Battery-Powered Trains
Feasibility Study for Battery Energy Storage and Propulsion on Trains

by J Molyneux (Lloyd's Register Rail), H Bird, T Rasalingam (TRL) and T Bradbury (TRL)

PPR551
Client's Project Reference No.

PUBLISHED PROJECT REPORT
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Prepared for: Project Record: Client's Project Reference No.
Battery Powered Trains

Client: DfT, Rail Research Programme
(Chris Brown)

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Executive Summary

The Department for Transport (DfT) commissioned TRL and its partners, Lloyd’s Register Rail and the University of Birmingham to conduct a study into the feasibility of battery-powered trains. If feasible, battery-powered trains could be used to provide electric traction where there are no distributed sources of electrical supply along the route, providing an alternative to diesel traction and contributing to Government targets to reduce CO$_2$ emissions by 80% by 2050.

The study comprised two components:

1. Investigation of the technological means of onboard electrical energy storage to meet the energy and power requirements of selected case study routes.
2. Conceptual design of a mechanical system for rapidly exchanging discharged batteries, with charged units at stations.

The investigation into battery technologies examined many currently available and emerging technologies and concluded that battery-powered traction is feasible when a suitable battery is paired with a super capacitor or flywheel to deliver the power peaks required to accelerate the train and cope with climbing gradients along the route.

This approach of using a battery with high energy density coupled to a power delivery device means that a relatively modest battery of 1 to 2 tonnes could be used to provide a range of approximately 80km.

The conceptual design of the mechanical battery changer considered the safety and operational aspects of the battery exchange process at intermediate stations. The final design proposed utilised an under-platform storage area where the batteries could be recharged between uses. This was combined with a powered track to move the batteries from the enclosure into position under the stationary train. The final part of the battery transport mechanism used a lifting table to lift the batteries in and out of a mechanical interlock on the underframe of the stationary vehicle.

However, the battery technology investigation showed that with a larger battery of around 8 tonnes and battery exchanges at a depot between peaks in service demands, it would be possible to achieve an operational range of nearly 1000km and there would not be a need to exchange batteries at stations. The preliminary investigation of the operational cost implications of this approach was carried out by comparing the annual costs of a battery-powered train with a DMU running on similar routes.

The comparison showed that the DMU would be cheaper to operate, but if the price of diesel rose to approximately £0.80 per litre (from £0.42 per litre), the DMU and battery-powered train could achieve operational cost parity. It is unlikely that there will be a rise in diesel prices of this order, even taking into account additional levies from CO$_2$ emissions. The study concludes that an economic case for battery-powered trains could be made if the cost of the batteries could be reduced or the life of the batteries, measured in cycles, could be increased. This would reduce the battery replacement costs, which are the largest of the operational costs considered in the study. Therefore, research should be focused on developing batteries that are cheaper or have longer life.

The cost comparison included a number of assumptions and caveats not least that the power unit in the battery-powered train, a flywheel or super capacitor, would not require replacing or servicing. In reality this would be required, so a more complex and robust economic assessment is needed to address this assumption and to also extend the analysis to include capital costs.

The overall conclusion of this initial work appears to be that DMU fleets could be replaced with self-powered electric trains and these may be cheaper to run if/when the price of diesel reaches twice the current price relative to (green) electricity.
1 Introduction

The aim of this study was to examine the feasibility of deriving a reasonably practicable solution to the problem of providing electric traction where there are no distributed sources of electrical supply along the route i.e. no overhead wires or third rail systems. Such a solution would provide an alternative to the use of diesel traction for these routes and, if implemented, could contribute to Government targets to reduce CO\(_2\) emissions by 80% by 2050.

The study comprised two components:

1. The first part of the study (reported in the main body of this report) concentrated on aspects of electrical energy storage on the train. It consists of an examination of the physical and electrical characteristics of such systems, an analysis of the electrical specifications of such a system to drive a train along two typical routes and an assessment of the ability of present, and future, energy storage systems, i.e. batteries, to deliver these requirements.

2. The second part of the study (reported in Appendix A) related to the development of a conceptual design for a mechanical system for rapidly exchanging discharged batteries, with charged units at stations. These battery exchangers could be used to extend the operational range of battery-powered trains in situations where the installed energy is limited by the available battery technologies or practical limitations on the design of the rolling stock, (e.g. the available space for batteries to be installed on the train).

1.1 Review of High Energy Electric Power Storage Systems

The current interest in electrical energy storage systems has been engendered by the issues of global warming and the diminishing world supply of liquid and gaseous fossil fuels. Electrical energy storage systems are required to smooth the load/supply balance between both intermittent and pseudo constant power generation systems.

Local electrical energy storage is used to provide power when intermittent systems, e.g. wind/solar, are not generating and to absorb and release power to cater for fluctuating demand deviations from the main grid base load. This storage can also defer costs for grid reinforcement and some forms can be used as a primary source for motive power applications. The most prevalent railway applications fall into the latter categories.

Low levels of energy storage on a train can be used to power it through short sections where the cost of electrification is high (e.g. tunnels, stations) and provide a lower cost alternative.

Larger levels of energy storage may be used to replace fossil fuel traction systems (diesels) or make their use more efficient.

The large scale types of energy storage such as pumped and natural hydro are unsuitable for the railway and so this study concentrates on smaller scale of sources that may be mounted directly on the train, i.e. this study examines aspects of electrochemical storage of energy, using batteries, and its applicability to provide traction power for a train\(^1\) in the absence of a distributed electrical supply.

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\(^1\) Auxiliary supplies and hotel loads are not considered as the base data for this study only references traction power.
2 Electrochemical Energy Storage Systems

During the following discussion the reader should take care to distinguish between the

- Cell: the basic container for reactants which produces a low voltage in the range 1 to 4 volts; and the
- Battery: a collection of cells electrically interconnected to produce practically useful voltages (and energies)

This is an important distinction as much of the published literature uses the terms interchangeably leading to either confusion or misunderstanding.

The following discussion considers general factors relating to battery systems and it is intended to inform the reader regarding the basic concepts. Many of the statements are of a general nature and are not intended to be applied to all of the possible variants that are on the market. Cell couples are normally referred to by their chemical abbreviation. Cells are of two types:

- primary which generally cannot be recharged; and
- secondary which can be electrically recharged.

A glossary of the cell couples is included in the Glossary section at the end of the report.

2.1 Electrochemical Batteries

2.1.1 Power and Energy Density

A major disadvantage of any electrochemical storage system is its perceived energy density.

The average energy density of a fossil fuel is approximately 12,000Wh/kg (10,000Wh/l) and the specific power available is equally high. Compared to an electrochemical system with an energy density of 200Wh/kg (150Wh/l) and power density of 200-400W/kg the difference as a source of energy seems insurmountable. However, these figures do not reflect the practical consequences of realising the system. Any diesel system requires an engine to generate power; this engine has an intrinsic mass. Moreover, in a railway application, the diesel engine is frequently used to generate electrical energy which then supplies electrical power to the traction motors. The mass of the diesel engine must be carried in perpetuity, and any analysis should therefore consider the actual energy density and power density of the energy generation. Equally, for the electrochemical system the mass of any system power convertor/inverter or battery hardware² should be included in the assessment.

Consider the train used as a baseline for this study, Class 150:

- Power of traction system - 375kW;
- Mass of diesel engine - 2632 kg (Cummins NT855R5 Diesel * 2);
- Mass of fuel tank plus fuel (assuming the fuel tank size as <2m cube i.e. 2000l fuel) - 1600 kg; Range - 2000 miles at average of 50mph; Time between refuelling - 40hrs;
- Energy delivered = 375kW*40=15MWh;
- Total mass = 4200kg.

² Most electrochemical systems, and especially those which are ‘new’ or laboratory based will quote energies and powers at the cell level. This therefore ignores the interconnections and mechanical assemblies which are needed in any practical commercial scale system.
Energy density of the diesel system is approximately 3500Wh/kg. Although this is approximately 30% of the theoretical energy density of a fossil fuel, nevertheless, it is still a factor of ten times on a normal battery system. The estimated power density of the system is approximately 90W/kg which approximates to that available from a battery system. A battery system would therefore be able to match the power required but will probably not be able to match the energy required.

2.1.2 Safety

Any useful chemical energy storage system needs to be compact. It is a truism that energy stored compactly poses a potential safety hazard if that energy is released quickly. All such systems have the potential to cause fire and electrochemical storage is no different in this respect to other fuels. In general, electrochemical systems do not generally burn in the sense of aggressive combination with atmospheric oxygen to produce flame. However, solid/ molten state systems based on alkali metals (Li, Na & K) are the exception and these will burn in air.

However, electrochemical systems almost invariably contain aggressive substances (acids or alkalis) or create these as by-products. Hence, any containment breach is potentially a corrosion/burn hazard. By contrast, containment breaches in fossil fuel systems are relatively benign.

Electrical hazards from batteries lie broadly in the same category as electrical hazards on any electric powered locomotive or EMU. DC link voltages on battery systems tend to be lower than the DC link voltages used for electric traction power (300-600V versus 750-1500V).

2.1.3 Environmental

Fossil fuels and biomass fuels create oxides of carbon, nitrogen and sulphur and significant particulate (carbon inorganic oxides and complex hydrocarbons) emissions. Electrochemical systems do not generally create emissions during discharge and emissions during charge for aqueous systems are normally limited to hydrogen evolution for a small proportion of the cycle. Certain electrochemical cells contain toxic materials, which need to be recycled. However, it is often the case that these materials have a high intrinsic value and the cost of recycling may be offset by this.

2.1.4 Power-Energy-Life Tradeoffs

The power of an electrochemical system depends upon the voltage of the system and the internal resistance (impedance) of the cells and the resistance of the interconnections between the cells. The energy of the system depends upon the voltage and the amount of reactants in the system.

The cell voltage is only dependent on the active electrode materials and hence is geometry independent.

---

3 Aqueous electrolytes are usually strongly acidic, (e.g. sulphuric acid in a lead acid system is 4 molar or alkaline e.g. potassium hydroxide in a NiCd system is 4-7 molar). Some Lithium ion systems have benign electrolytes but containment breaches of Lithium systems create LiOH on contact with the air which is strongly alkaline.

4 Recombinant technologies normally eliminate such emissions other than at times of excessive overcharge.

5 For most applications the cell resistance is the dominant factor. There are capacitive effects and inductive effects but these tend to be of academic interest for the most part e.g. lead acid cells have capacitances of several farads due to the ‘double layer’ phenomenon; however, the energy stored in this layer is insignificant compared to that stored in the cell itself.
The internal resistance of a cell depends upon the cell geometry and construction. Ideally, a high power cell has a large surface area of reactant and short interconnections. These constraints can restrict the cell geometry and hence restrict its energy. Battery power and energy densities are also somewhat of a compromise. To achieve high power and energy densities, systems are highly compacted both to keep interconnection lengths short and reduce wasted space. However, a highly compacted system is difficult to manage thermally and temperature has a major degradation effect in ambient temperature systems. Hence, achieving high power and high energy tend to require compromises in design.

The lifetime of an electrochemical storage system relates to the loss of the system’s ability to deliver energy. Normally the end of life is defined by the system capacity falling to 80% of its beginning of life value. Loss of capacity is usually caused by either:

- Unintended reaction products being formed which ‘lock up’ active elements of the system; these can be either loss of electrode materials or contamination of electrolytes.
- Breaches of containment which allow active elements to react with the atmosphere (air, water, pollutants) or with each other causing these elements to become unavailable for the primary reaction.

Lifetimes are usually sensitive to ‘abuse’ which includes factors such as overcharge, over-discharge, discharge rate and operating temperature extremes. The reasons for these factors affecting life are complex and vary from system to system. Unfortunately, it is usually the highest performing batteries that are most sensitive to lifetime degradation from abuse. In addition, when cells are configured into a battery system the current flow through the system is not totally uniform. Some cells, which may have differences in internal resistance or capacity, may come to different states of charge to their neighbours. In these circumstances, a battery may become ‘unbalanced’ leading to a loss of delivered capacity.

In certain circumstances, the loss of capacity of the system may be restored (either partially or fully) by special electrical conditioning. Typically, after the end of life of a battery system is reached capacity decays rapidly and physical recycling is required to re-constitute the system.

Lifetimes of electrochemical cells are usually measured in cycles. This is defined by the cell delivering its rated capacity to a load and then that capacity being restored by a recharge. Cell lifetimes range from ½ cycle (primary cell: only delivers energy, cannot be electrically recharged) to 10,000 or more cycles. For a secondary cell (one which can be discharged and recharged successively) cycle lives are usually in the range of 300 - 1000 cycles (without abuse). Secondary batteries have a similar range of lifetimes but these are necessarily lower due to imbalance and abuse can degrade a battery lifetime by a factor of five or more.

Thus, there are compromises to be made in the design of most battery systems between power, energy and life. High power and high energy systems tend to have short lives whereas more robust systems tend to be less powerful or energetic.

### 2.1.5 Cost

Although cost optimisation is not a specific driver for this study the cost of systems should be considered. It is the case, as with many other systems, that the better the
electrochemistry of the system the more costly the system. A comparative cost for four battery systems is shown in Table 1.

<table>
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<th>System</th>
<th>Cost/Wh</th>
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<tr>
<td>Lead acid</td>
<td>£0.15</td>
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<tr>
<td>NiMH</td>
<td>£0.60</td>
</tr>
<tr>
<td>NiCd</td>
<td>£0.90</td>
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<tr>
<td>Li-ion</td>
<td>£2.50</td>
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Cost is influenced by a combination of the availability of materials and the processing needed to convert these into the required physical form (including such factors as material purity, particle size, collector meshes etc). The figures in Table 1 are approximations taken from Original Equipment Manufacturers (OEM) sources at current pricing and do not include any costs associated with particular applications, (e.g. containment, chargers, conditioners, thermal management).
3 The Battery System Applied to the Train

3.1 The Power/ Energy System of the Train.

Currently most traction systems are designed with a relative disregard to the source energy consumed during running. This is not to say that designs are inefficient or wasteful but the energy source for any single journey is assumed to be, for all practical purposes, inexhaustible. Conversely, much effort is put into the power capability of the system to ensure the ability to keep to timetable and/or achieve maximum line-speed on its target route.

However, this study must also constrain the energy of the system to some quantity that may be carried along with the train. The concept is akin to operating a diesel train with a very small fuel tank which needs filling at frequent intervals. An additional constraint of the electrical alternative is that the power of the system may be limited and is the equivalent of having an underpowered engine on a fossil fuel train.

Any analysis of traction (of either electrical or fossil fuel type) quickly leads to the conclusion that the power to energy (consumed) ratio of a train is quite high. This is because:

- Trains must offer the advantage of fast, convenient travel to compete with automobiles and aeroplanes (i.e. high power); and
- In the main, railway systems are quite efficient in an engineering sense as rails, wheels, streamlining and route design are deliberately chosen to minimise losses, (i.e. low energy consumption).

Unfortunately, as can be seen from Section 4.1, conventional (current) electrical energy storage systems (batteries, capacitors, flywheels) tend to have conflicting specifications for the application. High energy density systems tend to have low power densities and conversely, high power systems tend to have low energy densities. Hence, to achieve a high power with even medium energy within a single package requires consideration of a hybrid system.

The analyses described in this section start with the assumption that the traction system of the target train\(^8\) will be a hybrid system. A diagram of the power/energy flow arrangement for the target traction system is shown in Figure 1.

The initial target system consists of a battery (to supply energy) and a flywheel or super-capacitor system (to supply power). Assume, for the purposes of this text, the power storage is via a super-capacitor\(^9\). Figure 1 shows that energy is derived from the battery and this flows both into the super-capacitor array and to the motor. Some smaller energy flows reversibly between the super-capacitor and the motor. This allows the regenerative braking energy to be returned where it is most useful. The majority of the power of the system flows from the super-capacitor system with a smaller amount from the battery. Flow of power and energy between the three main components (battery, super-capacitor, motor/inverter) is controlled by a device which is shown in the diagram as a series of electronic switches. Such a device is currently not available commercially ‘off the shelf’, however, its implementation is technologically achievable using current semiconductor/computer technology and similar systems have been implemented in other applications.

At this point of the analysis, no specific systems are considered

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\(^8\) In fact the analyses indicate that, potentially, the solution may not need to be hybrid.

\(^9\) All references to capacitor or super-capacitor may be interchanged with flywheel as the primary analysis does not discriminate between power sources.
3.2 Analysis

Two example routes, created using train simulation software from the University of Birmingham, were analysed to examine the factors affecting the trade-off between battery energy and power:

- Cardiff Central to Rhymney
- Stratford Upon Avon to Birmingham Moor Street

The simulations used variable traction power between 125kW and 875kW per train to investigate the effects of power limitation on the journey time and ability to maintain line-speed on each route.

A typical route power profile is shown in Figure 2.

The power and energy required to perform each journey are available or can be calculated from the output of the simulation. The methodology for calculating the individual contributions from battery and capacitor power and energy is detailed in Section 3.3.
3.3 Methodology

Since all the traction energy required for the journey must come from the battery the total delivered energy is calculated by integrating the power demand. Figure 3 shows the cumulative energy accumulating over a typical journey (solid line). It can be seen that the accumulation is approximately linear with small ripples during periods of acceleration and deceleration. If a simple linear ramp (dotted line on Figure 3) is subtracted from this curve then the energy difference represents the variation in average power from the
system over a constant discharge of the battery over the journey time. By changing the slope of this line the average power difference may be minimised\(^\text{10}\).

Assume that the endpoint of the line defines the nett energy of the battery if it had been discharged at a constant rate. Assume now that the battery may be discharged at the 1 hr rate\(^\text{11}\). This defines the baseline power of the system. The difference between this power level and the demanded power of the traction system is supplied by the capacitor system. Now, the excess power is supplied by the energy stored in the capacitor. This can be calculated second by second from the simulation. An examination of the ripple on the power curves of the simulation reveals that this differential power is supplied in bursts with frequent intervals of zero or negative power in between (Figure 2 and Figure 4). Assuming that the periods between the positive pulses are sufficient to recover the energy (either from the battery or from regeneration) and any excess power during regeneration can be absorbed by the battery the energy that needs to be stored in the capacitor for each individual pulse may be calculated. To satisfy the demands of the route the capacitor energy must be available to cope with the most demanding pulse.

![Figure 4: Details of Profile](image)

It should be noted that this methodology is simplistic in that:

- It does not allow for the fact that the distribution of demand times for the capacitor system may be highly skewed e.g. there may be only one particularly arduous power demand on the route\(^\text{12}\).

- It assumes that there is sufficient time between pulses to recover enough energy to the capacitor for the next pulse.

The limitations\(^\text{13}\) can be overcome by a more sophisticated analysis but the method is able to show trends at this stage and this is sufficient for the feasibility study.

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\(^{10}\) This differs from a formal linear regression which results in a line which does not pass through zero hence gives a slightly different result for the battery energy.

\(^{11}\) Battery lifetimes and thermal management of systems are highly dependent upon discharge rate. A discharge rate of 1 hr i.e. power = energy is chosen as this seems to be a reasonably optimistic projection of the ability of battery systems to perform without deleterious effects on lifetime.

\(^{12}\) A statistical analysis of power peak duration has been performed for these routes. On both routes there is a particular section that requires higher energy than all other parts of the route.
3.4 Results from the Simulations

It should be noted that the methodology makes no assumptions about the route or the battery/super-capacitor type. Hence, the methodology may be applied to sections of the route to examine the effects of battery replacement at various points and to assess the relative effects of altering battery and capacitor parameters.

The simulations were performed using a series of power limitations applied to the traction system. Thus, the speeds attained and the time for any given journey differ in each case. In the data supplied there are 25 power levels ranging from approximately 125kW to 875kW.

Initially the full route can be assessed.

The journey times and total energy demand for the two routes are shown in Figure 5 and Figure 6. It can be seen that, as the power is limited, the journey time increases but the actual energy consumed falls\(^\text{14}\). Above a certain level, increases in power do not substantially affect either journey time or energy consumed by the traction system. This is presumably due to line-speed restrictions and other conditions e.g. stopping at stations.

It may be noted that both routes examined require a similar range of energies and journey times although the routes are perceived to be quite different.

![Power and energy for route 1](image)

**Figure 5: Journey Time and Energy Consumed for Route 1 - Cardiff Central to Rhymney**

\(^{13}\) Both of these limitations can be seen in Figure 4 over the time period 350-470 seconds.

\(^{14}\) The energy is that delivered at the wheels. It does not include any losses in the system at idle or any auxiliary loading. Hence, it can be assumed that the actual energy consumed ‘at source’ for each journey will be higher for longer journeys.
Applying the methodology described above allows the residual power and energy of the capacitor to be calculated. The required capacitor power for Route 1 is shown in Figure 7. It can be seen that, for certain low powers, the required capacitor power is negative i.e. capacitor is not required.

Figure 8 is a plot of the peak energy from the capacitor for the route. The capacitor energy for the negative powers is naturally zero however with increasing power the required capacitor energy rapidly climbs with train power becoming asymptotic at higher powers.
Note that the step in the energy requirement evident in Figure 8 is due to the second simplification detailed in Figure 4 and is an artefact of the simulation. The peak energy is defined by the double pulse seen between 350 and 470 seconds; at lower power limits this pulse merges into a single longer pulse requiring more energy. Hence, it is sensible to extrapolate the trend of energies according to the dotted line of Figure 8.

Figure 8: Super-Capacitor Energy requirement for Journey without Battery Exchange

Therefore, the required energy from the capacitor is also relatively constant above a certain power limit.

The capacitor power required for route 2 is similar to that for route 1 but the required energy is only about 9kWh rather than the 12kWh for route 1.

3.4.1 Effect of Shorter Routes/ More Frequent Battery Changes

To evaluate the effect of changing battery packs mid-route the simulation data used above may be split. Since the simulation result alters with power level the data must be split by finding equivalent distances travelled. The variability within the simulation is such that the distance is not exactly equivalent when the train is stopped for all power levels hence an arbitrary distance was chosen and then the data was split at the next occurrence of zero speed.

Using this technique, the journeys were split into roughly half. The above analysis was then repeated using the same assumptions. Since the train consist is not altered significantly (neglecting the change in mass due to the lower capacity battery which should be a second order effect) the energy required at each point of the half route will remain approximately the same.

The results show, as might be expected, that the energy consumed and time for each journey are approximately halved on the half routes. However, the balance of energy and power required from the capacitor system increases and, significantly, there are no power limits where a boost capacitor system is not required (Figure 9).
Even higher capacitor energies are required for the quarter route scenario (Figure 10). Again, there are no power limits where the system does not need the capacitor to boost the power to an acceptable level.

Of course, these results assume that the battery discharge rate is limited to 1 hour. At higher permissible discharge rates (Note: see Section 3.5 why this may not be an appropriate option) the details of the scenarios modelled here will change but the basic trends will not.
Therefore, it may be concluded that, whilst it may be feasible to exchange battery systems along the route, the engineering consequences mitigate against such a strategy. Beyond a certain power limit most of the analysis shows that the curves tend to an asymptote. This means that, if super-capacitor power is limited for any reason e.g. due to ambient temperature or other effects, its impact on performance will be minimal.

A similar analysis may be performed for batteries capable of being discharged at the 15 minute rate. (Normally considered a very high power application). In this case, for the full route battery, the capacitor is only needed for the higher power demands (Figure 11).

![Figure 11: Super-Capacitor Energy Requirement for Journey without Battery Exchange](image)

Similarly for the 3 battery exchange case the resultant super-capacitor size is given by Figure 12. It can be seen that, although the capacitor size is smaller in the more frequent exchange case there is still a requirement for a capacitor with a high energy storage at most of the power levels in the simulation.

Hence, for the higher rate batteries, although the requirements are less the more frequent exchange scenarios are less attractive based on the engineering considerations.
3.5 Battery Heating Effects.

All batteries generate heat during operation. At low discharge and charge rates the heat generated is absorbed by the thermal mass of the battery and is lost through natural processes to the environment. At higher rates, the thermal energy must be actively removed from the system. For the application considered in this study the discharge rates are moderate to high and therefore thermal management of the system will be a practical consideration.

A typical train is designed to achieve sufficient performance to keep to a particular timetable. This normally means that its power is designed to a specification and, for any given route and train consist the profile of power demand will remain invariant. Suppose that this train is now powered from a local battery system which is energy limited to a proportion of the total energy required for a route and these local battery systems are exchanged as necessary along the route.

Let the required energy for the route be $E_{\text{route}}$.

Let there be $N$ batteries each supplying equal energy during the journey.

$$E_{\text{battery}} = \frac{E_{\text{route}}}{N}$$

Furthermore, assume that each battery is constructed of an array of cells each of voltage (EMF) $V_{\text{cell}}$ (volts), internal resistance $R_{\text{cell}}$ (ohms) and energy $E_{\text{cell}}$ (Wh). These cells are constructed into a series parallel array that provides a constant (open circuit) output voltage $V_{\text{batt}}$ to the system.

Assume that there are $N$ series cells in series needed to create the battery voltage.

Number od cells in series:

$$N_{\text{series}} = \frac{V_{\text{battery}}}{V_{\text{cell}}}$$
Number of cells in battery:

\[ N_{\text{cells}} = \frac{E_{\text{battery}}}{E_{\text{Cellbattery}}} \]

Number of cells in parallel:

\[ N_{\text{par}} = \frac{N_{\text{cells}}}{N_{\text{series}}} \]

The internal resistance of the battery is:

\[ R_{\text{battery}} = R_{\text{cell}} \frac{N_{\text{series}}}{N_{\text{par}}} \]

Heat generated in batteries comes from two main sources, the heat generated by ohmic effects (cell and electrolyte resistance) and entropy effects of the chemical reaction. The entropy factor is normally expressed as a temperature dependent energy for the Faradaic charge passed through the system. At high discharge rates this factor is small relative to the ohmic heating and for the purposes of this calculation it may be neglected\(^ {15} \).

The heating effects can be assessed by making some realistic assumptions based on experience.

Suppose the route energy is 300kWh as in the example routes explored in the previous section.

Assume the battery has an open circuit voltage of 300V and is made up of cells with characteristics\(^ {16} \).

\[ V_{\text{cell}} = 2\text{V} \quad E_{\text{cell}} = 20\text{Wh} \quad R_{\text{cell}} = 10\text{mΩ} \]

For these characteristics the maximum power draw for batteries sized for portions of the route energy is shown in Figure 13.

The heating effect for batteries sized for portions of the route may be calculated assuming a realistic range of power draws\(^ {17} \) from 150kW to 300kW (note the 300kW power is above the maximum available power for batteries sized at less than 30% of the route (Figure 13) i.e. it is not possible to discharge the battery at any higher power.

The results of the calculation are shown in Figure 14. It can be seen that, at the lower capacities there is a very high heat generation and, in certain cases, the trace becomes nonexistent where the demanded power is greater than the maximum power available (Figure 13).

Even where the generation is calculable, it is obvious that low capacity batteries will require much more thermal management than with the higher capacity ones. This thermal management will impact on both the size and weight of the system, further degrading the attractiveness of frequent battery replacement.

Even though it is claimed that cells exist that can deliver high powers (higher rates) the analysis is still relevant: Batteries which are discharged at high rates need significant cooling.

\(^{15}\) Entropic effects are significant when performing actual calculations for battery thermal management. However, they are highly dependent on temperature and the actual chemistry of each reaction. For a simulation calculation such as this, since ohmic heating is a quadratic function of current and entropic heating is only a linear function, the quadratic function will dominate.

\(^{16}\) Note these are reasonably optimistic values of what a high performance cell would be capable of.

\(^{17}\) The power from the battery is limited by its internal resistance and is a maximum at the point where the load voltage is half the open circuit voltage.
Figure 13: Maximum Power of Batteries.

Figure 14: Heat Generation
3.6 Conclusions

The analyses of Section 3.4 shows that, for a medium-high train performance, it is only practicable to use a battery/super-capacitor hybrid system in the design\textsuperscript{18}. The effects of more frequent battery exchanges need to be offset by higher capacities in the super-capacitor system. This means that the system weight decrease that might be achieved by more frequent replacement will be offset by increases in the system weight added by the increase in the required super-capacitor energy. Since the energy densities of present super-capacitors are low this offset may be dominant.

Hence, it is concluded that these considerations drive the system design to that of a less frequent replacement, with the logical optimum being battery replacement at terminal stations.

The analysis of Section 3.5 shows that heat generation in batteries, which are frequently replaced, creates thermal management problems. The increased need to remove waste heat energy would impact on the battery design and hence weight, volume and cost. Hence, this analysis also indicates that less frequent battery replacement is the better design option.

Therefore, it may be concluded that, whilst it may be feasible to exchange battery systems along the route, the engineering consequences mitigate against such a strategy.

Hence it is advised that, unless other factors (e.g. cost) override these considerations the best strategy for a replaceable battery concept in battery powered trains is to use a single battery sized to supply the total required route energy.

\textsuperscript{18} The trend of the analysis shows that a battery capable of multiple journeys may be even better from an engineering viewpoint, however, this is beyond the remit of this particular study.
4 Battery (Energy Storage) and Super-Capacitor (Power Storage) Options

4.1 Expectations for Specific Energy and Specific Power of Various Battery Types

4.1.1 Materials

There are many different electrochemical cells, most are designed for a specific application and all have different characteristics, advantages and disadvantages. Many are used in the industrial synthesis of chemical reagents or surface coatings and are unsuitable for energy storage purposes. Of the energy storage systems available this study will focus on those with the necessary energy and power characteristics which may deliver independent electric traction for rail vehicles.

The most common basis for an electrochemical cell is the redox process (reduction/oxidation). The amount of energy that can be derived from a cell is given by the 'Gibbs energy':

\[ \Delta G = n \times E \times F \]

Where \( n \) is the number of molar electrons of reagent i.e. the quantity of reactant, \( E \) is the electrode potential and \( F \) is the Faraday constant.

The quantity of reactant is variable and only affects energy and the Faraday constant is constant hence the choice of \( E \) is defined by the cell reagents. A list of various potentials for common cell components is given in Table 2. These are only useful as a guide to reactivity; the actual cell potential is governed by more complex factors which need not be discussed here\(^{19}\).

Classically the most energetic systems are those which have anodes from the Groups 1 and 2 and cathodes from Groups 6 and 7 of the elements of the periodic table\(^{20}\). In many cases, particularly for anodes, the element is not used in its natural form but it is associated with other reagents for practical reasons (e.g. gaseous chlorine is difficult to manage hence it is normally hydrolysed in the form of hydrochloric acid).

---

\(^{19}\) This potential is theoretical. Paradoxically, it is only available if the reaction is perfectly reversible i.e. takes place at an infinitely slow rate. Any real electrochemical reaction takes place in finite time and hence will deliver less energy; in addition, the concentration of the reactants will create differences in real cell voltage (potential) according to the Nernst equation and other factors.

\(^{20}\) There are systems which do not use reactions between elements but which have complex electrode formations and the reaction chemistry of these is more complex.
Table 2: Cell Constituent Potentials

<table>
<thead>
<tr>
<th>Element (or ionic form)</th>
<th>Half Cell Potential (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>3.04</td>
</tr>
<tr>
<td>Na</td>
<td>2.71</td>
</tr>
<tr>
<td>Zn</td>
<td>0.76</td>
</tr>
<tr>
<td>Fe (2+)</td>
<td>0.44</td>
</tr>
<tr>
<td>Cd</td>
<td>0.4</td>
</tr>
<tr>
<td>Pb</td>
<td>0.126</td>
</tr>
<tr>
<td>H+</td>
<td>0</td>
</tr>
<tr>
<td>Cu (2+)</td>
<td>-0.337</td>
</tr>
<tr>
<td>I</td>
<td>-0.535</td>
</tr>
<tr>
<td>Fe (3+)</td>
<td>-0.771</td>
</tr>
<tr>
<td>O (normally hydrolysed)</td>
<td>-1.23</td>
</tr>
<tr>
<td>Cl</td>
<td>-1.36</td>
</tr>
<tr>
<td>O (atomic or O3 )</td>
<td>-2.07</td>
</tr>
</tbody>
</table>

It is clear from Table 2 that Lithium or Sodium combined with Oxygen or Chlorine would be favoured reactants for highly energetic cells.

However, there are cells which do not rely on the redox process. Two which have a high prominence at present are the Lithium Ion system (which operates on absorbing lithium ions into a crystalline matrix; an intercalation mechanism) and the metal hydride system which uses the ability of certain metals to absorb hydrogen into their atomic lattices.

4.1.2 Energy and Power

Regardless of the actual chemistry of the system the critical parameters of any target system are the discharge Energy density and Power density. These quantities are often quoted as abstract numbers but both are dependent upon the discharge rate of the cell. This is because there are losses incurred during the discharge process. Suppose a cell has an open circuit potential of E volts and an internal resistance\(^{21}\) of R ohms.

The delivered energy from a cell at a discharge current of I for a time T will be:

\[
\text{Useful energy} = I\times(E - (I\times R))\times T
\]

For the same cell at twice the discharge rate (for half the time as the capacity will remain the same) the delivered energy will be:

\[
\text{Useful energy} = 2\times I(E - (2\times I\times R))\times T/2 \quad \text{i.e. } I\times(E - (2\times I\times R))\times T
\]

The ratio of delivered energies is \(\frac{I\times(E - I\times R)\times T}{I\times(E - 2\times I\times R)\times T} = \frac{(E - I\times R)}{(E - 2\times I\times R)}\) which is always greater than one i.e. higher discharge rates deliver lower energy.

\(^{21}\) All cells have to conduct electrons to do useful work and these require conductors to carry them. Ion transfer within the cell also requires ionic conductors. Hence, the cell will have a certain resistance to current flow. Although mechanisms differ these are normally lumped together and expressed as an equivalent resistance to electronic current flow
For delivered power, higher discharge rates deliver higher power but this is limited to a maximum of: \( \frac{E^2}{4R} \)

**Hence, Energy and Power densities must be assessed at equivalent (practical) discharge rates otherwise comparisons are meaningless.**

Only technologies that have been demonstrated at the vehicle level have been considered. There are reports of higher energy density systems that exist at laboratory scale but these are not considered here.

Using available information from open sources it is possible to normalise the parameters of various ‘high energy’ battery types to a common basis. The normal way of assessing these is the Ragone plot which plots delivered energy against delivered power. This allows a comparison at any given rate. A Ragone plot of several battery types currently available in the market is shown in Figure 15. The raw data is abstracted from a 2007 paper and so should be reasonably up to date. It is augmented by other target system data taken from manufacturers. Although there are numerous claims of higher energy (and power) densities it is believed that the data in the plot is reasonably representative of what may be achieved for the various technologies. It is also believed that the numbers in Figure 15 may only represent the demonstrated energy densities at the cell level. However, known figures from battery level studies tend to suggest that the lead acid and sodium metal chloride energy densities are more representative of a battery level system. Battery level systems based on the other technologies would be expected to be some 20% poorer.

![Figure 15: Gravimetric Ragone Plot](image)

It is obvious, from the plot that the lithium batteries are the most energetic and can be discharged at the \( \frac{1}{2} \) hr rate (black sloping line in Figure 15). There are some contradictions in the technical reports of the operation of the cells at very high discharge rates.

---

22 Often, laboratory scale processes quote energy densities at low discharge rates and power densities at maximum power. This makes characteristics seem attractive as it is naturally assumed by laymen that both figures may be realised at the same time.
rates viz. it is claimed that the Lithium Iron Phosphate systems can be discharged at 100°C but the stated internal resistance parameter for the commercially available 4 AH cell is 10mΩ (DC) and 8mΩ at 65kHz (AC). At 400A and 3.2V open circuit this gives a load voltage of zero volts even with the lower resistance value. Obviously, zero load volts cannot deliver power to an external system. It may be that the discharges quoted are short pulse ratings or that the cell acts as a super-capacitor for short pulses and the energy that is delivered is coming from the double layer effect rather than the continuous electrochemistry of the cell. Unfortunately, there is insufficient detail in the commercial specification to resolve this issue.

However, gravimetric energy density is not the only consideration in this application. The physical size of the system is also important. For this the relational parameter is the volumetric energy density. Not many of the available Ragonne plots use this as a parameter and so Figure 16 has been generated by taking average densities for each system from the weight and dimensions of the cell specifications.

This alters the considerations somewhat with there being a less obvious separation between the candidate technologies and the Nickel Metal Hydride and Sodium Metal Chloride systems showing a performance near to that of the lithium system (This will also have consequences for the overall cost).

---

23 C is battery technologist's shorthand for Capacity. Capacity is defined as a discharge for a battery that takes place over 1 hour. i.e. the power and energy delivered by the system are numerically equal. Consequently a discharge at 100°C would be at 100 times the 1 hour rate i.e. the whole capacity of the battery would be discharged in 36 seconds.

24 Assuming that cylindrical cells are HCP.

25 It is believed that the Sodium Metal Chloride figures may represent battery level; if this is the case then these may match lithium systems on a volumetric figure. This may be why there is considerable interest in the system for locomotive traction power in the US.
4.1.3 Mechanical recharge systems.

The analysis in Sections 4.1 and 4.1 uses conventional secondary electrochemical systems, however, there are other systems that are mid-way between the secondary battery types and fuel cells. These are the so-called mechanically rechargeable systems. These systems are essentially electrochemical batteries such as those described above but which have one electrode that may be replaced mechanically. In this category there are four potential systems Zinc-Air, Iron-Air, Aluminium-Air, and Lithium-Air. Only the Aluminium-Air and Zinc-Air systems have been demonstrated at what may be considered as a reasonable battery level (tens of kWh). Aluminium-Air was abandoned in the 1990’s as presenting intractable technical problems and Lithium-Air and Iron-Air have been restricted to laboratory and military systems. Mechanical electrode replacement may not seem to be a particular advantage in this application however there are benefits to the system as they are normally much more energetic than conventional rechargeable systems. This can be seen by adding data from Zinc-Air systems which have been demonstrated at battery level to the general cell level Ragonne plots shown in (Figure 17). It should be noted that, Zinc-Air, in this context is not the most energetic of the four systems. Aluminium-Air is claimed to have achieved 600Wh/kg and Lithium-Air 1000wH/kg. Iron-Air is potentially similar to the Zinc-Air system.

![Figure 17: Gravimetric Ragonne with Mechanically Rechargeable Systems](image)

It can be seen that the Zinc–Air system is more energetic than the Lithium systems, however, it has the disadvantage that it is not capable of high powers at these high energy densities. This is attributed to the Air electrode component.

---

26 Fuel cells are outside the remit of this study. This is because they use a widely different technology which is considered to be both long term and, for organic based systems, not particularly amenable to ‘green’ generation technologies. Secondary Hydrogen generation systems have been studied elsewhere.

27 There is a commercial Zinc-Air system available with a claimed energy density of > 200 Wh/kg
4.1.4 **Battery Cost**

There are numerous arguments about the relative cost of battery systems. Many of these relate to the availability of the target materials. It is beyond the scope of this study to examine these arguments in any detail. However, it is possible to state that the raw material for all the Lithium systems is relatively scarce when compared to the relative abundance of Iron, Aluminium, Sodium, Zinc and Nickel. Since the demand for batteries is increasing from all quarters it may be that, for railway applications, the cost of the system may dominate any choice.

4.2 **Battery Size: Weight and Volume for Energy Duty**

Using these parameters the weight and volume of the target system may be estimated. The weights and volumes of the various battery types are shown in Table 3 and Table 4 respectively.

Two battery sizes are considered in alignment with the analyses performed in Section 3.4. These are 75kWh and 300kWh. The sizing is given based on the data available at the time of writing this report. Since there are considerable uncertainties in whether the quoted data refers to battery or cell level these figures are given as is on the grounds that if the densities are based on cell configurations a battery configuration using ambient temperature systems will represent only approximately a 20% burden. All the batteries in the table are capable of discharge (in pulse mode) of the power densities required for the 1 hour rate.

<table>
<thead>
<tr>
<th>Type \ Rating</th>
<th>75 kWh Weight kg</th>
<th>300kWh Weight kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead_Acid</td>
<td>2143</td>
<td>8571</td>
</tr>
<tr>
<td>NiCd</td>
<td>1442</td>
<td>5769</td>
</tr>
<tr>
<td>NiMH</td>
<td>938</td>
<td>3750</td>
</tr>
<tr>
<td>NaAl(x)Cl*</td>
<td>682</td>
<td>2727</td>
</tr>
<tr>
<td>LiFeP</td>
<td>833</td>
<td>3333</td>
</tr>
<tr>
<td>Li-ion</td>
<td>441</td>
<td>1765</td>
</tr>
<tr>
<td>Zn-Air**</td>
<td>250</td>
<td>1000</td>
</tr>
</tbody>
</table>

*High temperature system

** Zinc Air is incapable of the required power densities at present

---

28 It has been suggested that there is abundant lithium in seawater, however, this method of production is not yet realisable on commercial scales due to the overwhelming abundance of other seawater alkaline metals such as Sodium and Potassium in the salt melt and the difficulty of isolating the lithium component.
Table 4: Battery Size (Volume)

<table>
<thead>
<tr>
<th>Type \ Rating</th>
<th>75kWh Volume litres</th>
<th>300kWh Volume litres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead_Acid</td>
<td>857</td>
<td>3429</td>
</tr>
<tr>
<td>NiCd</td>
<td>541</td>
<td>2163</td>
</tr>
<tr>
<td>NiMH</td>
<td>292</td>
<td>1169</td>
</tr>
<tr>
<td>NaAl(x)Cl*</td>
<td>341</td>
<td>1364</td>
</tr>
<tr>
<td>LiFeP</td>
<td>550</td>
<td>2198</td>
</tr>
<tr>
<td>Li-ion</td>
<td>272</td>
<td>1089</td>
</tr>
<tr>
<td>Zn-Air**</td>
<td>167</td>
<td>667</td>
</tr>
</tbody>
</table>

** Zinc Air is incapable of the required power densities at present

4.3 Super-Capacitor or Flywheel Size; Weight/ Volume for Power Duty

There are two types of practical power storage systems available for transport applications; Flywheels and super-capacitors. Both have been demonstrated on vehicles. In almost every case the devices have been used as power storage systems rather than energy storage.

Flywheel power storage is a technology which pre-dates the internal combustion engine; however, in its most potent form it has only been under serious development since the mid1970's. The basic principle of the system is that a spinning mass can store energy and, by removing this energy in a short time, a high power may be extracted. In general, flywheel power/energy storage systems have a longer response time than capacitors and hence they will need very different control and interface technologies. As with the other power storage systems there is very little readily available information on practical power and energy densities of the systems. The best systems have been developed for space/satellite applications. There are intrinsic material property limits to such systems. Lower levels of technology are available in various forms using conventional materials but these tend to have energy and power densities much lower than the available battery systems (although with longer cycle lives).

There are two types of super-capacitor system. One operates on the double layer principle and the other on the redox principle. The charge/discharge mechanisms of the two are different but this study is only concerned with their pulsed power performance. The advantage of these as power storage devices lies in their ability to survive hundreds of thousands of cycles rather than the hundreds common for batteries, (see Section 4.4). Super-capacitor power density information is also very difficult to quantify correctly and there are many claims for the power (and energy) densities which are not wholly substantiated or require particular interpretation.

In general, super-capacitors, even when assembled into arrays, are low voltage devices and so they will need interface and control electronics to make the hybrid system work properly.

29 Technically power cannot be stored however the term ‘power storage’ is an easily understood précis of the term “a device which is capable of storing and releasing (small amounts of) energy at a high rate.”
Bearing these comments in mind it is possible to estimate the size and weight of the power storage needed for this application. It is envisaged that the power system will not be exchangeable (as there is no energy to deplete) hence the weight and volume of the system will need to be incorporated into the train baseline design. The required energy and power of the power storage system is again taken from the analysis in Section 3.4. Since the power storage requirement is dependent both on the frequency of battery exchange and the power capability of the battery system, eight alternatives may be calculated using the base data in Table 5.

### Table 5: Power Storage Systems

<table>
<thead>
<tr>
<th>Power device</th>
<th>Energy density storage range</th>
<th>Power density storage range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flywheel</td>
<td>0.6-18Wh/kg</td>
<td>160-1200 W/kg</td>
</tr>
<tr>
<td>Super-Capacitor</td>
<td>2.3-5.6Wh/kg</td>
<td>1700-13000W/kg</td>
</tr>
<tr>
<td>Flywheel</td>
<td>1-18Wh/l</td>
<td>211-1200 W/l</td>
</tr>
<tr>
<td>Super-Capacitor</td>
<td>2-6Wh/l</td>
<td>1100-6200W/l</td>
</tr>
</tbody>
</table>

The systems considered are taken from the analysis in Section 3.4. These are chosen for two power levels, a medium power system (325kW) and a full power system (875kW), and for two replacement strategies, three battery replacements and single journey.

### Table 6: Power Storage Options

<table>
<thead>
<tr>
<th>Rate</th>
<th>Batteries/journey</th>
<th>Train Power</th>
<th>Energy Required kWh</th>
<th>Weight kg</th>
<th>Volume l</th>
<th>Power available kW</th>
<th>Weight kg</th>
<th>Volume l</th>
<th>Power available kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Hr</td>
<td>1</td>
<td>325kw</td>
<td>3.3</td>
<td>589</td>
<td>550</td>
<td>9429</td>
<td>183</td>
<td>183</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>875kw</td>
<td>12.5</td>
<td>2232</td>
<td>2083</td>
<td>35714</td>
<td>694</td>
<td>694</td>
<td>833</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>325kw</td>
<td>13.6</td>
<td>2429</td>
<td>2267</td>
<td>38857</td>
<td>756</td>
<td>756</td>
<td>907</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>875kw</td>
<td>19.2</td>
<td>3429</td>
<td>3200</td>
<td>54857</td>
<td>1067</td>
<td>1067</td>
<td>1280</td>
</tr>
<tr>
<td>15 min</td>
<td>1</td>
<td>325kw</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>875kw</td>
<td>3.75</td>
<td>670</td>
<td>625</td>
<td>10714</td>
<td>208</td>
<td>208</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>325kw</td>
<td>3.3</td>
<td>589</td>
<td>550</td>
<td>550</td>
<td>183</td>
<td>183</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>875kw</td>
<td>12</td>
<td>2143</td>
<td>2000</td>
<td>2000</td>
<td>667</td>
<td>667</td>
<td>800</td>
</tr>
</tbody>
</table>

It can be seen, from the results shown in Table 6, that there can be a considerable burden placed on the train weight by the power storage system. It can also be seen that, in all cases, the power available from the capacitor system is much more than is required to supplement the battery power but that the main system impact is caused by the energy that needs to be stored to deliver the pulses of power required. Although the figures used are from commercial manufacturers’ data sheets or from tests performed by independent agencies.

---

Many higher figures have been quoted however these are somewhat unsupported by test evidence.
power of the flywheel systems are limited (but adequate) the energy density of the system makes it potentially smaller as a power/energy storage system.

4.4 Expectations for Life in the Railway Environment

The railway environment will place electrical, mechanical and operational burdens on the battery and super-capacitor system. There is very little general data on the interactions of the environment with battery life because of the specifics of electrochemistry and construction unique to each battery type. Hence, it is impossible, under the terms of this feasibility study to do anything more than suggest trends and give qualitative arguments.

4.4.1 Electrical/ Electrochemical

It is a common observation, with almost all battery types that the duty cycle affects life. Normally any abusive battery conditions will shorten life. These conditions will include:

- High charge/discharge rates; high rates mean the concentration gradients of reactants in the electrodes/electrolytes are high. This usually leads to the formation of reaction products that are not normally part of the desired electrochemistry. Often these reaction products are either more aggressive (in terms of corrosion) or cause some capacity loss (by creating insoluble/inaccessible compounds that are removed from the potential reaction quantities). In addition, high rates usually mean high heat generation rates. These create temperature variability within the battery (leading to non-uniform operation). They also increase the corrosive reactions within the cell. Increasing the temperature can have positive benefits for a system but this is usually more than offset by the decrease in lifetime caused by increased corrosion.

- Top of charge condition on charge; At top of charge several phenomena can occur which either cause imbalance in the battery (causing cells to get out of step\textsuperscript{31}) or create adverse states in the electrochemistry (e.g. the evolution of undesirable products, usually gaseous or extremes of temperature).

- End of discharge condition; Similar imbalance conditions can occur at bottom of discharge and these may create inaccessible compounds that are corrosive, inactive or both.

- Pulse discharge; there is little available information about pulse discharge versus steady state discharge. Some authorities state that pulse discharge/recharge within the limits of the double layer capacity are benign others claim that pulse discharge can generate local hot spots and hence temperature non-uniformity within cells.

4.4.2 Environment

The railway environment can cause batteries to experience severe mechanical vibration and shock. These can cause reactants to become separated from the current collection components in cells. If the separation is sudden it can cause a step change in the cell performance however even separation caused by low level vibration can lead to gradual loss in capacity and hence adversely affect the system life.

The normal operating position for a battery system within a train is within the underframe. This exposes the battery to heat, cold and damp. Assuming that the system can be sufficiently waterproofed a low ambient operating temperature can mean that the

\textsuperscript{31} A battery is a series parallel system of cells. For proper operation all cells should operate identically. However manufacturing tolerances, temperature variability and current flow differences can cause some cells to work harder than others. This can limit the performance of the overall battery.
battery internal resistance would be higher than normal or reactants may freeze. Assuming that the increase in internal resistance is not severe enough to stop the system operating the increased heat generation within the system can lead to temperature non-uniformity and hence loss of available capacity.

Battery lives are normally measured in cycles. The nominal definition of the end of life is when the battery can no longer deliver 80% of its nameplate capacity\textsuperscript{32}. There are no definitive figures for battery life as manufacturers normally use specific conditions (in terms of cycle rate, temperature control and other factors) to determine their published figures. Although cycle lives of up to 10,000 cycles have been claimed, these have been under very controlled or specific conditions\textsuperscript{33}. A figure of between 300 and 1000 cycles might be expected to be reasonably achievable for full capacity cycling. This application assumes that the target batteries operate over a full capacity discharge. The target journeys use a fixed energy for the route hence it is irrelevant what size of battery is used or how often it is replaced from a purely energy related viewpoint\textsuperscript{34}. The journey takes approximately two hours. For a daily service operation of say eight journeys this means that each battery will receive eight cycles per day. Even with a 1000 cycle lifetime the operational life of a battery within the system will be only 120 days i.e. approximately 4 months. It should be stressed that this is regardless of battery size or frequency of replacement.

Considering the factors discussed in Sections 3.4 and 3.5 this means that the engineering considerations will favour larger batteries with fewer changes.

The lifetime of the capacitor system is more difficult to assess. Lifetimes of capacitors are normally limited by such factors as manufacturing anomalies and inconstant operation. A normal capacitor might be expected to achieve $10^8$ operations however, for super-capacitors; a life of $10^5$-$10^6$ operations is more often quoted. Assuming that each pulse operation shown in Figure 2 is a cycle (pessimistic) then there are some hundred cycles per journey. Assuming a lifetime of $10^5$-$10^6$ cycles, this equates to between 125 days and 4 years. Hence, for a train based system an improvement in capacitor life must also become a goal of any research effort.

Such short working lives for the components have considerable cost implications.

\section*{4.5 Prospects for Near Term Implementation}

This part of the feasibility study is only required to examine the technical aspects of the system. If we disregard, for the moment, the life and cost implications then it is possible to show that a suitable design could be implemented using near term power and energy storage systems. Considering all the factors from the analyses together then, although further optimisation may be made, a system using a state of the art battery from the lithium types could perform the duty. For the various reasons outlined in the discussion, the system would be sized for the single full journey. Considering the fact that such batteries are capable of power pulses at the fifteen minute rate, operating the train at a lower peak power demand would have benefits in reducing or eliminating the need for a power storage system. Hence, the target system for a preliminary design is for a 300kWh battery weighing approximately 2 tonnes and occupying approximately 1.1 cubic metres operating at a train power of 325kW.

\textsuperscript{32} New batteries normally deliver more than the nameplate capacity this normally decays to nameplate after a few tens of cycles.

\textsuperscript{33} For example a car battery will normally be expected to start a car four times a day over its 5-year operational life, i.e. it will perform the required duty approximately 6000 times. However, the same battery, if discharged to its full rated capacity, would only be expected to survive full capacity cycling a few tens of times.

\textsuperscript{34} Each battery exchanged on the route will experience one cycle per journey regardless of size. The only effect that exchange will have is that, for a quarter route sized battery, after a journey there will be four batteries that have each completed one cycle rather than the single battery cycle experience by a battery sized for the full route.
4.6 Prospects for Medium Term Implementation

A four month replacement may place an unacceptable financial burden on any system. Hence, this study has considered the option of a metal fuel cell as part of the range of battery types. Potentially these systems have very long cycle lives as the cells are essentially re-built with each discharge. The available technology of these systems is not currently capable of supporting the power requirements assumed in the analysis and any lifetime projections are necessarily speculative, however, as a medium term solution it is possible to envisage a developed version of the metal-air fuel cell capable of a 1 hour rate with electrode replacement at journeys’ end as a feasible solution. This battery would be supplemented with an on-board power storage system as it is probable that, even with development, the power capability of such systems will be limited35. Using the figures from Table 3, Table 4 and Table 5 and again assuming a single journey capacity and 325kW train power limit then the whole system would contain two sub systems:

- A metal-air battery of capacity 300kWh weighing approximately 1 tonne and occupying approximately 0.7 cubic metres; supplemented by
- A 220kW power storage flywheel system weighing approximately 200kg and occupying 0.2 cubic metres on board the train.

A further advantage of the metal air systems is that their potential raw material cost is lower36 than for the lithium systems. This is due to the relative abundance of the primary reactants and other materials considerations.

4.7 Prospects for Long Term Implementation

It is difficult to predict what advances may be made in battery technology over the next decades. There is no doubt that the twin drivers of climate change and increasing scarcity of fossil fuels will create inordinate amounts of research effort. It is impossible to state where advances may be made however, in the realm of electrochemical systems there are theoretical limits imposed by the fundamental laws of chemistry and physics. It is the opinion of this report that any existing system will only advance in a Pareto fashion i.e. 80% of what can be achieved has already been achieved. Hence, for existing systems it is probable that no major breakthroughs will suddenly allow a battery of ten times the power and energy density to appear. Factors of two for energy storage are however possible from the theoretical point of view for some, more exotic, systems.

The areas where technological advances may be made are in lifetimes and in the supplemental power storage systems. Lifetime, as outlined in Section 4.4 is a matter of uniformity, detailed material properties and resistant materials technologies. It may be possible to envisage a factor of ten improvement in lifetimes for many systems. Power storage is both an old and new technology. Again, developments in flywheel technology are limited by pure physics and materials properties; the materials used in advanced aerospace flywheels are state of the art and so little dramatic improvement is available. Super-capacitors are a relatively infant technology and here advances, particularly in energy density, may be possible37.

All these technology improvements will require a steady stream of finance and inevitably many will not be realised. It is difficult to predict which research will be productive,

35 This statement should also apply to fuel-air cells (fuel cells) many of which have two gaseous electrode systems which normally constitute the power limiting element of the design.
36 Approximately a factor of 3 to 5.
37 There is reportedly a super-capacitor system based on conventional capacitor technology with a Barium Titanate separator. This is claiming an energy density of 287Wh/kg i.e. 3 times the energy density of Lithium systems with million cycles lifetimes. If this claim is true then it would be feasible to remove the battery altogether and supply ready charged capacitors at each station. Although little is known about the capacitor, many of its claims appear to be “At or beyond what is considered to be possible” according to academics at Texas University.
which is pure fiction and which is doomed to failure. Many of the more speculative areas are currently seeking finance and this may inevitably lead to some exaggerated claims.

From this background it is possible to make some conservative estimates of what a longer term solution might be. For this it is assumed that technology advances will allow a higher power storage system that removes any power constraint i.e. power device energy storage densities increase by a factor of 10. A full replacement of the energy storage system with a power storage system may be feasible; however, the basic energy must still be supplied and hence would involve either massive interim power supply or power system replacement (with a charged power system) at frequent intervals.

For example, assume that the energy storage of the power system may be increased by a factor of ten. This is the equivalent of making the super-capacitor the equivalent of a battery system with an energy density of 56Wh/kg (Figure 15). Feeding this into the equations used to generate Table 3 for comparison gives the equivalent of a current NiCd system which would weigh approximately 500kg (for eight replacements per journey). This would probably require eight intermediate power supplies to recharge the capacitors between replacements. A system which was not replaceable would require such high local power that the impact of the power supply infrastructure would probably suggest that it would be better to electrify the route either partially or entirely.

What remains is the basic energy storage system. Even if the lifetime of the energy storage system is no longer a barrier, then it is probable that larger systems will be more favourable from an engineering viewpoint, and so it is probable that a conservative estimate of the battery system would be approximately 20% better than that for the mid-term solution with a battery mass of approximately 600kg and volume of 0.5 cubic metres with a small power system of approximately 50kg.

Hence, a more frequent replacement than 1/15th of the journey cannot sensibly be achieved. A more accurate analysis will involve the simulation of the detailed energy transfer between systems. It is beyond the scope of this study to investigate this further.

---

38 Assume that at each exchange a depleted super-capacitor is delivered. This must be re-charged in time for it to be used on the return journey. The power for each device will be constant but the energy will be that required for 1/8th of the journey. Hence, 1/8th of the journey energy must be supplied in the time taken to complete the journey. This seems to imply a reasonable charge to discharge ratio of 8:1 However, it should be noted that the energy of the capacitor cannot be supplemented and so the required energy will be that to supply the maximum discharge energy of the pulses shown in Figure 4 which may be greater than the average energy. The analysis shows that, for some scenarios the capacitor energy is 18kWh however, the total energy for the route is 300kWh.
5 Electrical Energy Storage Conclusions

From the analyses and simulations it may be concluded that the scheme for battery/super-capacitor powered trains is technically feasible with near term technologies. This view is essentially conservative and does not rely on any dramatic technological advances. The financial cost (of any of the systems) will however be significant. This is because of the intrinsic manufacturing cost of the system and/or the limited life expectancy of current solutions. Much research and development will be needed to implement these systems. This research will not be exclusively electrochemical but will involve the development of new power electronic systems, cooling systems and controls.

The analyses performed in this study are necessarily superficial in order to achieve the results within the project timescale. A more detailed analysis, particularly on the interactions and efficiencies of the power/energy conversions would need to be performed to validate the conclusions in detail. Nevertheless, the broad numerical conclusions from the analysis and the translation of these into a practicable system are believed to offer a good estimate of what is possible from energy and power storage technologies.

Two possible systems are outlined:

- The first is a near term solution based on best estimates of available technologies that are projected to the system size for this application. This gives a battery system of approximately 2 tonnes in weight and approximately 1.1 cubic metres volume.

- A medium term solution is also described. This potentially overcomes some of the intrinsic problems with the near term solution of cost and lifetime and also offers a lower weight and volume for the replacement portion of the system at 1 tonne and 0.7 cubic metres.

The long term prospect for energy storage systems makes a long term prediction impossible. The solution on this timescale may involve a technology such as a super energetic capacitor whose performance cannot be predicted.

Equally well, there may be only relatively small advances made. It should be remembered that, even though there are several ‘breakthroughs’ announced every month, the basic electrochemical limitations of all the systems have been understood for a half a century or more e.g. fuel cell technology was initially postulated in 1838.
6 Implications from the Findings of the Study

The review of electrical energy storage solutions presented a new possibility that had not been considered at the outset of the study: the feasibility of operating a battery-powered train without the need to exchange batteries at intermediate stations during normal service. By utilising a bigger battery and returning the train to the depot between demand peaks for battery exchanges it may be feasible to operate a battery-powered train with some limited impact to timetabling.

This operational concept would effectively remove the need for the battery exchanger as described in Appendix A, although the mechanical battery-changer may still be of use in situations where it is impractical or unfeasible to return the train to the depot to exchange batteries.

This section of the report examines some of the implications of operating battery-powered trains under this operational paradigm.

6.1 Cost implications

This section of the report contains a brief analysis of the potential operational costs of a battery powered train using Zinc-Air batteries, compared to a conventional DMU vehicle. For the purposes of the analysis it was assumed that the medium term technologies as described in Section 5 of the report are available to vehicle manufacturers.

6.1.1 Battery-powered train

As stated in Section 4.2 (Table 3) a 1 tonne Zinc-Air battery is capable of storing 300kWh, and the Lawrence Livermore National Laboratory estimated that the refillable battery could be produced for $60/kWh (Tahil, 2007). It has been assumed that a 1 tonne battery will provide enough power to travel a distance of 80km, based on the sample routes used in the study.

It is proposed that a 4 tonne battery is used; storing 1200kWh. With 2 battery swaps per day (and a further swap overnight) this will be sufficient to provide enough power to travel 960km. The Zinc-Air batteries are mechanically charged, with a physical replacement of the anodes. Recharging the anodes is a similar process to the liquid electrolyte slurry system outlined in the Zinc Air Battery and the Zinc Economy (Tahil, 2007). The recharging process takes 10 minutes to charge 30kwh.

There are no indicative costs for this type of power charging; therefore the cost of recharging the battery has been based on a typical electrochemical recharging of batteries, using electricity from the national grid. The average non-domestic price of electricity in 2009 was 7 pence per kWh for an ‘extra large’ consumer using more than 150,000MWh annually (DECC, 2010). This does not include the Climate Change Levy (CCL) which came into effect in April 2001; the current rate of levy for electricity is 0.430 pence per kWh (HM Revenue & Customs).

The Zn-Air batteries have a low cycle life of approximately 600 charge and discharge cycles (Tahil, 2007), which is presumed to be sufficient for one year of operation.

The battery-powered train consists of a battery and a flywheel or super-capacitor system to provide power, the feasibility study does not consider any specific system. The cost of the super-capacitor is difficult to estimate and has been excluded from this analysis. Energy recovery systems are already used in rail applications, Pentadyne energy recycling technology, using a flywheel, has been demonstrated on the London Underground in 2000. This technology has since been implemented on other metros including those in Paris, Lyon, Hong-Kong, and New York. With regular servicing the Pentadyne flywheel system has a life of approximately 20 years (Pentadyne website), whereas super capacitors typically have a shorter life, requiring more frequent
replacement. Following on from this study a detailed evaluation of suitable technologies and costs would need to be conducted.

6.1.2 Diesel multiple unit (DMU)

The British class 150 (DMU) train was used as a baseline for this study (Section 2.1.1). It delivers 15,000kWh of energy and can travel a distance of 2000 miles (3219km) without refuelling. The energy required to travel 960km was determined ((4474 kWh, consuming 597 litres of fuel daily) to enable comparison with the battery-powered train.

The average 2009 price of Gas oil (also known as red diesel) purchased by the manufacturing industry in Great Britain was £481.90 per tonne (DECC, 2010) for a ‘large’ consumer using more than 175 tonne of fuel. This figure excludes the Climate Change Levy, but includes the hydrocarbon oil duty, which from 1 September 2009 was £104.94 per tonne for Heavy Fuel Oil and £124.52 for gas oil. Assuming the density of diesel was 0.875 kg/l, the price of the diesel was calculated to be 42.2 pence per litre. The cost to maintain a vehicle was assumed to be 20 pence per km based upon estimates from DfT personnel.

6.1.3 Operational cost comparison

A like for like comparison exercises of the two energy types was carried out using the assumptions outlined earlier, for a 960km distance travelled daily over a year. The overall results can be seen in Table 7.

<table>
<thead>
<tr>
<th></th>
<th>Zinc-Air (£)</th>
<th>Diesel (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging cost</td>
<td>91,980</td>
<td>-</td>
</tr>
<tr>
<td>Battery replacement</td>
<td>151,200</td>
<td>-</td>
</tr>
<tr>
<td>Capacitor replacement</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fuel</td>
<td>-</td>
<td>91,808</td>
</tr>
<tr>
<td>Maintenance</td>
<td>(negligible)</td>
<td>70,080</td>
</tr>
<tr>
<td>Total</td>
<td>243,180</td>
<td>161,888</td>
</tr>
</tbody>
</table>

More detailed calculations are required, which will account for all the costs involved in operating a battery-powered system. Any future rise in fuel prices and corresponding rises in electricity price needs to be considered in order to determine the price at which the battery system would achieve cost parity with the DMU. Within this limited analysis the price of diesel would need to be more then 80 pence for operational cost parity assuming the costs for the battery-powered train are unchanged.

Unless there is a significant reduction in the use of fossil fuel in electricity generation, any future rise in fuel prices will result in a rise in the price of electricity. Therefore the fuel costs and battery charging costs will be linked. On this basis it is unlikely that any projected increase in diesel costs will make the battery-powered train economically attractive.

Research should therefore be targeted at improving, or developing alternatives to, the Zinc-Air batteries considered in this study, with a view to reducing the battery replacement costs, by approximately 50%. At this level of replacement cost based on
the simple cost comparison the battery-powered train becomes a viable proposition. Battery replacement costs could be reduced by developing batteries that are lower cost or improving battery life – increasing the number of charge and discharge cycles.

It is worth noting that the manufacturer’s claims of a maintenance free battery have not been proven in an operational railway environment.

6.2 Sustainability implications

The cost calculations have not taken into account any climate change levies or CO₂e charges. The shadow price of Carbon was initially proposed in 2007 (Department for Environment Food and Rural Affairs, 2007), as a basis for incorporating Carbon emissions in cost-benefit analysis and impact assessments. The document has since been superseded following reviews in 2008, and 2009. The current shadow price of carbon is £26.5 per tonne of CO₂e emitted.

Currently diesel trains account for approximately 35% percent of the total rail vehicle km on the UK network. Carbon emissions are measured in grams of CO₂ per passenger km. Studies carried out by NAEI show that the average carbon dioxide emitted by:

- an intercity train is 3187.8 g/km;
- a regional service is 467 g/km; and
- a freight train is 5262.6 g/km (NAEI website).

The shadow price of carbon was applied to these train services and the estimated daily and annual charges for CO₂e for train services are given in Table 8.

<table>
<thead>
<tr>
<th>Fuel consumption</th>
<th>Daily CO₂e charge (£)</th>
<th>Annually CO₂e charge (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercity train</td>
<td>3 tonne per 960km</td>
<td>80</td>
</tr>
<tr>
<td>Regional service</td>
<td>0.4 tonne per 960km</td>
<td>11</td>
</tr>
<tr>
<td>Freight train</td>
<td>5 tonne per 960km</td>
<td>130</td>
</tr>
</tbody>
</table>

The Shadow Price of carbon is based on the value of the damage caused by greenhouse gases, using the Stern Review. The DECC’s review in July 2009 set out a revised approach which is based on the cost of mitigating emissions, and follows a ‘target-consistent approach, based on the abatement costs that will need to be incurred to meet specific emissions reduction targets’ (DECC, 2009).

Transport policies which reduce/increase emissions is not covered under the EU Emissions Trading Scheme (ETS) and it is expected that appraisals will use a ‘non-trade price of carbon’, which is based on the Marginal abatement cost required to meet a specific emission reduction target. The short term non-trade price of carbon outlined in the DECC’s July 2009 document is £60 per tonne CO₂e in 2020, with a range of +/- 50% (i.e. central value of £60, with a range of £30 - £90). (DECC, 2009).

A battery-powered train would potentially produce less carbon dioxide, and bring financial benefits, especially if a carbon charge is applied to emissions from the rail industry. Therefore detailed cost estimations are needed to account for such a charge, and how this would change as countries are expected to become more carbon friendly.

If the Zinc-Air battery technology postulated in this study were to be adopted it is worth noting that currently Zinc production is very energy intensive, and uses large amounts of fossil fuels and emits correspondingly large amounts of carbon dioxide. This could have
a significant impact on the overall carbon footprint of the zinc battery system. However, Tahil (2007) describes a new technology which is capable of producing zinc from solar thermal energy and this process could be used to produce zinc with virtually zero carbon emissions and could also be used to recycle the Zinc-air batteries at the end of their life.

Finally consideration needs to be given to disposing of the battery system; the exhausted electrolyte would be removed at the time of refuelling, which can be recycled to regenerate the zinc. Cooper (1995) mentions that a small scale recycling machine was developed at the Lawrence Livermore National Laboratory for this purpose.

Other alternatives to Zinc-Air batteries exist such as Iron-Air batteries which could be investigated if Zinc supplies were a problem, but such technology is only at the laboratory stages of development.

6.3 Infrastructure implications

The feasibility of any battery powered train system needs to be evaluated against the route characteristics. Each candidate route will need to be evaluated, in terms of the power requirements and timetabling constraints in order to determine whether the use of battery-powered trains is viable and whether additional infrastructure is required, i.e. intermediate exchange points or partial electrification. In low cost electrification schemes the use of battery power is already being considered for lengths where installation of overhead electrification is prohibitively expensive, e.g. tunnels.

The route evaluation should also consider the logistics required for recharging the batteries based on the required exchange points along the route or ideally at rail depots.

6.4 Implications for rolling stock

Rolling stock are long life assets with operational lives of around 30-40 years; therefore it will take time before any new technologies can be implemented across the fleet. It may therefore be necessary to ensure that any new train stock procured is flexible enough to adapt to future changes in power-supply.

A study is needed to develop an implementation plan for battery-powered trains and evaluate the financial implications, capital and operational, of their introduction. This study could use the existing DMU fleet as a baseline for comparison purposes to develop a business case.

It is worth noting that the development of a tender vehicle to house the batteries and supporting systems may overcome some of the barriers to the introduction of battery-powered trains. If the battery tender vehicle was fitted with an inverter then existing rolling stock designs could be retrofitted to be ‘power agnostic’ using power from either batteries, overhead electrification or both.
7 Conclusions

This study has shown that battery-powered trains are a feasible option for providing electric traction on parts of the rail network where full route electrification is not viable. By using battery technologies with a high energy density in combination with a super capacitor or flywheel to deliver the power requirements dictated by the route, it would be possible to operate a service without the need for rapid mechanically assisted battery exchanges at stations, provided the trains could be taken out of service and returned to the depot between peaks in demand during the day.

Using near to market technology the operating costs of a battery-powered train are estimated to be greater than for an equivalent DMU vehicle. Research and development into cheaper or longer life batteries could reduce the operational costs of the battery-powered train to a point where operational costs are similar to existing DMU rolling stock. A more detailed cost analysis to that carried out in this study is needed to quantify more precisely the reduction in battery replacement costs required to achieve this.
Acknowledgements

The work described in this report was led by the Infrastructure Division of the Transport Research Laboratory in partnership with Lloyd’s Register Rail and the University of Birmingham who conducted the review of battery technologies and route modelling respectively. Harry Bird produced the conceptual design for the battery exchanger units. The authors are grateful to Vijay Ramdas who carried out the technical review and auditing of this report.

References

Information has been extracted from the numerous manufacturer datasheets available on the web for various batteries including Lead-Acid, Nickel-Cadmium, Nickel Metal Hydride, Sodium Metal Chloride, Lithium Iron Phosphate, Lithium ion systems. Where possible these have been averaged/condensed to give a realistic average of the performance characteristics of each system. These are too numerous to reference individually.

Other sources include:


Department of energy and climate change (2010). DECC survey of energy suppliers,2010

- Table 3.1.1 Prices of fuels purchased by manufacturing industry in Great Britain


New Cathode Improves Performance of Li-Ion Batteries with Ionic Fluid Electrolyte , unattrib, 2006 Central Research Institute of Electric Power Industry (CRIEPI) Japan, Green Car Congress


Symons, Butler. Introduction To Advanced Batteries For Emerging Applications, Sandia National Laboratories, US Department of Energy


Glossary

AgO Silver Oxide: a primary battery used in very small scale systems (watches, calculators)

Al air Aluminium air: a primary (mechanically rechargeable) battery

ARL Above Rail Level

BRIC Brazil, Russia, India, China

BS British Standard

CENELEC Comité Européen de Normalisation Électrotechnique

CO₂e Equivalent Carbon Dioxide

COSH Control of Substances Hazardous to Health

CWR Continuously Welded Rail

DfT Department for Transport

EN Euro Norm

GPS Global Positioning System

HMRI Her Majesty’s Railway Inspectorate

HVAC Heating Ventilation and Air Conditioning System

ICA Industrial Conveying Australia

ISO International Standards Organisation

Li air Lithium air: a primary (mechanically rechargeable) battery

LiFePo Lithium Iron Phosphate: a secondary battery also known as the Ferrous battery.

Li-ion Lithium ion: a secondary battery also known as a polymer battery used extensively in portable appliances

LiS Lithium Sulphide: a secondary battery operates at very high temperatures (4-600°C)

LRR Lloyds Rail Register Limited

NaAl(x)Cl Sodium Aluminium (Iron or Nickel) Chloride: a secondary battery also known as a zebra battery; operates at high temperatures (250-300°C)

NaS Sodium Sulphide: a secondary battery; operates at high temperatures (350°C)

NaSOCl Sodium Thionyl Chloride: a primary (non rechargeable) battery used in military equipment

NiCd Nickel Cadmium: a secondary battery also known as Nicad used extensively in portable appliances

NiFe Nickel Iron: a secondary battery extremely rugged used in mining applications

NiMH Nickel Metal Hydride: a secondary battery used extensively in portable appliances

NR Network Rail

NRCS Network Rail Company Standards

PbH+ Lead acid: a secondary battery used extensively in cars, energy storage and electric traction for road, rail and marine vehicles (submarines)
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>PSV</td>
<td>Public Service Vehicle</td>
</tr>
<tr>
<td>RGS</td>
<td>Railway Group Standards</td>
</tr>
<tr>
<td>RoHS</td>
<td>Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment Regulations</td>
</tr>
<tr>
<td>RoSCo</td>
<td>Rolling Stock [Leasing] Company</td>
</tr>
<tr>
<td>RSSB</td>
<td>Railway Safety and Standards Board</td>
</tr>
<tr>
<td>RUS</td>
<td>Route Utilisation Strategy</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
</tr>
<tr>
<td>TRL</td>
<td>Transport Research Laboratory</td>
</tr>
<tr>
<td>TSI</td>
<td>Technical Standards for Interoperability</td>
</tr>
<tr>
<td>UoB</td>
<td>University of Birmingham</td>
</tr>
<tr>
<td>WCML</td>
<td>West Coast Main Line</td>
</tr>
<tr>
<td>Zinc-air</td>
<td>Zinc-air: a primary (mechanically rechargeable) battery used in its non-rechargeable form in medical appliances.</td>
</tr>
<tr>
<td>ZnBr/Cl</td>
<td>Zinc Bromine or Zinc Chlorine: a medium (80 C) temperature secondary battery intended for traction applications.</td>
</tr>
<tr>
<td>ZnC</td>
<td>Zinc Carbon: a primary battery (non-rechargeable) also known as the Alkaline battery. Used in small scale portable applications (MP3, Flashlight, Radios).</td>
</tr>
</tbody>
</table>
Appendix A  Battery Exchanger Conceptual Design

A.1 Abstract

This section describes a battery exchanger system for use with battery powered trains and is part of the feasibility study to investigate a solution to the problem of replacing diesel traction where there are no distributed sources of electrical supply along the route. The development of the design has taken on board the outcomes from the journey modelling and battery technology evaluation.

A review of existing techniques and literature identified battery exchanger technology being used in the automotive sector as well as a number of techniques used for cargo handling in the rail industry and provided inspiration for the proposed solution.

The exchanger system, consisting of a lifting table, traverser and battery conditioning enclosure, that is scalable to both the dimensions of the battery technology chosen and the number of batteries held as float required to service the individual route characteristics, has been designed using an iterative process. This section includes descriptions of the reasoning for the choices made at each stage.

The design study recommends that a prototype is developed to determine the ease with which lifting tables and traversers may be integrated, the possible impact of standards and legislation on the design and the likely duration of the battery exchange process.

A.2 Introduction

The aim of this part of the study was to develop a conceptual design for a battery exchanger taking account of the battery requirements identified in the earlier part of the study and on the aspects associated with the infrastructure to enable exchange of batteries during station dwells.

This Appendix covers solely the concept design of the battery exchanger system. Factors relevant to the first two stages of the study were identified during the iteration for design development and these are listed below such that their effects could be considered further;

- Factor in the provision for unplanned stoppages and hence the power required to restart the load – such as caused by trespass, animal incursions, crossing defect, train failures, natural event (e.g. flood) or infrastructure failure (e.g. signalling);
- Effect on the pool of batteries if there are significant gradients in one direction only leading to an unbalanced requirement for energy and a potential imbalance in the distribution of depleted batteries.
- Evaluation of the time penalties on the use of smaller batteries would lead to due to the more frequent changes perhaps requiring an increase in dwell time at a high number of stations, thus decreasing the competitiveness of the rail mode – However, these limitations are probably overshadowed by other findings in the second stage report associated with a smaller batteries inability to provide the energy when it is required, leading to the need for larger batteries which facilitate a change only at the end of each single direction journey.

A.2.1 Methodology

The iterative approach used was based on the key outputs of the battery scoping report and based on the general principles of the UK rail industry’s Engineering Safety Management publication, colloquially known as the Yellow Book (RSSB, 2007a), which amongst other things enshrines the “Vee-Process” systems engineering approach to projects, as shown in Figure 18. As such, each of the steps leading up to the concept design stage are described in the following sections.
A.2.2 Literature Review

The original aim was to review battery exchanger technologies in the automotive sector, however academic papers are limited on the subject and none were identified in battery exchangers specifically. However, on the internet, the company trading as Better Place (Better Place, 2010) have some informative video footage and general information on their prototypes for a concept for a standard battery exchange platform.

A prototype airline cargo container handling vehicle in the early 1990 provided useful inspiration (Ford, 1991). This vehicle comprised a floor containing embedded ball bearings to all but eliminate the effort required to position a loaded container and an industrially rated scissor lift of considerable tonnage capability positioned outside the vehicle in order to raise the containers to vehicle floor height. Unfortunately, this concept, marketed by British Rail’s Parcels sector as the “Track 29” business unit was not developed further and ultimately ceased during privatisation, so subsequent rail industry development did not occur.

The equipment used for this vehicle were derived from solutions in the industrial handling equipment sector. Nearly twenty years have passed in the intervening period and hence the current ‘state of the art’, was investigated. This found that the industrial/process handling equipment sector had evolved considerably in areas such as automated handling of pallet sized consignments in facilities such as storage warehouses, production lines and packaging equipment. Automated systems have progressed to a combination of piston operated positioning rams and powered track style conveyors, and an example of the later is shown in the final concept chapter as Figure 19.
A.3 Stakeholder Requirements

A number of stakeholder requirements were considered, both in the initial stages and during the design of the battery exchanger, in order to provide a holistic solution. This included;

**Infrastructure Manager (IM)**
- Network Rail’s current focus on modularisation in order to reduce installation costs;
- Maintainability in order to reduce life cycle costs by considering the effects of the design on the existing infrastructure, e.g. by designing out unnecessary interfaces and facilitating the continued use of mechanised track maintenance machines as much as possible;
- Industry norms, robust design for reliability, minimum of exposed fastenings, remote condition status, redundancy, elimination of single point failures where possible.

**Train Operator.**
- Ease of operation – a high level of automation such that the system is operable by existing non-technical train crew with minimal training.

**Passengers**
- While there is general understanding and acceptance of the likely pressures and increasing scarcity of fossil fuel in the future, so far there is little proof of a change in individual’s mobility and general consumption. As such, although market forces are the most likely means of changing habits, attempt has been made to design a solution that doesn’t result in any considerable inconvenience or obvious impact on current life;
- Chemical hazard requirements;
- Passenger expectations (punctuality and reliability/cancellations).

**Neighbours**
- A minimum of acoustic and electrical noise. The system must meet legislation on acoustic noise and electromagnetic compatibility.

A.4 Options Development

Throughout the conception stage, a range of general design groups were considered as outline solutions against which ideas could be considered. These are listed in Table 9 with the key decision points for or against alongside.
Table 9: Options Selection Table

From the options in Table 9, it was concluded that the most suitable exchange format when taking into consideration the likely tolerance issues involved, as well as reliability and availability, was one based on the industrial process handling equipment.

### A.5 Systems Requirements

Appropriate standards and legislation for guidance on specific issues were referred to during the concept development phase. However, it is recognised that as the concept develops toward a final design, greater cognisance of such documentation will be required. As such, a thorough review at the detailed design stage should include (but not exclusively);

- Technical Standards for Interoperability (TSI)
- International Standards (ISO), Euro Norms (EN), CENELEC and British Standards (BS)
- Specific supply industry standards (Water, Electricity and Telephone)
- Network Rail Company Standards (NRCS)
- Railway Group Standards (RGS)
- COSHH Control of Substances Hazardous to Health
- Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment Regulations (RoHS)
During the concept stage, the following Railway Group Standards were referred to in particular; however, the final list is likely to run into several dozen standards.

- GM/RT 2100 Structural Requirements for Railway Vehicles
- GM/RT 2149 Requirements for Defining and Maintaining the Size of Railway Vehicles
- GI/RT 7016 Interface between Station Platforms, Tracks and Trains

### A.6 Functional Decomposition

As mentioned in A.2.2, the inspiration for the design is a prototype rail vehicle from the early 1990’s which comprised a rolling floor and heavy duty scissor lift based loading platform. The key elements of that solution were taken and reconfigured based on the approximate size of the batteries derived during the battery scoping study. As such, it was decided that a conventional wholly under-floor solution was desirable and achievable as this would retain the benefits of minimal impact in the vehicle saloon and platform area. The general solution based on mainly industrial process equipment is expected to consist of five main building blocks; the batteries, lifting table, a charging enclosure, powered positioning dock, and vehicle interface.

The functionalities the system should include has been arrived at through an iterative process.

#### A.6.1 General Functionality

Each of the four infrastructure elements should incorporate features that support:

- Modular design – the elimination of bespoke designs for each location;
- The maximum automation of battery exchange and charging process so as to avoid dedicated / additional staffing. It is acceptable that existing train crew acquire limited additional roles, such as initiating and verifying the battery exchange process is completed;
- Robust design to provide an adequate level of vandal and theft proofing, especially noting the likelihood of potentially exposed sensors and the high value of metallic and novel battery equipment.
- The ability to withstand damage by acid / alkali corrosion and their potential to burn human tissue. Depending on the choice of battery, it may be required to avoid reactions with air, water and pollutants;
- Ensure high reliability and availability in adverse weather. The UK Railway Group Standard Rule Book Module M4 (RSSB, 2003) states that normal operation continues in snow up to a depth of 200 mm above top of rail, flood water at a depth of 50 mm below the top of rail and with speed restrictions in snow at a depth of up to 450 mm above top of rail with special requirements and flood water at a depth of 100 mm above the top of rail. Typical UK rail industry expectations of normal operation in terms of ambient temperature are -10 to +35°C and this should include in dry / fluffy and wet snow and with deep / prolonged ground frost with the resultant risk of cold welding and increased stiction affecting mechanisms;
- The system should inform the facility operator of either system health and / or system defects automatically to a remote location;
A.6.2 Charging Enclosure

- Charge the batteries, ideally within the exchange system enclosure, thereby removing double handling, additional off-line facilities and human intervention during normal operation;

- Consideration of the vehicle floor height of an under floor design, in order that it complies with stepping distance legislation (HMRI, 1996). Indeed this may be the basis for bringing lower than the standard height are up to current requirements or further increasing platform height requirements in order to provide level access, thus enabling a greater under floor volume to accommodate larger batteries (whilst noting that this is in contrast with the lower floor height of the proposed Tram-trains);

- The design should be suitable for installation in a range of platform construction styles, including the original conventional style with an outer retaining wall and earth etc infill and pre-fabricated assemblies, presumably by super-position of the required number of pre-fab sections by a charging enclosure;

- The enclosure’s volume must accommodate enough batteries to meet current, planned and foreseeable service frequency requirements for the particular route (the latter estimated as part of Network Rail’s Route Utilisation Strategy (RUS) programme of studies). As such, the enclosure design should be modular, with ‘passive provision’ in each installation in the form of careful positioning relative to the train within the platform to allow it to be expanded without necessitating replacement of the whole existing installation. It is suggested that the end modules could be replaced/moved back with additional battery charge middle sections inserted;

- Provide enough space/time of passage to allow a full recharge of each battery, with an amount of contingency incorporated so that the risk of loading a partly charged battery is eliminated;

- Intermediate station location on a single line - the design should be scalable to allow the exchange of batteries at twice the frequency of a terminal platform. This will enable the same design to be configurable for use on longer routes, with the facility to exchange batteries in both directions of travel;

- It is desirable that the exchanger/charger be adaptable/reconfigurable to developments in battery technology, ideally allowing an increasing number of batteries stored/conditioned;

- In order to prevent the insertion of an under-voltage battery into a train, the enclosure must allow for the non-rail removal (presumably by road vehicle) of defective batteries for offline rectification and their replacement to ensure the correct float is maintained. Therefore, enclosure access, provision for lifting out, road vehicle space and road access will be required. It is likely on such a low trafficked route, to be able to risk carrying out this operation overnight when public access can be restricted. However, ideally the operation should be able to be carried out without the requirement for what is classed as an ‘on-track possessions’;

- A means of propulsion to move the batteries around the enclosure;

- Enable safe access and maintainability of the charging enclosure outside of the ‘red and green zone’ on-track working requirements;

- An arrangement of mains services connections flexible enough to accept feeds arranged independently of each other and in accordance with the supply industry standards for electricity (charging, control, Heating Ventilation and Air Conditioning (HVAC), fire and alarm system), water (for distillation/de-ionising)
and telephony / broadband (security / perimeter integrity breach alarm / Supervisory Control and Data Acquisition (SCADA) systems);

- Depending on the battery technology selected, it may be a requirement to control the temperature within the enclosure, preventing conditions that are either too hot or too cold (or both) for good battery performance;
- Contain predictable gassing and therefore manage the resultant explosion risk (such as the production of hydrogen during charging of lead-acid cells) so that the safety of persons on the platform area in the event of an ignition is unaffected;
- Detect and curtail fire of the batteries or charging equipment (typically due to short circuit or reverse polarity of individual cells). Ventilation may need to be controlled in order to displace air from inside the enclosure and prevent platform users being exposed to fire suppressants, which are harmful to human health;
- Consideration of whether expected future energy price increases will provide a business case to utilise off-peak electricity to charge the batteries e.g. overnight, but against this will need to be balanced the increase in charging enclosure volume and the additional cost of batteries to achieve this due to the need to effectively quarantine a day’s supply. A break-even point may be based around the cost per unit of energy and the cost per square meter of enclosure, plus battery cost;

**A.6.3 Powered Traverser**

- Propels batteries to and from the lifting table and charging enclosure;
- Minimises the obstacle presented to self propelled tamping/lining on-track machines, such that maintenance of track geometry is unaffected. Thereby minimising impact damage and hence repair to the system and maintaining ride quality. However track slew will be heavily constrained;
- Isolation of direct inputs from dynamic track forces from damaging the charging enclosure (by components butting up exactly to one another), although vibration through the ground will be unavoidable;
- Adaptable to the range of sleeper spacing in use, which is dependent on length of rail (jointed, or continuous welded rail (CWR)) and linespeed (Cope & Ellis, 2001);

**A.6.4 Lifting Table**

- Consider the range of vehicle tolerances that may affect a successful interface between vehicle and fixed infrastructure – e.g. the above rail level (ARL) height range to cope with new/worn wheels and suspension, set-up, fit and build tolerances, as well as specific lateral position vehicle issues, such as body-roll on canted track;
- Consider the range of permanent way tolerances that may affect a successful interface between vehicle and fixed infrastructure and any additional constraints that may need to be applied in order to reduce them to an acceptable level;
- Ability to withstand the vibration at maximum permitted line speed (although this would be low if used exclusively in terminal platforms);
- Physically constrain movement of the battery to prevent movement outside of the desired envelope (in the event of powered track system control error);
- Maximise the ability to install and maintain adequate track quality;
- Interlocks/ hand-shaking to the vehicle and signalling system to prevent ‘drive aways’ when exchanging batteries, and/or if the lifting table is raised inadvertently when there is an approaching train (elimination of single point failure);

- Adaptable to the range of sleeper spacing in use, which is dependent on length of rail (jointed, or continuous welded rail (CWR)) and linespeed (Cope & Ellis, 2001)

A.6.5 Vehicle and Vehicle/Battery Interface

The interface between battery and vehicle should incorporate the following features:

- Capable of DC link voltages of between 300 – 600V and with suitable protection to prevent exposure of passengers, crew and maintainers to live equipment under normal operation and maintenance;

- Actuator for battery positioning - Whilst it is an aspiration that the solution is based on a single battery, the energy densities to achieve this in electro-chemical systems do not yet exist outside of a laboratory. As such an interim solution in the near term would involve multiple batteries. Whilst elements such as the charging enclosure should be scalable, this impacts the design of the vehicle interface design due to the need to manipulate the additional battery either on the ground or on-board the vehicle in a second aperture, the latter strictly being beyond the scope of this study;

- A bus-line connection to charge ultra-capacitor from the battery (optional, depending on train configuration);

- Interlocks/hand-shaking between infrastructure and vehicle to prevent ‘brake release’ until the batteries are proven to be correctly fitted and connected;

- Whilst approximate position will be assured by the vehicle position and powered track control system, exact positioning into the vehicle fixings should be assisted ideally by passive guidance;

- Correct location onto the bus-bar connections should be assisted ideally by passive guidance;

- The vehicle stopping position must be adequately controllable in order to ensure successful docking of the batteries.

A.7 Physical Decomposition

A.7.1 Charging Enclosure

The modular enclosure (read in conjunction with Figure 22) is intended to be installed as a complete replacement for an existing section of platform and therefore includes an exposed external retaining wall, which may be faced with traditional matching materials when the platform is in an architecturally sensitive location. The roof of the enclosure shall comprise semi-easily removable panels which also act as the platform walking surface. One roof panel as described in point 4 will be readily able to be lifted to provide access. The flow of batteries will allow them to work through the charger on a first-in, first-out basis. The enclosure will feature:

1. A wholly under platform design for an under-floor vehicle mounted battery thereby minimising the impact of this technology on the passenger environment both on and off the vehicle;

2. The enclosure volume required in each location will be the result of a combination of battery technology, route operated/consumption requirements, the time
required to re-charge each battery, service frequency (current, planned, foreseeable) and the redundancy afforded in the system;

3. Modular design will allow the footprint and therefore dimensions of each installation to be tailored to suit the location, ideally by adding or removing standard units, e.g. an entry unit, corner/turn back units, defective battery spur module, control cubicle and a number of intermediate charge units. This will aid situations particularly where platforms butt up against the railways perimeter and where no opportunity for additional land take is possible, e.g. adjacent building, rivers, tracks etc;

4. The enclosure should include a spur off the charging/conditioning circuit in which to place a defective battery, e.g. one with cell polarity reversion which will affect the energy storage capacity and under extreme conditions can lead to a risk of serious over-heating. Such a feature should include suitable access (presumably from above) in which the defective battery can be removed for further investigation, thereby not affecting the normal rotation of batteries during service. This therefore implies that the charging/conditioning enclosure will be sized to contain some redundancy of batteries;

5. Means to enable the maintenance, repair and upgrade of the control cubicle and other enclosure equipment, access to batteries, battery removal. External access doors should open to protect personnel inside the enclosure from and not obstruct the through passage of trains. If the access doors form the platform walking surface, they should feature anti-slip properties;

6. Means to provide security, prevent vandalism and enable detection – robust, unobtrusive design, with a minimum of exposed fastenings, security locks and substantial battery entry/exit door (roller shutters seem popular in similar industrial applications). It is suggested that the design of point motors used in a similar environment should be a benchmark for the design. Enclosure breached alert and an audible deterrent alarm should be able to be interfaced with the SCADA system to help detection;

7. Prefabricated platform designs are likely to present an additional challenge to the installation of the charging enclosure. The enclosure design should be capable of replacing a section or sections of typical pre-fab designs, and advise should be sought from Network Rail before the detailed design as to the most numerous prefabricated designs on low capacity routes;

8. Movement of batteries within the enclosure will be by the same design of powered track systems used in the other elements of the system;

9. The charging/conditioning bus bars should run for as much of the charging circuit as possible, in order to maximise charge time. Therefore if charging can also occur in the corner modules in which the batteries change direction, then the number of intermediate charging modules could be reduced. However, careful design will be required to eliminate the potential for battery terminals to short across bus-bars during movement around the enclosure. As such it may be required to install dual/offset battery terminals to facilitate this, perhaps at alternative heights;

10. Mains services connections (electricity) - Careful design will result in a need to balance between the ease of positioning to suit the application within the module and the need to meet the supply industry standard and practical requirements, such as access and routing;

11. Mains services connections (water for distilled/de-ionised refilling of cells) - Careful design will result in a need to balance between the ease of positioning to suit the application within the module and the need to meet the supply industry standard and practical requirements, such as access and routing;
12. Mains services connections (data communications for security and fault messaging from the SCADA system) - Careful design will result in a need to balance between the ease of positioning to suit the application within the module and the need to meet the supply industry standard and practical requirements, such as access and routing;

13. An intelligent battery charger and conditioning system specified to match the battery technology chosen. It should incorporate battery voltage measurement, drop-load/on-load tester and condition feedback to the SCADA system;

14. Depending on the method of actuating equipment such as the powered tracks and lifting table, a hydraulic system may be required comprising a hydraulic pump, controls within the equipment cubicle and hoses elsewhere in the enclosure;

15. The system controller for the fixed infrastructure element which is linked to the sequence initiation control on-board the rolling stock and the signalling system, in order to allow for the lifting table position to be interlocked with the signalling system. The latter is essential where the exchanger is fitted to through running lines. It is likely that the link to the vehicle could be adequately achieved wirelessly;

16. [Optional] Off-peak charging may be required to take advantage of lower unit costs of electricity, therefore the control system would require a timer function;

17. [Optional] The control system may include an output to a remote location for system health and limited self diagnostic capability;

18. Depending on the electro-chemical composition of the batteries, there may be a requirement for temperature reduction of the batteries in particular and therefore the enclosure in general, in the form of mechanical refrigeration;

19. Additionally, exposure to low ambient temperatures when the battery is mounted underneath the vehicle will reduce internal resistance, thus affecting storage capacity and therefore heating may need to be installed in the module to counteract this;

20. Trace heating to prevent weather related issues, particularly of the battery access/egress hatch;

21. Reduction of explosion hazard - Ventilation of gaseous emissions produced during (over-) charging shall be routed to a safe location (with respect to sources of ignition & human health); although platform areas are now non-smoking by law there is a high likelihood that gases will be harmful or irritant to humans (especially eyes & lungs), so the platform area should continue to be avoided. Also, it is not advisable to vent to the cess area due to the potential of ignition by the vehicle. As such, an arrangement similar to an automotive fuel station’s underground storage tank breather pipes maybe considered. Careful airflow management should result in the retention of the modular concept by installing the extract fan and external breather in the control cubicle, plus suitable internal ducting to cover all areas of the enclosure.

22. Careful material choice and containment measures to minimise the effects of any leakage of electrolyte. In the case of leakage within the enclosure itself, due to the high volume of electrolyte and the length of time over which leakage may occur, effective remedial action may only be possible if a means of sensing such fluid is installed and fed back to the control centre;

23. Fire detection and suppression equipment.
A.7.2 **Powered Track Traverser**

The Powered Track Traverser (read in conjunction with Figure 22) will feature:

24. A pair of over-length fabricated steel railway sleeper assemblies (thereby avoiding an additional interface between an intermediate traverser and conventional length sleeper ends), which have a gap sufficient to isolate movement of the permanent way from damaging the charging enclosure. It shall incorporate fixings to secure the rails to the range of sleeper chairs in general use;

25. Movement of the batteries shall be by means of powered tracks positioned in the sleepers to slightly above rail level and situated from the enclosure end to the centre line of the ‘four foot’ and controlled by the main control system housed within the charging enclosure;

26. Trace heating around the powered tracks to prevent weather related issues;

27. Care in material choice and containment measures shall minimise any negative effects of any leakage of electrolyte.

![Figure 19: Example Powered Transport Loading Tracks (Source ICA).](image)

A.7.3 **Lifting Table**

The Lifting Table (read in conjunction with Figure 22) will feature:

28. A one tonne (for two, one tonne batteries in the near term) rated lifting table with transducers to allow control which is adjustable to suit the range of vehicle heights that will be experienced due to tolerances in suspension, wheel wear, build and set-up;

29. A footprint that can accommodate the likely variety of sleeper spacings on low usage routes, this is generally in the range 600 – 800 mm between centre lines;

30. Enough space between each rail and the lifting table top to allow the widest design of wheel flange to run un-impeded and with sufficient tolerance at the maximum linespeed;

31. Security and vandalism – robust, unobtrusive design, with security locks, a substantial battery access hatch and a minimum of exposed fastenings. ‘Point motors’, used in a similar environment, should be a benchmark for the design;

32. Adequate constraint of lateral and vertical track positioning tolerances, perhaps by such means as increasing track fixity (such as by ‘ballast gluing’, absolute gauge positioning techniques or lateral restraints). Depending on the track engineers requirements (with respect to maintenance needs), a means of linking the relative positions of rail level and lifting table in the foundations in order to maintain respective tolerances between interfaces;

33. Trace heating to prevent weather related failures and delays;
34. Careful material choice and containment measures to minimise the effects of any leakage of electrolyte;

35. Controlled by the main control system housed within the charging enclosure. The control system is likely to be required to be interfaced with the signalling system, where applicable, in order to prove that the table is lowered. The transducers required to prove this, will also ensure that the control system prevents ‘drive-aways’ with the table raised. It is also expected that certain stakeholders will require the power to be removed from the lifting table when it is inactive in order to prevent inadvertent raising caused by a single point failure;

36. Lip on outer edge of lift to help retain battery position in case of inadvertent operation.

37. A means of locating the required vehicle stopping position to the desired accuracy in order that the battery exchange process is successful (see expanded comments in section A.6.4).

Figure 20: Example Industrial Stationary Lifting Tables (Source C&H Distribution).

A.7.4 Vehicle and Vehicle/Battery Interface

The vehicle to battery interface (see Figure 23) shall consist of:

- A shaped/self centring (wider entry, narrowing to a final fixed position), interface which exploits low adhesion materials (such as nylon) in order to allow manipulation of the battery despite the necessarily tight fit. This solution differing from conventional railway vehicle battery boxes which are traditionally located by means of ball-bearing sliders;

- Ideally, the means of securing the battery in the exchange dock would be capable of withstanding the proof and shock load requirements in traffic (RSSB, 2000); however, it may be permissible to have an empty space in this location when the vehicle is in motion if this cannot be achieved;

- V-shaped self centring bus-bar connections. The mechanical battery retention would provide enough pressure between battery terminal and bus-bar to avoid the risk of burn up given that the connections will be un-bolted;

- Spark suppression to prevent ignition of gases emitted by battery (typically hydrogen). The use of a line contactor to remove the electrical load from the battery will reduce the size of any spark. Additionally, gases are generally given off cells during charging, not during use, so there should be little risk of combustible gases when removing the batteries. Therefore the highest risk is of charged batteries. Depending on the type of electrochemical system to be used, it may be required that a battery ceases to be charged sometime before fitment
to the train, thereby increasing the number of batteries in the enclosure, and hence enclosure size and cost. It is even possible that forced ventilation of the battery area is required on the vehicle during connection, however this additional complication is not desirable;

- Positioning of the second battery on the vehicle. Two methods exist for this, a second lifting table adjacent the first, with additional powered tracks to move the battery longitudinally, with respect to the railway line, or by means of a hydraulic piston and slide arrangement on-board the vehicle (the author has provided a concept for the later);

- It would however be easier to manipulate battery positions on-board the vehicle rather than reposition the train a second time over a single lifting table;

- A push-to-make/break illuminated button to initiate exchange sequence mounted or probably located on the assistant’s side cab bulkhead, thus avoiding Driver/Trade Union concerns regarding cab ergonomic and safety whilst in motion. This also minimises the clutter on the cab desk, an already busy location;

- The rolling stock will require some control equipment for its own element of the exchange process, i.e. in order to control the battery interface, detachments and re-attachment, to interlock the system to the existing train circuits and also a means of hand-shaking between itself and the control element for the fixed infrastructure element in order to prevent drive aways/brake release when part way through the sequence;

- Trace heating to prevent weather related issues;

- Careful material choice and containment measures to minimise the effects of any leakage of electrolyte.

A.7.4.1 Stopping location confirmation

The need to accurately and repeatedly stop within a short distance, likely to be +/- 100mm is expected to produce practical difficulties due to the hysteresis inherent in train braking control systems caused by a typical one second (minimum) delay between initiation of a change and the start of pressure rise within a brake cylinder. The author is concerned that an automated system may prove to be necessarily complex for a supposed low traffic route.

Drivers (unaided) typically achieve a high level of positional accuracy if they first come to a stand and then creep forward by a couple of metres, as during a coupling operation. Established and simple means of manual control are already used for positional accuracy such as ‘precision stop boards’, currently used where it is essential that external vehicle doors are positioned on short platforms so passengers are not exposed to a risk of falling from height into the cess. The operation of achieving positional accuracy is likely to add additional journey time, and the designer should be aware of the human factor elements and hence trades union concerns in avoiding additional driver stress, particularly in a terminal platform location, although with due regard, these requirements should be able to be worked in to increase overall safety by reducing the speed a train approaches the buffers, thereby reducing the risk and severity of buffer stop collision.

Some use of technology maybe considered, such as GPS/Galileo, but in a railway application this often has to be combined with tachometer inputs due to certain locations inability to ‘see’ satellites, for example, under overall roofs, steep/deep cuttings and underground stations/tunnels. Tachometer systems themselves suffer from reduced positional accuracy due to wheel slip and slide, due to poor rail adhesion.

This concern has been adequately addressed in Metro applications at platforms fitted with a combination of platform screens and train doors, however, this is usually achieved by having a more controllable adhesion level, as these platforms are typically
underground and passengers are not able to introduce contaminates to the rail due to the platform screens. Above ground, mitigation measures already in use include; re-zeroing the position by means of a Euro-balise or an un-braked axle which provides an unaffected speed/distance input. However, these are unlikely to be effective in this application due to the poorest rail adhesion often being on terminal platforms and due to the lack of additional braking capacity on short train lengths respectively.

A.7.5 Concept Design
Throughout the above process has been an iterative approach whereby the early concepts have been changed and adapted in light of various emerging requirements, with one eventual clear successor. The outline drawings below illustrate a general layout of the battery exchange system (Figure 21). This is followed by Figure 22 which shows a plan view of the battery conditioning/charging enclosure and Figure 23 which shows cross section views of the vehicle battery interface.
Figure 22: Plan view of charging/conditioning enclosure

Figure 23: Cross section views of vehicle / battery interface
A.8 Operational Timelines

In order to help understand the concept design, it is suggested that the sketches are read in conjunction with the timelines below.

A.8.1 Battery exchange operation timeline

Train slows to a stand at platform/battery exchanger location;

- Exact location determined by a combination of precision stop board and/or treadle operated indicator (see A.7.4.1 above);

- Vehicle brakes applied, master controller/direction selector switched to the ‘Neutral’ position, thereby allowing the next step (these functions will be interlocked to prevent battery ejection inadvertently during movement). Other typical operations at platforms will also commence such as operation of ‘Door Enabled’ push-buttons (as required);

- Driver initiates battery exchange process by operating a push button;

- The key on-board function initiated by the above button will be the opening of a battery load contactor, thus taking the batteries off-line in order to reduce damage to terminals by arcing upon removal;

- A form of ‘hand-shaking’ will be required between the on-board and fixed equipment elements of the system. This is in order that the fixed infrastructure knows that the correct type of vehicle is present, in position and ready to exchange/release its battery and the process to start. Equally, the vehicle will need to know when it is acceptable for the battery securing components to release the battery;

- The lifting table will then raise to take the weight of the first depleted battery;

- Battery securing latches fixed to the vehicle open, the mass of the battery then fully transfers to the lifting table, with disconnection from the vehicle bus bars also occurring;

- The enclosure (roller shutter) door will then open afterwards or in parallel;

- The lifting table drops to the lowered position;

- The powered track traverser moves the first depleted battery into the under platform enclosure to commence its sequential circuit through the battery conditioning process ready for re-use;

- The lifting table meanwhile has risen again to remove the next depleted battery;

- Movement of the two batteries on-board is by (hydraulic) pistons to and from a single unloading position, resulting in a simplified fixed infrastructure. In order to allow as much tolerance as possible for alignment in this automated system, it is anticipated that shaped nylon runners are used to secure the battery boxes to the vehicle;

- This second battery is removed in an identical way to the first, and once clear of the conditioning enclosure entrance/exit, the first charged battery will emerge;

- The powered traverser moves this on to the lifting table;

- The lifting table raises, with the battery self centring onto the runners/guides and shaped bus-bars;

- The vehicles clamping runners then secure the first battery, which is moved down to the second battery area by the on-board pistons;

- The clamping runners can then open again, ready to receive the second battery, and the lifting table lowers again;
The cycle is repeated, with the second battery moving out of the enclosure, across the powered traverse and onto the lifting table;

The enclosure (roller shutter) door may then be closed;

The second battery is then raised, again self centring onto the runners/guides and shaped bus-bars;

The vehicle clamping runners then secure this second battery. Depending on the final design of the runners, due to the high forces any underframe mounting must withstand according to Standards, this second battery may need moving by the on-board pistons down to a transit position, leaving the loading/unloading position clear during vehicle movement. However, it is possible that the final designers reach a solution that doesn’t require an empty dock during movement by achieving a robust design;

The lifting table can then lowered as a final action for this exchange sequence;

Once the second battery is secured by the clamping runners, the cab bulkhead illuminated push-button will illuminate to signify a completed sequence;

The driver then pushes, to unmake the push-button which ceases the hand shaking sequence between mobile and fixed systems and the vehicle line contactor recloses, connecting the batteries to the vehicle power circuits;

The driver and train manager/guard can then commence the existing dispatch procedure for the train.

It is suggested that the duration for the above sequence is determined in order to understand the potential effect on the minimum dwell time this solution will require.

### A.8.2 Conditioning / charging enclosure operation timeline

The sequential process within the battery conditioning circuit could occur in either direction, presumably depending on the footprint of the individual site, although cost efficiencies will be maximised by having a standard design. The steps in the process will consist of:

- ‘Hand-shaking’ from the vehicle to the enclosure control system will initiate the system ready for an exchange sequence;
- The enclosure (roller shutter) door will open once the first removed battery is ready to enter the enclosure;
- Powered tracks will bring the battery inside the enclosure and into the first available charging point. These tracks run around the entire enclosure and are the sole means of propulsion inside the enclosure;
- After an initial period of charging, the battery will undergo a short load test to determine whether it is responding to its charge adequately and therefore will be fit for further service. This test will take place before the battery passes the defective battery module;
- The battery then either passes the defective battery module on its circuit around the enclosure or enters it if defective;
- The battery continues to move around the enclosure as fully charged batteries leave the enclosure to be installed as part of the exchange process;
- A limited amount of redundancy in the form of additional batteries ensures that the battery is only required after it has been fully charged, although in the event of a defective cell being sidelined, this redundancy will be reduced for a period until it is replaced;
Finally, the fully charged battery will be in the final charging position, and at the next exchange will be dispatched using the powered tracks back through the enclosure door and onto a waiting train.

A.9 Cost
The system costs can be estimated by benchmarking the individual components against similar proprietary equipment already available on the open market. This approach will need to take notice of approximate ratings and be from the industrial, not consumer sector as otherwise the costs will not factor in the required reliability. Project and design costs will also need to be added as one-off costs. The key list of components in order to ascertain ball-park costs are described in the following sub-sections.

A.9.1 Capital cost
A.9.1.1 Charging Enclosure
- Unfitted module fabrications – average price, including the complex but empty control cubicle;
- Anti-slip surface and access hatch;
- Roller Shutter;
- Powered track systems as elsewhere in the solution;
- Bus-bars;
- Electricity connections, consumer unit and meter;
- Water connection and meters;
- Telecoms connections;
- Battery charger, with timer function;
- Hydraulic pump, system – including controls (optional);
- Wireless link to railway vehicle;
- Control or SCADA system with optional link to Control room;
- HVAC system, either full or part thereof;
- Trace heating;
- Ventilation system;
- Fire detection and suppression equipment.

A.9.1.2 Powered Traverser
- Pair of over-length fabricated steel railway sleepers assemblies;
- Powered tracks;
- Trace heating.

A.9.1.3 Lifting Table
- A one or two tonne rated lifting table;
- Fabricated mounting tray between two sleepers or concreted foundations;
- Trace heating.
A.9.1.4 Vehicle and Vehicle/Battery Interface

- Vehicle stop position method;
- Battery case fabrication;
- Vehicle battery mounting raft;
- Bus-bar connections;
- Vehicle line contactor, wireless connection to ground and control system – i.e. circuit wiring, switches and relays or software revision;
- Positioning piston and hydraulic system;
- Trace heating.

A.9.2 Operational cost

Additionally, operational costs can be estimated. These will comprise;

- Batteries – given their relatively short lives, they could be categorised as consumables and therefore, after the initial batch, part of the operational costs;
- Electricity and water consumption;
- Telecommunications.

A.10 Conclusions

A.10.1 Findings

As illustrated in Figure 6, Figure 7 and Figure 8, an exchanger solution consisting of a lifting table, traverser and battery conditioning enclosure, that is scalable to both the dimensions of the battery technology chosen and the number of batteries held as float required to service the individual route characteristics has been designed. The former depends on the electro-chemical make-up selected for batteries, although there are hard constraints of platform height and vehicle floor height above the rail, which will directly affect vertical height dimension which are more intractable.

Traceability from the concept design back through the previous stages has been provided, such that as the concept is taken forward through to a detailed design, the reasoning for each requirement is understood, so that functionality is included or excluded with an appreciation of why it is suggested and to whom it is attributable.

A.10.2 Recommendations

- Produce a prototype installation, with a rail industry equipment manufacturer as the lead developer/systems integrator, supported by specialists in powered tracks and industrial lifting tables. There will be a strong requirement for the later two to work closely with the lead in order to successfully embed tracks into the table itself;
- As the concept is worked up into a final detailed design, a thorough analysis and expansion of the standards and legislation will be necessary to establish both mandatory and preferred requirements;
- In order to determine the design’s suitability for mid-journey battery exchanges, it is suggested that the duration for the battery exchange and charge sequences are identified in order to understand the potential affect on the minimum dwell time this solution will dictate. This is particularly pertinent if a multiple battery solution is necessary.
A.11 References

Documents:


Web Site Links: