UNIVERSITY OF BIRMINGHAM

Simulation of key freight routes to objectively establish the feasibility, or otherwise, for Freight Operations of discontinuous electrification with on-board battery storage

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1. INTRODUCTION AND BACKGROUND

Freight operations on the Great Britain (GB) railway network are currently delivered predominantly using diesel traction, with diesel locomotives hauling a wide range of freight load types. These operations underpin critical sectors of the UK economy, including ports and logistics, construction materials, energy supply, and intermodal distribution.

The freight market encompasses a diverse range of train formations and duty cycles, from long-distance intermodal services operating between ports and inland terminals, through to heavy bulk flows such as aggregates hauled from quarries to urban construction markets. These differing traffic types impose markedly different demands on traction systems in terms of power, energy consumption, gradients, and operational flexibility.

At present, the majority of GB freight services are operated by diesel locomotives, most notably the widely deployed Class 66, with additional use of higher-power diesel designs such as the Class 70. Historically, other high-power diesel types, including earlier classes such as the Class 56 and Class 60, have also played a significant role in heavy haul operations, particularly on aggregate and bulk flows.

Electric traction has long been recognised as offering significant advantages for freight, particularly in terms of energy efficiency, tractive performance, and decarbonisation potential. However, the application of electric freight traction in GB is constrained by the extent and continuity of the electrified network, with many strategically important freight corridors remaining partially or wholly unwired. As a result, pure electric locomotives have historically been limited to a relatively small number of corridors with continuous electrification and appropriate operational interfaces.

In response to growing pressure to decarbonise freight operations, recent years have seen the introduction of multi-mode and hybrid traction concepts. These vehicles can draw power from the overhead line where electrification is available, while also carrying on-board energy sources to enable operation beyond electrified sections. Early examples include bi-mode locomotives combining electric traction with diesel engines, and more recent designs — such as the Class 93 — which incorporate on-board battery storage to supplement diesel power and enhance performance under specific operating conditions.

These developments reflect a broader strategic question facing the freight sector: whether discontinuous electrification, supported by on-board energy storage, can provide a credible pathway to reduce diesel consumption and associated emissions, without requiring full route electrification.

Against this background, the overall aim of this project is to use digital simulation of representative freight routes to objectively establish the feasibility, or otherwise, of freight operations under discontinuous electrification with on-board energy storage. The work seeks to identify where such approaches can be technically and operationally viable, and where physical or operational limits are encountered.

The study has been conducted by Professor Stuart Hillmansen using a physics-based longitudinal train simulation framework. The modelling draws on a wide range of published literature, industry documentation, and publicly available data sources, which are referenced later in this report. The specific objectives of the study are set out in the following section.

1.1. SUMMARY OF FREIGHT LOAD TYPES CONSIDERED

The freight services modelled in this study span a range of load types that are representative of contemporary operations on the Great Britain (GB) rail freight network. These load types were selected to reflect both the diversity of freight markets and the markedly different demands that each places on traction power, energy consumption, and operational capability.

Intermodal / multimodal freight services typically comprise containers or swap bodies conveyed on flat wagons, often forming long, relatively uniform consists. These services are generally characterised by long-distance operation between ports and inland terminals, higher average speeds compared with bulk freight, and frequent utilisation of electrified main lines. Trailing loads for intermodal trains are moderate relative to heavy bulk flows, and energy consumption is often dominated by aerodynamic resistance at higher speeds rather than by extreme gradient or mass effects. As a result, intermodal services represent a class of operation where battery assistance and discontinuous electrification are expected to be potentially effective, especially for bridging short non-electrified sections.

Aggregate freight services transport crushed stone and construction materials from quarries to urban or regional distribution points. These trains are characterised by heavy trailing loads and relatively short to medium route lengths. Aggregate routes frequently include challenging gradients, particularly in quarry access sections, which impose high instantaneous tractive effort and power demands. Energy consumption on aggregate services is therefore strongly influenced by mass and gradient, making them a demanding test case for both diesel and battery-assisted traction, particularly under power-limited conditions.

Jumbo aggregate services represent the most demanding bulk freight operations considered in this study. These trains comprise extremely heavy trailing loads, often approaching the upper limits of what can be hauled within infrastructure and traction constraints. Operation is typically power-limited over significant portions of the route, especially on rising gradients, and such services provide a severe test of traction capability, energy availability, and thermal margins. Jumbo aggregate services are included specifically to explore boundary conditions and to identify where battery-assisted operation becomes constrained by fundamental physical limits.

For the purposes of this study, each freight load type has been represented using a single set of representative parameters, including trailing mass and resistance characteristics. These parameters are defined in the modelling methodology section and are intended to capture typical, rather than extreme, operating conditions. While actual loads on the GB network may vary in practice, this approach provides a consistent basis for comparative assessment across routes, locomotive types, and traction configurations.

The locomotives modelled in this study are synthetic representations of typical freight locomotive performance, rather than detailed models of specific locomotives currently operating on the GB rail network. The intention is to represent the typical performance envelope of the relevant locomotive classes without relying on proprietary manufacturer data.

Each synthetic locomotive model was therefore defined using a limited set of publicly available parameters.

From these parameters a representative tractive effort–speed curve was constructed and used within the train performance simulation model.

The locomotive types used in the study therefore represent "Class-type" performance envelopes rather than exact digital models of individual locomotives.

It should also be noted that these calculations assume sufficient adhesion to transmit the required tractive effort. In practice, locomotive performance on steep gradients may also be limited by adhesion conditions, which could reduce the achievable tractive effort below the theoretical values assumed in the model.

1.2. FREIGHT LOCOMOTIVE TYPES IN GB

Freight services on the Great Britain (GB) railway network are hauled by a relatively small number of locomotive families, reflecting the need for high power, high tractive effort, and operational flexibility across a mixed-traffic and partially electrified network. Historically, the freight sector has relied heavily on diesel traction, with electrification playing a more limited role due to the discontinuous nature of the electrified infrastructure.

The backbone of contemporary GB freight operations is the diesel locomotive, most notably the Class 66. This class has achieved widespread adoption due to its robustness, route availability, and compatibility with a wide range of freight duties, from intermodal services to bulk commodity flows. Its flexibility and network-wide operability have made it the default traction choice for many operators, particularly where electrification is unavailable or intermittent.

For more demanding duties, higher-power diesel locomotives, such as the Class 70, are deployed. These locomotives offer increased tractive effort and power compared with the Class 66 and are typically used on heavier trains, steeper routes, or where higher performance margins are required. Such locomotives are particularly relevant to heavy aggregate and bulk freight operations, where power-limited running on gradients is a defining characteristic.

The GB freight sector has also historically relied on a range of heavy haul diesel classes, including the Class 56 and Class 60. While some of these locomotives are now approaching the end of their service lives or have been withdrawn from front-line service, they illustrate the long-standing dependence of bulk freight on high-power diesel traction, particularly for aggregate, steel, and energy-related traffics.

Electric locomotives offer clear advantages in terms of energy efficiency, tractive performance, and emissions reduction. However, their deployment in GB freight service has been constrained by the extent and continuity of the electrified network. As a result, electric freight locomotives have historically been confined to a limited number of corridors with continuous electrification and suitable operational interfaces, restricting their wider applicability across the freight market.

More recently, the introduction of multi-mode and hybrid locomotives, such as the Class 93 and Class 99, reflects an emerging strategy to bridge the gap between electrified and non-electrified operation. These locomotives are capable of drawing traction power from the overhead line where available, while also carrying on-board energy sources such as diesel engines and batteries to extend operational capability beyond electrified sections. Hybrid designs aim to combine the efficiency benefits of electric traction with the flexibility of on-board energy storage, particularly for routes with discontinuous electrification.

It is important to note that, while this report refers to specific locomotive classes for contextual clarity, the modelling undertaken does not attempt to reproduce the detailed behaviour of individual locomotives as operated on the GB network. Instead, the analysis is based on synthetic locomotive models, developed to be representative of the performance characteristics of broad locomotive types. These models are parameterised using publicly available data on tractive effort, power at the wheels, and mass, and are intended to support comparative system-level analysis rather than detailed vehicle-specific assessment. Further details of this modelling approach are provided in the methodology section of this report.

2. OBJECTIVES OF THE STUDY

The overarching objective of this study is to develop an objective, simulation-based assessment of the feasibility, performance, and limitations of freight operations under discontinuous electrification supported by on-board energy storage, in comparison with conventional diesel and fully electrified traction.

In particular, the study aims to:

- Develop comparative energy consumption and performance data for a representative set of freight locomotive types currently operating, or proposed for operation, on the GB rail network.
- Quantify how electrification, bi-mode operation, and battery-assisted traction perform across a range of representative freight routes and duty conditions.
- Identify where electrification provides clear performance and energy advantages, and where battery-assisted operation may offer credible capability.
- Highlight physical, operational, and energetic limits, rather than assuming universal feasibility of battery-assisted freight operation.

To meet these objectives, the study considers:

- Four representative freight routes, spanning intermodal and heavy bulk operations, and including both favourable and challenging gradient profiles.
- Four locomotive types, selected to represent:
    - conventional diesel freight traction,
    - higher-power diesel traction,
    - modern bi-mode and hybrid concepts incorporating on-board battery storage.
- Three representative freight load types, spanning multimodal and standard and heavy aggregate operations.

The scope of the work extends beyond the minimum requirement of two to three routes specified in the original brief, to provide a broader and more robust evidence base for discussion. In addition, a stopping loop / siding scenario has been included to explore the energetic implications of braking, dwell, and re-acceleration events.

Consistent with the Scope of Work agreed following Workshop 4, the study is comparative rather than prescriptive. It is intended to inform strategic discussion within RIA and the Rail Freight Group, rather than to produce detailed vehicle designs, operational timetables, or business cases.

3. MODELLING METHODOLOGY AND ASSUMPTIONS

3.1 OVERVIEW OF THE SIMULATION APPROACH

The analysis has been undertaken using a physics-based longitudinal train simulation framework, developed at the University of Birmingham and refined over more than two decades. The simulator resolves train motion, traction power demand, and energy flows along a specified route profile, subject to vehicle performance limits and resistance forces.

The modelling approach is designed to capture the dominant physical effects governing freight train performance and energy consumption, while remaining sufficiently flexible to allow systematic comparison across a large number of scenarios.

3.2 LOCOMOTIVE REPRESENTATION

Given the comparative nature of the study, locomotive models have been implemented as synthetic representations whose performance characteristics are intended to be representative of real main-line locomotives, rather than exact digital twins.

Each locomotive model is defined primarily by:

- Maximum tractive effort,
- Maximum power available at the wheels,
- Locomotive mass,
- Traction mode (diesel, electric, or hybrid).

Published and publicly available data on tractive effort and power at the wheels have been used to parameterise these models. Detailed internal traction system characteristics (e.g. control algorithms, converter efficiencies, motor thermal limits) have not been explicitly modelled.

This level of abstraction is considered adequate and appropriate for the objectives of the study, as the focus is on system-level energy and performance comparisons rather than fine-grained differences between individual traction packages. Modelling locomotives in greater detail was considered out of scope, and any residual differences at that level are not expected to materially alter the comparative conclusions.

3.3 TRAIN RESISTANCE MODELLING

Train running resistance is represented using the well-established Davis formulation, expressed as:

$$R(v) = A + Bv + Cv^2$$

where:

$R(v)$is the total resistive force (kN),

v is train speed (m/s),

A represents constant (rolling and mechanical) resistance,

Bv represents speed-proportional resistance,

Cv^2 represents aerodynamic resistance.

Separate sets of Davis coefficients have been defined for the different freight load types (aggregate, jumbo aggregate, and multimodal), reflecting differences in trailing mass, consist length, and aerodynamic characteristics. These coefficients were treated as representative project inputs, consistent with the Scope of Work, and were not running data.

The Davis parameters used in the simulations represent aggregate characteristics of the trailing load rather than the detailed resistance of individual vehicles. This approach is appropriate for long freight trains where the locomotive resistance contribution is small compared with that of the trailing load.

The train is modelled as a point mass for longitudinal dynamics, such that the equation of motion can be expressed as:

$$M(1+\lambda)\frac{dv}{dt} = F_{tractive} - R(v) - Mgsin(\theta)$$

where:

M is total train mass,

F_{tractive} is the available tractive force,

g is gravitational acceleration,

θ is the track gradient angle,

λ is the allowance for rotational inertia (wheels, axles, drivetrain, etc.),

3.4 ROUTE REPRESENTATION

Each route is represented by a distance-based profile incorporating:

- Track gradient,
- Electrification status (electrified / non-electrified),
- Speed limits.

The simulation resolves speed, power, and energy continuously along the route, allowing identification of gradient-limited or power-limited operation where applicable.

3.5 ENERGY AND BATTERY MODELLING

The model explicitly tracks energy flows associated with:

- Traction energy drawn from the overhead line (where electrified),
- On-board energy consumption (diesel or battery),
- Regenerative braking energy.

For battery-assisted cases, a finite on-board energy store is assumed. Two indicative battery energy levels have been modelled:

- **4 MWh usable energy**, representing near-term (mid-2020s) battery capability,
- **8 MWh usable energy**, representing a plausible future case in the 2035–2040 timeframe.

These values are intended as representative and exploratory, rather than definitive. The quoted 4 MWh and 8 MWh figures refer to usable battery energy, not total installed capacity. These correspond approximately to 5 MWh and 10 MWh nameplate capacity respectively, reflecting assumed losses and reserve margin within the battery system. No detailed battery packaging or volumetric integration study has been undertaken at this stage; such work is identified as a potential next phase.

At the start of each simulated journey, the battery state of charge is assumed to be 100%, and no charging from the overhead line is assumed during the journey. Battery state of charge therefore generally decreases as energy is consumed on non-electrified sections but may increase locally due to regenerative braking events.

This approach allows the study to focus on single-journey feasibility and energy balance, rather than operational strategies for recharging between services.

The battery energy model used in the simulations tracks the state of charge (SOC) of the onboard energy storage system throughout the simulated journey.

At the start of each simulated route the battery is assumed to begin at 100% state of charge. The SOC then evolves according to the net energy balance during the journey.

The change in battery energy is calculated as:

$$E_{battery,final} = E_{battery,initial} - E_{traction} + E_{regeneration}$$

where:

- $E_{traction}$is the electrical energy drawn from the battery to provide traction power
- $E_{regeneration}$is the energy recovered during regenerative braking

Regenerative braking energy is returned to the battery whenever the train decelerates or descends significant gradients. As a result, the state of charge may increase temporarily during downhill sections of the route.

The modelling assumes that:

- the battery begins the journey fully charged
- no external charging occurs during the journey
- regenerative braking energy can be recovered and stored within the battery subject to available capacity.

The reported SOC change therefore represents the net energy balance over the complete route.

The analysis presented in this study focuses on energy capacity (MWh) rather than explicitly modelling battery power capability (C-rate). In practice, the ability of a battery system to deliver traction power is governed by its discharge rate relative to installed energy capacity.

For the battery sizes considered in this study (nominally 5 MWh and 10 MWh installed capacity, corresponding to approximately 4 MWh and 8 MWh usable energy), the implied C-rates required to support typical freight traction power demands are within the range of currently achievable lithium-ion battery systems, particularly when configured using multiple parallel modules.

For example, a locomotive requiring approximately 2–3 MW of traction power would correspond to a discharge rate of approximately 0.3C to 0.6C for a 5 MWh battery system, and proportionally lower for larger battery capacities. These values are consistent with established practice in high-power rail and heavy-duty battery applications.

On this basis, it is assumed that battery power capability is not a primary limiting factor for the scenarios considered, and that the dominant constraint is total onboard energy rather than instantaneous power delivery.

However, it should be noted that detailed battery system design would need to consider thermal limits, degradation effects, and sustained high-power operation, which are beyond the scope of the present system-level analysis.

4. LOCOMOTIVES, ROUTES AND SIMULATION SCENARIOS

4.1 REPRESENTATIVE LOCOMOTIVE MODELS

The locomotive models used in this study are synthetic representations, developed to capture the key performance characteristics of real freight locomotives operating on the GB network, rather than to reproduce the detailed behaviour of specific individual vehicles.

Each model is parameterised using published and publicly available data on tractive effort, power at the wheels, mass, and traction mode, but does not attempt to replicate proprietary control strategies or internal traction system details.

This approach is consistent with the objectives of the study, which focus on comparative performance and energy use, rather than detailed vehicle design or certification-level modelling.

Table 4.1: Representative Locomotive Models Used in the Simulation

Locomotive model (synthetic)	**Representative of**	**Traction modes modelled**	**Key characteristics captured**
General battery loco	Conventional diesel freight locomotive	Diesel	Power at wheels, tractive effort–speed characteristic, mass
Heavy haul battery loco	Higher-power diesel freight locomotive	Diesel	Higher tractive effort and power capability, mass
4 axle hybrid	Modern multi-mode / hybrid freight locomotive	Electric, battery	Electric traction under the wire, on-board diesel and battery support
Class 99–type	Bi-mode electric freight locomotive	Electric, battery	Electric traction on electrified routes, diesel off-wire

The models are intentionally simplified to ensure consistency across scenarios. Differences in detailed traction control behaviour are assumed to be second-order effects relative to the dominant influences of mass, power, resistance, gradients, and electrification availability.

4.2 ROUTES CONSIDERED

A set of four representative freight routes was selected to span a broad range of freight market segments, route lengths, gradients, and electrification coverage. Together, these routes provide a robust test of battery and battery bi mode and discontinuously electrified freight operation under both favourable and demanding conditions.

The modelling in this study assumes that the full electrified sections of the route are available for traction power. In practice, operational considerations may reduce the usable electrified distance slightly. This issue is acknowledged as an important practical consideration and could be explored further in future work.

The selected routes include intermodal corridors, mixed electrification routes, and a heavy aggregate flow representing one of the most challenging freight duty cycles on the GB network.

Table 4.2: Representative Freight Routes Modelled

Route	**Freight type represented**	**Key characteristics**
Felixstowe – Hams Hall	Intermodal multimodal	Major port-to-Midlands flow, mixed electrification, moderate gradients
Felixstowe – Coatbridge	Long-distance intermodal	Extended route length, significant non-electrified sections, cumulative energy demand
London Gateway – Doncaster	Intermodal / mixed freight	High utilisation of electrified main lines with short unwired gaps

Route	Freight type represented	Key characteristics
Merehead (Muirhead) – Acton	Heavy aggregate	Very high trailing loads, challenging gradients, severe test of power and energy capability

These routes were chosen not to represent every possible freight operation, but to provide credible exemplars of the types of duty cycles encountered across the GB freight network, including routes where battery assistance is expected to perform well and routes that represent boundary or worst-case conditions.

4.3 LOADS CONSIDERED

Each route was simulated using three representative freight load types:

- Multimodal / intermodal loads,
- Aggregate loads,
- Jumbo aggregate loads.

These load cases capture a wide range of trailing masses and resistance characteristics, allowing the interaction between train mass, route gradients, traction power, and energy storage to be explored systematically.

4.4 SIMULATION MATRIX AND SCENARIO COVERAGE

The modelling framework used in this study systematically evaluates all combinations of locomotive type, load type and route. This approach allows a consistent comparison of performance across the full scenario set.

However, some combinations of train type and route represent operational situations that would be unlikely in practice (for example very heavy aggregate trains operating over routes that normally carry container traffic).

These scenarios are retained in the modelling results primarily as stress-test cases that illustrate the limits of traction and energy capability. They should therefore be interpreted as indicative performance bounds rather than representative freight operating patterns. It may be appropriate for some of these unrealistic combinations to be removed from any publicly released version of the report to avoid misinterpretation. The simulation study adopts a brute-force, combinatorial approach, in which every combination of:

- locomotive model,
- route, and
- load type

is simulated.

This results in a comprehensive matrix of scenarios spanning:

- four locomotive models,
- four routes,
- three load types,

and multiple traction and energy configurations.

All scenarios were executed using a batch simulation framework, with no pre-filtering to exclude challenging or potentially infeasible cases. As a result, the output dataset includes:

- scenarios that operate comfortably,
- scenarios that are marginal, and
- scenarios that prove unviable due to physical or energetic constraints.

This approach ensures that the study reveals the limits of feasibility, rather than selectively reporting favourable outcomes. Infeasible or unrealistic scenarios are retained in the results dataset and identified as such, providing valuable insight into where battery-assisted or discontinuously electrified freight operation does not close.

4.5 BATTERY LOCOMOTIVES AND ON-BOARD ENERGY STORAGE

EXISTING BATTERY AND HYBRID BATTERY LOCOMOTIVES

A small but growing number of battery and battery-hybrid locomotives have been developed and deployed internationally, primarily in yard, industrial, or niche main-line applications. These vehicles provide useful insight into the current state of the art, while also highlighting the constraints associated with on-board energy storage for rail traction (Table 4.1).

Table 4.1: Examples of Existing Battery and Battery-Hybrid Locomotives

Manufacturer & model	**Power system type**	**Battery energy (approx.)**	**Max traction power**	**Axles**	**Typical freight role / operator**	**Status**
Wabtec FLXdrive – Heavy-haul	**Battery-only** electric	**7.0 MWh** (heavy-haul version) (Wabtec Corporation)	**3.2 MW** (Wabtec Corporation)	Co-Co	Heavy-haul freight in consist with diesels (iron ore, bulk). Orders / deployments with **BHP**, **Roy Hill**, others in Australia & N. America. (Wabtec Corporation)	In service / delivery (production units)
Wabtec FLXdrive – Switcher / Shunter	**Battery-only** electric	**~1.2–2.7 MWh** (yard/switcher variants) (Wabtec Corporation)	**0.7–1.7 MW** (Wabtec Corporation)	Bo-Bo / Co-Co	Yard and industrial shunting, short transfer moves, often in freight terminals.	In service / demo with several N. American operators
Progress Rail EMD® Joule	**Battery-only** electric	Up to **14.5 MWh** (progressrail.com)	Around **2.4 MW** for main variant (Anacostia Rail Holdings)	4, 6 or 8-axle (various)	Designed for **yard switching, regional freight** and use in consist with diesels (e.g. Vale in Brazil). (progressrail.com)	In service / early fleet deployments
Alstom Prima H3 Battery	**Battery-only** electric	n/a publicly (battery output **600 kW**) (Wikipedia)	**600 kW** (battery) (Wikipedia)	C (three powered axles)	**Shunting and short-distance freight** for DB, SBB and industrial operators; fully battery version has no fuel tank. (hoppecke.com)	In service (small fleets)
Vossloh DE 18 SmartHybrid (for DB Cargo / leasing fleets)	**Diesel + battery hybrid** (battery can power traction for limited periods)	Battery power about **2 × 36 kW** (small pack; kWh not given) (kiepe-group.com)	**1,800 kW** total loco rating (nexrail.lease)	Bo-Bo	**Heavy shunting & short mainline freight** with zero-emission / low-noise operation in stations and yards (DB Cargo & others). (nachhaltigkeit.deutschebahn.com)	In service (growing fleet)
Toshiba HDB 800 (DB Cargo hybrid)	**Diesel + battery hybrid**	Battery output **≈750 kW** (SCiB Li-ion traction battery) (toshiba-railway.eu)	**750 kW at wheel; 300 kN** TE; 100 km/h max (toshiba-railway.eu)	Bo-Bo	**Yard shunting and short-distance mainline freight** for DB Cargo (Germany). (rollingstockworld.com)	Prototypes / initial series under testing (2025)
JR Freight Class HD300 (Japan)	**Diesel + battery hybrid**	Li-ion battery banks (detailed module spec published, overall kWh not usually quoted) (global.toshiba)	**~500 kW** total output (Wikipedia)	Bo-Bo	**Freight yard shunting** for JR Freight, replacing older diesel shunters with lower emissions and noise. (Wikipedia)	In service (fleet >30 locos)
CRRC "Bison" hybrid loco (Rail Cargo Hungaria)	**Electric + battery hybrid** (can run in battery-only mode)	Not public; designed for rapid recharge from 25 kV AC in ~2.5 h (RAILMARKET.com)	**5,600 kW** rated power; **300 kN** starting TE (RAILMARKET.com)	Co-Co	25 kV electric freight loco with substantial traction battery, tested in **battery-only operation** on non-electrified sections / yards. (RAILMARKET.com)	Testing / pilot freight operation (Europe, 2025)

These examples demonstrate several common features:

Battery locomotives are typically deployed where:

- duty cycles are well defined,
- recharge opportunities are available,
- and peak power demands can be managed.

Even in the most advanced current examples, battery energy capacity is modest relative to the total energy required for long-distance or heavy-haul freight operation.

Battery systems are often used to:

- reduce fuel consumption,
- smooth power demand,
- or enable zero-emission operation over limited distances,
  rather than to replace diesel or electrification entirely.

These observations reinforce the importance of assessing battery-assisted freight operation in a system context, rather than assuming batteries can act as a direct substitute for continuous power supply.

5. BATTERY TECHNOLOGY: CURRENT AND FUTURE CAPABILITY

In parallel with vehicle development, battery technology itself continues to evolve, with improvements expected in both gravimetric energy density (Wh/kg) and volumetric energy density (Wh/L) over time (Table 5.1).

Table 5.1: Indicative Battery Performance – Present Day and Future

date	Chemistry / tech class	**Cell specific energy** (Wh/kg)	**Cell volumetric** (Wh/L)	**Pack specific energy** (Wh/kg)	**Pack volumetric** (Wh/L)	**Railway package** (Wh/kg)	**Railway package** (Wh/L)	Notes / refs
2026	**LFP (rail-friendly, safer, long life)**	~160–200 (example ~186) (Battery Design)	~350–450 (example ~419) (Battery Design)	~110–150	~220–320	**~90–130**	**~180–280**	LFP is widely used; lower energy density but robust. Cell range context: Li-ion ~90–300 Wh/kg. (IEA Blob Storage)
2026	**NMC/NCA (higher energy density)**	~250–300 (nickel-rich typical) (irena.org)	~600–750 (varies by design) (IEA Blob Storage)	~170–220	~400–550	**~140–190**	**~330–480**	Higher density but usually tighter thermal/safety constraints than LFP.
2035	**Improved Li-ion (Si anodes, cell-to-pack, better structural integration)**	~300–380 (credible) (IEA Blob Storage)	~750–900 (credible) (NASA Technical Reports Server)	~200–260	~500–700	**~160–220**	**~420–620**	"Pack/system improvement" tends to be slower than cell improvement (integration/safety dominates).
2040 (best-case)	**Solid-state / Li-metal class**	**up to ~500** (isi.fraunhofer.de)	**up to ~1150** (isi.fraunhofer.de)	~280–350	~750–950	**~220–300**	**~600–850**	This is *best-case* performance; timing/qualification for rail duty is the uncertainty. (isi.fraunhofer.de)

The values presented in this table are indicative and are intended to represent rail-qualified battery systems, rather than laboratory or automotive best-case figures. They reflect the additional mass and volume associated with containment, cooling, safety systems, and structural integration required for railway applications.

The table illustrates a clear prospective improvement in battery capability over the medium to long term. However, even with these improvements, battery energy density remains orders of magnitude lower than liquid fuels and therefore places fundamental constraints on the amount of energy that can be carried on board a locomotive.

The 5 MWh installed / 4 MWh usable case should be regarded as being at the highly optimistic end of near-term feasibility for a GB-gauge freight locomotive, particularly for a hybrid platform. Likewise, the 10 MWh installed / 8 MWh usable case represents an optimistic future scenario, intended to test the upper bound of what improved battery technology might permit rather than to imply a near-term deployable product.

5.1 PACKAGING AND INTEGRATION CONSIDERATIONS

At present, there is no off-the-shelf, GB-gauge battery freight locomotive platform capable of accommodating very large on-board energy storage without significant design effort. In practical terms, battery capacities in the 5 MWh installed range are already close to the upper end of what appears plausibly packageable within a GB-gauge locomotive, particularly for hybrid locomotives which must also accommodate transformer, converter and rectifier equipment. The larger 10 MWh installed scenario should therefore be interpreted as an optimistic stress-test assumption, not as a near-term packaging proposition.

Packaging a multi-megawatt-hour battery system within a GB-gauge locomotive would require:

- careful management of mass and axle loads,
- provision of adequate cooling and fire protection,
- structural integration consistent with crashworthiness requirements,

Therefore, deployment of large on-board battery systems would require investment by train manufacturers to develop products specifically suited to the GB network. However, there is also an opportunity for modular battery integration. By adopting modular battery arrangements:

- locomotives could be introduced initially with smaller battery capacities, aligned with near-term capability,
- battery modules could potentially be upgraded or augmented as technology improves,
- future enhancements could be delivered without wholesale redesign of the locomotive platform.

This approach could provide a pragmatic pathway for gradual capability improvement, while managing technical and commercial risk.

5.2 TREATMENT OF BATTERY CHARGING IN THIS ANALYSIS

In the simulations undertaken as part of this project, explicit charging of the battery from the overhead line has not been modelled.

For each simulated journey:

- the battery state of charge is assumed to start at 100%, and
- battery energy is depleted during non-electrified operation,
- with partial recovery through regenerative braking where applicable.

Charging under the wire has been excluded deliberately, as its inclusion would introduce a range of additional considerations beyond the immediate scope of this work. Modern electric and bi-mode freight locomotives already impose high power demands on the overhead line system, simultaneous traction and battery charging could result in very significant current draw, this may have implications for:

- power supply capacity,
- voltage stability,
- and network capacity.

Accurately assessing these effects would require detailed electrical power system modelling, including interaction with the traction power supply network. Such analysis is identified as a potential future extension of the work, rather than something that can be addressed within the current study.

6. RESULTS PRESENTATION AND INTERPRETATION

6.1 OVERVIEW OF RESULTS PRESENTATION

The results of the simulation study are presented primarily in tabular form, supported by a set of illustrative figures showing representative simulation outputs and route characteristics.

Rather than splitting the results across multiple small tables, the outputs have been consolidated into a single comprehensive results table, presented in landscape format. This approach allows consistent comparison across locomotive types, routes, loads, and energy configurations, while retaining transparency over the underlying parameters (Table 6.1). Blank cells indicate scenarios that were infeasible or could not be solved due to traction or gradient limits.

Battery-only scenarios were included in the modelling to illustrate the maximum capability that might be achieved using onboard energy storage without drawing power from the overhead electrification system.

It should also be noted that electric freight locomotives typically incorporate ballast to achieve sufficient axle load for adhesion. In some designs a proportion of this ballast mass could potentially be replaced by battery systems, partially offsetting the additional mass of the energy storage equipment.

For the diesel locomotive types included in the analysis (Class-66-type and Class-70-type), the battery-only cases represent hypothetical configurations in which the diesel prime mover is replaced by onboard battery energy storage. These scenarios are not intended to represent currently available locomotives, but instead provide an indication of the level of performance that could potentially be achieved by future battery only freight locomotives.

For the multi-mode locomotive types included in the study (Class-93-type and Class-99-type), the battery-only scenarios represent operation using onboard energy storage without drawing power from the overhead line, illustrating the potential capability of future battery-electric freight locomotives.

It should also be noted that the battery capacities assumed in the simulations (4 MWh representing current technology and 8 MWh representing a potential future capability) are used for indicative energy analysis only and do not imply that such systems could necessarily be packaged within the volume constraints of a GB-gauge locomotive without further engineering development.

Table 6.1: Summary of Simulation Results Across All Scenarios

locotype	routename	loadname	time_hr	dist_km	non_elec_km	elec_km	elect ratio	avg_speed_kmh	pantograph_MWh	onboard_MWh	pantograph_kWh_per_tkm	onboard_kWh_per_tkm	train_mass_kT	pantograph_kWh_per_train_km	onboard_kWh_per_train_km	battery_range_km 4MWh	soc_change 4MWh	trips_possible (4MWh)	trips_possible (8MWh)
Gen_Batt	Felix_Hams	aggregate	5.162	281.9	244.1	37.8	0.134	54.62	0	8.8482	0	0.014266	2.2	0	31.3855	127.4474	2.212	0.45207	0.90
Gen_Batt	Felix_Coat_s	aggregate		774	25	749	0.968		0		0		2.2	0					
Gen_Batt	London_G_Don	aggregate	5.441	316	4.5	311.5	0.986	58.08	0	7.9623	0	0.011453	2.2	0	25.1972	158.7481	1.9906	0.50237	1.00
Gen_Batt	Merehead_Acton	aggregate	2.699	172	91.33	80.67	0.469	63.72	0	3.72	0	0.0098308	2.2	0	21.6278	184.9472	0.93	1.0753	2.15
Gen_Batt	Felix_Hams	Jumbo aggregate		281.9	244.1	37.8	0.134		0		0		4.8	0					
Gen_Batt	Felix_Coat_s	Jumbo aggregate		774	25	749	0.968		0		0		4.8	0					
Gen_Batt	London_G_Don	Jumbo aggregate		316	4.5	311.5	0.986		0		0		4.8	0					
Gen_Batt	Merehead_Acton	Jumbo aggregate	3.039	172	91.33	80.67	0.469	56.59	0	4.7676	0	0.0057747	4.8	0	27.7184	144.3084	1.1919	0.839	1.68
Gen_Batt	Felix_Hams	multimodal	4.799	281.9	244.1	37.8	0.134	58.75	0	6.8762	0	0.015244	1.6	0	24.3905	163.9983	1.719	0.58172	1.16
Gen_Batt	Felix_Coat_s	multimodal	15.29	774	25	749	0.968	50.63	0	16.0031	0	0.012922	1.6	0	20.6758	193.4626	4.0008	0.24995	0.50
Gen_Batt	London_G_Don	multimodal	5.214	316	4.5	311.5	0.986	60.61	0	6.1189	0	0.012102	1.6	0	19.3635	206.5744	1.5297	0.65372	1.31
Gen_Batt	Merehead_Acton	multimodal	2.583	172	91.33	80.67	0.469	66.59	0	2.8545	0	0.010372	1.6	0	16.5959	241.0235	0.71362	1.4013	2.80
Heavy_Batt	Felix_Hams	aggregate	4.887	281.9	244.1	37.8	0.134	57.68	0	9.3261	0	0.015037	2.2	0	33.0806	120.9169	2.3315	0.4289	0.86
Heavy_Batt	Felix_Coat_s	aggregate	15.52	774	25	749	0.968	49.88	0	21.8202	0	0.012814	2.2	0	28.1915	141.8869	5.455	0.18332	0.37
Heavy_Batt	London_G_Don	aggregate	5.265	316	4.5	311.5	0.986	60.02	0	8.3142	0	0.011959	2.2	0	26.3107	152.0293	2.0785	0.48111	0.96
Heavy_Batt	Merehead_Acton	aggregate	2.608	172	91.33	80.67	0.469	65.95	0	3.8823	0	0.01026	2.2	0	22.5718	177.2124	0.97059	1.0303	2.06
Heavy_Batt	Felix_Hams	Jumbo aggregate	5.81	281.9	244.1	37.8	0.134	48.52	0	13.6254	0	0.010069	4.8	0	48.3307	82.7632	3.4063	0.29357	0.59
Heavy_Batt	Felix_Coat_s	Jumbo aggregate		774	25	749	0.968		0		0		4.8	0					
Heavy_Batt	London_G_Don	Jumbo aggregate	5.786	316	4.5	311.5	0.986	54.62	0	11.5208	0	0.0075955	4.8	0	36.4583	109.7145	2.8802	0.3472	0.69
Heavy_Batt	Merehead_Acton	Jumbo aggregate	2.861	172	91.33	80.67	0.469	60.12	0	5.0776	0	0.0061502	4.8	0	29.5208	135.4976	1.2694	0.78778	1.58
Heavy_Batt	Felix_Hams	multimodal	4.64	281.9	244.1	37.8	0.134	60.76	0	7.1044	0	0.01575	1.6	0	25.2001	158.7296	1.7761	0.56303	1.13
Heavy_Batt	Felix_Coat_s	multimodal	14.86	774	25	749	0.968	52.1	0	16.326	0	0.013183	1.6	0	21.0931	189.6358	4.0815	0.24501	0.49
Heavy_Batt	London_G_Don	multimodal	5.106	316	4.5	311.5	0.986	61.89	0	6.296	0	0.012453	1.6	0	19.9241	200.7618	1.574	0.63532	1.27
Heavy_Batt	Merehead_Acton	multimodal	2.537	172	91.33	80.67	0.469	67.8	0	2.9344	0	0.010663	1.6	0	17.0605	234.4598	0.7336	1.3631	2.73

locotype	routename	loadname	time_hr	dist_km	non_elec_km	elec_km	elect ratio	avg_speed_kmh	pantograph_MWh	onboard_MWh	pantograph_kWh_per_tkm	onboard_kWh_per_tkm	train_mass_kT	pantograph_kWh_per_train_km	onboard_kWh_per_train_km	battery_range_km 4MWh	soc_change 4MWh	trips_possible (4MWh)	trips_possible (8MWh)
4 axle hybrid	Felix_Hams	aggregate	6.802	281.9	244.1	37.8	0.134	41.45	1.8648	5.3636	0.022424	0.009987	2.2	49.3323	21.9713	182.0553	1.3409	0.74576	1.49
4 axle hybrid	Felix_Coat_s	aggregate		774	25	749	0.968			0.60481		0.010996	2.2		24.1922	165.3424	0.1512	6.6137	13.23
4 axle hybrid	London_G_Don	aggregate	4.882	316	4.5	311.5	0.986	64.73	8.6797	0.11079	0.012665	0.011191	2.2	27.8641	24.6197	162.4714	0.027697	36.1048	72.21
4 axle hybrid	Merehead_Acton	aggregate	3.044	172	91.33	80.67	0.469	56.5	2.0321	1.6428	0.01145	0.0081759	2.2	25.1908	17.9871	222.3819	0.41069	2.4349	4.87
4 axle hybrid	Felix_Hams	Jumbo aggregate		281.9	244.1	37.8	0.134						4.8						
4 axle hybrid	Felix_Coat_s	Jumbo aggregate		774	25	749	0.968						4.8						
4 axle hybrid	London_G_Don	Jumbo aggregate		316	4.5	311.5	0.986			0.16504		0.0076408	4.8		36.6759	109.0635	0.04126	24.2363	48.47
4 axle hybrid	Merehead_Acton	Jumbo aggregate		172	91.33	80.67	0.469						4.8						
4 axle hybrid	Felix_Hams	multimodal	5.844	281.9	244.1	37.8	0.134	48.24	1.4828	4.3024	0.024517	0.011015	1.6	39.2275	17.6241	226.9613	1.0756	0.92971	1.86
4 axle hybrid	Felix_Coat_s	multimodal	13.54	774	25	749	0.968	57.18	15.2402	0.4621	0.012717	0.011552	1.6	20.3474	18.4839	216.405	0.11552	8.6562	17.31
4 axle hybrid	London_G_Don	multimodal	4.737	316	4.5	311.5	0.986	66.71	6.4548	0.083494	0.012951	0.011596	1.6	20.7218	18.5543	215.584	0.020874	47.9076	95.82
4 axle hybrid	Merehead_Acton	multimodal	2.703	172	91.33	80.67	0.469	63.64	1.4365	1.304	0.011129	0.008924	1.6	17.8066	14.2784	280.1439	0.32601	3.0674	6.13
6 axle hybrid	Felix_Hams	aggregate	5.142	281.9	244.1	37.8	0.134	54.83	2.0688	6.7186	0.024877	0.01251	2.2	54.7296	27.5216	145.3403	1.6796	0.59536	1.19
6 axle hybrid	Felix_Coat_s	aggregate	13.33	774	25	749	0.968	58.06	21.0522	0.67253	0.012776	0.012228	2.2	28.1071	26.9011	148.6928	0.16813	5.9477	11.90
6 axle hybrid	London_G_Don	aggregate	4.685	316	4.5	311.5	0.986	67.45	8.9749	0.11641	0.013096	0.011759	2.2	28.8118	25.869	154.625	0.029103	34.3611	68.72
6 axle hybrid	Merehead_Acton	aggregate	2.453	172	91.33	80.67	0.469	70.12	1.9793	1.9349	0.011152	0.0096298	2.2	24.5355	21.1856	188.8071	0.48372	2.0673	4.13
6 axle hybrid	Felix_Hams	Jumbo aggregate		281.9	244.1	37.8	0.134		3.111		0.017146		4.8	82.3029					
6 axle hybrid	Felix_Coat_s	Jumbo aggregate		774	25	749	0.968			1.0885		0.0090706	4.8		43.5387	91.8723	0.27212	3.6749	7.35
6 axle hybrid	London_G_Don	Jumbo aggregate	4.969	316	4.5	311.5	0.986	63.59	12.9971	0.19563	0.0086925	0.0090571	4.8	41.7241	43.474	92.0091	0.048908	20.4465	40.89
6 axle hybrid	Merehead_Acton	Jumbo aggregate	2.797	172	91.33	80.67	0.469	61.5	2.7534	2.5376	0.0071108	0.0057886	4.8	34.1317	27.7852	143.9616	0.63441	1.5763	3.15
6 axle hybrid	Felix_Hams	multimodal	4.697	281.9	244.1	37.8	0.134	60.02	1.6228	5.3167	0.026832	0.013612	1.6	42.9318	21.7791	183.6624	1.3292	0.75234	1.50
6 axle hybrid	Felix_Coat_s	multimodal	13.09	774	25	749	0.968	59.15	15.3963	0.5111	0.012847	0.012778	1.6	20.5558	20.4441	195.6553	0.12778	7.8262	15.65
6 axle hybrid	London_G_Don	multimodal	4.612	316	4.5	311.5	0.986	68.52	6.6013	0.083166	0.013245	0.011551	1.6	21.192	18.4813	216.4349	0.020791	48.0966	96.19
6 axle hybrid	Merehead_Acton	multimodal	2.299	172	91.33	80.67	0.469	74.83	1.4715	1.4671	0.011401	0.01004	1.6	18.2414	16.0642	249.0015	0.36678	2.7264	5.45

In several locations in the results tables blank cells appear in the output columns.

These occur where the simulation model determines that the locomotive is unable to complete the route within the available traction capability or energy storage limits. In these cases the numerical solver does not produce a feasible solution for the duty cycle and the corresponding table entries are therefore left blank.

This most commonly occurs where gradients exceed the available tractive effort of the locomotive for the given load.

6.2 CONTENTS OF THE RESULTS TABLE

The results table includes the following categories of information:

Route and Operational Parameters

- Total route length
- Proportion of electrified and non-electrified running
- Average speed and journey time

Energy Consumption Metrics

- Total traction energy drawn from the overhead line
- Total on-board energy consumption (battery)
- Energy consumption normalised by:
- train-kilometre, and
- tonne-kilometre
- These normalised metrics allow direct comparison between routes and load types of differing length and mass.

Battery-Specific Metrics

For battery-assisted and battery-only scenarios, the table also reports:

- Change in battery state of charge over the journey
- Estimated number of complete journeys achievable for a given battery capacity
- Two indicative battery capacities are considered:
    - 4 MWh usable energy, representing near-term capability
    - 8 MWh usable energy, representing a future capability case

Two indicative battery capacities are considered: 4 MWh usable energy and 8 MWh usable energy. These correspond approximately to 5 MWh and 10 MWh installed (nameplate) capacity respectively. Throughout this report, results are presented in terms of usable energy, since that is the energy available to support traction.

6.3 VISUAL ENCODING AND COLOUR CODING OF RESULTS

To aid interpretation of the large results table, colour coding has been applied to selected key metrics, most notably the number of trips achievable on a single battery charge.

The colour coding is used to provide an immediate visual indication of feasibility:

Red:

- Fewer than 1 complete trip achievable
- Indicates the duty cycle is not feasible without recharging or operational intervention

Amber (Yellow):

- Between 1 and 1.5 trips achievable
- Indicates marginal feasibility, with limited operational robustness

Green:

- Greater than 1.5 trips achievable
- Indicates robust feasibility for the defined duty cycle

This visual approach allows rapid identification of routes and scenarios where battery-assisted operation is robust, cases where operation is marginal and sensitive to assumptions, and scenarios that are not physically viable under the assumed conditions.

6.4 FULLY BATTERY-ONLY STRESS-TEST SCENARIOS

A subset of scenarios has been modelled assuming 100% battery operation, with no electrification available along the route.

These cases are intentionally challenging and are included to:

- illustrate the physical and energetic limits of battery-only freight traction,
- provide a clear contrast with discontinuously electrified operation,
- demonstrate how rapidly feasibility erodes as electrification is removed.

The results of these cases should be interpreted as boundary conditions, rather than as practical near-term deployment scenarios.

6.5 REPRESENTATIVE SIMULATION OUTPUTS

In addition to the tabular results, a figure is included to illustrate typical simulation outputs for one of the four routes.

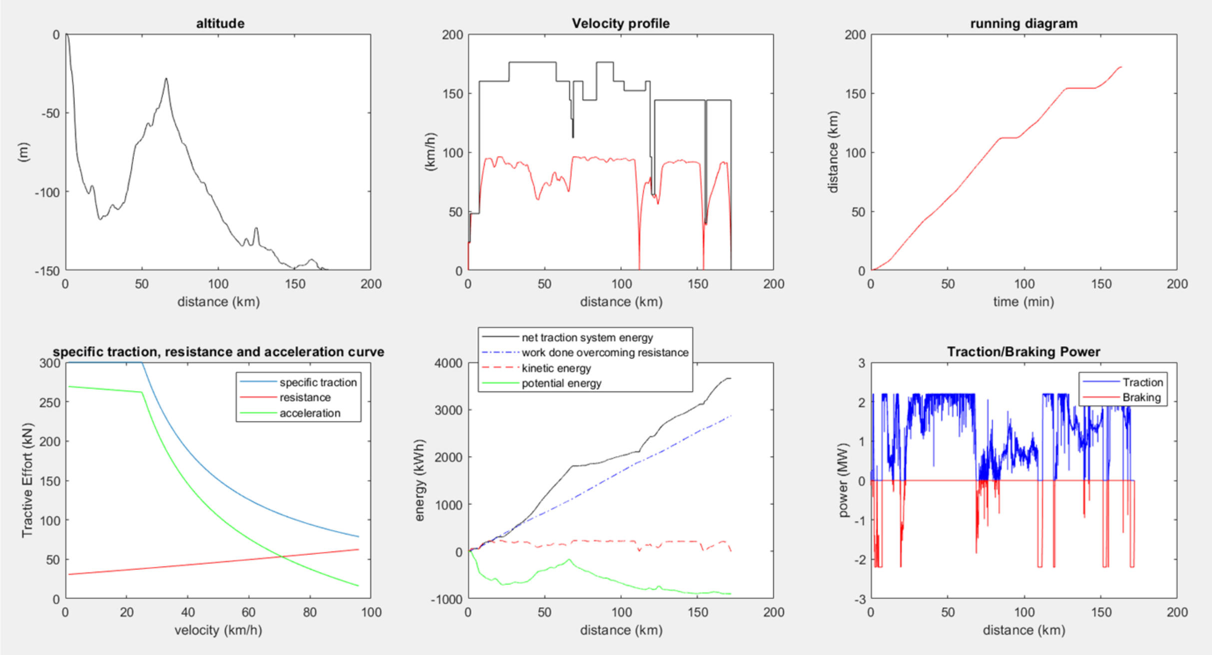

Figure 6.5: Representative Simulation Outputs

A representative locomotive–load combination is shown, illustrating:

- route altitude profile,
- speed and power demand,
- energy consumption along the route,
- journey time.

This figure is intended to provide qualitative insight into how and why energy is consumed, rather than to present exhaustive quantitative data.

6.6 ROUTE GEOMETRY AND GRADIENT PROFILES

To provide additional context, the layout and gradient characteristics of each route are illustrated using mapping-derived profiles. Figure 6.6.

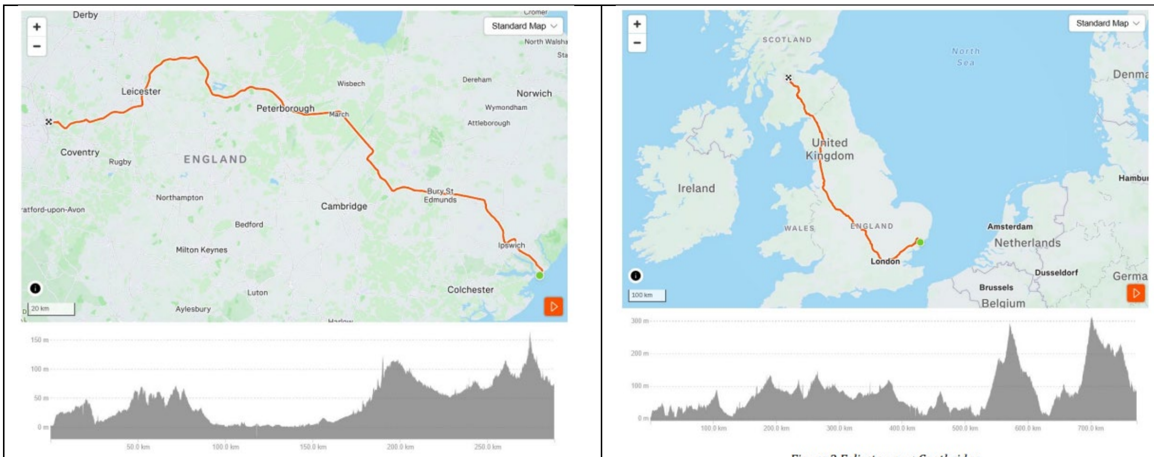

Figure 1 Felixstowe → Hams Hall

Figure 2 Felixstowe → Coatbridge

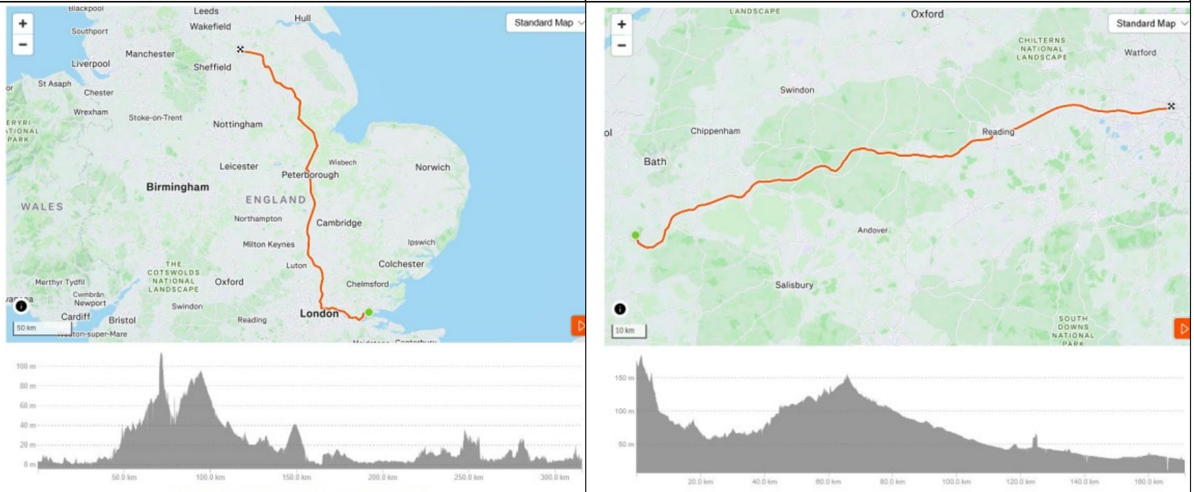

Figure 3. London Gateway → Doncaster

Figure 4 Mendips → Acton

Figures 6.6 Route Maps and Gradient Profiles

These figures show:

- route alignment,
- major gradient features,
- locations of significant climbs and descents.

Together with the simulation outputs, they help explain why certain routes are more challenging for battery-assisted operation, how gradients interact with train mass and power limits, and why some scenarios become infeasible despite sufficient nominal energy capacity.

6.7 CRITICAL GRADIENT AND BALANCING SPEED ANALYSIS

In addition to the route-based simulations described in the main report, an additional analysis was undertaken to investigate the maximum gradients that can be sustained by different locomotive and train load combinations.

Several reviewers raised questions regarding the ability of heavy freight trains to climb steep gradients on some of the routes considered in the study, particularly the Westbury–Savernake climb and the Nuneaton–Arley gradient.

To address this point, a supplementary gradient capability analysis was undertaken for each locomotive and trailing load combination. The analysis determines the theoretical maximum gradient that can be sustained based on locomotive tractive effort and the Davis resistance parameters used in the simulation model.

In addition, balancing speeds were calculated for two representative gradients corresponding approximately to the Westbury–Savernake climb (1 in 100) and the Nuneaton–Arley gradient (1 in 110). The results of this analysis are presented in Table 1.

This analysis determines the balancing speed of the train on a given gradient.

The balancing condition occurs when the available locomotive tractive effort is equal to the total resistive forces acting on the train:

$$F_{traction} = F_{resistance} + F_{gradient}$$

where:

- $F_{traction}$is the locomotive tractive effort available at the wheel
- $F_{resistance}$is the rolling and aerodynamic resistance calculated using the Davis equation
- $F_{gradient}$is the gravitational force due to track gradient

The Davis resistance formulation used in the simulations is:

$$F_{resistance} = A + Bv + Cv^2$$

where v is train speed.

The gradient force is calculated as:

$$F_{gradient} = Mg\sin(\theta)$$

where:

- $M$is the train mass
- $g$is gravitational acceleration
- $\theta$is the track gradient angle.

Table 1 – Maximum theoretical gradient capability of representative locomotive and freight load combinations.

The maximum gradient is derived from locomotive tractive effort and Davis resistance parameters assuming sufficient adhesion. The final two columns show the calculated balancing speed on representative critical gradients corresponding approximately to the Westbury–Savernake climb (1 in 100) and the Nuneaton–Arley gradient (1 in 110). Where the available tractive effort is insufficient to overcome resistance on the specified gradient, no balancing speed exists and the entry is left blank.

Locomotive model	**Load type**	**Train mass (t)**	**Davis A (kN)**	**Max tractive effort (kN)**	**Maximum gradient (1 in N)**	**Savernake speed (km/h)**	**Arley speed (km/h)**
Class-S66 type	Aggregate	2200	32	300	1 in 81	30.7	33.2
Class-S66 type	Jumbo aggregate	4800	46.8	300	1 in 186	–	–
Class-S66 type	Multimodal	1600	23	300	1 in 57	41.7	44.9
Class-S70 type	Aggregate	2200	32	427	1 in 55	38.1	41.0
Class-S70 type	Jumbo aggregate	4800	46.8	427	1 in 124	–	–
Class-S70 type	Multimodal	1600	23	427	1 in 39	51.5	55.3
Class-S93 type	Aggregate	2200	32	290	1 in 84	54.2	58.2
Class-S93 type	Jumbo aggregate	4800	46.8	290	1 in 194	–	–
Class-S93 type	Multimodal	1600	23	290	1 in 59	72.8	77.8
Class-S99 type	Aggregate	2200	32	500	1 in 46	80.6	86.1
Class-S99 type	Jumbo aggregate	4800	46.8	500	1 in 104	–	45.3
Class-S99 type	Multimodal	1600	23	500	1 in 33	107.0	113.7

7. INTERPRETATION OF RESULTS AND CONCLUSIONS

The results of this study demonstrate that battery-assisted freight operation can be technically feasible, but only within clearly defined operating envelopes. The simulation outputs consistently show that feasibility is governed by a combination of route characteristics, train mass, available electrification, and the amount of on-board energy storage, rather than by battery capacity alone.

Across the scenarios modelled, multimodal and intermodal routes with a high utilisation of existing electrification and relatively short non-electrified gaps exhibit the strongest alignment with battery-assisted operation. On these routes, batteries function effectively as a bridging and optimisation technology, enabling trains to traverse unwired sections without relying solely on diesel traction. In such cases, the battery contributes to improved energy efficiency and reduced diesel usage, while electrification remains the dominant source of traction energy.

In contrast, more demanding routes — particularly Merehead to Acton, representing heavy aggregate traffic — provide a severe test of battery-assisted freight concepts. These routes combine very high trailing loads with challenging gradients, resulting in substantial power and energy demands. The modelling indicates that, under certain assumptions, single end-to-end journeys may be feasible, even for the heaviest load cases, provided sufficient on-board energy is available.

However, a critical finding of the study is that single-journey feasibility does not equate to full operational viability. In many scenarios, the results demonstrate that while a train may complete one journey using on-board energy, it would not be able to undertake repeated trips without recharging. As such, the analysis does not support the assumption that battery-assisted freight can be treated as a direct, drop-in replacement for diesel traction across full daily duty cycles.

This observation introduces significant operational and infrastructure considerations. Battery-assisted freight operation would require careful management of recharging opportunities, whether through access to electrified sections of route, dedicated charging infrastructure at terminals or loops, or the use of battery tender vehicles. Each of these options has implications for infrastructure investment, operating flexibility, and network power supply capability, none of which can be assumed to be trivial.

The results also highlight the importance of discontinuous electrification as part of an integrated strategy. In many cases, targeted electrification of key sections — such as steep gradients, terminal approaches, or heavily trafficked corridors — delivers substantially greater benefit than attempting to compensate for long unwired sections through large on-board batteries alone. Battery technology, when deployed in conjunction with electrification, can therefore enable more flexible and cost-effective decarbonisation pathways.

Overall, the study reinforces that battery technology should be viewed as a complementary enabler, rather than a wholesale substitute for electrification. While ongoing improvements in battery energy density are likely to expand the feasible operating envelope over time, fundamental physical constraints related to mass, volume, and energy density remain. Consequently, physics, infrastructure, and operational realities ultimately define what is feasible.

Taken together, these findings provide an evidence-based foundation for strategic discussion within the rail freight sector. They suggest that the greatest system-level benefits will be achieved through a balanced approach, combining targeted electrification with modest, realistic on-board energy storage, rather than relying on large batteries to overcome the absence of infrastructure.

8. LIMITATIONS AND FUTURE WORK

8.1 LIMITATIONS OF THE CURRENT STUDY

While the modelling framework developed in this study provides a robust, physics-based assessment of battery-assisted freight feasibility, a number of limitations should be acknowledged.

First, the treatment of battery operation is deliberately simplified. The simulations assume a fixed usable battery energy capacity, with the battery state of charge initially set to 100% and subsequently depleted during non-electrified operation, subject only to recovery through regenerative braking. Detailed battery charging strategies, including charging under electrification, power-limited charging, and optimisation of charge–discharge cycles, have not been modelled. Inclusion of such strategies would require additional assumptions and, critically, detailed modelling of traction power supply constraints.

Related to this, battery depth of discharge limits, ageing effects, degradation over time, and maintenance considerations have not been explicitly considered. These factors would influence usable energy, long-term performance, and whole-life costs, and are therefore important topics for future investigation.

Second, the study does not include a detailed packaging or mechanical design assessment for battery-equipped locomotives. While indicative battery capacities have been selected based on plausible near-term and future technology, no explicit analysis has been undertaken of:

battery volume and mass integration,

- axle-load distribution,
- thermal management,
- fire protection and safety systems, or
- compliance with GB loading gauge and structural requirements.

Addressing these issues would require close collaboration with vehicle manufacturers and would form a natural next stage of work.

Third, the locomotive models used in the simulations are synthetic, representative models, rather than detailed digital twins of specific vehicles. They are parameterised using publicly available data on tractive effort, power at the wheels, and mass, but do not capture proprietary traction control strategies or detailed subsystem behaviour. While this level of abstraction is appropriate for comparative, system-level analysis, it could be refined in future studies where higher-fidelity vehicle data are available.

Finally, the freight load cases modelled in this study are representative and derived from published literature and industry sources. Actual operating loads on the GB network may exhibit greater variability, influenced by operational practices, route restrictions, and commercial considerations. Future work could refine these assumptions using more detailed empirical data to better reflect the diversity of real-world freight operations.

8.2 AREAS FOR FUTURE WORK

Building on the findings of this study, several clear areas for further investigation are identified:

- Detailed modelling of battery charging under electrification, including interaction with the traction power supply system and assessment of network power and voltage constraints.
- Investigation of battery lifecycle performance, including ageing, degradation, depth-of-discharge limits, and implications for maintenance and replacement strategies.
- Packaging and integration studies for GB-gauge battery-equipped locomotives, including assessment of modular battery concepts and upgrade pathways.

- Refinement of locomotive and load models using higher-fidelity data and empirical operational information.
- Extension of the analysis from single-journey feasibility to full daily duty-cycle assessment, incorporating timetable constraints, dwell times, and recharging opportunities.

Together, these areas would enable a more complete assessment of the operational, technical, and economic viability of battery-assisted freight traction in the GB context.

9. REFERENCES

The following key references have informed the modelling approach, assumptions, and interpretation of results presented in this report.

Train Resistance and Dynamics

Davis, W.J. (1926). *The Tractive Resistance of Electric Locomotives and Cars*.

Rochard, B.P., & Schmid, F. (2000). *A Review of Methods to Measure and Calculate Train Resistance*. Proceedings of the IMechE, Part F.

Szántó, Z. (2016). *Rolling Resistance Revisited*.

Railway Traction and Energy Modelling

Hillmansen, S., et al. University of Birmingham. Development of longitudinal train simulation tools for traction and energy studies.

EN 14067-4: Railway applications – Aerodynamics – Part 4: Requirements and test procedures for aerodynamic drag.

Battery Technology and Hybrid Traction

Manufacturer technical literature and publicly available specifications for battery and hybrid locomotives.

Industry and academic reviews of rail traction energy storage systems and battery integration.

Freight Operations and Decarbonisation

Railway Industry Association (RIA) and Rail Freight Group (RFG) publications on freight decarbonisation.

Publicly available route, gradient, and electrification data sources.