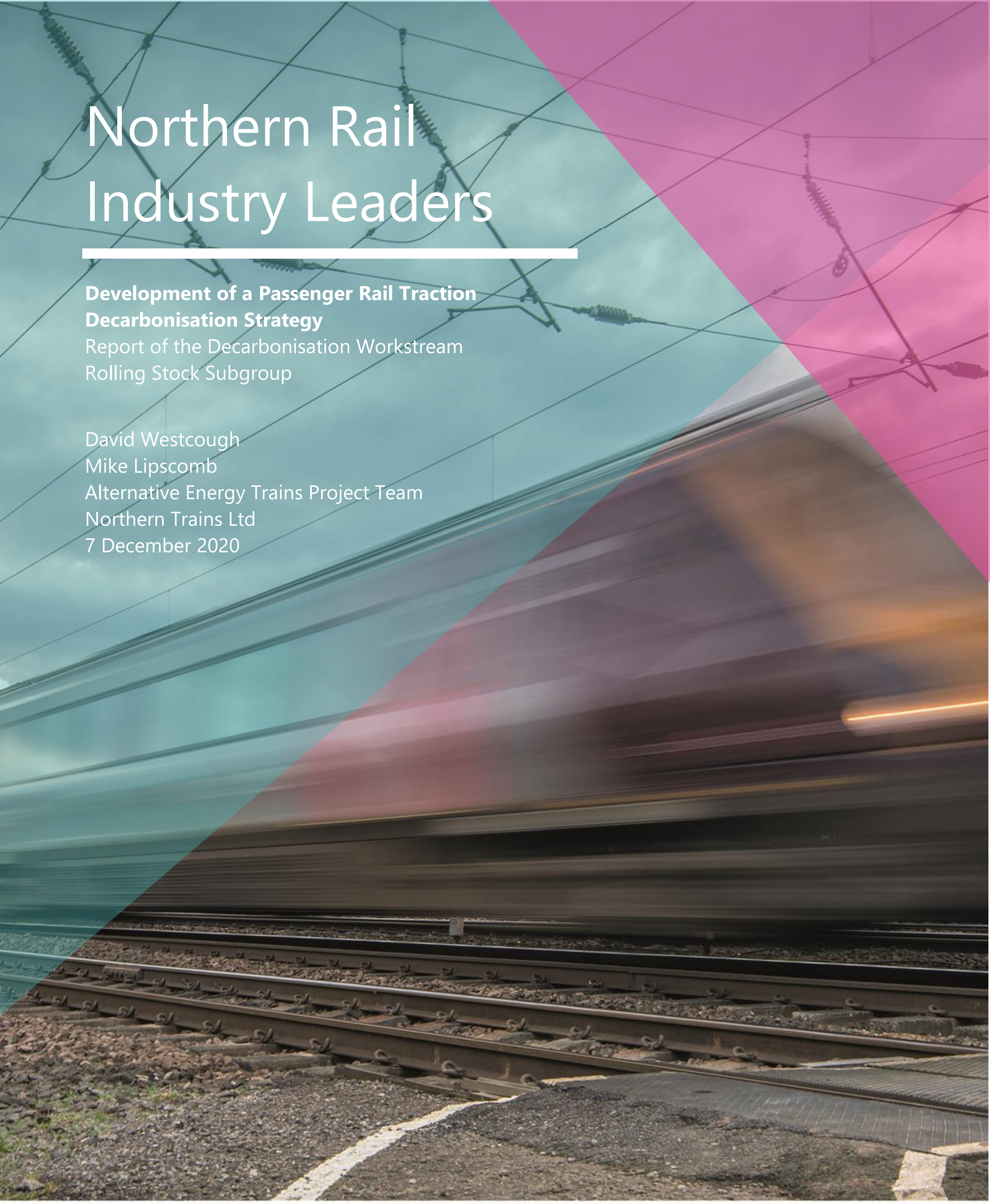

Northern Rail Industry Leaders

Development of a Passenger Rail Traction Decarbonisation Strategy

Report of the Decarbonisation Workstream
Rolling Stock Subgroup

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Railway Industry Association
The voice of the UK rail supply community

Northern
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FOREWORD

As the UK Government looks to stimulate an economic recovery following the Coronavirus pandemic, decarbonising the North's railways stands as a good candidate for investment, helping to level up the region, creating jobs and economic growth, whilst also supporting the development of a low carbon mass form of transport.

In *Building the North's New Railways,* our White Paper setting out how the rail supply industry could deliver investment across the North's rail network, NRIL set out a number of recommendations for 'levelling up' the Northern rail network. Decarbonisation featured heavily, and remains a key issue as the rail industry seeks to achieve the Government's target of removing all diesel-only trains off the network by 2040 and achieving net zero by 2050.

Much, however, has changed since our White Paper was published in February 2019. The Coronavirus pandemic has significantly changed our way of life and the way we work. And, whilst it has impacted our rail industry significantly too, there is a clear case for investing in the North's rail network now, in order to provide the jobs and economic growth we so vitally need, and to ensure we have a rail system ready for the future after this pandemic is over. What's more, focusing this investment on deploying green technologies on our railways will mean we leave a low carbon legacy for future generations too.

Progress has also been made on the rail industry's plans to decarbonise, with the publication of Network Rail's interim Traction Decarbonisation Network Strategy, which this report uses as a starting point. It also builds on the recommendations in *Building the North's New Railways* where NRIL committed to working with Transport for the North, Network Rail, Government and other key partners in developing a route map to a decarbonised Northern rail network, utilising the various technologies available to the industry.

This report sets out the opportunities and challenges available to the North's decision makers in setting out a strategy for decarbonisation, including how different technologies can best be utilised by client organisations and Government. We hope it is a useful guide from the rail supply industry as to what practical steps can be taken between now and 2050 to decarbonise the region's rail network.

Northern Rail Industry Leaders stands ready to support the decarbonisation of the rail network. There are some 300 rail companies in the North, supporting 58,000 jobs across a range of disciplines. NRIL's 150 member companies are ready to support the Government's aims to level up and decarbonise through rail investment.

Since the publication of the White Paper, NRIL's five workstreams of 'Delivering Value', 'Decarbonisation', 'Digitalisation', 'People and Skills; and 'Innovation' have been working hard to develop follow on papers that help achieve the vision we set out last year. We would like to thank all of the Decarbonisation Workstream team who have supported this report, particularly the Workstream Chair Julie Carrier and authors of this report David Westcough and Mike Lipscomb.

We hope this report helps support the North's journey as it seeks to decarbonise its rail network.

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EXECUTIVE SUMMARY

In response to increasing concerns over transport emissions, the UK Government is seeking to curtail the use of fossil fuels in transport in favour of renewable alternatives. These emissions contribute to global warming, as well as being damaging to health. The rail industry has been tasked with removal of all conventional diesel traction from service by 2040.

In response to increasing concerns over transport emissions, the UK Government is seeking to curtail the use of fossil fuels in transport in favour of renewable alternatives. These emissions contribute to global warming, as well as being damaging to health. The rail industry has been tasked with removal of all conventional diesel traction from service by 2040.

Railways in the North of England are heavily dependent on diesel traction, and alternatives must be found if services are to continue. Possible solutions are electrification, battery power and hydrogen power. In the short term, some advantage may also be gained from modification of existing mid-life diesel fleets with more efficient propulsion systems. Use of low or zero-carbon fuels may also be considered.

Given the size of the task ahead, it is vital that operators begin to develop strategies for the planned fleet-wide replacement of diesel traction by environmentally-friendly alternatives. Although electrification is the optimum solution for intensively used routes, there will be locations where electrification cannot be justified due to the cost of the infrastructure or where electrification is some time away. In these situations, priorities for conversion should be driven by the condition of existing diesel assets, combined with consideration of local air quality hotspots which could benefit from early replacement of diesel.

This is now a particularly important consideration given that, during the final preparation of this document, Network Rail published the interim programme business case for the Traction Decarbonisation Network Strategy (TDNS), which proposes up to 12,000 single track kilometres (stk) of electrification over approximately 30 years [1].

This increases the relevance of this strategy as it offers practical solutions to ‘bridge the gap’ from today to net-zero carbon and deliver early carbon reductions by offering solutions that can be deployed quickly, in many cases, in advance of ultimate electrification.

This report by the Rolling Stock subgroup of the Northern Rail Industry Leaders (NRIL) Decarbonisation workstream focuses on the contribution that trains can make to the decarbonisation of the north’s passenger railways. It thus offers both the opportunity to optimise the proportion of electrification but importantly to accelerate carbon reduction.

Strategy development and initial implementation will rely heavily on the lessons learnt from early deployment schemes. As uptake increases and experience of these new technologies increases, implementation strategies can be expected to evolve and become more refined. However, this will not happen without early deployment schemes to kick-start the process.

Cost is a vital factor, if the delicate socio-economic balance that justifies provision of many services, is to be preserved. The cost of decarbonisation will be substantial and it is imperative that diesel-replacement technologies can evolve quickly to the point whereby new fleets are comparable in both purchase and operating costs to the diesel vehicles they replace.

The ultimate goal of these strategies is the removal from service of all conventional diesel rail vehicles by 2040, with all remaining diesel-powered bi-mode and hybrid vehicles following by 2050. This paper discusses the issues and challenges to be considered by operators and planning authorities as part of the strategy development process.

CONTENTS

1. INTRODUCTION

Climate change, caused by the emission of greenhouse gases (GHG), is becoming an increasing concern, both in the United Kingdom (UK) and worldwide. As a result, Government is introducing measures to reduce the quantity of GHG, particularly that of carbon dioxide (CO_2), that the UK produces. Transport is now the biggest generator of CO_2 in the UK, and whilst other industries have demonstrated significant reductions in emissions over recent years, the transport sector has only managed a reduction of 3% [2].

Furthermore, emissions found in diesel exhaust, particularly oxides of nitrogen (NOx) and particulate matter (PM) have been identified as significant contributors to poor health due to their effect on the respiratory system. This forms a major driver behind current Government efforts to significantly reduce diesel use, particularly in urban areas.

In early 2018, the Secretary of State for Transport announced that a ban would be introduced on the use of diesel-only rail vehicles from 2040. Whilst various studies have shown that further electrification will permit a significant reduction in diesel use across the network [3] [4] [5], it is unlikely that a case can ever be made to electrify the entire UK rail network.

Therefore, whilst further electrification of many routes will be justified by the requirements of high speed, high frequency passenger and freight traffic, alternatives to diesel propulsion will also be required to permit continued provision of the remaining non-electric services, many of which operate in the North of England.

To address this issue, Northern Rail Industry Leaders (NRIL) has set up a dedicated low carbon working group, in order to set out a strategy for decarbonisation of the railways in the North of England. As part of this working group, a rolling stock subgroup has been established to identify where emissions can be reduced through improvements to rolling stock.

In response to the proposed diesel ban, Arriva Rail North (ARN), which is now Northern Trains Ltd (NTL), set up a dedicated project team to investigate the use of alternative energy trains (AETs) on a number of the routes operated by the Northern franchise. As evidenced by the findings of Network Rail's Traction Decarbonisation Network Strategy (TDNS), these routes are unlikely to see electrification in the near future, but account for significant operating mileages.

For this work, the AET project team investigated the various possible energy sources available. This work resulted in the selection of battery-electric multiple unit (BEMU) trains for the Manchester Airport to Windermere route, and hydrogen multiple unit (HMU) trains for the rail network in the Tees Valley.

Based on the lessons learned by the AET project team, this document provides guidance on evaluation processes for the selection of appropriate decarbonisation solutions for different types of route and service.

It should be noted that the discussions within this paper refer specifically to passenger operations; due to its significant power requirement and large geographical coverage, freight poses further technical challenges which are likely to require different approaches to those applicable to rail passenger transport. This view is reflected by the findings of the TDNS report, which favours electrification as the most appropriate solution for the bulk of rail freight flows.

2. ALTERNATIVE ENERGY TRAINS

2.1. WINDERMERE BATTERY-ELECTRIC TRAINS

The Windermere branch line is approximately 10 miles long, connecting into the electrified West Coast Main Line (WCML) at Oxenholme Lake District. The branch was originally planned for electrification, but subsequent cost increases made this financially unjustifiable. Issues regarding the visual intrusion of the overhead line structures in this visually sensitive area were also cited in the Government decision to cancel the electrification scheme.

The Windermere route is particularly suited to a battery solution employing electric multiple units (EMU) fitted with traction batteries, to produce a battery-electric multiple unit (BEMU). This allows a degree of self-powered operation away from electrified routes. BEMU vehicles are technically simpler than the diesel multiple unit (DMU) vehicles they replace and are expected to have maintenance costs and reliability levels more akin to EMUs than DMUs. Energy costs are also significantly lower than diesel on a per-mile basis.

The TDNS supports the view that this route is likely to be suitable for battery based alternative traction and so any effort on this route is not likely to be superseded by electrification.

Branch services are operated largely as a self-contained shuttle between Windermere and Oxenholme. However, due to the popularity of the southern Lake District as a tourist destination, a number of journeys are extended daily through to Manchester Airport via Manchester Piccadilly. The route between Oxenholme and Manchester Airport is some 87.5 miles in length and is fully electrified. The entire route is illustrated in Figure 1.

It can therefore be appreciated that today's DMU service results in considerable diesel mileages operating 'under the wires' without taking any advantage of the electric traction supply they offer. By replacing DMU operation with BEMUs, full advantage can be taken of the electrification system, where available, switching to battery power to cover the last 10 miles of non-electrified route. In so doing, significant savings are made in CO_2 and other harmful emissions in comparison to the current operation.

Furthermore, whilst electric propulsion already represents a considerable saving in carbon emissions per mile compared to diesel, the carbon footprint of electricity used by BEMU vehicles will continue to improve as the national grid supply decarbonises.

However, battery storage systems, even those based on the latest lithium-ion chemistries, have limited energy densities; this limits the practical range of battery vehicles to the point where the required battery mass, volume, carbon footprint of manufacture and cost becomes impractical.

Therefore, whilst battery technology is ideal for short, non-electrified branches from largely electrified networks, or to cover short breaks in electrification on routes with restrictive infrastructure (intermittent electrification), a more energetic fuel source is required to power trains operating on longer non-electrified routes. This is where hydrogen has the advantage.

2.2. TEES VALLEY HYDROGEN TRAINS

Hydrogen is stored on rail vehicles at high pressures (350 bar or more). Even at these pressures, the energy density achieved is significantly less than for the equivalent volume of diesel fuel. Additionally, the storage tanks required to hold hydrogen at these pressures have significant volume and mass, setting a practical limit to the quantity of hydrogen that can be stored on board. This means that for a realistic on-board storage volume, the range of a hydrogen train is significantly less than that of an equivalent DMU. Typically, a range of around 600 miles is currently achievable, compared to 1,400 – 1,500 miles for the equivalent diesel unit.

Nevertheless, such vehicles have sufficient range to operate typical daily diagrams of up to 450 miles, once a 25% fuel contingency (for emergency or unusual situations) has been accounted for. Their limited range means that unlike the equivalent DMU, an HMU must return to a depot or servicing point nightly for refuelling. This calls for a re-configuration of the diagrams currently used, which often see diesel units berthed overnight at stations and other remote stabling points with no refuelling facilities.

Once these obstacles are overcome, the use of hydrogen trains lends itself to non-electrified regional routes away from electrified networks, where the required range is beyond that which is realistically achievable using battery storage. An example is the Tees Valley rail network, which provides local services from Bishop Auckland to Saltburn, Middlesbrough to Whitby and Middlesbrough to Hartlepool. The network is illustrated in Figure 2.

It is understood from the TDNS that these routes are a lower priority for electrification and are not likely to be electrified until late in the programme, potentially in the 2050s. Therefore, any technology deployed here could have a circa 30-year life and would be reducing carbon from the date of implementation.

A further consideration is the need for a ready supply of fuel-cell grade hydrogen fuel, along with specialised hydrogen storage and dispensing equipment. The capital costs of introducing HMU vehicles, with their need for supporting fuelling infrastructure, are therefore likely to be somewhat higher than those of BEMU vehicles, which can make use of existing electrification infrastructure for battery charging.

The means by which the hydrogen fuel is produced has a major effect upon the overall benefits of the scheme. Hydrogen is principally produced industrially in large quantities by steam reformation of natural gas (Steam Reformed Methane – SMR), resulting in significant CO_2 emissions. Use of hydrogen produced in this way has little overall benefit in terms of carbon emissions compared to continued use of conventional diesel fuels.

Only if the production of hydrogen is achieved by low or zero-carbon means will the true benefits of the technology be realised, in return for the significant investment required.

One example of low-carbon hydrogen is that produced by SMR, combined with carbon capture and storage (CCS), where the CO_2 produced is separated out and placed in to long-term underground storage.

However, natural gas (methane) is still a finite fossil fuel and is a significant GHG in its own right, having similar properties to CO_2 in this regard, trapping heat within the Earth's atmosphere. Recent studies have shown that the oil and gas exploration industry is responsible for significant emissions of methane in to the atmosphere, making a significant additional contribution to climate change [6].

Dependence on SMR-produced hydrogen, even when combined with CCS, is therefore only a partial solution to the problem of transport-related GHG emissions. Production by electrolysis, however, using renewable energy (wind, solar, hydro, tidal etc.) is a zero-carbon process, realising the full environmental benefit of hydrogen propulsion.

2.3. CHOOSING THE RIGHT SOLUTION

From the above, it can be seen that both battery and hydrogen technologies have their strengths and limitations; thus, a thorough evaluation process is required in order to determine the optimal solution for any particular railway route and/or service.

3. METHODS OF DECARBONISATION

3.1. INTRODUCTION

As of writing, the following are the principal methods available, including combinations thereof, for decarbonisation of railway services:

- Continued diesel usage with carbon offsetting,
- Continued diesel usage with biofuels or synthetic fuels,
- Electrification,
- Hydrogen propulsion,
- Battery propulsion,
- Retrofit of existing diesel fleets with more efficient drivetrains
- Retrofit hybridisation of existing diesel fleets,
- Service withdrawal/line closure.

Each of these options is dealt with in more detail below.

3.2. CONTINUED DIESEL USAGE WITH CARBON OFFSETTING

This option would see diesel railway vehicles retained on the network, with their carbon emissions offset in order to achieve net zero. Carbon offsetting methods include tree planting and investment in CCS.

Even assuming that zero overall carbon emissions can be fully achieved through this method, the localised emission of NOx and PM will remain an issue. Since Government has set a target of taking all diesel-only rail vehicles off the national rail network by 2040, such an approach would only apply to diesel bi-modes until the removal of these vehicles is also mandated.

Therefore, without a change in Government policy towards the long-term use of diesel on the UK national rail network, carbon offsetting appears to have little to offer to the field of railway propulsion. For this reason, it will not be considered further in this paper.

3.3. CONTINUED DIESEL USAGE WITH BIOFUELS OR SYNTHETIC FUELS

Liquid fuels can be produced directly from certain crops and this was once thought to be the answer to our reliance on fossil fuels. However, the land-take required to grow sufficient quantities of crops to fully replace fossil fuels has been shown to be unrealistic, leading to competition with food production.

There are also concerns regarding the carbon footprint of the cultivation process itself. Therefore, whilst blending of biofuels with fossil fuels provides a useful reduction in the usage of the latter, it can only really act as a stopgap in the eventual replacement of fossil fuels with zero-carbon alternatives [7].

It is possible to produce liquid fuels from hydrogen, combined with CO_2 from the atmosphere. If this hydrogen is zero-carbon, produced from electrolysis, or obtained as the waste product from industrial processes that would otherwise be vented or flared off, then the fuel can be said to be zero-carbon. Whilst CO_2 will be released during combustion of the resulting fuel, this will only be the CO_2 that was taken from the atmosphere in the first place [8].

However, the production of synthetic fuels is very inefficient in terms of energy usage. The capture of CO_2 and subsequent combination with hydrogen requires energy. This is in addition to the energy required to produce the hydrogen used in the process. In vehicles, the fuel will be converted to mechanical power for propulsion using a conventional internal combustion (IC) engine, which will have a thermal efficiency of only around 32% [9], even before reductions in efficiency due to driving cycle are considered.

The equivalent hydrogen-powered vehicle will use a fuel cell to produce power for propulsion; fuel cells used in mobile applications have a typical energy efficiency of around 60% [10]. The energy requirement to produce synthetic fuel from CO_2 and hydrogen, combined with the much lower efficiency of the IC engine means that, whilst technically possible, the process is quite inefficient in comparison to use of hydrogen directly in a fuel-cell propulsion system.

Additionally, the burning of either biofuel or synthetic fuel in IC engines still causes the problem of localised NOx and PM emissions, this being one of the key drivers for the replacement of diesel engines in the short term.

Because of the disadvantages described above, combined with current Government policy preventing the use of conventional diesel drivetrains after 2040, the use of biofuels and synthetic fuels will not be considered further in this paper; they represent only a short-term stop-gap solution and are described here only for completeness.

3.4. ELECTRIFICATION

From an energy-efficiency perspective, electrification remains the optimum solution for decarbonisation, with the ever-improving carbon footprint of UK electricity generation and the high energy efficiency of electrical transmission and propulsion systems. This view is endorsed by the recommendations of the TDNS, which recommends that the electrified proportion of the UK network will increase from 40% to approximately 80% by around 2050.

The main disadvantage of railway electrification is its high capital cost, as well as associated infrastructure maintenance costs. This precludes electrification of routes where the traffic on offer cannot justify such an investment.

Even where traffic is sufficient to support the required investment, some locations are encountered where electrification is technically difficult or potentially unreliable. Examples are routes with significant lengths of tunnel which do not offer the required electrical clearances, or coastal areas exposed to frequent high crosswinds and/or corrosive sea-spray. In these cases, diesel traction has been a traditional mainstay, but an alternative must now be found.

It is noted that good progress is being made in risk assessed techniques to reduce electrification clearances and in higher overhead line tensions to reduce the impact of cross winds. However, in some cases even these measures may be inadequate.

An alternative solution in such instances may be a form of discontinuous electrification, where electric trains are fitted with an on-board power source, allowing short breaks in electrification at these challenging locations to be traversed. This power source may be in the form of batteries or hydrogen fuel cells, the resulting vehicles therefore being battery-electric or hydrogen-electric hybrids.

3.5. BATTERY PROPULSION

Batteries enable energy for traction and auxiliaries to be stored on board the vehicle, removing the need for lineside electrification infrastructure. However, due to the low energy density of batteries, there are practical limits to how much capacity can physically be accommodated on a vehicle, both in terms of mass and volume. As a result, battery trains have a very limited range on a single charge. This means that periodic recharging of the batteries will be required throughout the working day.

As a standalone solution, this may be impractical, since regular charging breaks may lead to a significant loss of vehicle utilisation. This may be acceptable on short routes where the battery can be sufficiently small, allowing battery charging times short enough to be accommodated within terminal station dwells. However, on longer routes, the required volume and mass of batteries required to permit charging only at termini may be excessive or uneconomic. An alternative solution is to provide charging facilities at intermediate locations, but the extended station dwells for charging are likely to extend journey times and erode the advantage of rail over other travel modes.

Operation of trains powered by batteries alone is therefore most suited to short routes with sufficient terminal dwell time available to permit battery charging.

Longer routes with some electrified sections are better served using battery-electric bi-mode vehicles, where battery propulsion is used for short hops off the wire. The train used will essentially be an EMU fitted with batteries; these vehicles will normally operate in electric mode but will be capable of covering short distances on non-electrified routes.

Battery charging will normally take place when the train is back on the electrified route, via the vehicle’s pantograph (25kV ac systems) or collector shoes (750V dc systems). For longer range autonomous travel, intermediate charging points can be provided to provide charging current via short sections of overhead line (25kV ac systems) or conductor rail (750V dc systems) at stations, where the train is stationary. This will ideally be provided at termini, where dwell times can be better accommodated.

This is an ideal solution for short, non-electrified branches within largely electrified areas, which are currently diesel-worked. This will eliminate the current wasteful and polluting practice of operating significant diesel mileages 'under the wires', whilst avoiding the cost of electrifying branches which, whilst providing a socially vital service, are unlikely to generate sufficient traffic in their own right to justify electrification.

As described earlier, use of battery-electric bi-mode vehicles also permits discontinuous electrification, avoiding the need for expensive and complex infrastructure at difficult locations.

Traction batteries, at time of writing, are costly and have a limited lifespan, requiring periodic replacement. Battery manufacture also has a significant carbon footprint of its own, and relies on the availability of a variety of rare elements which are only found in sufficient quantities in specific parts of the world; mining for these materials and their subsequent transport and processing also has its own environmental and carbon footprint, which should not be ignored. Therefore, given the high first and replacement cost of traction batteries, combined with their environmental footprint, full lifecycle financial and environmental costs must be taken into consideration when appraising this solution against the alternatives.

Battery-electric bi-mode traction can act as an intermediate step to full electrification. If a route is first converted to battery-electric passenger bi-mode operation so as to eliminate diesel, the scheme may be designed to permit conversion to full electrification at a later date at reduced cost. Since the battery vehicles are basically EMUs fitted with batteries, the batteries can be removed upon electrification and the trains operated in fully electric mode thereafter. Any charging stations provided en-route should ideally be constructed so as to permit their conversion to feeder stations for the electrified route at a later date. In this way, none of the investment required for initial battery-electric operation will be wasted.

Battery-electric traction can therefore be utilised in a number of different ways:

- To permit the elimination of small islands of diesel operation on non-electrified branches within largely electrified networks,
- To permit discontinuous electrification, where specific route features make full electrification impractical at certain locations,
- To enable the elimination of diesel in the short term to meet immediate environmental concerns, whilst permitting full electrification in the longer term, if required.

3.6. HYDROGEN PROPULSION

Hydrogen propulsion enables vehicles to be self-powered, eliminating the need for lineside electrification infrastructure. As discussed earlier, whilst the range achievable is far greater than that possible with battery power, the volume and mass of high-pressure on-board storage leads to practical limits on the amount of hydrogen that can realistically be carried on a vehicle. This means that the range of a hydrogen train is typically somewhat less than that of an equivalent diesel (around 600miles vs 1,400-1,500 miles).

Whilst the range achievable with hydrogen is sufficient to operate most current daily vehicle diagrams, it does necessitate nightly refuelling. This is more onerous than for current diesel fleets, which typically only return for fuelling every two to three days; some re-working of vehicle scheduling patterns and/or the provision of additional fuelling facilities may be required.

As hydrogen systems are somewhat new and do not yet benefit from the economies of scale in manufacture enjoyed by diesel technology, vehicle prices can be expected to be significantly higher than those of equivalent diesel vehicles. This is exacerbated by the perceived technical risk of this new technology, which will further inflate costs of early schemes. Costs can be expected to fall as the technology becomes established, with increased production volumes driving unit prices down, whilst confidence resulting from operational experience will reduce the perceived financial risk of the technology.

A further factor to consider is the provision of hydrogen fuel itself. As discussed above, whilst hydrogen is produced in large quantities industrially, this process has a large carbon footprint and its use in transport applications would largely negate the carbon savings achieved. Industrially produced hydrogen, whether from SMR or other means, also normally requires further purification to make it useable in fuel cells, adding to its cost.

Finally, we must consider the matter of hydrogen distribution. Bulk distribution of industrial gases is usually undertaken by dedicated pipelines within industrial complexes; distribution to remote locations is by rail tanker or articulated road vehicles in either compressed or liquefied form.

Since direct hydrogen pipeline connections to rail fuelling points are likely to be impractical in most cases, distribution to these locations from a centralised production facility would necessarily be via rail or road delivery, as is the case with diesel fuel.

As with the hydrogen storage on board trains, the energy density of hydrogen aboard an articulated road tanker or rail tank car is significantly less than that of an equivalent vehicle carrying diesel fuel. As a result, replacement of diesel with hydrogen distributed by road or rail from centralised production facilities will require very many more lorry movements than are currently required for diesel fuel distribution. Work undertaken by the NTL's AET project suggests that distribution of compressed hydrogen could require as many as 30 fuel delivery movements to replace one diesel movement; this would significantly erode the environmental credentials of hydrogen, as well as its financial performance.

Liquefied hydrogen represents a much more efficient means for transporting bulk hydrogen, but requires very costly liquefaction, storage and transportation equipment; furthermore, the energy required to liquefy the gas is significant (in the region of 30% of the energy content of the hydrogen being liquefied), reducing the overall energy efficiency of hydrogen transported in this way.

A preferable solution is manufacture of hydrogen at the point where it is needed; this is done at many of the new hydrogen fuelling stations being built for road use and involves the provision of electrolysers, compressors and storage tanks at the fuelling facility. Inputs to the plant are piped water and grid electricity, and thus the transport costs of the hydrogen are greatly reduced; this currently appears to be the most suitable long-term solution to the provision of hydrogen in the quantities required for rail applications.

Local production via electrolysis helps to reduce the provision of hydrogen to the level of buying a commodity (in this case electricity), in the same way that the railway currently buys electricity and diesel fuel for traction purposes. However, the electrolysis and storage plant represent a significant additional cost, on top of the cost of the vehicles themselves.

A solution to the capital cost problem of hydrogen production plant is for the hydrogen supply chain to finance the construction and operation of the equipment on the operator's depot, recovering their investment as part of the cost per kilogramme of hydrogen delivered to the fuelling nozzle at the depot.

This is the approach adopted by the AET Project for Teesside and places the provision of hydrogen firmly with the specialist hydrogen industry, rather than the train operator. In this way, the capital cost of the production plant is spread over the lifetime of the project, rather than requiring a substantial initial investment by the operator.

By putting the purchase of hydrogen on to the same basis as the purchase of electricity and diesel for traction, a major cost barrier will be removed, aiding the rate of adoption of hydrogen propulsion in rail,. This also puts the purchase of hydrogen on to the same footing as the purchase of diesel fuel from the operator's point of view.

As with the vehicles themselves, the capital cost of hydrogen production and storage equipment for transport fuelling is currently high due to the relative immaturity of the industry and the currently small production base. The high costs of the production equipment will inevitably add to the cost of hydrogen for early schemes.

In the longer term, as deployment increases, confidence and competition within the supply chain are expected to grow and equipment costs to fall, reducing the cost of hydrogen and the choice available to operators. However, this can only happen if the costs of early adoption schemes are accepted, and the industry is permitted to learn and grow.

As renewable hydrogen prices fall, they will eventually reach a point where the cost of electricity itself is the main limiting factor.

With the increased range possible from hydrogen, this technology allows unelectrified routes to be covered which are beyond the practical range of battery-powered vehicles. However, as with battery propulsion, the whole-life costs of deployment must be considered alongside those of any technically viable alternative (typically electrification but, battery in some cases) when investigating the introduction of hydrogen to a particular route.

In addition to the initial capital costs of plant and vehicles, the lifecycle cost of the operation must be considered, particularly in terms of energy and carbon costs. Rail electrification is highly energy efficient with transmission, conversion and mechanical losses between the point of generation and the wheel/rail interface accounting for around 16% of the energy supplied, giving an energy efficiency of 84%.

Turning to hydrogen production and assuming a transmission efficiency of 5%, the production of hydrogen by electrolysis is typically only 60-80% efficient, and re-conversion of hydrogen to electricity via the fuel cell on the train is around 60% efficient [10]. Adding the energy expended to take hydrogen from the electrolyser and compress it to high pressure (350 bar or more) needed for on-vehicle storage, we lose perhaps another 3%. Once we factor in transmission losses within the electrical power conversion equipment and traction motors (assumed to be the same as for an equivalent electric vehicle), we get to an overall energy efficiency at the wheel/rail interface of perhaps only 29-39%.

The energy cost of hydrogen propulsion is therefore significantly higher than that of an electrified railway; the overall energy and carbon costs over the project lifetime must therefore be factored into any consideration of the relative merits of hydrogen versus electrification for any particular route. From the above, it can also be seen that production of hydrogen using electricity generated from fossil fuels makes little sense in terms of decarbonisation.

3.7. RETROFIT OF DIESEL FLEETS WITH EFFICIENT ENGINES OR DRIVETRAINS

Here, the aim is to improve vehicle fuel efficiency. A typical approach for locomotives is the replacement of the engine with a unit of modern design, offering improved fuel efficiency, emissions performance and reliability [11]. The greatest benefits of this approach tend to be applicable to older locomotive types, which are likely to have the least efficient and most polluting engines.

For DMUs, engine replacement is more complex due to the additional equipment carried by modern engines in connection with emissions controls, and the limited space available on the underframe. However, replacement of the inefficient hydrodynamic transmissions fitted to older types is less demanding of space and offers some promise if the cost can be justified by the likely savings in fuel use and emissions [12].

Obviously, this approach does not represent full decarbonisation, but can be used to quickly improve emissions and carbon footprint if the emissions savings are sufficient to justify the cost. In making this calculation, the manufacturing carbon footprint of the new transmission equipment and conversion work should also be considered.

3.8. RETROFIT HYBRIDISATION OF EXISTING DIESEL FLEETS

This involves the replacement of the existing diesel-hydraulic or mechanical drivetrain with a hybrid arrangement, incorporating both a diesel engine, alternator, traction motor(s) and battery storage. The drivetrain configuration can either be ‘parallel’ or ‘series’.

In the parallel arrangement, there is still a direct link between the engine and road wheels, with the alternator and traction motor connected in parallel with the mechanical transmission. This provides assistance to the engine during acceleration, via power taken from the batteries, and can also provide regenerative storage of surplus energy during braking and when traction demand on the engine is low.

This arrangement helps to level the load on the engine, allowing it to operate more efficiently, reducing fuel consumption and emissions. Capture of braking energy for re-use provides additional savings. The alternator and traction motor may be a single electrical machine, capable of acting as either a motor or generator – this reduces the overall mass and complexity of the assembly.

The series configuration severs the direct mechanical connection between engine and road wheels. The engine now drives an alternator, which in turn drives a traction motor(s) linked to the road wheels. The electrical transmission provides an almost infinitely variable torque/speed ratio between the engine and road wheels, allowing the engine to operate within its most efficient power/speed range, again increasing its efficiency and this reducing fuel use and emissions.

Battery storage is used to supplement the engine output during acceleration and other times of high peak power demand; it can also store energy produced by the traction motor(s) acting regeneratively during braking.

Both parallel and series systems have advantages and disadvantages. The parallel system tends to be lighter, since some of the engine power is transmitted directly to the road wheels, allowing the electrical machines to be smaller and lighter; however, the direct mechanical connection means that engine speed cannot be fully de-linked from vehicle speed, limiting the efficiency savings obtainable from the engine.

The series arrangement tends to be heavier, since the alternator and traction motor(s) must be rated to take the full traction power output, but the virtually complete delinking of engine and vehicle speed permits much more efficient engine operation. In practice, the parallel configuration will be more suited to lightweight, lower powered DMUs, with the series configuration applicable to heavier, more highly powered vehicles with higher maximum operating speeds.

Neither of these options provide complete decarbonisation, since they still rely ultimately on the diesel engine as the prime mover. They may, however, be considered as a stopgap for retrofit of more modern DMU vehicles. Such retrofits may retain the existing engine, but are more likely to involve the complete replacement of the existing transmission with an integrated traction pack. This will incorporate an engine compliant with current emissions standards (currently this is EU NRMM stage 3B, rising to stage 5 for engines placed into service from January 2021).

This type of retrofit will represent a considerable investment that is unlikely to be applicable to older types, including British Rail-era classes 150 to 156, which are approaching the ends of their service lives. The equipment is also typically heavier than the conventional driveline it replaces, and requires additional space to accommodate traction batteries and electrical machines; this is likely to rule out installation on express units such as classes 158 and 159, which have lightweight body structures in order to minimise track forces, and which have very limited spare underframe space.

More modern DMU types, such as class 195,196 and 197, have much lower engine NOx and PM emissions, combined with efficient mechanical transmissions units; the efficiencies in both carbon emissions and air quality to be gained from hybridisation of these fleet may therefore be limited, lengthening any payback period. However, if the 2040 diesel ban were to exempt hybrid units, such a solution may permit use of these vehicles beyond the current 2040 deadline for their (premature) withdrawal.

The issue of hybrid exemption from the 2040 diesel ban must be explored further with Government before any investment is made on vehicles which could still be in service by that date. Technically, a hybrid is really no more than a more efficient conventional diesel. This is unlike a bi-mode, which can draw energy from an external power source, typically lineside electrification, resulting in real carbon savings in comparison to diesel operation ‘under the wires’ on electrified sections.

Government could therefore easily justify the future inclusion of hybrids within the 2040 ban on conventional diesels, as has now happened with the inclusion of hybrids within the sales ban on petrol and diesel cars from 2035. Even if hybrid rail vehicles were still legally permitted, they would unlikely be accepted by the public when diesel road vehicles are not. Diesel bi-modes may similarly be unacceptable in the eyes of the public following the diesel road vehicle ban.

This solution is therefore most applicable to mid-life DMU fleets (classes 165-170), since these are still relatively modern, but have engines and drivelines that largely predate modern emissions considerations. There does appear to be some interest in retrofit to make these units cleaner and more saleable for the remainder of their lives up to 2040 [13]. Again, any assessment of benefits, including emissions and carbon savings, should include the manufacturing carbon footprint of the new equipment required.

3.9. SERVICE WITHDRAWAL/LINE CLOSURE

Any rail passenger service operating over the UK national rail network today is provided either because it is profitable, or it is considered to be socially necessary. If operating costs were to increase significantly, then this delicate balance of profitability and/or social value may be adversely affected.

Diesel propulsion, being relatively inexpensive and well understood, has enabled a number of lines and services that are on the margins of viability to remain in operation; if the technologies available to replace diesel are significantly more costly, the balance of cost vs benefit which justifies their retention may be tipped in favour of closure.

As explained earlier, battery and hydrogen propulsion systems are currently significantly more costly due to their limited development and smaller manufacturing base to date. It is therefore imperative that these costs come down to a level closer to that of current diesel technology if they are to be useful for widespread adoption. Early deployment schemes, such as Windermere and Tees Valley will be vital in allowing knowledge and confidence to be gained by operators, suppliers and funding bodies, allowing efficiencies to be identified, designs to be refined and costs to be reduced.

It is certainly not the intent of this paper to advocate the closure of railway routes or withdrawal of services as a valid means of decarbonisation, rather to point out that if such routes and services are to remain attractive and be retained in the longer term, an *affordable* alternative to diesel is required.

Conversely, given the current ‘Beeching reversal’ initiatives, the solutions advocated in this paper could be a way of establishing a new service on a re-opened line using rolling stock cascades as a result of renewal or electrification elsewhere.

Urgent steps must therefore be taken towards the development and adoption of diesel-replacement technologies in order that their reliability, performance and costs are understood and are comparable with those of diesel by the time that the latter must be finally phased out.

4. DEPLOYMENT STRATEGY DEVELOPMENT

4.1. GENERAL

An operator's traction decarbonisation strategy must have four key objectives:

- It must consider the likelihood and timing of electrification based on the TDNS and subsequent decisions,
- It must determine whether there is any benefit to modification of existing fleets or services to reduce the impact of diesel operation ahead of replacement by 2040,
- It must determine the optimal diesel replacement technology for each route or group of routes,
- It must determine the order of priority in which routes and services are to be converted from diesel operation.

4.2. DETERMINATION OF BENEFITS FROM VEHICLE MODIFICATIONS

As described earlier, there are some potential carbon savings to be obtained from modifications and retrofit works to existing fleets. Some of these, subject to Government confirmation, may even permit modified vehicles to remain in service past 2040. However, such modifications will only provide a partial reduction in emissions and carbon footprint and will require significant investment.

As will be described later, it is possible to assign financial values to emissions savings. It is also possible to work with suppliers to calculate the manufacturing 'carbon cost' of any replacement equipment. This carbon cost can also be given a financial value. The manufacturing carbon cost and value of predicted emissions savings can then be put alongside the capital cost of modification, along with any reductions in operating costs due to fuel efficiencies or reduced maintenance, to determine if a business case can be made.

4.3. DETERMINATION OF DIESEL-REPLACEMENT SOLUTION

As discussed earlier, there are currently three available alternatives to diesel propulsion, and combinations thereof, for use in the full decarbonisation of rail transport:

- Electrification,
- Battery propulsion,
- Hydrogen propulsion.

A number of factors drive the decision as to which is most suitable for a particular route or group of routes:

a. Traffic levels: These must be sufficiently high to justify electrification, otherwise battery or hydrogen technologies may be more appropriate. Methodologies for determining the thresholds for electrification are already well established. The TDNS is currently defining the potential limits of the electrified network.

b. Number and type of operators using a route: A particular route may, at first glance, carry sufficient traffic to justify electrification. However, if much of this traffic originates from other non-electrified regions, then electrification of the route will bring little benefit, since these services may remain diesel operated to cater for non-electrified sections in other areas. In this case, conversion of local services to hydrogen or battery propulsion might be more realistic.

c. Lifecycle cost of the different options: It is important that the cost of the chosen solution is proportionate to the level of traffic on offer. If the cost is too great, there is a risk of upsetting the social value/cost balance that justifies the retention of a route on the basis of its social value or profitability.

d. Availability of adjacent electrification infrastructure: This may present an opportunity for only a small amount of additional electrification to allow fully electric operation of additional routes. Alternative, it may permit BEMU operation using the existing electrification, where available, in a form of discontinuous electrification. If no electrification infrastructure is available on or near the target route, this would necessitate the provision of charging infrastructure for battery vehicles, potentially increasing the attractiveness of hydrogen as an alternative. Note that any available electrification infrastructure may be considered for the purposes of battery charging; some areas in the North of England are electrified at 25kVac, whilst others have 750Vdc third rail infrastructure. If routes shared with tram-train and light rail systems are included, there is also potential for charging from 750Vdc or 1,500Vdc overhead systems in some locations.

e. Service scheduling requirements: Stopping patterns and running times help to determine the overall energy requirement during a journey, whilst dwell times, particularly those at termini, determine how much energy can realistically be returned to the battery of a BEMU during recharging. These limitations may favour electrification or hydrogen in some cases.

f. Diagrammed mileages: Some current daily diagrams for diesel vehicles cover up to 700 miles per day, These may be beyond the capabilities of batteries or hydrogen, unless the vehicles used have bi-mode capabilities and can cover some of this distance on external electric power. If these diagrams cannot be broken down to cover lower daily mileages, then at least partial electrification, permitting BEMU of hydrogen-electric hybrid use, may be the only technically viable solution.

g. For battery vehicles, frequent battery charging will be required. Since full recharging of traction batteries can take anything between 10 minutes and one hour (depending on type and capacity), route timings must be able to accommodate the dwell periods required. This may be achievable on short routes with adequate stand time at termini, or on routes with intermediate stretches of electrification where the batteries can be recharged on the move. However, on long unelectrified routes, extended stops at intermediate stations for battery charging are unlikely to be acceptable. In this instance, discontinuous electrification with BEMUs, or alternatively HMU deployment, are indicated.

h. Passenger loadings and journey lengths: Saloon air conditioning and heating requirements tend to be higher for passengers on longer journeys, since they will spend longer on board the vehicle. Air conditioning and heating represent significant drains on on-board energy reserves, reducing achievable mileages.

i. Route characteristics within the service group – individual route lengths, gradients, line speeds, number and spacing of stations all have a significant effect upon the amount of energy required to complete a journey. If the energy requirement is greater than that which can be supplied by a realistically sized traction battery, then hydrogen or some form of electrification will have the advantage. However, the presence of tunnels or other restricted structures, such as station canopes, along the route may count against hydrogen due to concerns regarding fire safety; this may favour discontinuous electrification.

j. Infrastructure and skills base within the local area: hydrogen production by electrolysis requires strong local power supplies, combined with a local workforce with the skills to support the process. Such facilities are therefore most suited to industrialised areas. Battery technology, by contrast, requires much less in the way of local infrastructure and skills.

k. Route compatibility: Electrification requires sufficient space for electrical clearances, and usually requires upgrading of signalling and communications systems to provide electrical immunisation from traction currents. Both battery and hydrogen propulsion can be less demanding in these regards, since they do not require additional clearances and generate no return currents when operating autonomously.

l. Degree of interworking with other routes: In order to operate their fleets with maximum efficiency, operators often employ a high degree of interworking, whereby a particular unit may operate over a number of different routes during a working day. This practice ensures a very high level of vehicle utilisation. Therefore, whilst a particular route may be ideally suited to battery traction, if it is interworked with a number of other routes for which hydrogen is the only viable option, then the most efficient overall solution may be to convert this route to hydrogen as well. This will permit continued interworking and thus efficient vehicle utilisation.

m. Facilities available at service and stabling points: A BEMU solution might be problematic if the stabling points are at unelectrified locations – will the batteries hold sufficient charge to get the unit back to a location where it can recharge after an overnight stay off-power? If not, charging infrastructure will need to be installed, along with the requisite grid supplies. Alternatively, an HMU solution will be of little use if the relevant stabling points cannot be equipped for hydrogen fuelling.

From the above, it can be seen that many factors influence the optimal solution, and that this cannot be determined simply be considering each route in isolation. A systems approach is necessary, encompassing various functions within the operator's organisation.

Strategy development must include commercial and business planning functions, so as to understand the commercial performance required of the chosen solution, including any requirements in terms of passenger environment, on board facilities etc., all of which will affect the vehicle energy requirement.

Operating costs must be considered. As explained above, some services are loss-making, but deemed socially necessary; others are profitable and form the core of the operator's financial base. It is therefore important to understand the financial performance of the selected option. In cases where more than one solution is technically viable, financial performance is likely to be a deciding factor in the ultimate choice. However, it is the whole cost of the solution that needs to be considered in selecting the most appropriate solution and not just that to the operator.

Train planning input is also vital to determining the extent to which individual routes can be operated separately, so that the most appropriate traction source can be employed. In some cases, this might result in allocation of the stock for a particular route to a different depot, in order to maintain fleet interchangeability. If this is not possible, then it may be necessary to compromise and choose the solution most appropriate to a number of interworked routes, in order to achieve an adequate level of vehicle utilisation.

It is also necessary to understand the capabilities of existing depots, servicing points and stabling locations; some of these may be more suited to one technology than another, or may require specific upgrades to accommodate any form of alternative traction. Given the lower range of both hydrogen and battery technologies in comparison to diesel, it may be necessary to provide additional sub-depots or service points in some locations. This has proven to be the case with the Tees Valley scheme.

As described earlier, battery and hydrogen technologies both have their strengths and weaknesses, in terms of range and performance. Both lack the flexibility of diesel traction in some regards. It is vital, therefore, that the operational requirements for any battery or hydrogen fleet are clearly defined and agreed with rolling stock suppliers. Expected performance levels must also be verified at the design stage via extensive modelling using well-defined performance requirements and accurate vehicle and route models.

In some cases, it may be determined that no non-diesel solution is able to meet the required parameters at an acceptable cost. This will require further rounds of discussions amongst the operator's specialist functions to determine whether changes can be made to existing infrastructure, diagrams and allocations in order to accommodate an alternative to diesel traction. Such measures might include:

- Further additional electrification,
- Amendment of particular diagrams to reduce overall daily mileage,
- Reallocation of services to a different depot,
- Use of different service points,
- New depot locations,
- New service point locations,
- De-linking of currently inter-worked services, or inter-working with different services.

4.4. DETERMINATION OF REPLACEMENT PRIORITIES

4.4.1. AGE AND CONDITION OF EXISTING FLEETS

Several factors will determine the priority given to conversion of a particular route or group of routes from diesel. Similar considerations will inform any decisions to modify existing fleets. First amongst these is the age of the incumbent diesel fleet. Vehicles approaching the end of their economic life will normally require replacement first. However, condition and reliability of existing vehicles may also be a determining factor for replacement priority; the oldest fleet is not always the one requiring the most urgent withdrawal.

4.4.2. PLANNED ELECTRIFICATION SCHEMES

Any plans for future electrification may influence the conversion priority for the affected routes. If a particular route is to be electrified in a few years' time, it may be worth the additional cost of extending the life of the incumbent diesel fleet until it can be replaced by a suitable new electric fleet.

4.4.3. LOCAL AIR QUALITY

Local air quality may be another significant determinant of priority in removal of diesel traction from a particular area. As has been demonstrated earlier, although decarbonisation and air quality are different fields, they are closely tied together when diesel propulsion is considered, and it is difficult to consider them separately.

Air quality represents an immediate hazard to public health, whilst carbon emissions represent a medium to longer term environmental threat.,. For this reason, both issues should be considered to be closely allied; savings in diesel emissions will help to improve air quality today, whilst reducing the effects of climate change tomorrow.

A particular problem for the UK is the exceedance of NOx levels, largely as a result of transport and industrial activity. This is particularly acute in urban areas. Of the 43 UK zones for ambient air quality reporting in 2018, only seven were compliant with the annual mean limit value for Nitrogen Dioxide (40 μg/m^3) [14]. Within the area of the North's rail network, the following locations exceeded these limits in 2018:

- Greater Manchester,
- West Yorkshire,
- Tyneside,
- Liverpool,
- Sheffield,
- Nottingham,
- Teesside,
- Kingston upon Hull,
- The Potteries,
- North West & Merseyside,
- Yorkshire & Humberside,
- North East.

Figure 3 graphically illustrates NOx levels across the North. Whilst rail in itself generally contributes little to these levels, significant diesel rail activity at major stations in urban centres already suffering poor air quality may help to worsen the local situation. Equally, the availability of a cleaner alternative may make it easier for local authorities to promote modal shift away from polluting road transport. These considerations may result in areas with poor air quality being prioritised for conversion of rail services to non-diesel alternatives.

Local air quality management is a statutory process introduced by the Environment Act 1995 (Part IV), which places a legal duty on all local authorities to regularly review both the current and future air quality within their areas [15]. The development of an Air Quality Action Plan is a statutory requirement once an Air Quality Management Area (AQMA) has been declared as a result of high pollution levels. A typical example is the action plan developed by Cheshire East [16], which has a number of AQMAs, resulting from levels of nitrogen dioxide due to emissions from vehicles. The action plan details the measures which the local authority proposes to take in improving air quality in all of the AQMAs.

Curiously, local authority Air Quality Action Plans tend not to consider rail within their inventory of possible solutions; there appears to be a perception that railway emissions are a subject over which they have little control. For example, the action plan for Greater Manchester has only this to say on the subject within their 84-page action plan [17]:

> *'Manchester Airport, Highways England and Network Rail have their own Environmental or Air Quality Plans. TfGM will engage with these organisations to ensure that activities are aligned.'*

Clearly, Network Rail can have little effect upon emissions on its own, since it is not a train operator; therefore, there appears to be a case for train operators to play a leading role in decisions regarding air quality, initiating a dialogue on the subject with local authorities in order to prioritise and target the move away from diesel. It must also fall to operators, in their role of rolling stock procurers, to drive the rolling stock supply industry to develop suitable solutions.

As discussed earlier, the strategy for areas of low air quality may, in the short term, look at the modification of existing mid-life vehicles to reduce emissions, whilst targeting the replacement of older fleets with non-diesel vehicles.

5. BUSINESS CASE DEVELOPMENT

5.1. DECARBONISATION STRATEGY

It is assumed that diesel replacement, along with any modifications to existing fleets for near-term environmental gains, will be achieved as a result of a number of separate projects, each with their own business cases. As discussed above, the timescales for completion are quite long, extending to 2040 for conventional diesel traction and 2050 for removal of all forms of diesel.

The scale of the task is also very large, and so it is important that the operator develop an overall 'traction decarbonisation strategy', detailing the operator's long-term programme for decarbonisation of its network. This strategy will be driven by the priorities described in section 4.4 above, combined with any other priorities relevant to the operator's specific circumstances or obligations.

Alternative energy technology can be expected to develop as time progresses, improving the capabilities and costs of the technical solutions on offer; many of these developments will be driven by experience gained from earlier deployment schemes. For this reason, the strategy should not attempt to determine the technical solution to be applied to every route over its entire lifetime.

Any attempt to lay out a full technical proposal for diesel removal covering a period of 20-30 years hence will be likely to misjudge both cost and capability of the possible solutions available in later years, leading to sub-optimal choices for fleet renewals. Therefore, the strategy should dictate broadly when diesel traction is to be removed, but not necessarily with what it will be replaced; this decision will be made at the appropriate point when detailed planning for fleet replacement is required and the current 'state of the art' in rail propulsion technologies is known.

Only at this point will the most suitable technical solution be identified and a business case developed. Thus, the strategy will be able to evolve as experience is gained and technology develops, rather than being straightjacketed into a technical delivery plan based upon a possibly outdated set of assumptions.

The operator's traction decarbonisation strategy is likely to form part of its wider corporate decarbonisation strategy, covering all areas of their business, including infrastructure, equipment/materials procurement, non-traction energy usage and waste management.

5.2. SELECTION OF TECHNICAL SOLUTION

Development of business cases for individual schemes will follow the following steps:

- Identify the service or group of services affected, along with the required timescales for modification or replacement of the existing fleet,
- Identify key performance parameters which replacement vehicles must meet (passenger capacity, passenger environment, requirements for climate control, ratio of seating to standing capacity, maximum speed, acceleration rate etc.),
- Identify key characteristics of routes over which these services will operate (gradients, line speeds, number of intermediate stopping points (stations, junctions, road crossings etc),
- Quantify passenger traffic levels to be handled by the new fleet,
- Examine existing infrastructure and that under construction in the vicinity of the service group (existing electrification infrastructure, capabilities of depots and servicing points etc); this may favour one solution over another if use can be made of existing infrastructure, at least in part,

- Consider possible synergies with adjacent service groups. For instance, are other service groups in the area all-electric? In this case, the additional cost of electrification might be offset by allowing a compatible fleet of EMU vehicles to be procured, providing a single homogenous, interchangeable fleet in the region.
- Identify plans by other operators running services over the routes being considered; would a shared approach to traction choice allow a pooling of resources in terms of supporting infrastructure (electrification, battery charging stations, hydrogen fuelling plant etc)?

Consideration of the above factors may show one particular solution to be the clear winner on a particular route, or allow for one or more solutions to be discounted as obviously unsuitable. We have previously discussed the limitations of both battery and hydrogen technology in terms of range, and of electrification in terms of gauge clearance and compatibility requirements; these may prove to be unsurmountable issues, resulting in the discounting of certain traction options.

However, since we are likely to be dealing with routes that have, to date, not been found to justify electrification, it is likely that in many cases there will be no clear winner at this stage. It will therefore be necessary to look deeper into the implementation costs of each remaining solution in order to determine which is most cost-effective.

Unless the operator has sufficient capability in-house, the necessary appraisal work is likely to require specialist input from suitably skilled consultancies or suppliers. The work will almost certainly require the creation of route and vehicle simulation models in order to assess the performance of different options and to size and cost the necessary on-board components (electric propulsion equipment, batteries, hydrogen storage, fuel cells etc.) and supporting infrastructure (electrification, battery charging stations, hydrogen production & storage etc.).

In some cases, it may not actually be possible to meet the required performance criteria with any of the options available; this will necessitate further iterations with input from the operator's commercial, engineering, operating and service planning functions to examine diagramming changes, revised depot allocations, de-linking of interworked services etc. until an achievable service specification can be reached.

The ultimate goal of this work will be to determine the optimal technical solution and indicative whole system costs for implementation, leading to submission of a business case for authorisation to proceed. For this reason, the route and service data generated by the operator must be of sufficient quality to accurately define the performance required of the new vehicles and their supporting infrastructure.

Railway electrification and electric traction are well known and therefore the easiest to cost. Currently, battery and hydrogen traction are relatively new, having limited deployment worldwide. However, a number of vehicle and infrastructure manufacturers already offer, or plan to offer, solutions in one of more of these areas.

There is therefore sufficient knowledge within the rail industry supply chain now to enable indicative prices to be determined and a final choice of technology to be made. This knowledge base can be expected to expand greatly in coming years, as early schemes provide additional understanding of the technology amongst both suppliers and operators.

5.3. THE BUSINESS CASE

At this point, we have determined the preferred technical solution and have indicative prices for its implementation. If the appraisal to date has been run along commercial competitive lines, the operator may also have chosen its preferred suppliers. This will allow an outline business case to be assembled for board-level submission, detailing project objectives, benefits, costs and implementation programme in the normal way.

At this point, senior management will have the opportunity to examine whether the proposal meets wider corporate goals and also to commence discussions with partners and funding bodies to determine if the scheme is affordable in its current form. Any required changes as a result of this consideration will be fed back to permit development of the final business case for submission to the relevant authorising and funding body (typically TfN/DfT in the North of England).

Within its assessment of the overall implementation and lifecycle costs of the project, the business case should include any costs or savings resulting from the replacement of the current diesel fleet, including:

- Lease cost savings from withdrawal of existing diesel vehicles,
- Lease cost increases for modified vehicles,
- Lower maintenance costs for the new or modified fleet (particularly in the case of electric and battery-electric vehicles, due to simpler drivetrains),

- Fuel cost savings, particularly as a result of the lower cost of electricity per unit of energy compared to diesel. This is further enhanced by greater drivetrain efficiency and savings achieved via regenerative braking.

Environmental benefits in terms of emissions savings should also be accurately quantified, since these are the key basis of the drive for decarbonisation and diesel replacement. These emissions have assigned financial values under the DfT Transport Analysis Guidance (TAG) process for transport project modelling and appraisal.

These values represent the real costs to the economy resulting from exhaust emissions. Whilst carbon emissions result in penalties and mitigation costs for the UK as a whole, poor air quality has costs in terms of additional healthcare expenditure and the loss of productivity within the workforce due to resulting poor health.

Key savings associated with replacement of diesel traction by electric, battery or renewable hydrogen are in CO_2, NOx and PM:

- Carbon dioxide (CO_2) is a major contributor to global warming, with output proportional to fuel consumption. CO_2 is also produced by power generation from combustion (gas, coal, oil and biomass).
- Oxides of nitrogen (NOx) can reduce respiratory efficiency and is also a cause of respiratory infections and conditions such as asthma. Limits are set for modern diesel engines. NOx is also produced by power generation from combustion (gas, coal, oil and biomass).
- Particulate matter (PM) is composed of particles of unburnt fuel which can cause respiratory illnesses and diseases. Particles smaller than 2.5 micrometres (PM2.5) can enter the bloodstream, causing further damage to health.

For older diesel fleets, with little or no emissions controls, the savings in NOx and PM can be particularly significant.

Of course, the national grid electricity supply, from which electricity is drawn for traction, also has a carbon footprint, since some current generation is produced from fossil fuels (mainly natural gas, but with some coal). However, emissions per unit of electrical energy are significantly lower than for diesel. The national grid supply is also continuing to de-carbonise and become cleaner, with increased use of renewables. The environmental footprint per unit of traction electricity will therefore continue to reduce.

The monetary values assigned by DfT for emissions savings of CO_2, NOx and PM for the period 2020 to 2050 is detailed in table 1 below [18] [19]. The sums resulting from emissions reductions due to replacement of diesel with an alternative energy solution can make a substantial contribution to the bottom line of a business case.

	Value Per Tonne Saved		
Year	**CO_2**	**NOx**	**PM**
2020	£34.58	£6,500.80	£107,155.47
2021	£33.89	£6,323.11	£104,621.13
2022	£33.68	£6,152.83	£102,180.30
2023	£32.99	£5,988.99	£99,817.86
2024	£32.32	£5,839.62	£97,671.33
2025	£31.64	£5,702.90	£95,710.54
2026	£30.98	£5,590.19	£93,902.53
2027	£30.33	£5,485.88	£92,229.36
2028	£30.06	£5,389.14	£90,677.28
2029	£29.41	£5,296.74	£89,192.21
2030	£28.78	£5,210.98	£87,812.89
2031	£30.21	£5,130.13	£86,450.46
2032	£31.84	£5,050.09	£85,101.78
2033	£33.00	£4,970.53	£83,761.04
2034	£34.36	£4,892.72	£82,449.83
2035	£35.30	£4,817.54	£81,182.87
2036	£36.41	£4,746.32	£79,982.71
2037	£37.14	£4,676.74	£78,810.28
2038	£38.04	£4,608.29	£77,656.71
2039	£38.58	£4,540.15	£76,508.46
2040	£39.29	£4,471.98	£75,359.77
2041	£39.66	£4,405.05	£74,231.89
2042	£40.20	£4,339.15	£73,121.25
2043	£40.43	£4,273.68	£72,017.99
2044	£40.82	£4,208.30	£70,916.25
2045	£40.92	£4,143.50	£69,824.38
2046	£41.18	£4,079.47	£68,745.23
2047	£41.17	£4,015.64	£67,669.66
2048	£41.31	£3,952.40	£66,604.02
2049	£41.21	£3,890.29	£65,557.37
2050	£41.44	£3,848.52	£64,853.48

Table 1 – DfT TAG values for emissions savings 2020 to 2050

6.SUMMARY

In response to increasing concerns over transport emissions, the UK Government is seeking to curtail the use of fossil fuels in transport in favour of renewable alternatives. These emissions contribute to global warming, as well as being damaging to health. As rail's contribution, the industry has been tasked with removal of all conventional diesel traction from service by 2040.

Railways in the North of England are heavily dependent on diesel traction, and alternatives must be found if services are to continue. Possible solutions, including combinations thereof, are:

- Electrification,
- Battery power,
- Hydrogen power
- Combinations of battery-electric or hydrogen-electric hybrids and bi-modes

The appropriate solution will be determined by route and service characteristics, combined with the level of demand. In some cases, where electrification is a long way in to the future, battery or hydrogen options may offer a valuable low-carbon transition stage between current diesel operation and future full electrification. All of these solutions can be provided using renewable energy, offering the prospect of clean, zero-carbon rail transport in the future. However, each solution has strengths and weaknesses and costs are significant.

Given the size of the task ahead, it is vital that a start be made on this process, a first step being to establish operator strategies for the planned replacement of diesel traction by environmentally friendly alternatives using renewable energy.

These strategies, which will fit within the operator's wider decarbonisation strategy, will dictate the programme for network conversion away from diesel. This programme will be influenced by the condition of existing diesel assets, any confirmed schemes for electrification and the presence of local air quality hotspots which could be benefited by replacement of existing diesel services with clean alternatives.

Since the strategy is expected to cover the period up to 2050, it is not expected that it will dictate the technical solution to be applied to every route covered in some cases many years ahead of implementation. Solutions will be determined as routes become due for diesel replacement, allowing decisions to be made based upon the current 'state of the art'.

Early stages of the strategy implementation will rely heavily on the lessons learnt from early deployment schemes, such as the Windermere BEMU and Tees Valley HMU projects; these will help to inform planners of the strengths, weaknesses, costs and benefits of different technical approaches, helping to kick-start the traction decarbonisation process.

Cost is a vital factor if the delicate socio-economic balance that justifies provision of many services is not to be undermined. It is imperative, therefore, that diesel-replacement technologies can evolve quickly to the point whereby new fleets are comparable in both purchase and operating costs (including energy or fuel costs) to the diesel vehicles they replace.

In the short term, some advantage may be gained from modification of existing diesel fleets with cleaner, more efficient propulsion systems or by use of low or zero-carbon fuels; these could produce useful environmental benefits, particularly in terms of air quality, during the remainder of the lives of these fleets.

In some cases, modification may even allow newer diesel fleets to remain in service past 2040; currently, these fleets are set to enjoy a much shorter service life than would otherwise be expected.

The ultimate goal, however, will be the removal from service of all conventional diesel rail vehicles by 2040, with all remaining diesel vehicles following by 2050.

7.FIGURES

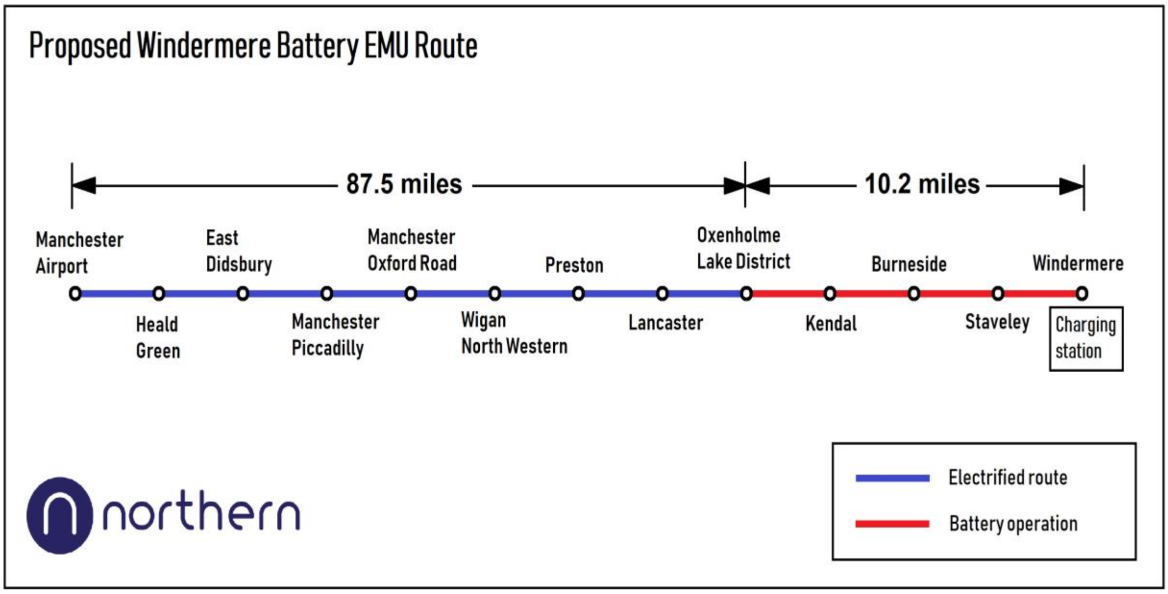

Figure 1 – Proposed Windermere Battery EMU Route

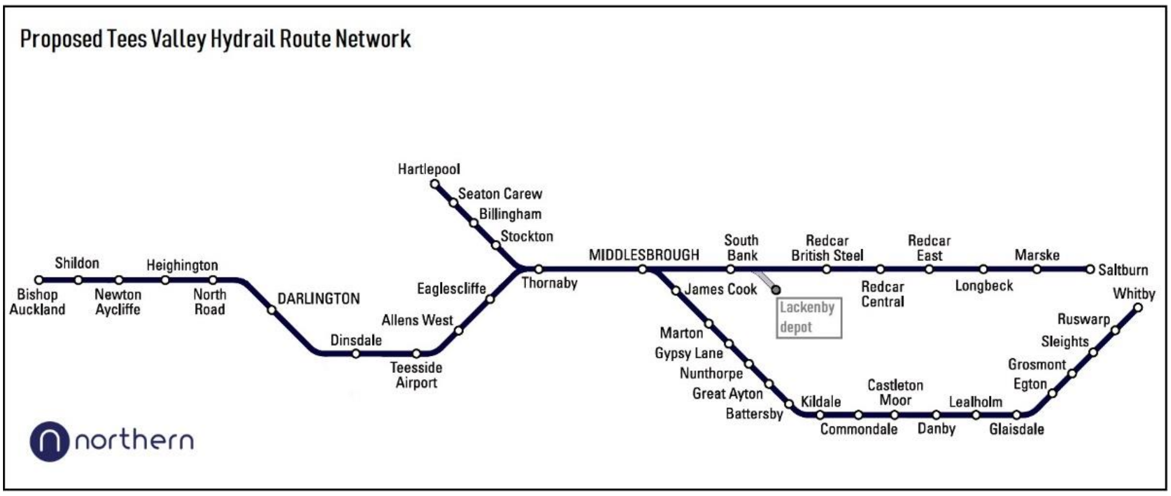

Figure 2 – Proposed Tees Valley Hydrail Route Network

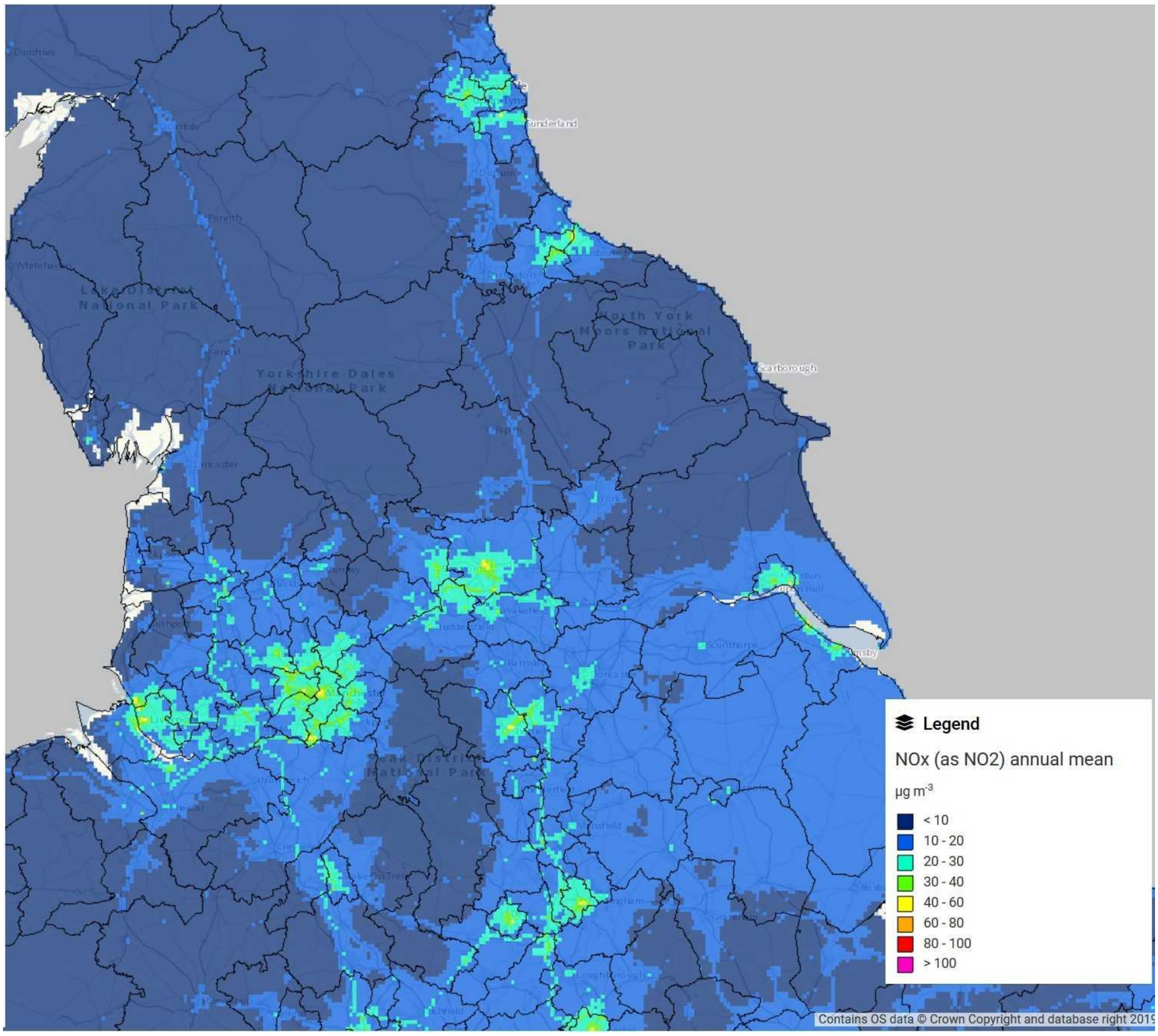

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Figure 3. 2018 NOx concentration levels across the North of England [20]

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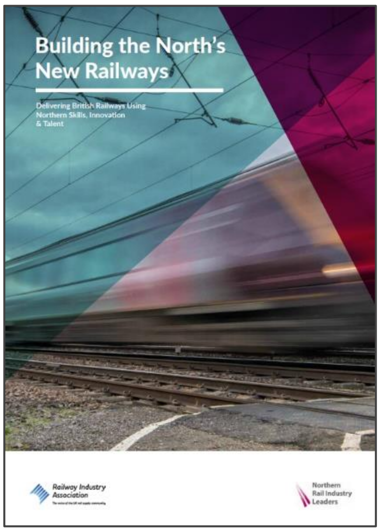
ABOUT NRIL

As the traditional heart of the rail industry, the North has always been central to the success of British business. The future also holds huge potential for the region, with significant investment being delivered through rail projects like HS2 and Northern Powerhouse Rail.

Northern Rail Industry Leaders (NRIL) brings together businesses to help develop and support the rail industry in the region. By providing leadership and industry expertise, the group is defining, shaping and delivering a journey of success for the North.

NRIL consists of an East and West contingent, which in total represent around 150 organisations in the rail industry. By working with Transport for the North (TfN), the sub national transport body, NRIL is looking to influence rail policy across the region.

Building the North’s New Railways



Following the re-launch of NRIL in March 2018, the group held a series of workshops around the region to engage with suppliers and stakeholders and establish their views on the implications for the local supply chain of the regional rail investment programme.

This resulting report details the capabilities of the North’s rail supply base before looking at what more can be achieved with the right policy environment, through collaboration with TfN, Network Rail, HS2 Ltd, the Government and local decision makers.

The Building the North's New Railways report sets out a number of recommendations for delivering a new rail network for the North.

Each recommendation sits within a Workstream. The Workstreams are each led by a Workstream Champion who is taking these recommendations forward over the coming years.

The Workstreams are:

- **Delivering Value,** led by Workstream Champion Ken Kyle (telent);
- **Decarbonisation,** led by Workstream Champion Julie Carrier (SYSTRA);
- **Digitalisation,** led by Workstream Champion Lucy Prior (3Squared)
- **People and Skills**, led by Workstream Champions Tracey Barber (Rail Safety Week);
- **Innovation,** led by Workstream Champion David Taylor (Thales).

Find out more:

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NRIL is supported by the Railway Industry Association (RIA).

9. DOCUMENT REVISION STATUS

Issue	Date	Author	Details of changes
Issue 1	23/10/2020	David Westcough Mike Lipscomb	First issue

Railway Industry Association
The voice of the UK rail supply community

Northern Rail Industry Leaders