With electrification schemes cancelled, what are the pros and cons of partial electrification, and how would it work? Beyond that, will it be an irrelevant argument with advancements in new technology? PHILIP HAIGH reports

Converting a railway to electric operation demands considerable capital investment. Erecting masts and wires, arranging supply points and replacing rolling stock all need money. Project planners need to carefully assess which tracks need wires above and which do not. A railway with bi-directional tracks will need crossovers wired, whereas one that only uses crossovers for engineering trains will not, for example. Thoughts are now turning to leaving sections of running lines without wires. This could save money, particularly where there is little space for overhead line equipment, such as under bridges and through tunnels. The key to this is reliably moving the electric train from one side of the gap to the other.

Trains can coast, as Virgin Trains East Coast occasionally demonstrates when problems force Network Rail to isolate current from overhead wires. Any coasting driver will be hoping he does not need to brake and stop, because the train will then be marooned. Given favourable gradients and signals, a train can coast for several miles. Longer gaps can be bridged by providing secondary power supplies on a train. This might be a diesel engine (as in Hitachi’s bi-mode trains that are about to enter service), batteries (as tested a couple of years ago by NR in East Anglia), flywheel energy storage or hydrogen power.

However, unless those secondary sources can supply the same power as a train’s primary electrical system, performance will be worse: Top speed might be lower or acceleration more tardy, leading to longer journey times when compared with electric operation. Even so, an end to un-electrified lines will be engineered, using a mix of power supplies than it is today on diesel alone.

Cost is the driving force behind consideration of partial, or discontinuous, electrification. This cost is not so much in erecting masts and wires, as in altering structures to provide sufficient space around those wires to satisfy electrical clearance rules. Britain traditionally used 2.75 metres as its clearance distance, but latest European rules demand 3.5 metres. Imagine a station that sits by a tunnel - or worse, between two tunnels. Without rebuilding the tunnels, the OLE might stand closer than 3.5 metres to platform tops. Although the rules permit clearances under 3.5 metres, Network Rail would need to provide a risk assessment to justify any derogation. To date, standards body RSSB has received no application from NR for derogations. Instead, the network owner has opted for expensive rebuilding work which, in turn, led Government to postpone or cancel electrification work in the face of rocketing costs.

Return to our imaginary station sitting between its tunnels, and discontinuous electrification would remove the overhead wire from the platform line. There may just be a gap on an isolated and earthed wire.

If there’s a gap, then the train will need to have a pantograph that doesn’t extend to its full height when it leaves its contact wire, but remains at a suitable height to regain contact with the OLE after the platform. Using an earthed cable allows the pan to continue running as normal, but designers will need to consider the possibility of the earthed cable becoming live as the train bridges both live and earthed OLEs.

Batteries could provide the power to restart the train and see it back under the wires. Those batteries could have been charged from regenerative brakes as the train slowed to a stop. This concept could be extended to the complicated trackwork approaching a major station and into the station itself, to save the cost of erecting equally complicated wiring. Trains moving in and around the station would run on secondary power before regaining their OLEs.

This might make the OLE cheaper, but it adds costs elsewhere. Any electric train running through the station would need to have a secondary power source - standard EMUs would not be permitted. NR and Government would save money, but train operators would face higher costs which might cut premium payments to Government or increase the subsidy it needed to provide.

Such decisions demand detailed analysis. And this analysis should extend to considering what secondary sources trains use, because passengers will be unimpressed if trains run on diesel in stations.

Hydrogen is an alternative. Used in a fuel cell, it directly generates electricity with water as its only emission. It has been the subject of considerable research from the University of Birmingham - Senior Lecturer Stuart Hillmansen tells RailReview that the university built a narrow-gauge locomotive powered by hydrogen five years ago. It took part in the Institution of Mechanical Engineers’ railway challenge in 2012 and acquitted itself well. Since then, Alstom has built a full-size hydrogen multiple unit which is now on test in Germany.

Hillmansen argues that hydrogen is safer than diesel as a fuel – it might burn, but it doesn’t set other things alight because it’s not highly radiative. He reckons that its power density is similar to...
Hydrogen is secondary energy because, like electricity, it is produced from something else. And that something else is very common. Water contains hydrogen, as do classic hydrocarbon fuels such as natural gas, petroleum or coal. Sewage sludge can also be used. Producing hydrogen from hydrocarbon fuels gives carbon dioxide as a by-product, which makes hydrogen use not free from carbon emissions. Using electrolysis consumes electricity to split hydrogen from the oxygen it's bonded to in water (the reverse of the fuel cell process). If the electricity comes from renewable sources, then the hydrogen can be claimed to be low-emission.

With suitable storage, a rail depot may be able to produce hydrogen by electrolysis using cheap, off-peak electricity. Alternatively, a small steam methane reforming (SMR) plant could take up a small amount of natural gas to produce hydrogen on site. The resulting gas is held in tanks on a train at pressures of 250–
700 bar, before being fed into fuel cells. These cells are usually put together in stacks of hundreds of individual cells to generate the primary energy needed to power the train. Each cell is a fuel cell that converts hydrogen and oxygen to electricity with the help of electrically charged particles that move through an electrolyte.

Alstom’s Coradia iLint hydrogen-powered train.

Hydrogen-powered train

Traction motor
Traction inverter & DC/DC-converter
Auxiliary converter
Battery composition
Fuel-cell composition
Hydrogen fuel tank

The hydrogen train tipped the scales at 77 tonnes, giving an axle load of 22.5t. The diesel-electric and hybrid were around 70t, giving 80kph in Germany. Hydrogen tanks and fuel cells sit on the roof of the train, while traction converters and batteries sit under the floor. The trains are powered by an electrical traction drive. Electrical energy is generated on-board in a fuel cell and intermittently stored in batteries. The fuel cell provides electrical energy by combining hydrogen stored in tanks on-board with oxygen from environmental air. The only exhaust is water as steam and condensed water. The battery stores energy from fuel cells when not needed or from kinetic energy of the train during (electrical) braking and allows the support (boosting) of energy delivery during acceleration phases.

Alstom’s iLint multiple unit uses hydrogen as fuel and has batteries than can store energy recovered from braking, making it a hybrid. It is on test as a self-powered train, rather than one that can also take direct electrical power from overhead wires. In this way, it’s a direct replacement for conventional diesel multiple units, rather than a unit that could cope with discontinuous electrification. Alstom based the train on its established Coradia Lint DMU. It expects the same 140kph (87mph) top speed, and has tested it at 80kph in Germany. Hydrogen tanks and fuel cells sit on the roof of the train, while traction converters and batteries sit under the floor. The batteries store energy from braking and supply it to boost that provided by the fuel cells when the train is accelerating. Following its 80kph test last spring, Alstom Vice President Didier Pfleger said: “This test run is a significant milestone in environmental protection and technical innovation. With the Coradia iLint and its fuel cell technology, Alstom is the first railway manufacturer to offer a zero-emission alternative for mass transit trains. Today our new traction system, so far successfully proved on the test ring, is used on a train for the first time – a major step towards cleaner mobility in Europe.”

To make the case for using hydrogen as the secondary power on partially electrified lines, it must be combined with an EMU to form a bi-mode train. There’s a great opportunity for a rolling stock owner with redundant EMUs to use one as a test bed – indeed, Angel Trains Chief Executive Malcolm Brown told RailReview in early August that he could foresee just this.

Hoffrichter’s and Alstom’s work shows that hydrogen can replace diesel as the fuel in a train with electric transmission. It follows that it should be possible to combine hydrogen fuel cell stacks with straight electric power, as Hitachi and others have done in combining diesel engines into electric trains. Space for equipment and gas storage will be important, as will overall weight, but with most redundant EMUs comprising four cars there should be scope for conversion – at least as a test bed.

The other consideration for partially electrified lines is the effect of gaps on performance and journey times. This is another area that has come under Birmingham University’s study. It looked at the Great Western Main Line and put gaps where tunnels exist, including the 7km (4.3-mile) tunnel under the River Severn and Chipping Sodbury’s 4km (2.5-mile) tunnel.

“Whether the small cut in journey time is worth the cost of electrifying between tunnels and providing a new fleet is something for transport economists to debate. It’s possible that passengers might see only minimal improvements in journey times for considerable expense.”

Secretary of State for Transport, July 2017.

It compared the HSTs that Great Western Railway uses on the route today with Class 390 EMUs (as Virgin uses on the West Coast Main Line) and with Hitachi’s IEP in its electric and bi-mode variants. Birmingham’s work dates from a few years ago, when IEP’s specification was changing. The Department for Transport has settled on all IEP units being bi-mode, but this doesn’t negate Birmingham’s conclusions because they show the comparison between types.

The Class 390 and electric IEP variant would need to coast through unwired sections, and so their resistance to motion as derived from the Davis Equation is important. This depends on the mass and velocity of a train.

Results gave a 112-minute journey for an HST between Paddington and Cardiff. With the line fully electrified, a Class 390 achieved 108 minutes, which grew to 103 minutes with partial electrification. Without wires through the Severn Tunnel, the ‘390’ was reduced to a low of 25kph in the tunnel (which dips at 1 in -100 before climbing at 1 in -90 towards Wales). Meanwhile, an eight-car electric IEP took 104 minutes with wires all the way and 107 minutes with gaps, while the equivalent bi-mode reached Cardiff in 105 minutes.

It’s no surprise that full electrification gives the faster journey, but even with gaps for tunnels journeys are quicker than with a diesel HST (see table, page 48). Whether the small cut in journey time is worth the cost of electrifying between tunnels and providing a new fleet is something for transport economists to debate. It’s possible that passengers might see only minimal improvements in journey times for considerable expense.

As NR plans stand, there is doubt that wires will be erected through the Bath and on to Bristol. A bi-mode train on that route will run 83 miles from London to Wootton Bassett Junction on electric power, and then switch to diesel for the 24 miles to Bath and the further 11 miles to Bristol Temple Meads. That’s 30% of the Paddington-Temple Meads route under diesel power, compared with tunnels comprising 6.5% of the route between London and Cardiff in Birmingham University’s study.

In the absence of figures from modelling London-Bath-Bristol, these percentages hint that passengers will experience only a small reduction in journey times between the capital and a
Meads, despite the cost and disruption of electrification. They should, however, see some benefit from new trains replacing HSTs that date from 1976.

TransPennine Express has ordered 19 bi-mode trains from Hitachi for use from 2019. It also has 66 Mk 5 coaches on order, to be hauled by diesel locomotives. When NR had plans to electrify the line from York through Leeds to Manchester, it would have been simple to switch the diesel locomotive for an electric one and run the coaches between Newcastle and Manchester/Liverpool. The bi-mode trains would run as electric before diverging to serve Hull or Middlesbrough with diesel. These bi-mode trains could cope with partial electrification if, for example, revised plans meant OLE wasn't erected through Huddersfield’s or Stalybridge’s tunnels, or through Standedge’s 5km (3.1-mile) darkness under the Pennines.

While Standedge is level, there’s a 1-in-96 rising gradient through the tunnels at Huddersfield for trains heading west. Eastbound trains must cope with a rising 1-in-145 at Stalybridge and Scout Tunnel’s 1-in-125. At Morley, an underground summit marks the switch between 1-in-410 and 1-in-500 gradients.

That makes switching the coaching stock from diesel to a straight electric locomotive very difficult, particularly westbound at Huddersfield where all TPE trains on that route stop. Switching to Class 88s provides a chance that little time might be lost because they pack a 710kW diesel engine, although their performance is considerably better when using their 4,000kW electric power. This makes partial electrification a possibility for trans-Pennine.

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**Paddington-Cardiff journey times**

<table>
<thead>
<tr>
<th>Train</th>
<th>Power (MW)</th>
<th>Journey time</th>
<th>Vehicle energy consumption (kWh)</th>
<th>Well-to-wheel energy consumption (kWh)</th>
<th>Well-to-wheel CO₂ emissions (kg)</th>
<th>Lowest Severn Tunnel speed (kph)</th>
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<tbody>
<tr>
<td><strong>Not electrified</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>HST (8-coach)</td>
<td>2.6</td>
<td>112</td>
<td>8,607</td>
<td>10,008</td>
<td>2,634</td>
<td>-</td>
</tr>
<tr>
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<td></td>
<td></td>
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<tr>
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<td>100</td>
<td>4,101</td>
<td>12,062</td>
<td>2,502</td>
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</tr>
<tr>
<td>Class 390 with regenerative braking (9-car)</td>
<td>5.1</td>
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<td>3,164</td>
<td>9,306</td>
<td>1,930</td>
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<tr>
<td>IEP 8-car electric without regenerative braking</td>
<td>3.2</td>
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<td>IEP 8-car bi-mode</td>
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<tr>
<td>IEP 5-car IEP</td>
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<td>105</td>
<td>3,064</td>
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<td>95</td>
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<tr>
<td><strong>Discontinuous electrification with Severn Tunnel wired</strong></td>
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Source: Birmingham University.

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**Birmingham University journey time comparison route**

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“Hoffrichter’s study found that hydrogen was a suitable energy carrier for rail vehicles, and that it offered lower emissions and well-to-wheel efficiencies similar to electric and diesel traction.”

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Source: Birmingham University.
A Class 185 approaches Standedge Tunnel (5km under the Pennines) in May 2012. TransPennine Express has ordered 19 bi-mode trains from Hitachi that could cope with partial electrification that does not include OLE through this tunnel.

Paul Shannon.

An artist’s impression of the Class 802 bi-mode trains that TPE has ordered from Hitachi.

HITACHI.

“Whether the small cut in journey time is worth the cost of electrifying between tunnels and providing a new fleet is something for transport economists to debate. It’s possible that passengers might see only minimal improvements in journey times for considerable expense.”

And there’s a similar case for the Midland Main Line, where the Department for Transport cancelled its wiring north of Kettering in July.

Bidders for the next Midland franchise will be required to procure bi-mode trains, according to the DfT. “Bi-modes will deliver passenger benefits sooner than electrification would without the disruption from putting up wires and masts along the whole route,” it said in its July public consultation document.

How much faster London-Sheffield journeys become remains to be seen. The next franchise’s bi-mode trains will run on electric power for their first 74 miles to Kettering North Junction, before becoming diesels for the remaining 90 miles to their South Yorkshire terminus. They will need sufficient diesel power to cope with MMUs’s stiff gradients, not least the 1-in-100 to Bradway Tunnel (a few miles south of Sheffield), that affects trains in both directions.

Partial electrifications and bi-mode trains provide the possibility of filling in the missing parts later. This can deliver a substantial slug of improvements to journey times and pollution levels, by wiring the easy stretches first. It also provides the opportunity for extending current limits of electrification. This means that should the DfT be convinced to execute another electrification U-turn, then MMUs’s wires could be extended from Kettering to Leicester, then Derby/Nottingham, and then on to Sheffield.

Partial electrification and bi-mode trains provide the possibility of filling in the missing parts later. This can deliver a substantial slug of improvements to journey times and pollution levels, by wiring the easy stretches first.

Partial electrification provides a route to recover something from the mess of recent electrification projects, although there are problems still to solve, notably around pantographs if short sections of line are to be left without any constraining wire against which a pant could run.

Should raising or lowering the pantograph be left to the driver, or should it be automated to reduce the risk of human error? If automation is the way forward, should it be linked to systems such as ETCS that monitor a train’s position? Should Britain (once again) develop systems that make its trains different from others in the world?

The railway must remove its reliance on burning diesel. Hydrogen appears to satisfy many of the requirements, but it’s still to be tested within Britain’s tighter loading gauge and still to be combined within an EMU to make a hydrogen bi-mode.

Work could usefully extend to mapping how to swap from diesel bi-mode to hydrogen bi-mode in a cost-effective manner that doesn’t involve scraping trains and building new.

Such a project could extend beyond just one train operator, and this invites some form of central co-ordination. This could fall to the DfT, but Government has a poor record of creating plans and then sticking to them. Decarbonising rail travel is a suitable strategic goal for a government. But should it embark on such a course, it must be careful not to change its mind as it’s done with electrification.

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Rail efficiency

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Efficiency at rail</th>
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</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>76%</td>
</tr>
<tr>
<td>Diesel-electric</td>
<td>30%</td>
</tr>
<tr>
<td>Hydrogen fuel cell</td>
<td>40%</td>
</tr>
</tbody>
</table>

Note: Figures assume 100% at the pantograph and fuel/gas storage tank.
Source: University of Birmingham.
Partial electrification

Zena Dent
Projects & Technical Director, Porterbrook

Bi-modular hybrid technology on trains is quickly becoming the popular answer to the problem of escalating costs of electrification. Partial electrification is being heralded as the most affordable option, but it should clarify what is meant by “partial”, as this will drive different bi-mode train requirements.

Let’s say the Midland Main Line is electrified from London to Sheffield, a high-speed train could then run directly to Sheffield, while a local service could use the older network and call at all stations. Alternatively, a high-speed electric train with a small battery or super-capacitor may then be appropriate. If the electrification is only from London to Kettering, then significantly more energy will be needed to carry on board in the form of diesel, or hydrogen, to power the train at speed for sustained distances and periods of time.

In this debate we must consider the whole economic case - full electrification reduces journey times, cost and complexity of the trains (initial capital and ongoing maintenance costs), and emissions, and is the most energy-efficient solution. If we move away from full electrification then we will lose some of these benefits, so the challenge is to get the balance right. Electrification is expensive, but we should consider the full costs of developing trams to operate bi-modes - for example, what is the true cost of running a diesel train? How does hydrogen cost to produce, store and distribute? What is the cost of carrying a secondary engine and fuel source around, during periods when it is not needed?

In the near future we will see many more bi-mode trains on our network - the Stadler FLIRT, Hitachi IEP and Porterbrook’s ‘Flex’. In a few years’ time we might choose four or five trains that could widen its operation beyond the electrified network. Flex takes an existing electric train and adds a generator that meets the latest safety requirements. Alternative power sources are being considered for the next Flex fleet. The surplus of electric trains provides opportunities for innovations to meet passenger needs. Flex changes could use hybrid battery/diesel power and regenerative charging, was the world’s first high-speed hybrid train. Hitachi went on to launch the D501A train in Japan in 2016, running primarily on diesel, but with a battery that is able to carry it a further 40km off the wires. Crucially, battery power offers the ability to run EMUs in a mixed fleet of electric and diesel units as required. What a great way of linking communities while having less environmental impact.

Historically, the challenge with batteries has been their cost, weight and length of charge, limiting their use to shorter distances. However, the technology is advancing, with the development of innovative technology to be the automotive industrial, with its greater economies of scale. Beyond the questions of fuel and the ‘need for speed,’ passengers’ experience of the railway is being transformed as we realise the potential in digital technologies. Dynamic headway, for example, allows train services to real-time demand, which increases utilisation and passenger satisfaction while saving on energy.

It is clear that in the longer term we will be burning less diesel. Pure electric trains offer many benefits, but Network Rail has, to-date, not established the benefits to the infrastructure. Our long-term plan means we need to consider this in the context of new electrification proposals. We are considering the options of a super-capacitor, where the train is able to operate as a train without an overhead, or to use regenerative braking when it is in traction, to save on energy and emissions. The technology to achieve this is not yet mature.

The key to this is that Network Rail has recently invested in state-of-the-art testing facilities. Railfuture’s state-of-the-art testing [of] electric trains and the UK’s research capability in rail systems engineering is super-flexible, but still requires a non-diesel technology that can be very powerful, signalling a clear direction for optimisation and for the delivery of this to get on with. This generates confidence that brings investment in both plant and people, so that delivery and productivity improves. This is, for me, the main message of the article.

So let me suggest an optimum destination that it is easy for us to agree on. How about developing our railway system as a mass transport mode that cheaply and sustainably does what it is good at? Large volumes, big loads, with high speed between nodes of economic activity in near absolute safety and with high levels of reliability and concentrated traffic so that railways are indispensable for commuting and the life of cities; bulk loads define its contribution in freight; and reliable, safe speed lays down the marker for inter-urban travel at UK prices.

But let’s not get away from the ball. If air quality is a big issue for the diesel locomotive, then electrify the route, missing out any tunnels and complex bits. For discontinuous electrification, they are given through trains by adding a single-mode locomotive at the end of the electrified section, which we know can be done safely and quickly within the normal time that the doors are open for passengers (British Railways Southern Region 1960s). If air quality is a big issue for the diesel locomotive, then electrify the route, missing out any tunnels and complex bits. For discontinuous electrification, they are given through trains by adding a single-mode locomotive at the end of the electrified section, which we know can be done safely and quickly within the normal time that the doors are open for passengers (British Railways Southern Region 1960s).

So let’s restate the destination. An all-electric railway.

Then how do we get there? Through a steady programme of electrification, a small step at a time, but progressively, so it is possible to test and develop the technology productively. Evidence and common sense suggest that this may be lower than 100 route miles per year, but even that means in three or five decades we will have caught up with the Swedish. Bi-mode traction capability will provide a stepping stone, a relatively short-term and short-distance requirement, fuelled by the application to rail of whatever technology our automotive colleagues settle on for lorries and big plant. This can do with their vast market and research budgets.

I suspect that rail was first in the use of mobile high-pressure steam power because the low rolling resistance of wheel on rail was necessary for it to work at the time, and the early 19th century roads were inadequate for the loads required. This need has passed - there is absolutely no reason for rail to be first in technology selection and saddle itself with the costs of its own search for the right solution, be it mechanical energy recovery (which seems to work for Formula 1), compressed fluids, hydrogen cells or superconductors, all of which have been demonstrated in working locomotives at the IMechE’s Railway Challenge over the past five years.

If the identification of the current problem is a key, so that energy recovery provides only the means to bridge short gaps in the wire that would be expensive to install. Long-distance unelectrified routes are also worthwhile, and can be electrified from the end of the electrified section, which we know can be done safely and quickly within the normal time that the doors are open for passengers (British Railways Southern Region 1960s).

The interaction of train and infrastructure, European regulations and the technology being developed can be very powerful, signalling a clear direction for optimisation and for the delivery of this to get on with. This generates confidence that brings investment in both plant and people, so that delivery and productivity improves. This is, for me, the main message of the article.

So let me suggest an optimum destination that it is easy for us to agree on. How about developing our railway system as a mass transport mode that cheaply and sustainably does what it is good at? Large volumes, big loads, with high speed between nodes of economic activity in near absolute safety and with high levels of reliability and concentrated traffic so that railways are indispensable for commuting and the life of cities; bulk loads define its contribution in freight; and reliable, safe speed lays down the marker for inter-urban travel at UK prices.

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