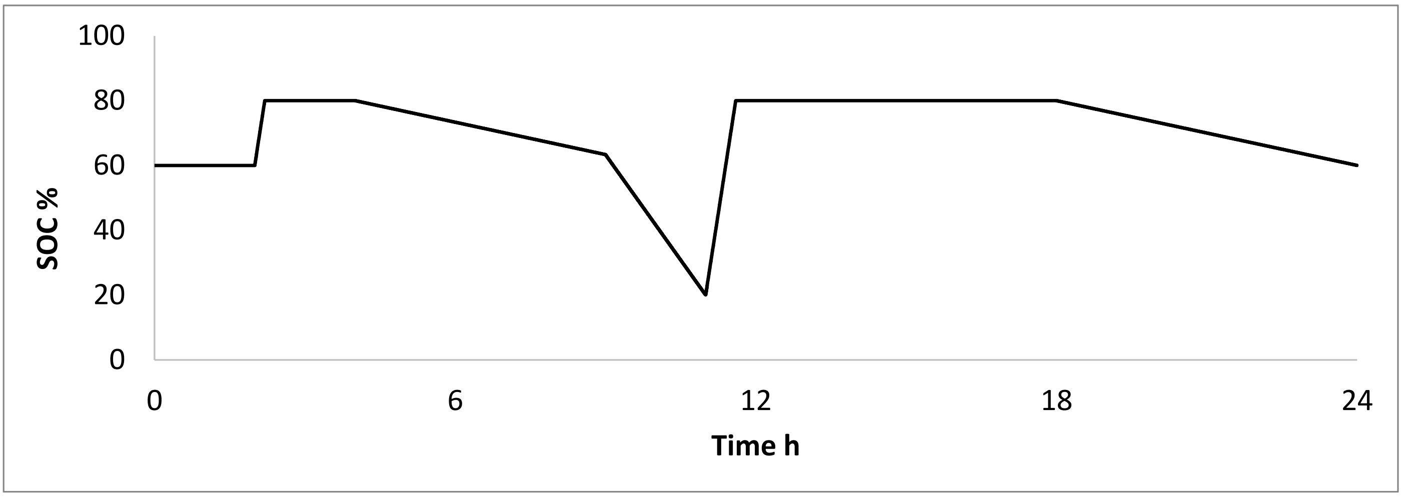

Figure 9. State of Charge (SOC %) versus time (h) for the Boxer vehicle. The SOC has plenty of capacity remaining at the end of the cycle (the end of the Base Camp rest period), and recharging in transit is rapid, so more Export Power could have been used in the Base Camp rest period, depleting to 20% SOC if needed.

Table 4. Analytically sized battery parameters for both platforms. The required battery size is the same for parallel-hybrid and series-hybrid architectures, as the sizing is based on phases 3 and 4 (SW and SM) which use similar components for these functions.

Parameter	Foxhound LPPV (4×4)	Boxer MIV (8×8)	Unit
Battery capacity, C_bat	69.2	216.5	kWh
Battery pack mass, m_bat	692	2165	kg
Battery mass as percentage of GVM	9.2%	5.6%	—

3.2. Engine Power Sizing

The power requirements are shown in Table 5.

Table 5. Minimum engine power by architecture and platform.

Architecture	Platform	P_eng,min (kW)
ICE only	Foxhound LPPV	110.4
Parallel hybrid	Foxhound LPPV	110.4
Series hybrid	Foxhound LPPV	118.7
ICE only	Boxer MIV	293.4
Parallel hybrid	Boxer MIV	284.2
Series hybrid	Boxer MIV	349.6

Target maximum speed for Foxhound = 114 km h^{-1}; for Boxer = 100 km h^{-1}. Engine power values are the minimum required to sustain maximum speed with full aux load and no battery charge or discharge.

3.3. Powertrain Costs

ePOP Concept contains estimated costs for powertrain components that are scalable, i.e. once it has determined the size of each component, it can estimate the cost. The parameters for estimation are calibratable within the program, so the user can adopt default values for a first estimate, and refine them later as more accurate information is obtained. Tables 6-7 show the resulting costs in four groupings.

Table 6. Powertrain component capital costs (US$) and weight (kg) for ICE-only, parallel hybrid, and series hybrid architectures for the Foxhound vehicle.

	Cost ($) ICE Only	**Cost ($) Parallel Hybrid**	**Cost ($) Series Hybrid**
Engine	44,164	44,160	47,485
Electric Power / Drivetrain	14,766	23,180	53,532
Battery	0	23,065	23,054
Other	1,536	1,417	1,584
Total Powertrain Cost ($)	**60,466**	**91,822**	**125,654**
Total Powertrain Mass (kg)	**436**	**1,095**	**1,365**

Table 7. Powertrain component capital costs (US$) for ICE-only, parallel hybrid, and series hybrid architectures for the Boxer vehicle.

	Cost ($) ICE Only	**Cost ($) Parallel Hybrid**	**Cost ($) Series Hybrid**
Engine	117,380	113,664	139,830
Electric Power / Drivetrain	32,498	78,011	148,047
Battery	0	70,672	70,672
Other	4,638	4,165	4,806
Total Powertrain Cost ($)	**153,401**	**266,511**	**363,395**
Total Powertrain Mass (kg)	**1,124**	**3,419**	**4,031**

Table 8. Estimated lifetime JP-8 fuel consumption, by platform and powertrain architecture.

Parameter	**Foxhound**	**Foxhound**	**Foxhound**	**Boxer**	**Boxer**	**Boxer**
	ICE-Only	**Parallel Hybrid**	**Series Hybrid**	**ICE-Only**	**Parallel Hybrid**	**Series Hybrid**
Total lifetime cycles	120	120	120	120	120	120
Single-cycle JP-8 consumption (L/cycle)	238.6	218	245	687	612	702
Lifetime fuel usage (L)	28,632	26,172	29,412	82,380	73,428	84,276
Forward deployed fuel cost † at $4 / litre ($)	114,528	104,688	117,648	329,520	293,712	337,104
Comparison (%)	Baseline	-8.6%	2.7%	Baseline	-10.9%	2.3%
Fuel Cost Delta ($)		-$9,840 (saved)	$3,120 (added)		-$35,808 (saved)	$7,584 (added)

† *JP-8 lower heating value: 9.55 kWh/L.* JP-8 standard fuel price ≈ $4.57/gal (~$1.21/L) [1] and 15/gal (~$4/L) in forward operational environments [2].

Single-cycle consumption figures are outputs from ePOP Concept.

4. Discussion

4.1. ICE-Only Architecture

A baseline ICE-only powertrain is less expensive than either hybrid. However, this architecture cannot deliver the Silent Watch, Silent Mobility or Export Power requirements of the mission profile.

4.2. Parallel Hybrid Architecture

A parallel hybrid comprises a single MGU and is classified by one of five types, P0 – P5. P0 and P1 hybrids have an MGU permanently connected to the engine, denoted P0 if at the front or P1 if at the rear (i.e. the drive end) of the crankshaft. A P0 or P1 hybrid configuration could deliver Export Power, and Silent Watch by charging a large battery, but could not deliver Silent Mobility, as the MGU cannot be disconnected from the engine while driving the wheels, unlike P2-P5, all of which can do this. For the purposes of this study P2-P5 are all equivalent, but P2 is assumed for the parallel hybrid, on the grounds that this is the most common architecture for parallel hybrids.

4.3. Series Hybrid Architecture

A series hybrid comprises two MGUs and two inverters in series, arranged as engine-generator-inverter-inverter-motor-transmission, and each component must have sufficient capacity to transfer the full engine power to the wheels. Efficiency is worse than parallel hybrids since every component in the chain loses a few percent of the transmitted energy, so more fuel is used, and a slightly larger engine is required, than with a parallel hybrid. But the advantages include simplifying the transmission and allowing a much more flexible architecture (given a complete vehicle redesign), the ability to run the engine at the desired operating point regardless of road speed, and the possibility to support higher generation power for DEW's or Export Power.

4.4. MGU Sizing

It can be seen from Figure 7 that the power requirement during Silent Mobility is less than 50 kW for the Boxer vehicle, but this power level is far too low for the MGU (and the inverter), as it would take over 6 hours for it to recharge the battery. Battery recharge therefore drives the MGU size in parallel-hybrid architectures, whereas the series-hybrid architecture MGUs are sized for the full maximum power of the engine. No recharging-time target can be identified in published literature, but if we assume a practical recharging target of 1h for the 60% span from 20% to 80% SOC, then using the battery capacities in Table 4, the MGU size must exceed 69.2*0.6 = 41.5 kW (Foxhound) and 216.5*0.6 = 130 kW (Boxer).

4.5. Architecture Selection

Both parallel-hybrid and series-hybrid architectures are capable of delivering the requirements of the Mission Profile, whereas the ICE-only vehicle cannot deliver Silent Watch, Silent Mobility or Export Power. The parallel hybrid adds to the vehicle cost (Tables 6-7) but saves some money on fuel over lifetime (Table 8), whereas the series hybrid adds to both. In both cases the total cost of ownership is increased, but the series hybrid is very much more expensive.

The advantages of the series hybrid include design flexibility by eliminating the mechanical connection from engine to wheels, the ability to operate the engine at more optimal operating points regardless of road speed, and the availability of more electrical power for future requirements such as DEW. However the cost advantage of the parallel hybrid is compelling, and its reduced fuel consumption can also translate into a capability advantage, in the case of remote theatres of operation where fuel supply lines are both costly and tactically vulnerable. The choice of hybrid architecture would depend on strategic considerations specific to the application, of which the power requirements of a DEW might be the most compelling.

4.6. Sensitivity of Architecture Ranking to Mission Profile Assumptions

The ICE-only architecture was eliminated because it cannot deliver Silent Watch or Silent Mobility or engine-off Export Power. Since these requirements are explicitly required in future military programmes for tactical wheeled vehicles, this elimination is robust to mission profile adjustments.

If parts of the CEMP-H were adjusted to different vehicle speeds, durations or electrical power demands, and the hybrid architectures were re-sized to meet the new requirements, it is important to check whether the ranking order would reverse. In other words, assuming that both architectures meet all the functional requirements, could a change in the mission profile mean that the series hybrid would be less expensive, either in initial cost or in total cost including future fuel costs, than the parallel hybrid? A phase-by-phase analysis follows in Table 9.

Table 9. Sensitivity Analysis for the CEMP-H

Phase	Hardware Impact	Could Reverse Architecture Ranking?
Transit Departure — Road	Maximum speed defines ICE power and series-hybrid electrical power.	No
Transit Departure — Cross-Country	Battery must recharge in 0.6 hours during this phase (60% SOC at 1C).	No
Silent Watch	SW and SM define battery capacity	No
Silent Mobility Patrol	SW and SM define battery capacity; speed defines parallel MGU sizing.	No
Transit Return — Cross-Country	None	No
Engagement — Stationary, Engine Running	Additional hardware e.g. DEW could drive larger parallel MGU.	No
Transit Return — Road	Battery must recharge in 0.6 hours during this phase (60% SOC at 1C).	No
Base Rest — Export Power, engine on	If Export Power is greatly increased could drive larger battery for both, and larger MGU for parallel hybrid (but no larger than series hybrid).	No
Base Rest — Export Power, engine off	If Export Power is greatly increased could drive larger battery, but for both architectures.	No

Table 9 shows how the duration and power requirements for each phase could impact the sizing of the powertrain components. In all cases,

- The series hybrid powertrain connection from engine to wheels contains two inverters and two MGU’s, whereas the parallel hybrid contains one of each. Any increase in required electrical capacity scales at least proportionally, and typically more strongly, in the series architecture.

- There are changes that could increase the power and battery capacity requirements for the parallel hybrid, but those of the series hybrid always equal or exceed those of the parallel hybrid.

Within realistic ranges of tactical mission parameters (Silent Watch 6–10 hours, Export Power up to ~100 kW class, recharge within one transit segment), the relative cost ranking remains unchanged. However, the addition of a high power laser DEW may overturn the ranking and make the series architecture the preferred option. This scenario will be developed in a future paper by the same author.

5. Conclusions

A 24-hour mission profile has been prepared and offered for open access, to support the standardization of analysis methods, and its use has been demonstrated on two classes of tactical wheeled vehicle in hybrid form. The ICE-only vehicle used as a baseline comparator was not equipped to meet the requirements for Silent Watch, Silent Mobility or Export Power, so the added cost and weight for the hybrids represents the price of the added capabilities.

A battery capacity of 69.2 kWh (Foxhound) and 216.5 kWh (Boxer) is sufficient to cover silent-watch and silent-mobility requirements for both hybrid architectures. The parallel hybrid powertrain adds a capital cost per vehicle of \$31k (Foxhound) and \$113k (Boxer) over the ICE-only baseline respectively, while the series hybrid adds \$65k and \$210k. The added weights are 659 kg and 2,295 kg respectively for the parallel hybrid, and 929 kg and 2,907 kg for the series hybrid. Over the platform service life, taking data from Table 8, the parallel hybrids consume 8.6% (Foxhound) and 10.9% (Boxer) less fuel than the ICE-only vehicles, but the series hybrids consume 2.7% (Foxhound) and 2.3% (Boxer) more.

These results may be instructive in themselves, but the principal value of the method is its speed. This was enabled through the use of the mission profile, data preparation with the Microsoft Excel worksheet provided with this paper, and the ePOP Concept simulation tool. The data requirements are limited to the parameters in Table 3, all of which were obtained from publicly available sources, unlike conventional simulation tools, which require detailed BSFC maps and component efficiency tables. This reduces data gathering time. The analytical steps are straightforward even for a non-expert in simulation, and are documented in full in Appendix A.

Supplementary Materials: The CEMP-H mission profile Excel workbooks and associated input datasets are publicly available in the Zenodo repository at https://doi.org/10.5281/zenodo.18837007.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating Current
AECV	Advanced Energy Combat Vehicle
ADVISOR	ADvanced VehIcle SimulatOR
BSFC	Brake Specific Fuel Consumption
C4ISTAR	Command, Control, Communications, Computers, Intelligence, Surveillance, Target Acquisition and Reconnaissance
CEMP-H	Central European Mission Profile for Hybrid-Electric Tactical Vehicles
CHPS	Combat Hybrid Power System
DCDC	Direct Current – Direct Current
DEW	Directed Energy Weapon
DoD	Department of Defense
eJLTV	Electric/Enhanced Joint Light Tactical Vehicle
FMTV	Family of Medium Tactical Vehicles
FTP-75	Federal Test Procedure 75
GVM	Gross Vehicle Mass
GVSC	Ground Vehicle Systems Center
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HVAC	Heating, Ventilation and Air Conditioning
ICE	Internal Combustion Engine
JLTV	Joint Light Tactical Vehicle
LMP	Land Mobility Programme
LPPV	Light Protected Patrol Vehicle
MGU	Motor Generator Unit
MIV	Mechanised Infantry Vehicle
MoD	Ministry of Defence
NATO	North Atlantic Treaty Organisation
OBVP	Leonardo DRS TITAN OBVP system; On-Board Vehicle Power
P0–P5	Parallel hybrid motor-generator position classification
PSAT	Powertrain System Analysis Toolkit
SAR	Selected Acquisition Report
SBIR	Small Business Innovation Research
SM	Silent Mobility
SOC	State of Charge
SW	Silent Watch
TARDEC	Tank Automotive Research, Development and Engineering Center
TD6	Technology Demonstrator 6
TVEK	Tactical Vehicle Electrification Kit
UDDS	Urban Dynamometer Driving Schedule

Appendix A

Instructions to replicate the Analysis using ePOP Concept.

A.1 – Data Preparation

The workbook comprises six worksheets:

Params:	User input page. Adjust calibratable parameters here.
Mission_Profile:	Details of the CEMP-H mission profile. Do not alter.
Trace:	Calculations. Do not alter.
ePOP_Input_ICE:	Output data to use for ePOP Input. Copy from here.
ePOP_Input_Hybrid:	Output data to use for ePOP Input. Copy from here.
ePOP_Input_Electric:	Output data to use for ePOP Input. Copy from here.

The user modifies the parameters in the Params worksheet as shown in Table A1, if necessary, e.g. to change the vehicle type, or if better data has been located. To replicate the work in this paper, leave them unchanged. The worksheet uses no macros, and it is set up for auto calculation (the default in Excel), so there is no "calculate" step to perform – the results will update after each adjustment.

Table A1. Calibratable input parameters for the CEMP-H workbook (Params sheet). Values are given for both baseline vehicles; the Active Vehicle column is the one to adjust. †

Parameter	Units	Foxhound LPPV	Boxer MIV	Active Vehicle †	Source / Notes
Vehicle Parameters					
Gross vehicle mass, m	kg	7,500	38,500	7,500	Table 3
Rolling resistance coeff, C_{rr}	—	0.015	0.015	0.015	Table 3
Aero drag coeff, C_{a}	—	0.70	0.75	0.70	Table 3
Frontal area, A^{i}	m²	3.5	6.5	3.5	Table 3
Max road speed, V_{ma}^{x}	kph	114	100	114	Table 5 footnote
Idle parasitic loss, mechanical	kW	4.1	15.9	4.1	Appendix A.1
Electrical Load Parameters					
Max Export Power, P^{expoRt}	kW	30	60	30	Table 2
Max continuous aux load, P^{elec}	kW	10	20	10	Table 2
Watch mode fraction	—	0.35	0.35	0.35	Table 1

Notes on Derivation of Idle Parasitic Loss for Table A1:

The idle parasitic loss parameter in “Params” represents the mechanical power required to sustain the engine at warm idle — overcoming internal friction and driving ancillaries (oil pump, coolant pump, cooling fan, and alternator) — with no traction or electrical output delivered to the drivetrain. It is used to calculate fuel consumption during engine-on stationary phases and does not affect battery sizing, which is governed by the engine-off silent phases. The values of 4.1 kW (Foxhound) and 15.9 kW (Boxer) are estimates for the respective engine classes and are calibratable inputs in the Params sheet.

For users applying the workbook to other vehicle types, idle fuel flow rates for a wide range of diesel engines (37 kW to over 400 kW) are available in the NREL ADVISOR tool [25], which provides idle fuel consumption directly in each engine data file. The equivalent mechanical idle power may then be calculated as:

P_idle = (Q_idle × ϱ_fuel) / BSFC

where Q_idle is the idle fuel volumetric flow rate (L/h), ϱ_fuel = 835 g/L for JP-8 [26], and BSFC is brake specific fuel consumption.

Outputs from the Workbook

The outputs from the workbook CEMP_H_PowerTrace_v9.*xlsx* can be found in the last three sheets:

ePOP_Input_ICE:	Inputs for ePOP to simulate ICE-only architecture.
ePOP_Input_Hybrid:	Inputs for ePOP to simulate Hybrid architecture.
ePOP_Input_Electric:	Inputs for ePOPfor battery sizing to cover SW and SM phases.

If more than one vehicle is modeled, then the user is advised to create copies of the workbook, and run one for each vehicle. In the example shown here, two vehicles are modeled (Foxhound and Boxer), resulting in two workbooks, CEMP_H_Foxhound.xlsx and CEMP_H_Boxer.xlsx, and 18 output csv files, as in Table A2.

Values from the three last sheets of each workbook are copied into the files listed in Table A2. It will be obvious, on inspection of these sheets and files, which cells are copied to which, but the source columns are noted in the last column of the table.

Table A2. Files to populate from the workbook outputs.

Filename	Workbook	Sheet	Copy Cols
`aux_BEV_Boxer.csv`	CEMP_H_Boxer.xlsx	ePOP_Input_Electric	A, C
`aux_BEV_Foxhound.csv`	CEMP_H_Foxhound.xlsx	ePOP_Input_Electric	A, C
`aux_hybrid_Boxer.csv`	CEMP_H_Boxer.xlsx	ePOP_Input_Hybrid	A, C
`aux_hybrid_Foxhound.csv`	CEMP_H_Foxhound.xlsx	ePOP_Input_Hybrid	A, C
`aux_ICE_Boxer.csv`	CEMP_H_Boxer.xlsx	ePOP_Input_ICE	A, C
`aux_ICE_Foxhound.csv`	CEMP_H_Foxhound.xlsx	ePOP_Input_ICE	A, C
`export_BEV_Boxer.csv`	CEMP_H_Boxer.xlsx	ePOP_Input_Electric	A, D
`export_BEV_Foxhound.csv`	CEMP_H_Foxhound.xlsx	ePOP_Input_Electric	A, D
`export_hybrid_Boxer.csv`	CEMP_H_Boxer.xlsx	ePOP_Input_Hybrid	A, D
`export_hybrid_Foxhound.csv`	CEMP_H_Foxhound.xlsx	ePOP_Input_Hybrid	A, D
`export_ICE_Boxer.csv`	CEMP_H_Boxer.xlsx	ePOP_Input_ICE	A, D
`export_ICE_Foxhound.csv`	CEMP_H_Foxhound.xlsx	ePOP_Input_ICE	A, D
`traction_BEV_Boxer.csv`	CEMP_H_Boxer.xlsx	ePOP_Input_Electric	A, B
`traction_BEV_Foxhound.csv`	CEMP_H_Foxhound.xlsx	ePOP_Input_Electric	A, B
`traction_hybrid_Boxer.csv`	CEMP_H_Boxer.xlsx	ePOP_Input_Hybrid	A, B
`traction_hybrid_Foxhound.csv`	CEMP_H_Foxhound.xlsx	ePOP_Input_Hybrid	A, B
`traction_ICE_Boxer.csv`	CEMP_H_Boxer.xlsx	ePOP_Input_ICE	A, B
`traction_ICE_Foxhound.csv`	CEMP_H_Foxhound.xlsx	ePOP_Input_ICE	A, B

A.2 – ePOP Parameter Setting

ePOP Concept has default parameters for powertrain components, accessed by selecting “Technologies” from the menu at top left. These may be used for a first estimate where no further information has been gathered, enabling a very quick initial analysis. Alternatively, the user may refine custom parameters with targeted information. For these military vehicles, the parameters were updated to form custom component values, which are shown in Tables A3-A7. The required data for custom parameters can be synthesized from similar components found in public sources.

Table A3. Custom inverter parameters for military wheeled tactical vehicles.

Inverter	**Cost** $/kW	**Mass Density** kW/kg	**Efficiency** %
`(All)`	115	2	96

Table A4. Custom fuel parameters for military wheeled tactical vehicles.

Fuel	**Cost per Litre** $/L	**Volume Density** kWh/L	**Mass Density** kWh/kg
`JP8_forward`	4	9.55	11.94

Table A5. Custom ICE parameters for military wheeled tactical vehicles.

Engine	**Cost** $/kW	**Mass Density** kW/kg	**Series BSFC** kg/kWh
`(All, JP-8 fuel)`	400	0.39	0.25

Table A6. Custom MGU parameters for military wheeled tactical vehicles.

MGU	**Cost** $/kW	**Mass Density** kW/kg	**Efficiency** %
`All not including transmission`	115	1	95
`All including transmission`	145	0.5	86

Table A7. Custom battery parameters for military wheeled tactical vehicles.

Battery	**Cost** $/kWh	**Mass Density** Wh/kg	**Minimum SOC** %	**Maximum SOC** %	**C Rating Continuous**	**Minimum †** kWh
`LFP_Mil_Fx (Foxhound)`	350	100	20	80	1	69.2
`LFP_Mil_Bx (Boxer)`	350	100	20	80	1	216.5

† *Minimum battery size is set by running ePOP Concept with a BEV architecture for the Mission Profile phases 3 and 4 only.*

Table A8. Custom transmission parameters for military wheeled tactical vehicles.

Transmission	**Cost** $/kW	**Mass Density** kW/kg	**Efficiency** %
`Trans_Mil (All)`	29	1	91

Table A9. Custom DC-DC converter parameters for military wheeled tactical vehicles.

DC-DC Converter	**Cost** $/kW	**Mass Density** kW/kg	**Efficiency** %
`All`	115	3	96

- On first opening ePOP Concept (as a full user, rather than the free demo version), the user is presented with a selection of demo projects. Choose the "+ New Project" button.
- Choose Blank Project. Name, Description and Type are all optional fields, although at least add a Name to locate the project, and fill in the others as desired.
- The project appears among the others on the page. Select it. You will land on the "Application" page, denoted by one of three round buttons at the top.
- Select "Import Data" and "Import Excel File". Navigate to your file location and select one of the csv files, as in Table A2. It will import.
- Repeat for the other csv files needed for the model. For our example, to set up Foxhound Hybrid, select aux_hybrid_Foxhound.csv, export_hybrid_Foxhound.csv and traction_hybrid_Foxhound.csv.
- For Power Delivery Type, select "Mechanical" for the traction file, and "Electrical direct" for the other two.
- Move from "Application" to "Configuration" with the round buttons. Make sure you are on Powertrain A, not B. Set Power Source to Series non-plug-in. Set Power Delivery to 1M, 1E, 1E.

- Set Architecture to Auto, and then Advanced. You will see the series-hybrid powertrain layout in a schematic similar to Figure 5.
- Switch to Powertrain B, then set Power Source to Parallel non-plug-in. Set Power Delivery to 1M, 1E, 1E.
- Move from Configuration to Results.
- On the graph at top left, ensure that both the black and the blue vertical line are moved to the far left of the graph.
- The output results may be found by clicking the Spec Sheet button once for Powertrain A, and once for Powertrain B. These sheets can be downloaded in pdf form, and computer tools (e.g. Claude) can be used to transcribe them into spreadsheets or other formats as required for reporting and analysis.

This produces results for Powertrain A (series hybrid) and Powertrain B (non hybrid) but they do not automatically have sufficient battery capacity for Silent Watch and Silent Mobility. In order to add this capability for the Mission Profile, you simply need to add the cost and weight for the required battery capacity to your results. This capacity, cost and weight are obtained by setting up a separate ePOP model using the _BEV files in Table A2. Results for ICE-only are obtained with a separate model using the _ICE files in Table A2.

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