Advice to Government on improving rail passenger access to data services

Spectrum for trackside connectivity solutions and rail passenger data demand

Advice to Government

August 2018

About this document

Following a request from the Government as part of its ongoing work to improve mobile connectivity on the rail network, this document outlines Ofcom's advice to the Department for Digital, Culture, Media and Sport (DCMS) on the following:

- current and future demand for data services from passengers on the UK's mainline railways;
- spectrum bands that have the potential to meet these data requirements and could, in principle, be used for track-to-train connectivity; and
- how, in principle, Ofcom might authorise the use of spectrum for rail connectivity (although we have not yet considered whether spectrum should be made available for these purposes).

We will continue to work with industry, DCMS and HM Government as they further develop their plans to improve passenger connectivity on rail routes.

Contents

1. Executive summary

1.1 The Department for Digital, Culture, Media and Sport (DCMS) wrote to Ofcom in December 2017 seeking technical advice to support its policy work on delivering high quality access to mobile data services for passengers along busy mainline rail routes. This document sets out our advice, based on the following three key areas as requested by DCMS:

a) The likely level of data required per train on mainline routes, to deliver a good Wi-Fi and mobile service to passengers, both today and over time;

b) Which spectrum solutions have the potential to meet these requirements using dedicated trackside infrastructure[1] (DCMS has identified that trackside infrastructure is likely to be the most effective approach for providing better passenger access to data services); and

c) How Ofcom could make the suitable spectrum band or bands available for this purpose, including the likely timescales.

Rail passenger data demand

1.2 Estimating future passenger data demand, although subject to significant uncertainties, is essential to the design of the trackside solution. The level of demand determines how much spectrum is required (i.e. spectrum bandwidth) and this in turn determines the spectrum bands that could, in principle, be used to meet the system's requirements, taking into account both the current use of the bands (i.e. any restrictions due to existing users, and the need to coexist with these) and any opportunity cost (i.e. denial of prospective future users).

1.3 Our analysis initially considers the data requirements of an individual train, based on indicative passenger loading for different configurations of intercity and commuter trains. We consider the demand from the train as a whole, aggregating demand from all passengers that are using their mobile phone, laptop or tablet on the train at the same time. We have focused on 'unconstrained' demand, meaning that passengers are assumed to have access either to free-to-use on-board Wi-Fi or their own mobile data service, each of which is able to provide a good quality connection that does not constrain their online activity in any way. The analysis indicates data requirements as in Table 1 below.

[1] By trackside infrastructure, we mean infrastructure that provides connectivity between trains and masts deployed alongside rail tracks, as well as infrastructure providing connectivity in tunnels and cuttings with the connectivity being dedicated to serving the trains. The train is typically equipped with rooftop antennas which transmit to base stations installed along the rail track. Trackside masts will need fibre connections to convey data to core networks.

Table 1: Estimated average data demand for a single train[2]

	2017	2025		
		Low scenario	*Medium scenario*	*High scenario*
550-passenger train (rising to 660 in 2025)	**80 Mbit/s**	400 Mbit/s	**790 Mbit/s**	**1.7 Gbit/s**
800-passenger train (rising to 960 in 2025)	**120 Mbit/s**	580 Mbit/s	**1.2 Gbit/s**	**2.4 Gbit/s**
1,200-passenger train (rising to 1,440 in 2025)	**180 Mbit/s**	860 Mbit/s	**1.7 Gbit/s**	**3.6 Gbit/s**

1.4 The current overall requirement[3] is shown as 80 Megabits per second (Mbit/s) for a busy mainline train of 550-passengers, 120 Mbit/s for a very busy, 8-carriage commuter train of around 800 passengers, and 180 Mbit/s for an overcrowded, 12-carriage commuter train of 1200 passengers. These numbers reflect a requirement of 150 kilobits per second (kbit/s) per passenger, averaged across all the passengers that are on the busy train (noting that not all passengers will be using their mobile devices at the same time, so the speed requirement for those users who are active at any one time will be higher than this). This level of connectivity would reflect a significantly improved service compared to that experienced by passengers on trains today, enabling them to browse the internet, stream videos, connect to social media and communicate via emails and messages, as they would when using their mobile device over a 4G network in locations with good coverage.

1.5 Investments in trackside connectivity, however, will need to be informed by the levels of demand some way into the future. It would not be sensible to consider solutions against future demand scenarios which have a time horizon of much less than ten years, because of the significant investments involved and because of the difficulty in upgrading capacity incrementally over time in a rail environment. Projecting future rail passenger demand over a ten-year period, however, is subject to very large uncertainties and requires a significant degree of judgement.[4] We have therefore considered three demand scenarios

[2] Figures have been rounded. These may appear relatively low if compared to current peak rates achievable over fixed and mobile broadband connections, or the 3GPP 5G specification for trains; however, our demand estimate looks at the *average* rate, blending together different services with different rate requirements (and averaged across all passengers, not all of whom are using mobile devices at the same time). Additionally, we have calculated data demand in a different way to the 3GPP specification, which is not specific to conditions in any given country.

[3] For simplicity, we refer to the 2017 figures (based on the most up-to-date information available) as current levels of demand, though we acknowledge that there may have been some changes to these demand levels in the last year.

[4] Broadly, these uncertainties centre around 1) the amount of data individual passengers will require in the future (based on, for example, changing consumer usage patterns and changing demands for different applications); and 2) passenger numbers, which are expected to grow but could be affected by an increase in remote working and changes to timetables which could mean longer or more frequent trains in the future, which we are unable to account for.

for 2025 (the furthest year for which we have quantified predictions) and then considered how these figures could be interpreted to reflect demand in the mid-late 2020s.

1.6 The low, medium and high scenarios for 2025 reflect monthly mobile data consumption per person figures of 10, 20 and 40 GB[5] respectively, which we then uplift by a factor of four to reflect Wi-Fi use on mobile handsets.[6] These translate into figures of 400 Mbit/s, 790 Mbit/s and 1.7 Gigabits per second (Gbit/s) for a busy mainline train of 550 passengers.[7]

1.7 Our assessment is that a pragmatic approach to thinking about demand post-2025, i.e. in the mid-late 2020s, would be to focus more on the medium and high scenarios in Table 1. On this basis, a plausible view of future requirements is that, in very broad terms, **a busy mainline train might need in the region of 1 Gbit/s, and a crowded commuter train between 2-3 Gbit/s, when looking over a ten-year time horizon**. We note however that demand figures would be significantly lower if passengers were charged for the on-board Wi-Fi service.[8]

1.8 The figure of 1 Gbit/s for a busy mainline train is equivalent to an average data requirement per passenger of around 1.5 Mbit/s in the mid-late 2020s, representing a ten-fold increase in average data consumption per passenger compared to 2017. In part, this reflects an assumption that more passengers will use their mobile devices at the same time on a train (the scenarios assume that the maximum percentage of passengers using their mobile devices at the same time increases from 45% in 2017 to 65% in 2025 and beyond). But the larger part of the increase implies the use of more data-hungry applications, such as increased video streaming and, within this, higher definition video streaming; and the development and use of new data-hungry applications that are not available today. This average data rate would enable almost half of the passengers on a train to connect and stream high-definition videos simultaneously; or 10% of passengers to play online games at the same time, whilst a further 30% stream videos (with over half of these watching in high definition and the others in standard definition), and a further 25% browse web pages whilst simultaneously listening to streamed music.[9]

1.9 As well as looking at the data requirements of a single train we have also analysed data requirements across different sections of the rail network. This is because trackside base

---

[5] These are the demand projections used in Ofcom's Mobile Data Strategy update published in 2016 (https://www.ofcom.org.uk/__data/assets/pdf_file/0033/79584/update-strategy-mobile-spectrum.pdf). These equate to annual growth rates of 16%, 27% and 38% respectively based on a 2017 consumption figure of 3 GB per month per population.
[6] The uplift factor is based on the current proportion of mobile data (25%) versus Wi-Fi use (75%) over mobile handsets.
[7] This can be recalculated for any other capacity of train, as in Table 1 above or otherwise.
[8] We have not conducted an assessment of demand when use is constrained by on-board Wi-Fi charges. Such an assessment would require a view (potentially by means of a survey) of passengers' willingness to pay for such a service.
[9] These estimates are based on average speeds of 4.0 Mbit/s for gaming, 3.2 Mbit/s for high-definition video, 1.5 Mbit/s for standard-definition video, 1 Mbit/s for general browsing and 300 kbit/s for music streaming (for mid-late 2020s scenarios). The second example is based on 65% of all passengers using their mobile devices at the same time, the maximum % that we assume in the scenarios for mid-late 2020s (the other 35% would not be using their mobile devices at this time, although they might use them at other times on their journey – or they might be using their mobile devices in a mode that does not require internet connectivity, e.g. watching pre-loaded content).

stations might need to provide connectivity along a section of track in which there may be more than one train at any one time. In particular, there can be multiple trains around junctions and on parallel tracks in the approaches to cities.

1.10 We have modelled passenger numbers from rail industry data along three mainline routes.[10] Our analysis suggests that, on the basis of the 2017 numbers, rail passenger demand for data on the East Coast Main Line could, across most of the network, be met by a system with a capacity of **200 Mbit/s** per two-mile segment of track.[11] Only in the sections of track approaching major urban centres and busy junctions (and in the approaches to London in particular) do demand levels surpass this. In these places a capacity of around **300 to 500 Mbit/s** per two-mile segment could be needed.

1.11 To meet our future demand scenarios much of the network could be served with a throughput of **2 Gbit/s** per two-mile segment, with the busiest areas coming into and out of London requiring **3-5 Gbit/s**. These numbers assume that all trains of all Train Operating Companies (TOCs) travelling along the route are being served by the trackside connectivity solution. However, if the connectivity was installed on mainline trains only, or on trains of one TOC only, then the required data rates would be substantially lower than these numbers in most cases.

1.12 All of our demand scenarios reflect peak demand. If this level of demand was just above the point which triggered a significantly more costly trackside connectivity solution, then a case might be made for not designing to meet this peak, particularly if the consequential impact on consumer experience was deemed acceptable (i.e. if this did not happen very often, happened for a very short time only or the impact on consumer experience was minor, e.g. through video streams dropping to lower resolutions through adaptive coding etc). However, this consideration will not change the order of magnitude of the capacity requirement for trackside connectivity from the numbers set out above.

1.13 More information on our assessment of passenger data demand can be found in **Section 3** and **Annex 1**.

Assessment of spectrum bands

1.14 We have considered a number of spectrum bands that could, in principle, have the potential to support dedicated rail trackside solutions, including all of the bands that were put forward by DCMS as possible options in its letter to Ofcom in December. We have assessed each band against the following criteria:

---

[10] The data was supplied to Ofcom by industry body the Rail Delivery Group (RDG) and the Department for Transport (DfT); the three routes analysed were the East Coast Main Line from London Kings Cross to Edinburgh Waverley, Great Western Main Line from London Paddington to Penzance and TransPennine Express from Manchester Victoria to York. The data provided to Ofcom was from the MOIRA 2.2 dataset which is a model providing estimates of passenger numbers rather than actual passenger numbers.

[11] The use of two-mile segments of track is explained in Section 3.

a) The capability of the band to support data services to meet the future demand scenarios for the mid-late 2020s taking into account limitations arising from the need to manage coexistence with existing users of the band;

b) The extent to which its use for rail connectivity might conflict with other potential uses of the same spectrum in future (the "opportunity cost");

c) The prospective ecosystem for equipment in this band; and

d) The time and effort likely to be required to authorise the use of this spectrum for rail connectivity, which will depend in large part on the nature and extent of the coexistence analysis required (and the degree of confidence that it will then be possible to authorise its use once the work on coexistence has been completed).

1.15 Considering the first of these criteria, only the mmWave bands have the capability to meet future demand levels in the order of 1 Gbit/s or more. We have assessed the following mmWave bands which have the potential to deliver Gbit/s services:[12]

a) The **upper 26 GHz band** (26.5-27.5 GHz): this should be relatively straightforward to authorise since we do not believe that there are material coexistence issues to resolve with existing users in the band and an ecosystem for 5G equipment covering this band is developing. This band is expected to be the focus for 5G mmWave applications, which means that future 5G deployments could need to be coordinated with rail connectivity deployments where they are in close proximity (so as to avoid interference between them), something that could be more relevant where rail routes pass through urban areas. However, the rail corridors are geographically defined and limited in their coverage, and rail connectivity solutions are likely to have a high degree of directionality, limiting the area around the rail track where this coordination could be required. Therefore, the opportunity cost of rail connectivity deployment, in terms of the impact on other potential future 5G uses, is likely to be modest.

b) The **lower 26 GHz band** (24.25-26.5 GHz): although similar to the upper 26 GHz band in its general capability, there is a significant distinction in that this band is used extensively by fixed links which are licensed by Ofcom on an individual basis. We believe that it may be possible to find bandwidth in amongst the existing fixed links (using different frequencies within the band at different locations as necessary) to accommodate a trackside connectivity solution in most places. However, this would require us to carry out work to analyse the coexistence issues with fixed links, and might need us to develop and implement changes to the associated technical assignment tools in our licensing system. The ecosystem for the lower 26 GHz band is expected to develop over the coming years, albeit behind that for the upper 26 GHz band.

c) The **66-71 GHz** band: this band is currently vacant and we are in the process of making it available on a licence exempt basis which would enable its use for trackside

[12] We have also assessed the potential for the 14.25-14.5 GHz mmWave band to be used for track-to-train connectivity, but have concluded that this band would be unable to support throughput of 1 Gbit/s or more.

connectivity. There is also an ecosystem partly based upon WiGig technology. However, the permitted transmit power will be relatively low and so base station antennas may need to be positioned close together along the track (possibly a few hundred metres apart), a requirement that tends to increase the cost of deployment (compared to if base station antennas can be positioned further apart). We plan to work within CEPT to achieve a harmonised European regulatory framework for this band, and this may include changes to power levels. This work may not be complete for several years but, if successful, it could enable an increase in base station antenna separation, though this will still be less than could be achieved in the 26 GHz band due to the different propagation characteristics of the bands.

1.16 Spectrum is already licensed at 28 GHz (as well as in the 32 GHz and 40 GHz bands) and, with the licence holder's engagement, this could also be considered for rail connectivity as it has similar properties to the 26 GHz band (although the bandwidth in individual 28 GHz licences is more limited).

1.17 We have also assessed a number of mid-frequency bands (below 6 GHz). These could probably support the data rates needed to meet today's levels of demand, with scope for limited growth in some cases (around 100 Mbit/s per train up to a few hundred Mbit/s). However, none have the realistic capability to meet our demand scenarios for the mid-late 2020s for busy trains and busy parts of the rail network. We do not therefore consider them to be credible candidates to meet projected future requirements across the mainline rail network in the mid-late 2020s. Each of the three bands considered also has some specific, additional challenges:

a) **2.7-2.9 GHz** could in theory deliver 100 Mbit/s on the basis of 40 MHz of cleared bandwidth being available almost everywhere, and could provide several hundred Mbit/s in some places where more spectrum could be made available. However, making this band available would require significant work to consider coexistence with air traffic radar and military systems. This would take time, not least because of the need to perform trials and develop safety cases, and the outcome of this work is not guaranteed. The specialised equipment ecosystem would also be dependent on only a few suppliers.[13]

b) **3.8-4.2 GHz:** use of this band, which could support up to several hundred Mbit/s in many places, could conflict with Ofcom's policy to enable sharing by new fixed and mobile applications in this band. There may also be significant lengths of rail track in the approaches to London and in a number of other areas where use for rail connectivity (which might operate at relatively high powers) would be restricted to protect satellite earth stations, meaning that this band could not support a single solution across the whole rail network.

[13] We are aware that 2.9-3.1 GHz has been suggested as a possible source of additional bandwidth to that in 2.7-2.9 GHz. This band would have many of the same issues as 2.7-2.9 GHz, including coexistence with MOD applications; however, there will be additional issues relating to coexistence with maritime radar use (in place of those relating to air traffic control radars in the 2.7-2.9 GHz band). We discuss this in more detail in Section 4.

c) **5.4 GHz** has an authorisation in place today, and it may be possible to achieve up to a few hundred Mbit/s. However, this band may suffer quality of service issues, particularly as the train passes through urban areas, due to the presence of outdoor Wi-Fi users who have access to this spectrum on an equal, licence exempt basis. The low permitted powers in this band (necessary to enable sharing with other users) would also mean that trackside base stations would likely need to be built closer together, thereby offsetting one of the advantages of mid-frequency spectrum bands.

1.18 Based on the above assessment, **we believe the 26 GHz band likely offers the best prospects for track-to-train connectivity solutions that meet our demand scenarios for the mid-late 2020s**. This is due to its combination of high bandwidth, more straightforward coexistence environment (for the upper part of 26 GHz in particular), large potential equipment ecosystem and comparatively modest opportunity cost in the rail connectivity application.

1.19 More information on spectrum options can be found in **Section 4**.

Other options for improved rail passenger connectivity

1.20 Mobile networks could also be used to support rail passenger connectivity (using their existing spectrum holdings and/or mobile spectrum that we plan to auction next year). Indeed, mobile networks provide the main backhaul for the limited throughput Wi-Fi services that are available on trains today, often supporting contracts for data connectivity with the TOCs. The capacity and coverage of these services could be increased through investment in new mobile network infrastructure near to the rail network that is planned with this objective in mind. Network infrastructure could also be deployed at the trackside, and in cuttings and tunnels, to provide new, dedicated track-to-train connectivity (using mobile spectrum as an alternative to the spectrum bands discussed above for the track-to-train link). For example, using a mix of mobile channels and bands might be possible to support speeds of a few hundred Mbit/s in a trackside solution.

1.21 More information on options using MNO networks and spectrum can be found in **Section 6** (along with brief comments on the use of satellite technology).

Authorisation and timing

1.22 There are a number of spectrum bands that could support rail connectivity where the necessary authorisations are already in place. These include the mobile spectrum bands and the 5.4 GHz Wi-Fi band, as well as a number of mmWave bands which are already licensed (including the 28 GHz band for example). We are also currently consulting on the implementation of new licence exemption regulations for the 66-71 GHz band.

1.23 However, the other bands considered above, including the 26 GHz band, would require a new authorisation for the trackside connectivity application to be put in place. We consider that this new authorisation would likely take the form of a licence product for the trackside base stations located along the rail corridor (as opposed to a licence exemption regulation). Any form of authorisation that allows for the use of the spectrum will need to comply with the requirements of both European and domestic law.

1.24 Subject to further consideration of specific proposals, our preferred approach is likely to be one in which we would make licences available on demand to any applicant for the purpose of providing track-to-train connectivity along a rail corridor (expecting that, in practice, only one entity is likely to have the incentive and ability to use its licence along any one section of track at any one time). This would mean that bidders in a competitive procurement process for a trackside connectivity solution would be in the same position as regards prospective access to one of these new rail connectivity spectrum licences (avoiding a situation in which one party could gain a competitive advantage by obtaining a licence to the exclusion of others ahead of a connectivity procurement process).

1.25 The length of time required to put a new rail corridor licensing regime in place will differ between the bands, reflecting primarily the time needed to examine and resolve arrangements to manage coexistence with existing users. The upper 26 GHz band does not face material coexistence issues and it could therefore be possible to put new licences in place for application in around 9 months to a year. The lower 26 GHz band might take up to 12 months longer to get that point because of the need to work through the coexistence scenarios with existing fixed links in the band and make any necessary changes to our licensing systems. The mid-frequency bands (2.7-2.9 GHz and 3.8-4.2 GHz) would probably take longer than a year to authorise because of the greater challenges of establishing workable coexistence arrangements on a UK-wide basis.

1.26 More information on our view of authorisation options can be found in **Section 5**.

Next steps

1.27 Designing a network to provide track-to-train connectivity will involve many different considerations other than the choice of spectrum band, such as determining the business model on which such a service would be run, how the deployment would be funded, and potential interoperability across multiple routes or TOCs.

1.28 We will continue to work with industry and HM Government as they further develop their plans for the enabling and deployment of any solutions to improve passenger connectivity on rail routes where these plans involve the use of radio spectrum.

1.29 This document represents our initial assessment of spectrum which could potentially be made available for this purpose, based on the evidence we have today. At this stage we have not come to any decision on whether the spectrum bands identified should be used for the purposes of enabling track-to-train connectivity, or whether certain entities should be authorised for providing these services. These matters would need to be considered further by Ofcom in light of specific requests for authorization, and we would do so in the context of our overall spectrum management functions, having regard to ensuring the optimal use of spectrum.

2. Introduction

Background

2.1 The Government set out in its 5G Strategy[14] its ambition to improve mobile coverage and connectivity for UK citizens and consumers wherever they live, work and travel. The Government also set out its support for the National Infrastructure Commission's view[15] of the importance of greater connectivity on the UK's road and rail networks.

2.2 On 28 December 2017, DCMS published a Call for Evidence on commercial options for delivering mobile connectivity on trains,[16] focusing on trackside infrastructure, which DCMS has identified as being likely to be the most effective approach for delivering high quality connectivity along busy mainline routes, where the passenger demand justifies the required investment.

2.3 As set out in its Call for Evidence, DCMS also wrote to Ofcom to request that we provide advice on the following three areas:

a) the passenger data requirements per train on mainline routes, to deliver what we consider to be a good Wi-Fi and mobile service to customers, both today and over time;

b) which spectrum solutions have the potential to meet these passenger data requirements, both today and over time; and

c) how Ofcom could make the suitable spectrum band or bands available for this purpose, including the likely timescales.

Ofcom's functions in relation to spectrum

2.4 Ofcom's principal duty, in carrying out its functions, is to further the interests of citizens in relation to communications matters and to further the interests of consumers in relevant markets, where appropriate by promoting competition. In doing so, we are required to secure the optimal use of the spectrum for wireless telegraphy.[17] Ofcom is required to have regard to (amongst other things) the extent to which the spectrum is available for use, or further use, for wireless telegraphy, the demand for the use of the spectrum, the demand

---

[14] DCMS and HM Treasury, *Next Generation Mobile Technologies: A 5G Strategy for the UK*, March 2017, https://www.gov.uk/government/publications/next-generation-mobile-technologies-a-5g-strategy-for-the-uk

[15] National Infrastructure Commission, *Connected Future*, 14 December 2016, https://www.nic.org.uk/publications/connected-future/

[16] DCMS, *Commercial options for delivering mobile connectivity on trains: Call for Evidence*, 28 December 2017, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/670551/Commercial_options_for_delivering_mobile_connectivity_on_trains__Call_for_Evidence.pdf

[17] Section 3 of the Communications Act 2003.

that is likely to arise in future for the use of the spectrum, and the desirability of promoting the efficient management and use of the spectrum.[18]

2.5 Ofcom also has duties to provide such advice as we consider appropriate for the purposes of facilitating or managing the use of the spectrum. In providing such advice, we have power to carry out research for the purposes of ascertaining the demands for the use of the spectrum, the effects of any such use of the spectrum, likely future developments in relation to those matters, and any other connected matters that Ofcom considers relevant.[19]

2.6 This document provides Ofcom's advice on the three areas set out in paragraph 2.4 above. In providing such advice, we have not come to any view or decision as to whether or not the spectrum should be used for the purposes of enabling track-to-train connectivity, or whether certain entities should be authorised for the purposes of providing such services. Any views or decisions made in relation to these matters would need to be considered further by Ofcom in the context of our overall spectrum management functions, as set out above.

The rest of this document

2.7 **Section 3** explains how we have estimated passenger demand for data services on mainline rail routes. We have modelled the online activities of passengers, assessing their data speed requirements both in the present day and looking forward. We have then modelled demand across specific routes using train schedules and passenger number information.

2.8 **Section 4** considers a range of spectrum bands that could be candidates for supporting dedicated track-to-train infrastructure, based on our modelling of passenger data demand.

2.9 **Section 5** outlines the steps we would need to take in order to authorise these bands such that they could be made available for trackside connectivity infrastructure on mainline routes across the UK.

2.10 **Section 6** briefly discusses alternative solutions for improving connectivity for rail passengers, including both mobile network and satellite options.

2.11 **Annex 1** outlines the detailed methodology used to assess the data demand of rail passengers along specific rail routes.

2.12 **Annex 2** outlines a baseline range for spectral efficiency based on a review of existing technologies.

2.13 **Annex 3** contains a glossary of terms.

---

[18] Section 3 of the Wireless Telegraphy Act 2006.
[19] Sections 1(1) and 1(4) of the Wireless Telegraphy Act 2006.

3. Passenger data demand

Overview of approach

3.1 In its letter to Ofcom, DCMS asked us to assess rail passenger demand for data, both now and looking into the future.

3.2 The prospective level of demand will determine the amount of spectrum which is required (spectrum bandwidth) to provide the system capacity to meet this demand; this, in turn, will have a significant impact on the potential spectrum options which may be suitable for trackside connectivity, as explored further in Section 4.

3.3 Our analysis considers various components of rail passenger data demand. We initially look at the data requirements of an individual train (in particular, the capacity that might be needed to serve the busiest mainline trains). However, we also analyse the way that data requirements can vary across different sections of the rail network, given that a trackside base station might need to provide connectivity along a section of track in which there may be more than one train at any one time.

3.4 Accordingly, our analysis of passenger demand for data across the mainline rail network is composed of two elements:

a) **Assessment of unconstrained passenger demand**, expressed in bits per second (bit/s) per passenger on a busy train. This is a blended average data rate per passenger on the train (only some of whom will be using their mobile devices at any one time) and refers to ‘unconstrained’ demand in the sense that passengers are assumed to use their mobile handset, tablet or laptop to access either:

   i) a free-to-use Wi-Fi service that is not subject to data caps and is not throttled because the capacity provided is able to meet passengers’ demand; or

   ii) their mobile service provided by an MNO.

b) **Assessment of numbers of trains and passengers in each part of the network** at any one time.

Assessment of unconstrained passenger demand

3.5 We have looked at passenger data requirements at busy times as it is this level of demand which will determine the capacity requirement when designing the trackside connectivity solution. The way that individual passengers use their devices will vary considerably, both over the course of the day when considering an individual passenger (for example a commuter may be checking emails in the morning but streaming music or videos in the evening), and from one passenger to another.

3.6 A trackside connectivity solution will consider the demand from the train as a whole, aggregating the usage of all passengers on the train at any point in time. The number of passengers on a busy train is sufficiently large for us to use a ‘blended average data rate per passenger' as the basis for deriving estimates of demand that are relevant to trackside connectivity capacity requirements.

3.7 Current connectivity on trains is limited, particularly in cuttings, tunnels and other areas of limited mobile coverage, often providing a very inconsistent user experience. This means that any information on today's actual passenger data consumption will not reflect the level of demand that would be present if there were to be consistently good connectivity on trains. It is therefore appropriate for our demand scenarios to assess general and unconstrained device usage which reflects the desired passenger data demand and which assumes that passengers are not expected to pay extra for on-board connectivity.[20]

3.8 Investments in trackside connectivity, however, will need to be informed by future demand. It would not be sensible to consider solutions against demand scenarios which have a time horizon of much less than ten years, because of the significant investments involved and because of the difficulty in upgrading capacity incrementally over time (particularly in the rail environment where access to the trackside is constrained for safety and operational reasons).

3.9 Forecasting future rail passenger demand over a ten-year period is, however, subject to very large uncertainties and requires a significant degree of judgement. In the past few years, we have experienced very high annual data growth rates. These are projected to continue into the 2020s but a point may come when the growth rate moderates as with the shape of an (upward sloping) S curve. It is not really possible to predict when the growth rate might moderate. However, we feel that applying a compound annual growth rate to the monthly data consumption figures for the period post-2025 would run the risk of amplifying inaccuracies in the numbers. We have therefore developed multiple demand scenarios for 2025 (the furthest year out for which we have projections) and then considered how these figures could be interpreted to reflect demand in the mid-late 2020s (i.e. looking around 10 years ahead).

3.10 We assessed rail passenger demand using two approaches:

a) **A 'bottom-up' approach** where we have looked at the typical online activity profile of a consumer and the average data download speeds required to conduct these online activities;[21] and

b) **A 'top-down' approach** where we have looked at real consumer monthly data usage and the average time spent on devices, and converted this into an average data speed per passenger.

3.11 To test the outcomes of these two approaches for our estimates of present demand, we have also obtained some real measurements from an organisation called LetsJoin which provides on-board Wi-Fi services across transport networks in the UK using connectivity

[20] This implies that connectivity costs are reflected in the train tickets and/or mobile service charges. We expect that extra charges would constrain the use of the service.
[21] We consider download data only as this drives the vast majority of demand.

from the MNOs' 4G networks.[22] This is discussed later in this section and outlined in further detail in Annex 1.

3.12 One of the main assumptions that influences the results in both approaches (and one that is subject to very significant uncertainty) is the assumption on the maximum percentage of passengers on a train who are connected to the internet at any one time. For the purposes of this analysis we have made an assumption that a maximum of 45% of passengers would be connected to the internet at any one time today (if they had good quality on-board Wi-Fi access without data caps and which they did not have to pay to access). We have made an assumption that by 2025 this figure will increase to 65%. These figures take note of a 2016 Steer Davies Gleave report for the Department for Transport (DfT) which found that 65% of passengers had either already connected to the internet during their journey, or intended to do so before they reached their destination (though these were not all connecting at the same time).[23] However, there is clearly a high degree of judgement in the specific percentage numbers we have assumed.

Bottom-up approach

3.13 The results of the **bottom-up approach** are driven by:

a) **The activities that users are conducting** (for example email, browsing, video streaming). Each activity is expressed as a percentage of the total average time that they spend using their devices.[24] In order to model unconstrained demand, we have assessed how people spend their time in a typical day, focusing on what they do when they are using their mobile devices in general, as opposed to looking at their online activity only whilst on public transport or on trains (which would reflect the effects of having limited on-board connectivity today).

b) **The average data usage rate of these activities**. We have estimated average data speeds for each activity which would provide an acceptable experience for consumers today. Looking towards the future, we consider that user expectations of quality and speed will increase, and we have therefore estimated average data speeds which reflect a better experience. For example, we estimate streaming video to be delivered at an average rate of 0.5 Mbit/s today (reflecting typical video streaming rates to

---

[22] LetsJoin works with transport operators (e.g. bus and train operators) to provide on-board Wi-Fi services. In providing passenger behavioural analytics services to operators, LetsJoin is able to monitor the use of Wi-Fi services and has shared some of its real-time measurements with us.

[23] Steer Davies Gleave, *Mobile connectivity research study: Final report*, March 2016, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/518976/mobile-connectivity-research-study_SDG-report-with-appendices.pdf

[24] We have used as a starting point Ofcom's 2016 Digital Day research, which looked at how much time people spend during the day on different online and digital activities, including watching video, messaging, listening activities and web browsing. https://www.ofcom.org.uk/research-and-data/multi-sector-research/general-communications/digital-day; http://www.digitaldayresearch.co.uk/

mobiles in a busy location which provide an acceptable, though not necessarily ideal, experience[25]) but 3.2 Mbit/s in the future (reflecting HD video).[26]

c) **The maximum percentage of passengers connected.** This is assumed to be 45% in 2017 and 65% in 2025 as explained above.

3.14 With this bottom-up approach we do not consider how demand may grow past 2025 due to the large number of unknown variables which could influence future data usage rates. For example, it is difficult to envisage which new applications people will be using and what types of data speeds they will require.

Top-down approach

3.15 The results of the **top-down approach** are driven by three main factors:

a) **The amount of total data (in GB) consumers will use on average per month**. Our starting point is the 2017 total data usage of 156 PB (petabytes).[27] This translates into 3 GB per adult population per month based on a population of 52.1m people aged 15 years and above as per the 2011 UK census.[28] We then forecast this figure to grow to 10, 20 and 40 GB per user per month by 2025 as low, medium and high scenarios respectively.[29] We expect the growth in total data consumption to be driven by more data-intensive applications as well as more time spent connected to the Internet using a mobile phone.

b) **The amount of mobile data used vs Wi-Fi.** We uplift the amount of mobile data used by consumers to reflect the fact that data is also consumed via Wi-Fi. We have assumed that 25% of overall mobile usage is via mobile data[30] and so have multiplied the data consumption that takes place over the mobile network by four to account for this (e.g. the medium scenario case of 20 GB per month per user of mobile data is increased to 80 GB per month per user of total data). We have applied this same

---

[25] For example, standard definition video would ideally require a speed of 1.5 Mbit/s today, but we have applied an acceptable speed of 500 kbit/s, as this speed would still enable the passenger to watch the video at an acceptable level of quality on their smartphone. Our present-day demand estimates reflect these acceptable speeds.

[26] Note that we are estimating *average* speeds; in general many activities require a periodic, and potentially large "burst" of speed, but use little or no data between these bursts. Web browsing, for example, may require 200 kbit/s for a few seconds to download a regular webpage, but then does not require any more data until the user clicks another link.

[27] Ofcom, *Connected Nations 2017 Report*, 15 December 2017, p. 42, https://www.ofcom.org.uk/__data/assets/pdf_file/0018/108513/connected-nations-mobile-2017.pdf; a petabyte (PB) is equivalent to 1,000 TB or 1,000,000 GB.

[28] We have applied the same methodology to this calculation as outlined in Ofcom's Mobile Data Strategy which contains the future consumption predictions. A population of 52.1m people of 15 years old and above was used in these calculations. We recognise that this does not account for younger mobile users and this has been addressed in 3.20a)

[29] Ofcom's Mobile Data Strategy update published in 2016 (https://www.ofcom.org.uk/__data/assets/pdf_file/0033/79584/update-strategy-mobile-spectrum.pdf) contains low, medium and high estimates of 10, 20 and 40 GB of monthly data consumption per person in 2025.

[30] Ofcom, *The consumer mobile experience: Measuring the consumer experience of using Android mobile services*, 9 May 2018, https://www.ofcom.org.uk/__data/assets/pdf_file/0028/113689/consumer-mobile-experience-2018.pdf. Note that our research on consumer mobile experience finds that consumers spend 25% of their time on a mobile data connection and 75% using Wi-Fi. For simplicity, we assume this corresponds to 25% of mobile data and 75% of data sent over Wi-Fi. We are conscious this may underestimate the proportion of data sent via Wi-Fi as mobile users tend to use this technology for more data intensive applications, such as video streaming.

assumption for both current and future demand scenarios. We are aware that this figure is unlikely to remain at this level over the coming years as there are many factors which could influence this figure in either direction; however, we are concerned with overall wireless data demand for these purposes, and not with the split between Wi-Fi and mobile data use within this. This issue is explored in more detail in Annex 1.

c) **The amount of time using the device each day.** We then average the daily figure of data consumption over the amount of time during which the average person is using their mobile phone. This was 2.03 hours in 2017 according to the Digital Day data used in the bottom-up approach. For the 2025 demand scenarios we use an assumption of 3.17 hours (based on the current average time spent on mobile phones from a younger demographic group, between the ages of 11-34). These assumptions are consistent with the hypothesis that the large increase in data usage will be driven in part by an increase in the average amount of time spent using mobile devices (as well as by the data intensity of the applications being used).

d) **The maximum percentage of passengers connected.** This is assumed to be 45% in 2017 and 65% in 2025 as explained above.

Comparison with real-time measurements over a well-served bus route

3.16 LetsJoin has provided us with some analysis based on real-time measurements of user traffic from on-board Wi-Fi services on a number of the bus routes it serves, as mentioned above.[31] These measurements were taken in June 2018.

3.17 These on-board Wi-Fi services use connectivity from the MNOs' 4G networks and are offered free of charge. The data reflects the download throughput rates obtained along bus routes with good 4G reception in order to reflect a good quality experience for passengers. We acknowledge that the behaviour of bus passengers might be different from that of rail passengers in an 'unconstrained' environment and, specifically, that the usage by bus passengers might be more limited due to the length of their journey (for example, due to shorter journeys on buses on average, passengers may be less likely to stream long videos). However, we think that this empirical measure will give a better indication of demand than an equivalent measurement on trains today would do (we would expect data on current Wi-Fi use on trains today to give much lower numbers as 4G coverage along rail tracks today is subject to limitations associated with tunnels, cuttings and occasional poor reception; in addition, current Wi-Fi services offered on trains are often constrained to low data rate applications such as email and web browsing and capped to low free data allowances e.g. 15 MB on Great Western trains).

3.18 We have looked at a range of values and made a number of assumptions in order to enable a meaningful comparison with the results of our demand analysis; these are set out in detail in Annex 1. The relevant data from LetsJoin indicates an overall average user data

[31] The analysis is based on traffic measures such as data downloaded, data uploaded and session duration of more than 730,000 individual user sessions established over the Wi-Fi connection provided within buses.

rate of between **55-145 kbit/s** (after applying the assumption that the maximum number of passengers connected at the same time is 45%).

Results of per-passenger data demand

3.19 The results of our approaches are shown in Table A1.6 below. These results account for the fact that we have assumed a maximum of 45% of passengers connected at any one time in 2017 and a maximum of 65% in 2025.

Table 2: Indicative per-passenger data demand, 2017 and 2025 (kbit/s)

	2017	2025
Bottom-up	100	690
Top-down (low/medium/high figures for 2025)	200	620 / 1,200 / 2,500
LetsJoin figure	55-145	*n/a*

3.20 Balancing the three different information sources for the 2017 column, we consider it appropriate to use an **average passenger demand of 150 kbit/s** to reflect current 'unconstrained' demand. We consider that, at these rates, passengers' experience during the journey would be similar to the level of service they currently receive when using their mobile phone in a well-served area over a 4G network connection. In arriving at this judgement, we note that the results of the bottom-up approach reflect acceptable activity speeds today and that the higher number of 150 kbit/s would be consistent with the delivery of somewhat higher speeds. Conversely, we note that the results of the top-down approach may overstate average passenger demand as this approach:

a) applies an average online time per day of 2.03 hours which is taken from a data source relating to 2016, and so is likely to be an underestimate of the equivalent figure for 2017 (the monthly data consumption figure is from 2017);

b) does not account for the younger population of 11-15 years. The exclusion of this age group was required to ensure consistency with the data source for monthly mobile data use; however, the inclusion of this younger age group would bring the average 200 kbit/s top-down figure down to 188 kbit/s per person;[32]

c) takes account of the use of multiple devices per user (e.g. tablet, mobile broadband or second mobile phone). Although this may reflect some passengers who use more than one device when travelling, e.g. listening to online music using their phone whilst working on their laptop, it may in other situations overstate a single passenger's

[32] We have maintained the same approach as in the Mobile Data Strategy and have based the calculation of the 2017 average consumption of 3 GB per adult population per month on a population of 52.1m people aged 15 years and above as per the 2011 UK census.

demand, e.g. when passengers are standing in a crowded commuter train and it may not be practical for them to use multiple devices.

3.21 In relation to future data demand levels, we use the figures from the top-down approach to illustrate the range of demand scenarios (although we note that the bottom-up approach gives a result which is similar to the low scenario in the top-down approach). One reason for doing this is that the bottom-up approach only takes account of increases in data rates needed by applications used today and does not make allowances for new types of data-hungry applications that we cannot currently predict.

3.22 These figures may appear relatively low if, for example, they are compared with Government Universal Service Obligation figures of 10 Mbit/s per household or current peak rates achievable over fixed and mobile broadband connections in the tens of Mbit/s. However, this is not a like-for-like comparison. Our demand estimate looks at the *average* rate on a busy train, blending together different services with different rate requirements and averaged across all passengers, not all of whom are using mobile devices at the same time. Within this overall average rate, individual customers will be getting much higher peak speeds when needed.

3.23 We have used these per-passenger figures to calculate indicative per-train demand figures based on three different levels of passenger loading, as set out in Table 3 and its footnotes below. These figures are derived from available data on passenger numbers and crowding from DfT, but are also consistent with our own analysis of rail industry passenger numbers and timetabling data (explained in the section below).

Table 3: Indicative demand figures per passenger and per train, 2017 and 2025[33]

	2017	2025		
		Low scenario	*Medium scenario*	*High scenario*
Blended average rate for single passenger	150 kbit/s	600 kbit/s	**1.2 Mbit/s**	**2.5 Mbit/s**
550-passenger train (rising to 660 in 2025)[34]	80 Mbit/s	400 Mbit/s	**790 Mbit/s**	**1.7 Gbit/s**
800-passenger train (rising to 960 in 2025)[35]	120 Mbit/s	580 Mbit/s	**1.2 Gbit/s**	**2.4 Gbit/s**
1,200-passenger train (rising to 1,440 in 2025)[36]	180 Mbit/s	860 Mbit/s	**1.7 Gbit/s**	**3.6 Gbit/s**

3.24 Table 3 presents demand scenarios for 2025 as this is the furthest out year for which we have projections. When thinking about demand in the mid-late 2020s we think that a pragmatic approach would be to focus on the medium and high projections in Table 1, which imply a year-on-year growth rate between 27% and 38%. A plausible scenario is that a **mainline train might need around 1 Gbit/s, and the busiest commuter train between 2-3 Gbit/s, when looking over a ten-year time horizon**. We note however that demand figures are likely to be significantly lower if passengers were charged for the on-board Wi-Fi service.[37]

[33] Figures have been rounded.
[34] This number is consistent with our own findings of passenger loading on a busy intercity mainline train, explained in more detail in Section 3. This would also be broadly equivalent to an 8-car Class 387 with 20% of passengers standing, or to 8 standard class Mark 3 carriages.
[35] This number would be broadly consistent with an 8-car Class 465 with all seats filled and 28% of passengers standing (the average percentage of passengers standing on arrivals into London at peak rush hour, according to DfT data: https://www.gov.uk/government/statistical-data-sets/rai02-capacity-and-overcrowding, file RAI0213.) This would also be consistent with a 12-car Class 700 with all seats filled and 28% of passengers standing (however, this would not necessarily be overcrowded as the Class 700 is designed to accommodate more standing passengers).
[36] This number is consistent with an overcrowded 12-car commuter train, based on DfT's published data on the ten most overcrowded train services of 2017: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728105/top-10-overcrowded-trains-2017.pdf. It is uncertain whether a single train will necessarily be able to hold as many as 1,440 passengers in 2025, though we are aware that upgrades to the rail network and rolling stock could make this more feasible in future. Additionally, while we accept that this is not a routine occurrence, the DfT data source given above shows that it is possible for a train today to have this many passengers on board in an extreme case. In addition to this consideration, there is also a question on whether all passengers would be able to use their mobile devices at all in the most overcrowded conditions.
[37] We have not conducted an assessment of demand when use is constrained by on-board Wi-Fi charges. Such an assessment would require taking a view (potentially by means of a survey) of passengers' willingness to pay for such a service.

3.25 The figure of 1 Gbit/s for a busy mainline train in the mid-late 2020s is equivalent to an average speed of around 1.5 Mbit/s per passenger. This average speed would enable nearly half of the passengers on a train to connect and stream high-definition videos simultaneously, or 10% of passengers to play online games at the same time, whilst 30% simultaneously stream videos (with over half of these watching in high definition and the others in standard-definition), and a further 25% browse web pages whilst simultaneously listening to streamed music.[38]

Assessment of passenger numbers at different places along the mainline rail network

3.26 The analysis above gives the blended average data requirements per passenger travelling on a busy train. In practice, the trackside network may have to serve more than one train through each trackside mast, as multiple trains travel in opposite directions or along parallel rail tracks. In addition, the number of passengers in each train will vary according to the location and time of day. If these aspects are not taken into account, the trackside network may not have sufficient capacity to deal with peak demand arising from the presence of multiple trains (if all of these trains are fitted out to use the connectivity service). Conversely, there will be certain sections of tracks which would rarely need to provide connectivity to multiple trains, or to very busy trains with very high numbers of passengers.

3.27 We have therefore analysed the way that the capacity required might change across different sections of track. To model passenger data demand for a given segment of track, we have used rail industry data supplied to Ofcom by the Rail Delivery Group (RDG)[39] which uses timetabling information and includes present passenger numbers and forecasted growth per TOC. This allows us to estimate the peak demand along the track based on both the number of trains present and how many passengers are on board the trains.[40] From the timetable we derive the average speed of the train between stops and, absent any other data, we assume the train is always moving at this average speed without modelling accelerations and decelerations.

3.28 We have used the rail industry data to analyse three UK mainline rail routes as examples:

a) **East Coast Main Line** (London Kings Cross-Edinburgh Waverley)

---

[38] These estimates are based on average speeds of 4.0 Mbit/s for gaming, 3.2 Mbit/s for high-definition video, 1.5 Mbit/s for standard-definition video, 1 Mbit/s for general browsing and 300 kbit/s for music streaming (for mid-late 2020s scenarios). The second example is based on 65% of all passengers using their mobile devices at the same time, the maximum % that we assume in the scenarios for mid-late 2020s (the other 35% would not be using their mobile devices at this time, although they might use them at other times on their journey – or they might be using their mobile devices in a mode that does not require internet connectivity, e.g. watching pre-loaded content).

[39] The Rail Delivery Group (RDG) is a membership body for the rail industry which includes both Network Rail and all of the TOCs which provide passenger services on the UK rail network.

[40] The validity of our analysis depends on the validity of the passenger forecasts, and assumes no delays. In Annex 1 we show that a few minutes' delay can lead to a substantial increase in passengers present in a given segment of track.

b) **Great Western Main Line** (London Paddington-Penzance)

c) **TransPennine Express** (Manchester Victoria-York)

3.29 These routes include very different track profiles, including long, cross-country sections, sections heavily used by commuters and, in the case of the TransPennine route, a route which does not originate or end in London.

3.30 The dataset of detailed passenger and train movements relates to today's position. We have also used the Government's predictions for changes in rail passenger volumes to 2025.[41] There is some uncertainty around these figures however, due in part to the ongoing growth in home working to replace commuting, and this should be considered a caveat along with the other mitigating factors discussed in paragraph 3.9, particularly with reference to our high projection of future passenger data demand.[42]

3.31 We present results in terms of the peak passenger numbers per segment of track and the corresponding data capacity requirement per segment of track.

3.32 The smallest length of track we can analyse is limited to approximately two miles (3.2km) because of the granularity of the rail industry timetabling and passenger modelling data we have used, which defines the arrival and departure of a train from/to stations to the nearest minute. We interpolate the position of a train along the track for every minute and observe that the maximum distance travelled by fast trains in a minute is just under two miles (i.e. they travel at 120mph). We therefore consider this two-mile distance to be the basic unit of track for these purposes, since the minimum increment of time used in the dataset is one minute and we are unable to make our assessment on a more granular level than this. We refer to this two-mile length as a 'segment of track' (more details in Annex 1).

3.33 Our analysis of passenger numbers along different sections of track provides us with a detailed demand profile: it allow us to estimate how much of the data demand takes place when the data requirement is greatest, i.e. at the peak period for that segment of track, when there are a lot of simultaneous users because the trains are heavily loaded and/or there are several trains in the same segment of track.

3.34 This can be best understood by an example, as set out below. We look at a single segment of track which includes Leeds train station along the TransPennine Express route (see map in Figure A1.10). The bars in Figure 2 show passenger numbers (vertical axis) by minute, across the whole day (horizontal axis shows time), in a single segment of track; the morning rush hour from 8:00-9:00 and the evening rush hour from 17:00-19:00 are clearly visible.

---

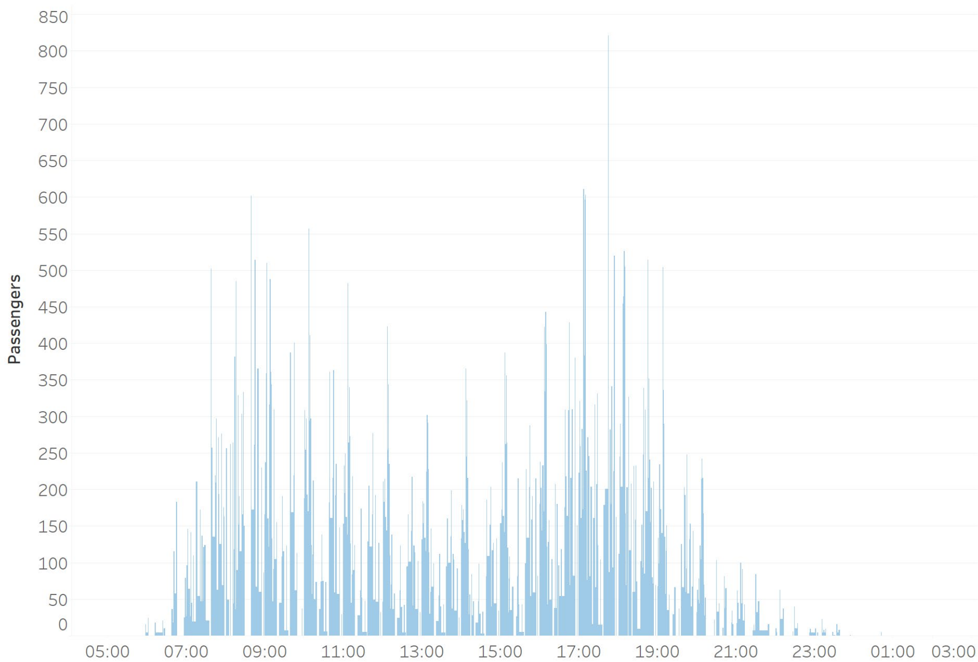
[41] Forecasts from the NMF model based on May 2018 WebTAG, supplied by DfT, https://www.gov.uk/government/publications/webtag-tag-unit-m4-forecasting-and-uncertainty-may-2018

[42] See, for example, Gwyn Topham, "Fall in rail journeys raises questions for train franchise firms", *The Guardian*, 9 October 2017, https://www.theguardian.com/business/2017/oct/05/fall-in-rail-journeys-raises-questions-for-train-franchise-firms; Rebecca Smith, "TfL 'doesn't fully understand' why passenger numbers are falling, says London Assembly Budget Committee", *City A.M.*, 16 January 2018, http://www.cityam.com/278852/tfl-doesnt-fully-understand-why-passenger-numbers-falling

Figure 1: Map showing TransPennine Express (blue) and other rail routes (grey), including section from Manchester Victoria to York (stations highlighted green)

Source: *http://www.projectmapping.co.uk/Reviews/Resources/tpe_map_geo_oct2016.pdf*

Figure 2: Sample 2-mile segment of track (Leeds on TransPennine Express route) showing number of passengers over a 24-hour period in 2017



3.35 Figure 3 below manipulates this data into a cumulative load duration curve which shows:

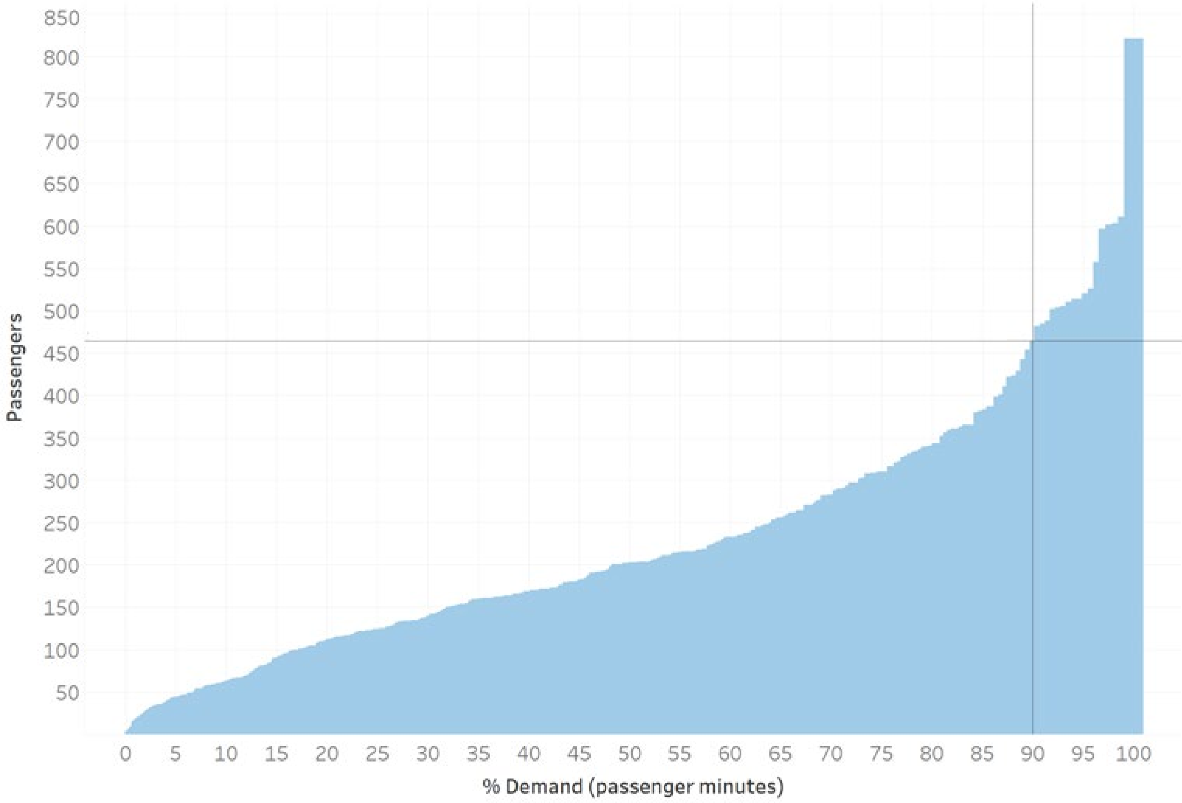
a) the number of passengers that are in the segment at the same time on the y axis (as in Figure 2 above); and

b) a cumulative measure of demand along the x axis (where demand is derived with reference to the number of 'passenger minutes' i.e. the height of each bar in Figure 2 multiplied by the width of the bar, measured in minutes).[43] In Figure 3, the level of demand has been normalised to 100% by dividing by the aggregate number of passenger minutes across the 24-hour period represented in Figure 2.

3.36 This cumulative load duration curve shows the percentage of total demand that takes place when the number of passengers in the segment at the same time is at, or below, the number on the y axis. In this example, the maximum number of passengers in the segment at any time is around 825 (as represented by the bar on the very right of Figure 3). This maximum passenger case is relevant if the rail connectivity solution needs to be sized so as to cope with the demand from all passengers. But this situation reflects only 2% of the total demand across the day (as represented by the width of this bar). Figure 3 also includes a vertical line at 90% on the x axis, with the corresponding measure on the y axis being around 460 passengers (i.e. 460 passengers in the segment at the same time). This implies that 90% of total demand in this segment occurs when there are 460 or fewer passengers in the segment at the same time (so if a trackside connectivity solution had enough capacity to serve the demand relating to 460 passengers only, then 90% of total passenger demand throughout the day would be met in full without constraints caused by the trackside connection). The graph also shows that if the trackside connection had this capacity, then the average data speed to passengers at the very peak would have to be slowed down by around 80% (825 / 460 = 1.79) because of the limitation on trackside connectivity.

[43] i.e. 400 passengers in the segment for 2 minutes would equal 800 'passenger minutes', and the number of passenger minutes can be used to derive a data requirement: e.g. if the blended average data rate per passenger is 150 kbit/s then 800 passenger minutes represents 7,200,000 kilobits (around 900 MB)

Figure 3: Cumulative load-duration curve of sample section of track (Leeds on TransPennine Express route), showing overall demand profile over a 24-hour period in 2017



3.37 The results we present below focus on the peak demand for each section of track (i.e. the very right hand side of Figure 3) since, in the first instance, it would be preferable to size a trackside connectivity solution so that it can meet all passengers' demand without needing to slow down services, even at the absolute peak of passenger demand, on account of a capacity limitation in the track-to-train link. However, it may be reasonable for commercial deployments to be designed in a way that does not plan to meet 100% of demand throughout the day if the incremental cost of doing so resulted in very expensive deployments. It is also possible that the impact of a reduction in the average data rate to the individual passenger at peak demand times may have a limited impact on consumer experience (particularly if it is for a short time only). For example, some applications adapt to lower speeds; e.g. many video-streaming platforms cope with a reduced data rate by lowering their resolution using adaptive coding. Media servers could also be used on the train itself to mitigate demand levels using pre-loaded content.

Findings

3.38 We have combined this analysis of peak passenger numbers with the average data rate per passenger (given above) in order to derive an implied capacity requirement for particular segments of rail track.

3.39 As previously explained, we are looking at overall passenger data demand both at current unconstrained usage levels and based on scenarios for 2025. The figures for 2025 (and associated interpretation for the mid-late 2020s) are more important in the context of the advice we have been asked to provide to DCMS, given a desire to build a future-proof network rather than one which has insufficient capacity only a few years down the line.

3.40 As shown in Table 4 below, our analysis suggests that, **today**, rail passenger demand for data on the East Coast Main Line could, across most of the network, be met by a system with a capacity of **200 Mbit/s** per two-mile segment of track.[44] Only in the sections of track approaching major urban centres and busy junctions (and in the approaches to London in particular) is demand likely to surpass this. In these places a capacity of around **300 to 500 Mbit/s** per two-mile segment could be needed.

3.41 According to our **2025 demand scenarios**, much of the network could be served with a throughput of **2 Gbit/s** per two-mile segment, with the busiest areas coming into and out of London requiring **3-5** Gbit**/s** (using our medium demand scenario). These figures correspond to our medium demand scenarios for the East Coast Mainline (discussed more in detail below). Higher levels of demand (deriving from our higher blended average rates per passengers) in very busy sections of track such as in those approaching central London, could reach **10 Gbit/s** under a high demand scenario.

Table 4: Demand per segment of track on mainline UK rail routes, 2017 and 2025 medium scenario

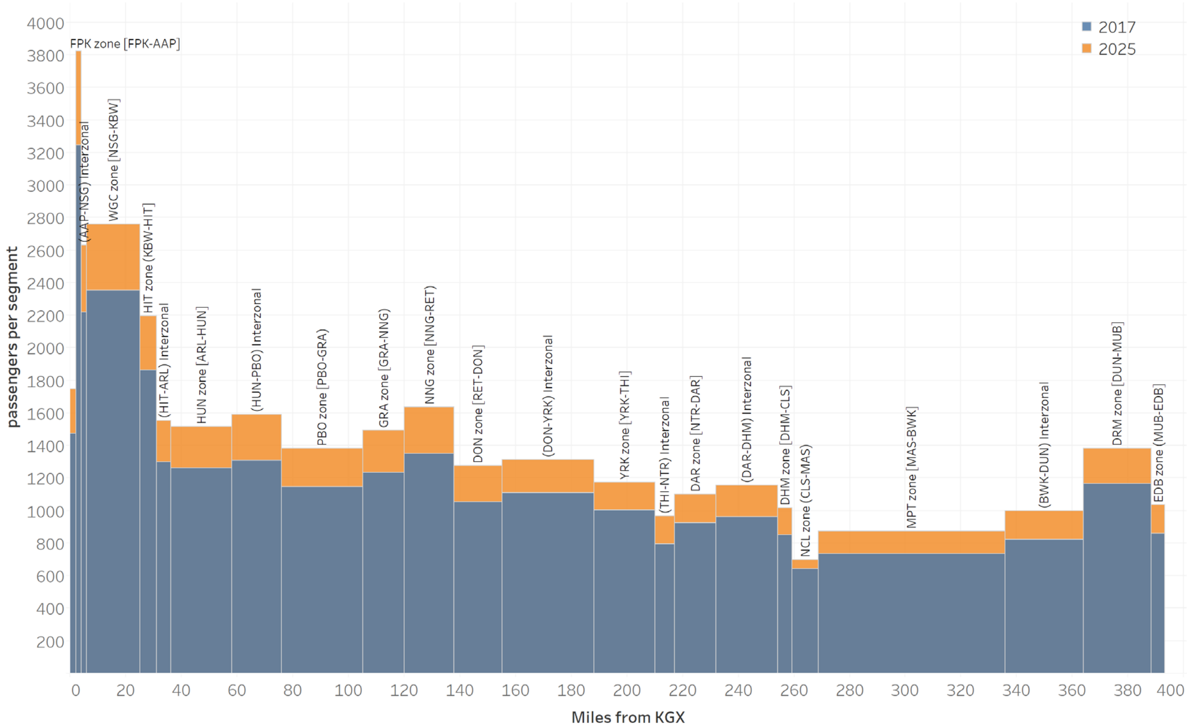
	2017	*2025*
Most of the line	200 Mbit/s	2 Gbit/s
Busier sections of track	300 Mbit/s	3-5 Gbit/s
Busiest sections of track	500 Mbit/s	10 Gbit/s

East Coast Main Line

3.42 We provide below more details about our analysis of the East Coast Main Line (ECML). Figure A1.6 below shows the ECML from London Kings Cross to Edinburgh Waverley, along with passenger numbers for different zones along the line in 2017 and 2025.[45]

[44] The use of two-mile segments of track is explained in Section 3.
[45] As the graph shows, the zones are not uniform in size. For more information on how the zones are derived, see Annex 1.

Figure 4: East Coast Main Line, peak passengers per zone in 2017 and 2025



3.43 The busiest part of this line (both in 2017 and 2025) is the roughly 30 miles between London Kings Cross and Hitchin in Hertfordshire. This is due to high numbers of commuter trains and passengers using this section of track, as well as converging tracks which serve other mainline routes. In particular, the mainline heading south from Kings Lynn and Cambridge joins the ECML just north of Hitchin. This area could require around 330 Mbit/s per mile to meet current levels of demand, and around 3.2 Gbit/s in 2025 (based on our medium future scenario for per-passenger data use of 1.2 Mbit/s).

3.44 However, as can be seen on the graph above, the 2-mile segment from Finsbury Park to Alexandra Palace is substantially busier than the rest of this 30-mile section. This area could require around 490 Mbit/s to meet current levels of demand, and 4.6 Gbit/s in 2025 (based on our medium future demand scenario). The route map below shows why this particular segment is so much busier than its neighbouring segments: the line into Moorgate station in the City of London splits off from the ECML south of Finsbury Park, and the Hertford Line splits off north of Alexandra Palace, running via Bowes Park to the east of the ECML, which runs via New Southgate. In addition to this, Finsbury Park is the first interchange with the London Underground for many commuters coming into London.

Figure 5: Route map showing ECML (stations highlighted green) and other rail routes passing through Finsbury Park

Source: Thameslink Railway website; Produced by FWT London 16/05/18 (GTR All Brands Diagram)

3.45 Other busy areas on the line are the sections from Hitchin to Peterborough and Grantham to Retford (approximately 75 miles in total); these could require around 200 Mbit/s per segment now, and around 2 Gbit/s in 2025. The fact that these areas are busier is due to a combination of having larger hub or interchange stations in these areas, having a higher number of commuter rail services, or having several rail lines converge in these areas (and therefore taking into account trains and passengers which are only on this line for part of their overall journey). An example would be the branch line from Lincoln which connects with Newark North Gate, or the line from Ely which joins the ECML just south of Peterborough.

3.46 Across the remainder of the line, a level of 175 Mbit/s per segment should suffice at present, although this could rise to around 1.7 Gbit/s by 2025.

3.47 The table below shows estimated demand figures for the East Coast Main Line across the busiest segments, moderately busy segments and the rest of the line, for today and 2025:

Table 5: Estimated passenger data requirement per segment across East Coast Main Line, ranked from busiest areas to least busy areas

		2017		*2025*			
Area	**Miles of track**	**Max passengers per segment**	**Data demand per segment**	**Max passengers per segment**	**Data demand per segment** *Low*	*Medium*	*High*
Finsbury Park Zone	*2*	3247	**490 Mbit/s**	3822	2.3 Gbit/s	**4.6 Gbit/s**	9.6 Gbit/s
London Kings Cross-Hitchin area, excluding Finsbury Park Zone (uses Alexandra Palace-New Southgate figures)	*30*	2220	**330 Mbit/s**	2630	1.6 Gbit/s	**3.2 Gbit/s**	6.6 Gbit/s
Hitchin-Peterborough and Grantham-Retford areas (uses Newark North Gate Zone figures)	*75*	1348	**200 Mbit/s**	1635	980 Mbit/s	**2 Gbit/s**	4.1 Gbit/s
Rest of line: Peterborough-Grantham, Retford-Edinburgh (uses Drem Zone figures)	*285*	1164	**175 Mbit/s**	1384	830 Mbit/s	**1.7 Gbit/s**	3.5 Gbit/s

3.48 Findings for the Great Western Main Line and the TransPennine Express can be found in Annex 1.

Implications

3.49 The results show that the largest capacity requirements are in the areas of densest train use in the approaches to London, with similar, but far less pronounced, increases in capacity requirements in the approaches to other large rail stations, especially in major urban areas with considerable commuter rail use. However, over the majority of the mainline rail network the capacity requirement is significantly lower. For example, for the East Coast mainline, the 30-plus miles coming into London would need a capacity of between 3 and 5 Gbit/s (in the medium scenario), but around 90% of the overall length of the line could be served with a capacity of 2 Gbit/s or below.[46] The picture for the other

[46] Note that we analyse the line considering all TOCs providing service over that line or stopping in the same stations, including commuter trains, local and regional trains. This is to make sure we include all passengers who could place demand on the trackside network. It also assumes that all trains over that line are equipped with the correct radio and antennas to provide data services to their passengers.

lines we have examined is similar, although the variability along the lines is somewhat less pronounced.

3.50 However, the results for the busiest segments in the approaches to London terminals need careful interpretation. For example, in areas such as in the 30 miles between London Kings Cross and Hitchin, peak demand is caused predominantly by the volume of commuter rail journeys, rather than long-distance intercity travel. If the trackside connectivity solution was provided only on longer-distance, intercity trains, or only the TOC running these services procured such a solution, then the capacity requirement of the trackside connectivity solution would be significantly less and would be much more uniform across the length of the line; for the ECML this would be around the lower level for the network, i.e. around 175 Mbit/s per segment now or 1.7 Gbit/s in 2025 (instead of 330 Mbit/s and 3.2 Gbit/s).

3.51 Additionally, there are some moderating factors which we are unable to model which could serve to reduce the peaks in data usage on the immediate approach to London. In particular, while business passengers and commuters may be some of the heaviest users of data services on trains if they are connected with laptops or tablets as well as phones, these same passengers may use the few minutes at the start or end of their journeys to set up or put away their devices, which could moderate demand in these busy areas.

3.52 We have also assumed that passengers on board trains will be connected to a specific on-board connectivity solution, and will not be sharing with passengers at stations who would be using either station Wi-Fi or mobile data from public networks.

3.53 Finally, it is worth keeping in mind that in areas of track with the 'peakiest' demand profiles, demand is generally heavily influenced by the presence of a smaller number of extremely busy trains, rather than a steady stream of equally busy trains throughout the day. This demand profile corresponds to areas where passenger numbers are driven by higher rates of commuter travel. As noted above, it may be reasonable for commercial deployments to be designed so as not to meet 100% of demand throughout the day if this were to result in much more expensive deployments; this reflects the potential for peak demands to be managed down with limited impact on consumer experience (e.g. through adaptive coding in video streaming applications).

4. Spectrum options to meet estimated passenger demand

Introduction

4.1 DCMS has asked us to advise on the capability of different spectrum bands to support trackside connectivity solutions in a way that could meet anticipated passenger data demand both today and over time. We set out in this section our assessment of the spectrum bands which might, in principle, be used to support track-to-train connectivity solutions and their relative advantages and disadvantages.

4.2 We have considered the following spectrum bands in this context:

- 2.7-2.9 GHz (and 2.9-3.1 GHz, as an extension to 2.7-2.9 GHz)
- 3.8-4.2 GHz
- 5 GHz (specifically 5150-5350, 5470-5725, and 5725-5850 MHz)
- 14.25-14.5 GHz
- 26 GHz (24.25-27.5 GHz)
- 66-71 GHz[47]

4.3 These include all the bands referred to us by DCMS as ones that industry stakeholders may be interested in. We do not consider the use of mobile spectrum bands in this section, but address this in Section 6.

4.4 The potential suitability of a spectrum band for supporting trackside connectivity solutions will depend on a variety of factors including:

a) The capability of the band to support data services at a given data rate and with a good quality of service (taking account of the limitations arising from the need to manage coexistence with other existing users of the band);

b) The extent to which its use for rail connectivity might conflict with other potential uses of the same spectrum in future (the 'opportunity cost');

c) The prospective ecosystem for equipment in this band (noting that bands which can take advantage of a large chipset ecosystem developed for mass-market applications at similar frequencies will be more attractive, all else being equal); and

d) The time and effort likely to be required to authorise the use of this spectrum for rail connectivity, which will depend in large part on the nature and extent of coexistence analysis required (and the degree of confidence that it will be possible to authorise its use once the work on coexistence with existing users has been completed).

---

[47] We supplied interim advice to DCMS in March in which we identified a longer list of potential bands. The list of bands included 4.8 GHz, 5.9-6.4 GHz, 10 GHz, 28 GHz, 32 GHz, 40 GHz, and 57-66 GHz. For a range of different reasons, we do not believe that these bands are as promising for providing track-to-train connectivity as the shortlist of bands we are outlining here.

4.5 The first section below presents our assessment of the generic capability of each band to support data services.

4.6 In the following section we consider the pros and cons of each band in turn with respect to coexistence challenges, opportunity cost, prospective ecosystem and degree of authorisation challenge. We bring together the results of our assessment of each band in a table towards the end of this section, before summarising the implications for the choice of spectrum band(s) to support trackside connectivity solutions.

4.7 Note that our work considers the potential suitability of different bands from a data service capability and spectrum policy perspective only. Other important factors will influence the choice of band(s) including, notably, the cost of deploying trackside solutions. This cost will be influenced by the choice of spectrum band(s) because the range (coverage) of a single base station, and hence the number of base stations that are needed to provide service along a given length of track, will differ between spectrum bands. The unit cost of the equipment will also vary by band depending on the technology and the scale of any existing equipment ecosystem. Consideration of these issues goes much wider than the scope of our work, although we do comment briefly on base station ranges at the end of this section.

Potential capability of different bands

4.8 The throughput that can be achieved through the application of suitable mobile technology in a band is a product of a number of factors including:

a) The **spectral efficiency** that is practically achievable;

b) the **typical bandwidth** that can be employed by a radio; and

c) the number of **radio channels** used.

4.9 In Annex 2, we have considered the typical spectral efficiency that is achievable with modern technologies, such as 4G LTE-Advanced, 5G New Radio, Wi-Fi, and WiGig. We think that a spectral efficiency of around 2-4 bit/s/Hz is a reasonable assumption for network deployments in a rail environment for all of these technologies. Note that 5G NR can achieve higher spectral efficiency using MIMO for access in a multi-user environment, but this spectral efficiency gain is not relevant in the case of a rail connectivity solution serving a single train (see Annex 2 for further information).

4.10 Bandwidth is a function of the channel size that the technology can employ that fits within the band (absent other systems). Whilst smaller channel sizes can often be used, the assumption is that it is more efficient to choose the largest possible channel size (based on spectral efficiency).

4.11 The capacity of the radio layer is then a product of the spectral efficiency and the typical bandwidth available.

4.12 Table 6 below shows the amount of bandwidth and an estimate of the data rates we would expect from the different bands given typical technology and typical maximum channel width for that band. For example, 400 MHz in the 26 GHz band could provide a data rate of 800 to 1600 Mbit/s (based on a spectral efficiency of 2-4 bit/s/Hz).

Table 6: Bandwidth available and estimated data rate based on typical technology

Band	Technology used to estimate maximum channel bandwidth	Maximum bandwidth available absent other users (MHz)	Typical maximum channel bandwidth (MHz)[48]	Expected average rate achievable for a single channel (Mbit/s)[49]
2.7-2.9 GHz	4G LTE	200	100[50]	200 – 400
3.8-4.2 GHz	4G LTE/5G NR	400	100	200 – 400
5 GHz	Wi-Fi	600[51]	80[52]	160 – 320
14.25-14.5 GHz	5G NR[53]	250	200	400 – 800
26 GHz	5G NR	3250	400	800 – 1600
66-71 GHz	WiGig	4320	2160[54]	4320 – 8640

4.13 The table shows that the lower frequency bands have enough bandwidth for a single channel to support rates in the low hundreds of Mbit/s, whereas the mmWave bands have enough bandwidth for a single channel to support Gbit/s rates. If greater capacity is required, then it may be possible to aggregate channels used by a base station (assuming that additional spectrum is available (for example, two 400 MHz channels in the 26 GHz band might support 1.6-3.2 Gbit/s).

4.14 The achievable rates given in Table 6 are directly relevant when considering connectivity to an individual train (cf. the indicative busy train demand numbers in Table 3 in Section 3). When considering the provision of connectivity to a number of different trains in a short section of tack at the same time (cf. the indicative demand per section of track numbers in Table 4 in Section 3), the distance between trackside base stations is also relevant (the closer together the base stations, the greater the overall capacity per mile of track can be). We pick up this point again at the end of this section.

[48] With typical technology, the largest single channel or aggregation of channels where carrier aggregation can be used.
[49] This is the average physical layer rate over a cell radius commensurate with the power budget; the rate experienced by an application may be lower and dependent upon other users in the cell.
[50] Assuming 4G carrier aggregation technology is used to bond together 20 MHz channels.
[51] This is fragmented due to sub-banding, owing to the nature of the allocation plan.
[52] Largest common channel size available in all sub bands.
[53] Assuming this band were to be supported by a 5G NR vendor with similar specifications to 26 GHz.
[54] Based upon 802.11ad channel widths.

4.15 Whilst Table 6 above shows maximum channel bandwidth for each of the candidate bands, the bandwidth that is available in reality may be smaller due to the need to manage coexistence with other users in the band. In the lower bands this may require geographic carve-outs to protect other users (as discussed in more detail below), whereas in the higher bands it is more likely that antenna beam steering technology and other sharing technologies will facilitate sharing without great restriction.

Assessment of individual bands

4.16 For each band, we now consider the nature and extent of coexistence challenges with other existing users of the band; the extent to which its use for rail connectivity might conflict with other potential uses of the spectrum in future (the 'opportunity cost'); the prospective ecosystem for equipment in this band; and the effort likely needed to authorise the use of this spectrum for rail connectivity.

2.7-2.9 GHz

Existing usage and coexistence issues

4.17 The 2.7-2.9 GHz band is mostly used for air traffic control in the proximity of civil and military airfields. Otherwise the band is used for radar surveillance by the military on land and at sea, and for weather research using radar by the Meteorological Office.

4.18 Since the band mostly contains ground radar with few assignments in use by many countries, the band has potential for sharing on a coordinated basis, and has been studied by CEPT for shared use,[55] which has led to sharing by Programme Making and Special Events (PMSE) for video in five nations, notably in France[56] (outside Europe video PMSE is also authorised in this band, such as in New Zealand).

4.19 In the UK, there are 98 locations where radar is used in the band, so sharing the spectrum would need to be coordinated on a geographic basis to ensure sufficient frequency separation to the closest radars. Sharing by rail would imply directional antennas to focus radiation along the track, providing additional isolation between the systems and improving the prospects of sharing.[57]

4.20 Accordingly, this band has already been identified by Ofcom and the Government's Spectrum Central Management Unit (CMU), which sets targets for sharing or release of

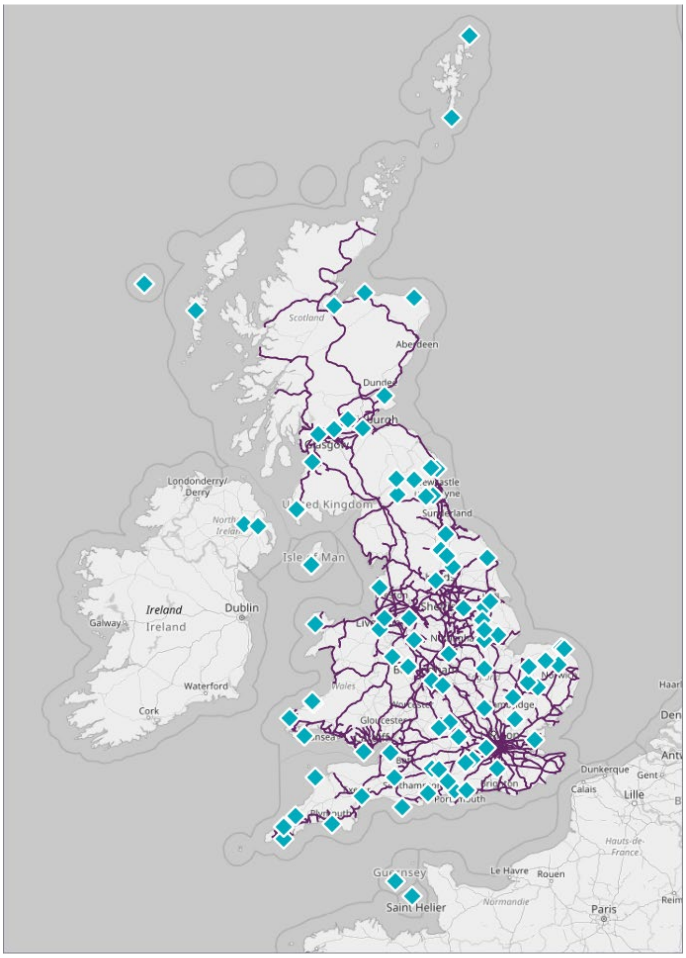
---

[55] CEPT, *CEPT Report 61*, approved 17 June 2016, https://www.ecodocdb.dk/download/9cc18925-6824/CEPTRep061.pdf
[56] CEPT, *ERC Recommendation 25-10: Frequency Ranges for the Use of Terrestrial Audio and Video Programme Making and Special Events (PMSE) applications*, amended 18 October 2016, https://www.efis.dk/views2/pmserec2510.jsp; see also Annex 2 of the Recommendation: https://www.efis.dk/report/report2510AnnexImplementation.do?annexId=2 (accessed 25 July 2018)
[57] Previously, our analysis for 2.6 GHz spectrum that was cleared and auctioned for mobile identified remedial action required to protect radar from blocking effects. This effect was planned due to the potential aggregation of signal of multiple high-power base stations from many operators. However, sharing by a track-to-train system implies a significantly different situation because base station operating powers in the proximity of radar would be several orders of magnitude lower as high-power aggregation would not be in effect and antenna directivity would limit any incident power.

spectrum currently used by the public sector, as a good candidate for sharing for other public-sector requirements.[58]

4.21 We have not carried out any specific analysis in this band, but we understand from industry that 40 MHz could be available nationally (using different frequencies in different locations), possibly with some specific exclusions in locations where there is defence use. Otherwise there may be enough to give up to 100 MHz in aggregate. This could deliver potential data rates of between 80-400 Mbit/s.[59]

Figure 6: Current use in 2.7-2.9 GHz band mapped against UK rail routes, showing radar locations (blue)



Equipment ecosystem

4.22 Whilst the band is not a standard mobile band (i.e. specified by 3GPP), there appear to be some 4G LTE products on the market which cover this band and some manufacturers have

[58] UK Government Investments, *Public Sector Spectrum Release Programme: 2nd Annual Report by UKGI Spectrum Central Management Unit*, August 2017, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/643037/CMU_2017_Annual_Report.pdf

[59] A rate of 80 Mbit/s corresponds to 40 MHz of spectrum in aggregate with an efficiency of 2 bit/s/Hz, and 400 Mbit/s to 100 MHz in aggregate with an efficiency of 4 bit/s/Hz.

suggested they can extend existing products to cover the band. However, the specialised ecosystem would be dependent on a few suppliers only. Reasonable throughputs can be achieved with current 4G LTE Advanced technology particularly when employing intra-band carrier aggregation.

Opportunity costs

4.23 The band is undergoing some change to modernise some air traffic control capabilities.[60] However, we are not aware of any future predicted use of the 2.7-2.9 GHz band which would be prevented by rail-based systems sharing the band. Accordingly, the opportunity cost of its use for rail connectivity should be modest.

Authorisation issues

4.24 Whilst Ofcom would authorise new spectrum uses such as mobile, the Civil Aviation Authority's (CAA) Safety and Airspace Regulation Group (SARG) is responsible for the safe and efficient use of both civil and military airspace. Civil licences for aeronautical radio navigation radar systems are distributed by the CAA on behalf of Ofcom. Responsibility for granting permissions for military radiolocation rests with the Ministry of Defence (MOD) and is coordinated with the CAA. All radiolocation frequency permissions are reserved exclusively for MOD use except where assignments for civil use are agreed with Ofcom.

4.25 Accordingly, further work with both the CAA and MOD will be required to ensure that no radar systems would suffer unacceptable interference from any rail system. This will likely require testing of critical systems in the presence of interference to determine safe operational limits, a process that may take some time to conclude.

4.26 Practically, meeting these operational limits will require that the spectrum in use by a given radar will be excluded for use around the radar location, which would result in different blocks of spectrum being available in different locations, and in some very specific cases there may be no availability at all. In order to authorise any use, we would require the development of a location-specific sharing plan that satisfies the safety case requirements for an operational licence.

4.27 The creation of a new nationwide authorisation for rail connectivity along rail corridors could take a couple of years as there are many tasks to develop a safe and comprehensive sharing plan.

2.9-3.1 GHz (as an extension to 2.7-2.9 GHz)

Existing usage and coexistence issues

4.28 The 2.9-3.1 GHz band is used globally for maritime radar, mostly for navigation purposes on larger shipping. This is relevant to ships' radar use around the UK coast and also, in

---

[60] MOD, "Project Marshall – Air Traffic Management", https://des.mod.uk/what-we-do/navy-procurement-support/marshall-air-traffic-management/ (accessed 25 July 2018)

principle, on inland waterways. It is also used for vessel traffic management by the coastguard and port authorities in a few key locations in the UK. The band is also used for radar surveillance by the military on land and at sea, as well as by DEFRA for monitoring bird strikes and migration in various locations such as at windfarms.[61]

4.29 We have not carried out any specific analysis in this band, but it is unlikely that the band could be shared near the coast and navigable waterways. However, there may be opportunities to share this spectrum inland and this could, in principle, add a potential source of bandwidth where spectrum in 2.7-2.9 GHz is constrained by radar use.

Equipment ecosystem

4.30 As with 2.7-2.9 GHz, some 4G LTE products may cover this band or could possibly be adapted to do so. However, this would not be a standard product.

Opportunity costs

4.31 Inland, we are not aware of any significant other uses of the band beyond what is currently in-use, and accordingly the opportunity cost for rail connectivity should be low.

Authorisation issues

4.32 The band is a key band for maritime radar use as part of safety of life systems, so any other use of this spectrum would require the active engagement of the Maritime and Coastguard Agency (MCA) to ensure that safety is not compromised. This may require technical trials to demonstrate safe operation inland. Furthermore, the same kind of coexistence work may be required with MOD as would be required in 2.7-2.9 GHz.

4.33 As with 2.7-2.9 GHz, a location-specific sharing plan satisfying safety requirements would be required to authorise use for an operational licence.

3.8-4.2 GHz

Existing usage and coexistence issues

4.34 3.8-4.2 GHz has allocations for fixed satellite which form the space-to-Earth segment (i.e. the ‘receive’ portion) of C-band, which is used by a number of services, including overseas broadcasting and data communications. The band is also currently used for fixed services including microwave links and Broadband Wireless Access (BWA).

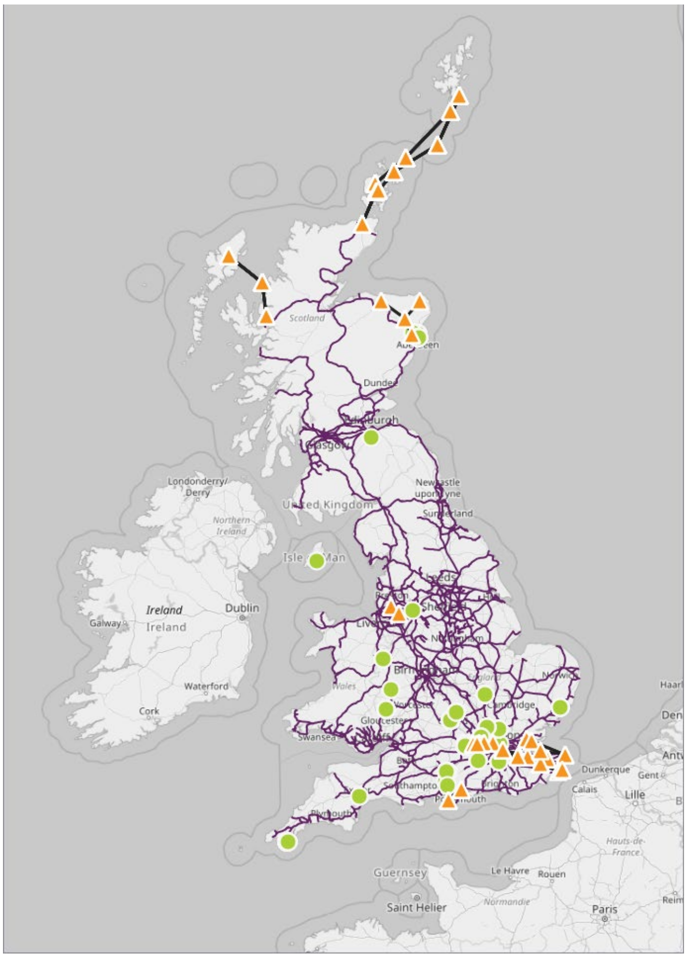
4.35 Taking satellite use, the band is used by Earth stations operating under Permanent Earth Station (PES) licences and grants of Recognised Spectrum Access for Receive-only Earth Stations (RSA for ROES), as well as on a licence-exempt basis. Any new system in this band would have to be coordinated in a way which did not produce undue interference into satellite Earth station sites operating under a PES licence or grant of RSA, which would

---

[61] Animal and Plant Health Agency, “Bird and bat tracking and radar”, http://apha.defra.gov.uk/apha-scientific/services/wildlife-management/bird-management/bird-detecting-radar.htm (accessed 17 August 2018)

imply that there will be zones around satellite Earth stations within which a track-to-train system would not be usable, at least over the licensed bandwidth. Earth stations receiving transmissions at these frequencies are located in various parts of the UK, but in particular there are several in and around London and the surrounding counties which could have a significant impact on the ability of any provider to roll out a system using this band on the mainlines approaching London (this could be tens of kilometres if Earth station frequencies are re-used by track-to-train systems and their antenna systems are aligned, but much less if not aligned or using frequencies not utilized by nearby Earth stations).

Figure 7: Current use in 3.8-4.2 GHz band mapped against UK rail routes, showing fixed links (orange triangles) and Earth station locations (green circles)



4.36 The fixed links in this band are used for distribution for terrestrial TV signals, high-speed financial trading and some backhaul services for MNOs. There are currently 43 fixed links in the 3.8-4.2 GHz band, but ongoing changes to the 3.6-3.8 GHz band[62] will mean that some fixed links currently paired with 3.8-4.2 GHz will move out of the band by the end of 2022 (and some may be able to move earlier than that).[63] Similar to PES, the operation of

[62] Ofcom, *Improving consumer access to mobile services at 3.6GHz to 3.8GHz: Statement*, 27 October 2017, https://www.ofcom.org.uk/__data/assets/pdf_file/0019/107371/Consumer-access-3.6-3.8-GHz.pdf

[63] This is because fixed links in this band operate on a duplex basis, paired with spectrum in the 3.6-3.8 GHz band. Therefore, when links are cleared out of 3.6-3.8 GHz, the corresponding paired link in 3.8-4.2 GHz will also be removed.

track-to-train systems in certain areas within the main beam of an antenna may be restricted, however the directionality of both the track-to-train system and of fixed links should help to limit the size of these zones.

4.37 Previous studies looking at mobile use in this band[64] showed the potential for spectrum sharing as being around 300 MHz, although this could be fragmented and may diminish to zero with restrictions close to certain key Earth stations. These restrictions would probably include parts of the Welsh borders, South West and approaches to London, meaning that this band could not support a single solution across the whole rail network.

4.38 Overall, however, this could mean that 200-400 Mbit/s would be achievable if a single channel system were deployed in areas with little restriction.[65]

Equipment ecosystem

4.39 Our understanding is that several vendors are planning 4G and 5G technology chipsets capable of covering this band from 2019, and as a 3GPP band with large potential bandwidth, a significant eco-system will likely develop.[66]

Opportunity costs

4.40 As outlined in our annual plan[67] we are planning to consult on proposals later this year to enable greater sharing in this band. We consider that this band could be used by a range of different players including broadband wireless access and low power industrial use on a localised basis.

4.41 We do not anticipate rail use of 3.8-4.2 GHz to have a substantial impact on future indoor or industrial use of this band. However, as mainline rail lines pass through large areas of the countryside, it is possible that rail use in some areas could compete with future BWA needs.

Authorisation issues

4.42 Sharing by rail applications could be facilitated by the sharing mechanism we are intending to consult on later this year. However, as noted above, there is no guarantee that spectrum could be available in all areas given that shared access will be on the basis of coordination with users already in the band.

---

[64] Transfinite Systems, *Geographic Sharing in C-band: Final Report*, 31 May 2015, https://www.ofcom.org.uk/__data/assets/pdf_file/0012/51303/c-band-sharing.pdf; the report looked at the whole 3.6-4.2GHz band but also stated that 'We find little difference between the whole frequency range and a separate analysis of 3.6 - 3.8 GHz and 3.8 - 4.2 GH' (p.7)

[65] Given more spectrum, higher rates may be achievable with 5G aggregation technologies.

[66] See 3GPP TR 38.813: New frequency range for NR (3.3-4.2 GHz), https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3296 (accessed 25 July 2018)

[67] Ofcom, *Annual Plan 2018/19: Making communications work for everyone*, 28 March 2018, https://www.ofcom.org.uk/__data/assets/pdf_file/0017/112427/Final-Annual-Plan-2018-19.pdf

5 GHz

Existing usage and coexistence issues

4.43 The 5 GHz band covers a range of allocations and is a key band for short-range devices that are licence exempt, notably Wi-Fi. The three 5 GHz bands currently available for fixed and mobile applications are 5150-5350, 5470-5725, and 5725-5850 MHz. All bands can be operated under an exemption, but the lower band is only authorised indoors with the others permitting outdoor use. All bands require the use of various spectrum sharing technologies including Dynamic Frequency Selection (DFS), which is used to protect various radar types, including the main rainfall radar network. Higher power outdoor use (4W) is possible under a light-licensing scheme, although this is only available to fixed systems in 5725-5850 MHz.

4.44 Rolling out track-to-train systems in these bands beyond current authorisation limits (e.g. using higher power) could cause interference to existing indoor and outdoor Wi-Fi systems, as well as the growing number of BWA deployments in the 5725-5850 MHz sub-band which comprise a significant proportion of the more than 12,000 registered stations and have averaged 25% annual growth over the last three years. There is also significant potential for interference from Wi-Fi to track-to-train systems in urban areas where Wi-Fi is densely used, something which is difficult to mitigate and would likely lead to throughput reductions and/or poor service in those areas.

4.45 Additionally, as these bands are much used for Wi-Fi, some consideration would have to go into how to ensure the track-to-train system did not itself interfere with the in-carriage Wi-Fi.

4.46 Assuming the largest size Wi-Fi channel common to all sub-bands, this would mean 160-320 Mbit/s could be achieved, although this figure would be diminished in the presence of interference from other users in the band, especially where there is significant licence exempt use by omni-directional systems in close proximity to rail.

Equipment ecosystem

4.47 These bands have a highly developed ecosystem, with standardised Wi-Fi and customised equipment. The band has several examples of products used in a rail environment to deliver mobile broadband and has been widely deployed including in the UK.[68]

Opportunity costs

4.48 The use of the 5 GHz bands is growing. Last year we made more spectrum available in 5725-5850 MHz with a licence exemption to facilitate greater use[69] and help satisfy this

---

[68] Cisco, "Reinventing the 08:15 from Glasgow to Edinburgh; Cisco and Partners Enable High-Speed Connectivity on Trains", 15 September 2017, https://newsroom.cisco.com/press-release-content?type=webcontent&articleId=1878932

[69] Ofcom, *Statement on improving spectrum access for consumers in the 5 GHz band and Notice of proposal to make Wireless Telegraphy Exemption Regulations 2017: Consultation on Regulations and proposed technical parameters*, 9 March 2017, https://www.ofcom.org.uk/__data/assets/pdf_file/0032/98159/5p8-Regs.pdf

demand. The future use of this band would likely be comprised of additional indoor and outdoor Wi-Fi, as well as additional BWA deployments. Changes to the current exemption to permit rail connectivity applications to use much higher power could impair the use of other licence exempt applications near rail lines, which could have material opportunity costs.

Authorisation issues

4.49 Sharing by rail applications is possible today with current exemptions in 5470-5725. This band has significant bandwidth and supports 1 W (30 dBm) use by mobile outdoors.

4.50 Adding new authorisations beyond existing authorisation limits could be quite challenging. In the lowest sub-band, this would require significant international work to coordinate with the satellite community, something that would take time to accomplish. In the highest sub-band fixed use is authorised at higher power (4W), so the impact of mobile use on fixed would require study, probably requiring coordination of use in the proximity of rail. In all cases careful analysis would be required to prevent an undue interference due to an imbalance of rights between users without effective sharing mechanisms to redress the balance.

4.51 In our decision to make more license exempt spectrum available in the 5725-5850 MHz band, we outlined some further options for improved spectrum access. Some of these, such as increasing power limits, could benefit rail. However, given the importance of these bands, higher power authorisation beyond current limits is unlikely even with significant effort and time. Accordingly, in the short term we only consider the middle sub-band, 5470-5725 MHz, to be suitable for rail.

14.25-14.5 GHz

Existing usage and coexistence issues

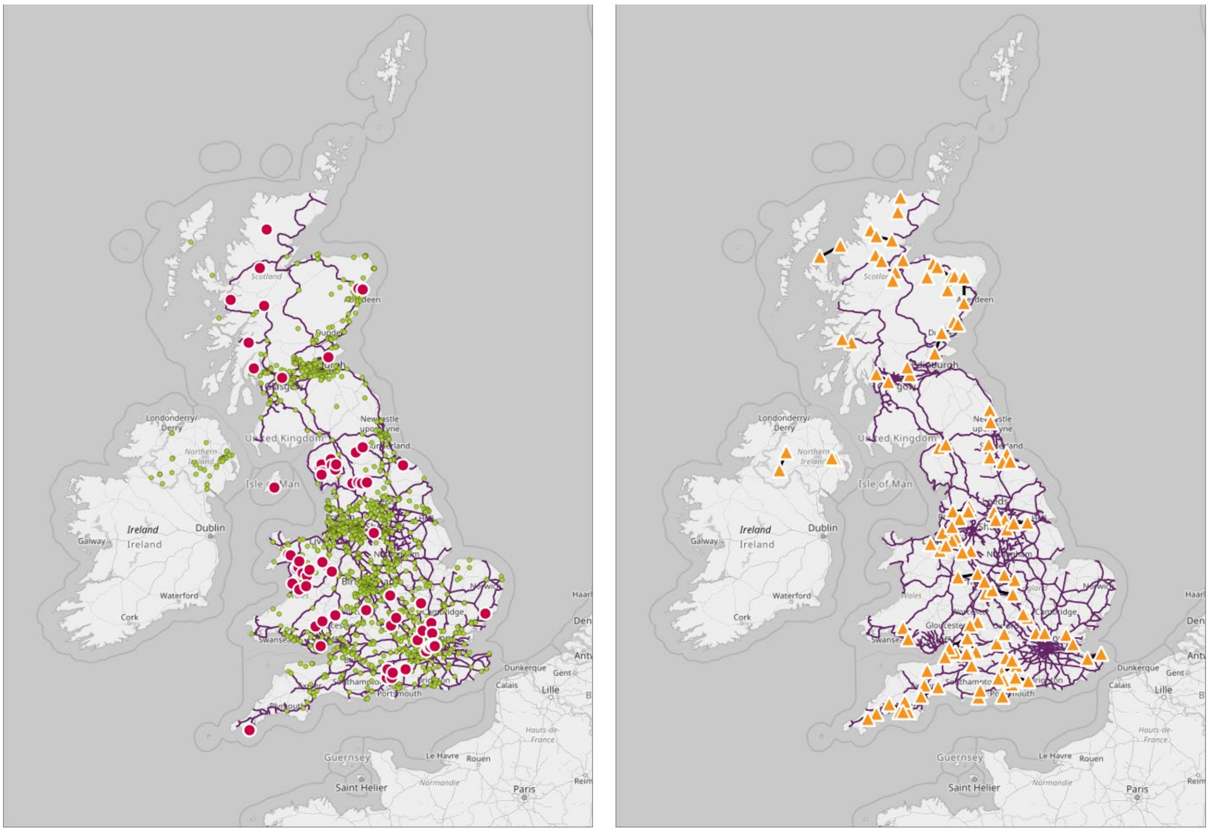
4.52 Whilst this band has a co-primary allocation to mobile, the band is mainly used for fixed links and for Earth stations as a satellite uplink band (Earth-to-space transmissions).

4.53 The band is not open to new licences for fixed links and their number is diminishing (currently around 110). In contrast the band is quite active for transportable Earth stations which are licensed on a temporary basis at a rate of around 700 per month over much of the geography of the UK for applications such as news gathering. In addition, there are 226 permanent Earth station locations.

4.54 In terms of coexistence, rail use could be coordinated with fixed link infrastructure, with exclusions around link receivers for example. With satellite uplink use, the risk of interference would mainly come from permanent and transportable Earth station systems into the track-to-train system, and this would require coordination (our systems already limit use around certain key locations such as airports).

4.55 If 5G mmWave technology were to be available in this band with a 200 MHz channel of spectrum, we estimate this band could deliver 400-800 Mbit/s. Given the size of this block is only 250 MHz, this could be limiting for any future capacity expansion.

Figure 8: 14 GHz band use mapped against UK rail routes, showing permanent Earth stations (red) and transportable Earth station deployments between 1 November 2017 and 1 May 2018 (green), left, and fixed links (orange), right



Equipment ecosystem

4.56 Whilst this band has been studied for 5G,[70] it is not currently a 3GPP band, and therefore we are not aware of any current plans by vendors to make equipment in this band.

Opportunity costs

4.57 The future use of this band could include low Earth orbit (LEO) satellite constellations, and there are proposals for satellite access links by mobile satellite terminals in this band.

[70] Peter Ökvist, Henrik Asplund et al, *15 GHz Propagation Properties Assessed with 5G Radio Access Prototype*, Ericsson, https://www.ericsson.com/assets/local/publications/conference-papers/15ghz-propagation.pdf (accessed 25 July 2018)

Authorisation issues

4.58 To permit use for rail would probably require a change in the authorisation of transportable Earth stations to limit use near rail, as otherwise rail use could suffer from a low quality of service.

4.59 If new evidence emerged that LEO networks required additional spectrum for uncoordinated terminals in this band beyond their current authorisation in 14-14.25 GHz, then this could require an assessment of interference potential from mobile satellite terminals.

26 GHz

Existing usage and coexistence issues

4.60 The 26 GHz band (24.25-27.5 GHz) is termed the 'pioneer' 5G mmWave band by the RSPG[71] and will likely be a key mmWave band for delivery of high bitrate mobile services in Europe. The band is formed of a large block covering a number of allocations from 24.25 to 27.5 GHz and is currently under international study to determine operating limits.

4.61 Whilst these international studies have yet to be concluded, studies show that 5G use in this band is feasible. However, a key factor regarding operating limits is the protection of passive services below the band where there are Earth exploration satellites, which may have bearing upon equipment operating in the lower part of the band.

4.62 In terms of use today in the UK, the band contains around 3,000 fixed links using the spectrum below 26.5 GHz with duplex frequencies separated by a 112 MHz gap and with a total of 96 MHz of guard bands at the top and bottom of the band. Whilst we have not conducted a specific study, there is potential to use some of this guard spectrum and possibly to re-use some of the assigned spectrum along the railways, probably at least 100 MHz in the shorter term.

4.63 The 26.5-27.5 GHz range is currently allocated for use by defence, however the MOD believes there is scope for 5G to be deployed in this band.[72] Otherwise Short Range Devices (SRDs) are authorised in much of the band on a licence exempt basis, with some historic short-range radar for automotive purposes (authorisation closed since 2013), tank level probing radar and radar level gauges, none of which should provide significant coexistence issues (they operate on a non-interference, non-protection basis).

4.64 Assuming that it is possible to use 100 MHz in the lower band in the short term and eventually 400 MHz, and that a single 400 MHz channel is possible in the upper band, Gbit/s speeds should be achievable, with rates in the range of 0.2-1.6 Gbit/s.[73]

---

[71] RSPG, *Strategic spectrum roadmap towards 5G for Europe: RSPG Second Opinion on 5G networks*, 30 January 2018, https://circabc.europa.eu/sd/a/fe1a3338-b751-43e3-9ed8-a5632f051d1f/RSPG18-005final-2nd_opinion_on_5G.pdf

[72] Ofcom, *5G spectrum access at 26 GHz and update on bands above 30 GHz: Call for input*, 28 July 2017, https://www.ofcom.org.uk/__data/assets/pdf_file/0014/104702/5G-spectrum-access-at-26-GHz.pdf

[73] Given more spectrum, higher rates may be achievable with 5G aggregation technologies.

Figure 9: Current use in 24.25-26.5 GHz band mapped against UK rail routes, showing fixed link end station locations (orange)

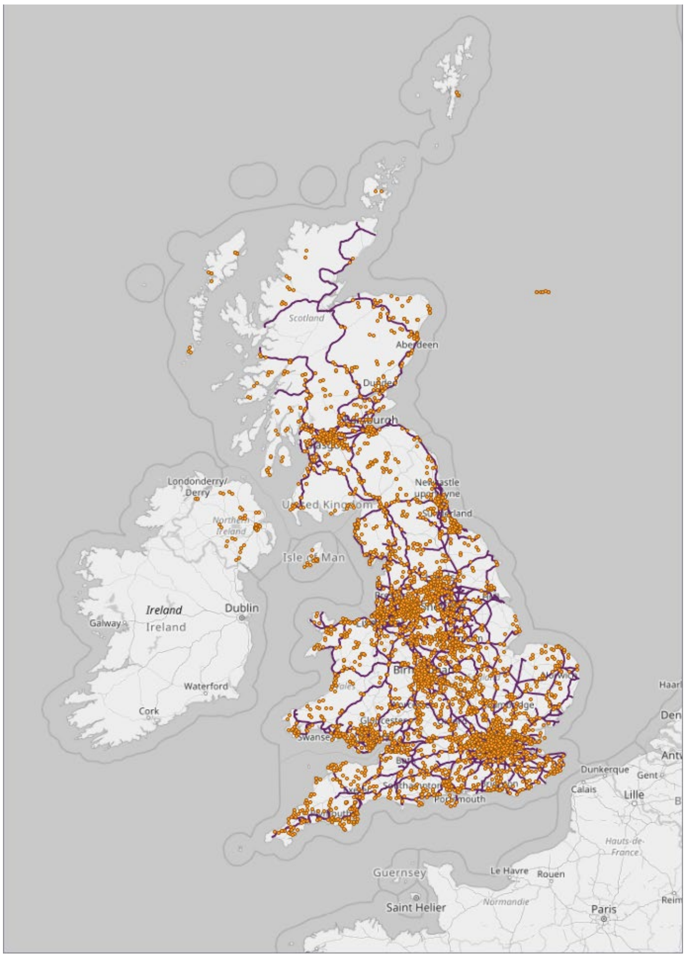
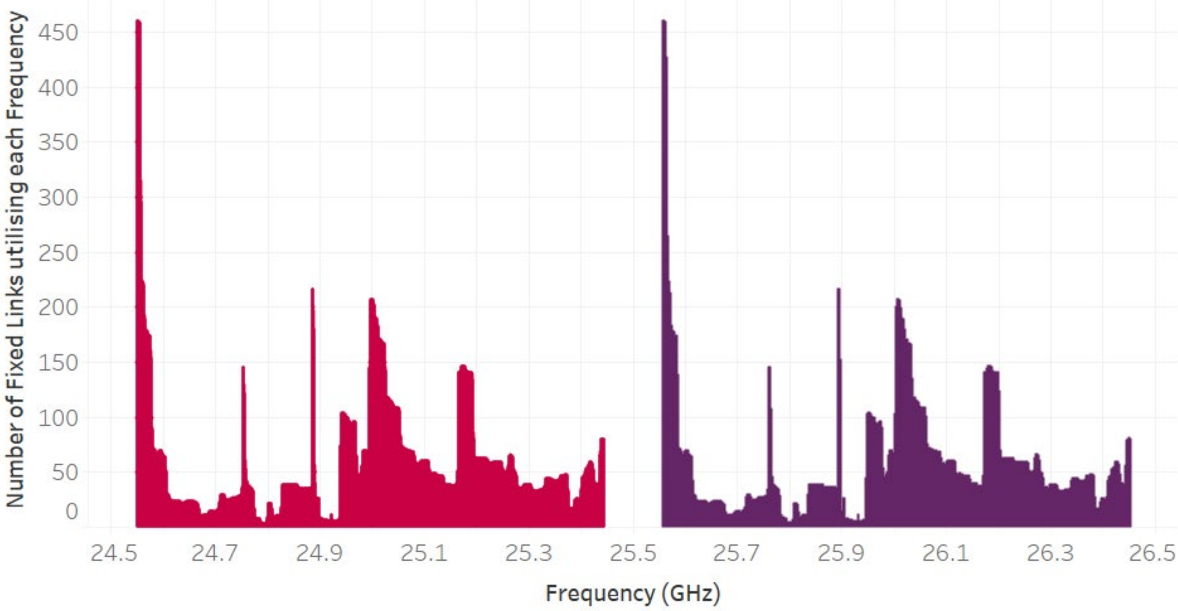


Figure 10: Fixed link deployments in 24.25-26.5 GHz band by frequency, showing lower duplex (red, left) and upper duplex (purple, right) as well as 112 MHz centre gap (blank, middle)



Equipment ecosystem

4.65 The upper 1 GHz of the band is within the tuning range of 28 GHz 5G equipment that is forecast to be available in 2019, with equipment covering the entire 24.25-27.5 GHz range sometime thereafter. Finally, whilst yet to be operational, there are current trials demonstrating 28 GHz technology in a rail environment in Japan.[74]

Opportunity costs

4.66 There are many applications that may be deployed in this band including fixed and mobile use cases. Responses to our 2017 call for input on the 26 GHz band indicated that it is likely to become important for 5G, however many suggested that it is too early to say how the band will be used, and for what purposes. A 5G status update document with more detail was published in March.[75] We will continue to gather evidence from stakeholders across different sectors and continue our engagement internationally to inform our understanding given the wide international interest in using high frequency spectrum for mobile.

4.67 Given the significant potential bandwidth, propagation losses and technology features such as beamforming, it is likely that there is good potential for future sharing. However, since this band is expected to be the focus for 5G mmWave applications, this means that its use for rail connectivity could need to coexist with other 5G applications in future and this might be an issue on rail routes passing through urban areas. Whilst the rail corridors are geographically defined and limited in their coverage, and rail connectivity solutions are likely to have a high degree of directionality, there may be an area around the rail track where other users of the same frequencies might need to be restricted (or close coordination would be required) so as to avoid interference between them and the rail connectivity service. Therefore, although there could be some opportunity cost with respect to potential future uses, the limited locational impact is likely to mean that this opportunity cost should be modest.

Authorisation issues

4.68 We are particularly keen to encourage trials at 24.25-27.5 GHz, as the pioneer 5G mmWave band, and further details on innovation and trial licensing can be found on our website.[76]

4.69 Authorising 5G use in the upper band would be relatively straightforward with no coexistence issues anticipated due to the relatively light use above 26.5 GHz, however, authorisation in the lower band would require significant coordination with existing users. For this reason, and due to the other differences between the lower and upper parts of the

---

[74] Monica Alleven, *FierceWireless*, “Japan’s DoCoMo claims 5G first in field trial involving 28 GHz and ultrahigh mobility”, 9 May 2018, https://www.fiercewireless.com/wireless/japan-s-docomo-claims-5g-first-field-trial-involving-28-ghz-and-ultra-high-mobility

[75] Ofcom, *Enabling 5G in the UK: Discussion document*, 9 March 2018, https://www.ofcom.org.uk/__data/assets/pdf_file/0022/111883/enabling-5g-uk.pdf

[76] Ofcom, *Innovation and Trial licensing: Guidance notes for applicants*, 9 March 2018, https://www.ofcom.org.uk/__data/assets/pdf_file/0014/53105/ofw357nonopguide.pdf

band listed above, we have considered the lower and upper parts of the band separately in our overall assessment of potential spectrum bands for track-to-train connectivity and in Table 7 below.

66-71 GHz

Existing usage and coexistence issues

4.70 The 66-71 GHz band is free of incumbent use in the UK. As part of our Fixed Wireless Strategy we consulted on this band, and consequently we are taking immediate steps to make this band available and to align it with the 57-66 GHz range. In particular the new arrangement means that the full 57-71 GHz band will shortly become available under an exemption that allows a radiated power of up to 40 dBm for SRDs and an exemption of up to 55 dBm for fixed wireless systems.[77]

4.71 This exemption brings the possibility for multi-Gbit/s speeds in a mobile context using technologies such as WiGig. However, delivering gigabit performance at longer ranges may be challenging considering rainfall. This can be mitigated with higher powers, but this would potentially cause coexistence issues for other licence exempt users operating in proximity of the railway line.

Equipment ecosystem

4.72 This band has an existing ecosystem from a number of manufacturers and includes WiGig-based technologies which is a standardised over the wider 57-71 GHz range. Today WiGig technology is mostly for short-range applications below 66 GHz,[78] however, above 66 GHz there are products for point-to-multipoint broadband wireless access systems. WiGig technology has already been used in several proof of concept trials regarding track to train systems in the UK.[79] Various other mobile technologies may emerge including those that are IMT-compliant.

Opportunity costs

4.73 There are many applications that may be deployed in this band for fixed and mobile use cases, and sharing should work well given technology features such as beamforming and dynamic channel selection. Accordingly, the opportunity cost should be low.

Authorisation issues

4.74 The exemption power limit means that ranges are somewhat limited, as rain and atmospheric absorption become significant over longer ranges. However, higher power is

---

[77] Ofcom, *Implementing Ofcom's decisions on the 57-71 GHz band: Notice of proposal to make the Wireless Telegraphy (Exemption and Amendment) (Amendment) (No. 2) Regulations 2018*, 5 July 2018, https://www.ofcom.org.uk/__data/assets/pdf_file/0016/115630/Implementing-decisions-5771-GHz-band.pdf

[78] Below 66 GHz signal propagation is limited by oxygen absorption so limiting useful range, whereas above 66 GHz the absorption is much smaller, permitting longer ranges.

[79] Nick Flaherty, "Researchers bring gigabit wireless to trains", *TechSPARK*, 18 August 2017, https://techspark.co/researchers-bring-gigabit-wireless-trains/

available for fixed links given some antenna constraints and, given some of the sharing technologies available, it may be possible to share at higher powers for mobile, but this would require study.

4.75 We are actively working within CEPT in the SRD/MG and SE19 groups to promote our regulatory approach to achieve a harmonised European regulatory framework, to allow equipment development to benefit from economy of scale. We will encourage industry to provide input where they believe power levels should be increased. Following completion of the CEPT work,[80] we will further review the regulation for systems operating at EIRP above 40 dBm.

Comparison of candidate bands

4.76 Table 7: Summary of spectrum bands for trackside infrastructure to provide passenger connectivityTable 7 below summarises our assessment of the different bands against each of the criteria discussed above:

a) **Potential channel capacity**, taking into account the amount of spectrum available in the band on a shared basis, and the maximum channel widths we expect to be usable in the band, based on current and emerging technologies.

b) **Equipment ecosystem**, which refers to the availability of suitable equipment using this band, or the potential timescales for developing this if this is not yet available.

c) **Opportunity cost**, considering whether authorising the band for rail use would preclude or inhibit deployment by other potential users of the band. Where we are not aware of other viable use cases of the band in the foreseeable future, or expected future users of the band would easily be able to share with rail use, the band scores highly (i.e. the opportunity cost is low).

d) **Ease of authorisation**, representing how straightforward we believe it would be to develop a suitable licence product for rail use in this band.

4.77 The table uses Harvey balls to give an indication of how each band 'scores' against each criterion; the fuller the ball, the better the band scores on that criterion. For example, if the use of a band for rail connectivity is likely to have a low opportunity cost, then its Harvey ball will be filled in more (e.g. the 66-71 GHz band); and the more challenging it is likely to be to put in place a rail connectivity authorisation in the band, then the less filled in the Harvey ball will be (e.g. the 2.7-2.9 GHz band).

4.78 We have used larger sized balls in the second column to signal that the potential channel capacity is the most important criterion and, in this context, our assessment is made with reference to the future demand scenarios described in Section 3 (as opposed to current levels of demand).

[80] For more information on the CEPT work which is underway, see https://eccwp.cept.org/WI_Detail.aspx?wiid=563

Table 7: Summary of spectrum bands for trackside infrastructure to provide passenger connectivity

Band	Potential channel capacity (Mbit/s)[81]	Equipment ecosystem	Opportunity cost	Ease of Authorisation	Indicative base station range
2.7-2.9 GHz[82]	 80-400				Large
3.8-4.2 GHz	 0-400				Large
5 GHz (5.45-5.725 GHz)[83]	 160-320				Short
14.25-14.5 GHz	 200-800				Medium
26 GHz – lower (24.25-26.5 GHz)	 200-1600				Medium
26 GHz – upper (26.5-27.5 GHz)	 800-1600				Medium
66-71 GHz	 4320-8640				Short

4.79 Note that the final column in the table gives an indicative range for a base station deployed in the band, and hence the spacing between adjacent base stations along the rail track (ranging from shorter distances which might be of the order of several hundred metres to

[81] This is an estimate of the lowest to highest capacity factoring in existing use over the UK. In some cases, notably 3.8-4.2 GHz and 26 GHz (lower and upper), additional capacity may be gained through aggregation.
[82] Considering 2.9-3.1 GHz as an extension to this band may yield 400 Mbits/s in more locations.
[83] The presence of other licence exempt users may cause significant degradation of capacity and quality of service in some areas. This can be mitigated in a number of ways such as reducing the separation between base stations.

larger distances that could be several kilometres). This is potentially relevant to the wider evaluation of trackside connectivity solutions in two respects:

a) If an individual base station is covering a short section of track only, then this will enhance the overall capacity in very busy sections of track where there might be more busy trains (as the number of busy trains that any individual base station might need to serve at the same time would be greater if its coverage range is greater); but

b) If an individual base station has a shorter range then more base stations are needed to serve a given length of track. This would increase the cost of deploying a trackside connectivity solution, all else being equal.

4.80 The first of these considerations will tend to accentuate the advantage of the mmWave bands for serving the busiest sections of track. But the shorter spacing will increase the cost per kilometre of track covered, so there is a potential trade-off between capacity and cost. However, the question of how far apart it may be possible to place base stations for mmWave solutions (so as to reduce costs in places where the highest capacity is not needed) is uncertain, and we return to this issue below.

Implications for suitability of bands to meet passengers' future data demands

4.81 Focusing on the first, key criteria relating to capability, the bands included in the table can be split into two main groups:[84]

a) mmWave options, which can provide 1 Gbit/s or more (in some cases, considerably more); and

b) mid-frequency bands (sub-6 GHz) which could provide up to a few hundred Mbit/s, but not more than this.

4.82 A key implication of the analysis is that only the mmWave bands look likely to have the capability to support the higher future demand levels that we outlined in Section 3 for busy trains and for busy sections of track in the mid-late 2020s.[85] We provide commentary with our overall assessment of these two different groups below.

mmWave bands have the best prospects to meet our future demand scenarios for the mid-late 2020s

4.83 mmWave spectrum can deliver capacity in the order of Gbit/s with the potential to serve the busiest trains or busiest section of tracks. The 26 GHz band has the prospect of delivering over medium ranges and importantly has a significant amount of bandwidth available nationwide, albeit different parts of the band have different availability:

[84] The 14 GHz band falls between these two main groups; we comment on it briefly below in the summary of the mmWave group.

[85] The 14.25-14.5 GHz band falls between these in terms of capacity, but we include this band in the mmWave category for simplicity.

a) The **Upper 26 GHz**, which is relatively free of incumbents, would be able to support the largest channel sizes, should benefit from the 5G ecosystem and we expect equipment to be available in 2019. This band is expected to be the focus for 5G mmWave mobile access applications, which means that its use for rail connectivity could need to coexist with other 5G applications in future. However, the rail corridors are geographically defined and limited in their coverage, and rail connectivity solutions are likely to have a high degree of directionality. Therefore, although there could be some opportunity cost with respect to potential future uses, the limited locational impact is likely to mean that this opportunity cost should be modest.

b) **Lower 26 GHz** would take longer to authorise because of the need to plan coexistence with fixed links. We believe that it may be possible to find bandwidth in amongst the existing fixed links (using different frequencies within the band at different locations as necessary) to accommodate a trackside connectivity solution in most places. However, this would require us to carry out significant work to analyse the technical arrangements needed to manage coexistence with fixed links, and might need us to develop and implement changes to the technical assignment tools in our licensing system. The ecosystem for the lower 26 GHz band is also expected to be less developed than that for the upper 26 GHz band in the near term.

4.84 The **66-71 GHz** band is currently vacant but about to made available for use via new exemptions which would enable trackside connectivity. There is an ecosystem partly based upon WiGig technology, and trials using it have been conducted in the UK demonstrating gigabit throughput. However, the permitted transmit power will be relatively low and so base station antennas may need to be positioned close together along the track (possibly a few hundred metres) in order provide consistent coverage for all weather conditions. We will work within CEPT to promote our changes to the band and achieve a harmonised European regulatory framework, and this may include changes to power levels. Whilst work is progressing, some work may not be complete for several years. However, if successful, it could enable an increase in base station antenna separation, though this will still be less than could be achieved in the 26 GHz band because of the different propagation characteristics of the bands.

4.85 The **14.25-14.5 GHz** band would have more capacity than the mid-frequency bands, but it does not have nearly as much as 26 GHz or 66-71 GHz. In addition, the band also has no prospective mobile equipment ecosystem which we are aware of. While details remain unclear, there could also be some opportunity cost with respect to other potential uses of this band.

4.86 The propagation characteristics of higher frequency bands suggest that mmWave solutions would need shorter inter-site distances than at lower frequencies. However, the ratio of required inter-site distances for 26 GHz and sub-6GHz solutions is uncertain. It may be possible, with suitable technology improvements in beam-formed antenna gain and transmitter power, to increase the inter-site spacing at 26 GHz and so decrease its cost of deployment. Whilst equivalent considerations could apply to the 66-71 GHz case, the propagation losses in this band will always be greater than for 26 GHz. Therefore, the range that can be supported at 66-71 GHz for the same power budget will be lower than at 26 GHz.

4.87 Getting a better understanding of range issues is a task for the industry through trials and technical development. We raise these issues here in general terms simply to make the point that the suitability of different spectrum bands for trackside connectivity involves a wider set of issues than only those summarised in Table 7 (which focuses on the narrower spectrum-related characteristics directly relevant to Ofcom's remit).

The bands below 6 GHz may meet current demand requirements but have significant limitations

4.88 Where demand is unlikely to exceed hundreds of Mbit/s (e.g. current demand estimates considered in Section 3), mid-frequency bands have the potential to deliver a significantly better consumer experience than that offered by today's on-board Wi-Fi (which can be slow, and intermittent due to patchy coverage and limited capacity). However, each of the three solutions has certain limitations as described below:

a) The **2.7-2.9 GHz** band could potentially provide around 100 Mbit/s on the basis that 40 MHz of bandwidth could be available (almost) everywhere and could possibly deliver up to 300 or 400 Mbit/s in some places. We believe the opportunity cost is low and that existing 4G technology can be leveraged, but there is a significant disadvantage in that it would take significant time to authorise due to coexistence situation which has to satisfy the safety requirements of aeronautical use as well as coexisting with military surveillance radar. Moreover, the outcome of this coexistence work is uncertain and a substantive amount of this coexistence analysis might need to be completed before a better picture emerges of how much bandwidth could ultimately be made available for rail connectivity.

b) The **3.8-4.2 GHz** band could support up to several hundred Mbit/s in many places but use of this band could conflict with Ofcom's policy to enable sharing by new fixed and mobile applications in this band. There may also be key rail sections, including in the Welsh borders, South West and, significantly, in the approaches to London, where use for rail connectivity (which might operate at relatively high powers) would be restricted to protect satellite earth stations, meaning that this band could not support a single solution across the whole rail network.

c) The **5 GHz** band has an authorisation in place today, and it may be possible to achieve up to a few hundred Mbit/s. However, this band may suffer quality of service issues, particularly as the train passes through urban areas, due to the presence of outdoor Wi-Fi users who have access to this spectrum on an equal, licence exempt basis. The low permitted powers in this band (necessary to enable sharing with other users) would also mean that trackside base stations would likely need to be built closer together, thereby offsetting one of the advantages of mid-frequency spectrum bands.

4.89 These mid-frequency bands could still have the potential to provide reasonable trackside connectivity in sections of the rail network that have much lighter passenger traffic (and some of these bands would have the advantage from a cost perspective of enabling larger spacing between base station antennas along a section of track). However, they would not be able to meet our future demand scenarios for the mid-late 2020s on most parts of the mainline network.

4.90 In this section we have considered a specific set of spectrum options based on bands which had been raised with us by DCMS or industry stakeholders. In Section 6, we comment on other spectrum, notably that already used by MNOs' networks, which could play a role in improving passenger connectivity.

4.91 Finally, whilst not discussed in this document, there are other licensed bands which could potentially be feasible options, including 28, 32 and 40 GHz, which are already licensed on a block assigned and technology/service neutral basis. Whilst we believe these bands are mostly used for fixed services today, they may be used for mobile in the future, especially the 28 GHz band as it would benefit from the same prospective equipment ecosystem as the upper 26 GHz band. The use of these licensed bands would need the engagement of the licence holders of course (either as part of the solution provider consortium or to trade or lease the associated spectrum access rights to the solution provider consortium).

5. Authorisation options for potential bands

Introduction

5.1 As set out in Section 2, DCMS has asked us to advise on how Ofcom could make any potentially suitable spectrum band or bands available for the purpose of enabling track-to-train connectivity, including the likely timescales. As set out above, Ofcom has not come to any view or decision as to whether spectrum should be made available for these purposes, much less, who might be authorised to provide such services. Furthermore, any form of authorisation that allows for the use of the spectrum will need to comply with the requirements of both European[86] and domestic law.[87] Subject to those further considerations, however, we set out below how the authorisation process might work in principle.

5.2 In all of the spectrum bands that would require a new authorisation for trackside connectivity solutions, we consider this new authorisation would likely take the form of a licence product for the trackside base stations (as opposed to a licence exemption regulation). This section therefore talks about our approach to 'licensing' spectrum to enable trackside connectivity solutions.

5.3 The section sets out our advice on the following aspects of authorisation:

a) The interaction between the mechanism for granting licence(s) for a trackside rail connectivity solution and the mechanism that leads to a particular entity having a concrete need for such a licence (e.g. the mechanism for competitive procurement of a trackside connectivity solution provider). The nature of this relationship is likely to be the same, irrespective of the band under consideration;

b) The implications of this interaction for the form of authorisation;

c) The factors that might influence the setting of spectrum fees for the trackside rail connectivity licences; and

d) The process and possible timescale for having the licence(s) in place to grant. This will differ between spectrum bands because of the different circumstances surrounding them, notably relating to the conditions for managing coexistence with incumbent users and with other potential future users of the same spectrum.

5.4 This section focuses principally on the authorisation of base station equipment that will be installed on the trackside. Authorisation of the on-train equipment may require a separate process, which we discuss briefly below.

[86] In particular, the European regulatory Framework which comprises the Framework Directive (Directive 2002/21/EC), the Authorisation Directive (Directive 2002/20/EC), the Access Directive (Directive 2002/19/EC), the Universal Service Directive (Directive 2002/22/EC) and the Directive on privacy and electronic communications (Directive 2002/58/EC), as amended.
[87] For example, the Communications Act 2003 and Wireless Telegraphy Act 2006.

Interaction of award mechanism with rail connectivity procurement process

5.5 There may be a material interaction between the way that the spectrum authorisation is granted and the way in which the trackside connectivity solution provider(s) are chosen. The existence of this interaction derives from the following points:

a) **'Rail corridor' licence approach**: The most appropriate approach is likely to be for the use of spectrum for trackside connectivity to be covered by a bespoke licence product that grants rights along each relevant rail corridor, as opposed to covering this use through national or regional licences. This 'rail corridor' approach will enable the spectrum to be shared on a geographic basis with other (non rail-related) applications that are spatially separated from the rail corridor, leading to more efficient use of the spectrum.

b) **'Single provider' outcome**: It seems sensible to assume that only one entity is likely to require spectrum access rights along any individual section of track. This is because it is unlikely that business cases could support competing trackside infrastructures (although different trackside connectivity solution providers could be selected for different routes or sections of track).[88] This 'single provider' outcome may result from the process that selects that provider, whether this be via a competitive procurement process or through a deal being struck with a provider that comes forward on a commercial basis. A single provider outcome could be reinforced by the exercise of landlord rights (e.g. Network Rail control over trackside access).

c) **Equality of access to new rail corridor spectrum licences**: we assume that the trackside connectivity solution provider (i.e. the entity needing the spectrum access rights) would be selected by means of an appropriate process set up by the rail industry. It would make sense for all prospective solution providers (competing in this process) to have the same ability to exploit the necessary spectrum access rights covered by a new rail corridor licence if they are chosen. In other words, it would be undesirable to have the ability to access these spectrum access rights become an influencing factor in the trackside connectivity solution procurement process itself.[89]

5.6 The implication of the above considerations is that the spectrum licensing should follow the connectivity solution selection process with all prospective solution providers being

[88] Even if the connectivity solutions are procured by the TOCs and different TOCs make separate procurements along the same bit of track, it seems likely that the economies of scale would drive them to procure solutions from the same connectivity provider where these are based on using the same spectrum frequencies (exploiting a single, shared trackside infrastructure and technology rather than building duplicate infrastructures along the same track).

[89] To illustrate this last point, it could be problematic for a prospective solution provider to be able to gain the spectrum access rights (to the exclusion of others) ahead of a rail connectivity procurement process if these rights then placed it in a unique, or excessively privileged, position to provide the trackside connectivity solution. This would likely give them control over a bottleneck in the solution provision and lead to a less competitive procurement process.

assured that they will be able to use the relevant spectrum if they are successful in the connectivity solution selection process.

Possible approaches for authorisation regime

5.7 The trackside connectivity solution is likely to comprise base stations located along the side of the track, together with radio equipment attached to the trains (onboard equipment). We consider these in turn below.[90]

Authorisation of trackside base stations

5.8 Our statutory duties require us to follow an open and transparent process for granting the relevant spectrum access rights. The way that this might be achieved, whilst also having the spectrum licensing process follow, rather than lead, the connectivity solution selection process (for the reasons set out above), would require more detailed consideration in light of any specific proposals that are brought to us. However, a key consideration in the design of an authorisation approach is whether or not it needs to limit the number of licences that are issued for the rights to access the same spectrum.

5.9 There are two broad approaches for designing the authorisation regime for the trackside base stations on the basis of the above considerations:

a) **Non-restrictive approach**: Make licences available on demand to any applicant (and, *de jure*, to any number of applicants) for the purpose of providing track-to-train connectivity. Although this would allow others to be licenced to use the spectrum, the ‘single provider’ hypothesis set out above would imply that only one entity would likely have the incentive, and ability, to use its licence in practice. We would therefore expect only the chosen ‘single provider’ to apply, doing so once it had won the contract for the section of track in question. Because the licence product would be available to all on demand, it would still be possible for other entities to apply at any time (ahead of, or after, the trackside connectivity being awarded). But if they did so, they are unlikely to be able to make use of this licence in practice and so should have no incentive to apply for it (however, we note below that coordination requirements could be used to manage the position in the event that other entities did, nevertheless, take out additional licences granting spectrum access rights along the same section of track). We also note that, if the deployment of duplicate services required trackside access then this would be controlled by the landlord as noted above (e.g. Network Rail).

b) **Restrictive approach**: this implies that we restrict the issue of a licence to only those applicants that meet certain criteria. Subject to meeting the relevant legal requirements, the licence product might be made openly available on application at any time, but with a requirement for the applicant to demonstrate that they meet the qualifying criteria as set out in regulations in order to obtain a licence. This approach

[90] The interior of the rail carriages will also have Wi-Fi access points and, potentially, mobile network femtocells or repeaters. These are already authorised under existing licence exemptions for Wi-Fi, or under the MNO licences in the case of femtocells and repeaters which are under the control of the MNOs).

would require us to set a condition that only the chosen solution provider would be able to meet (i.e. the qualifying criteria might say that the applicant needed to demonstrate that they had a contract to provide trackside connectivity or access to trackside infrastructure).[91]

5.10 Under either approach we would expect to include an obligation in the licence to coordinate with other licensees, with a backstop provision for Ofcom to notify licensees of a Coordination Procedure with which they must comply. In the event that more than one provider was operating in close proximity to another (be it with another train communications provider or other user of the spectrum), this should ensure that measures could be put in place to minimise any potential interference. Under the non-restrictive approach set out above, this would provide protection against a situation in which another entity applied for a licence relating to the same piece of rail track (as this could be set up in a way which prevented them being able to interfere with the operations of the chosen 'single provider').

5.11 Both approaches might potentially achieve the same outcome in terms of being able to license track-to-train connectivity solutions. The non-restrictive approach would likely be relatively simple to implement and is adaptable (e.g. new providers could easily be licensed when new contracts for rail connectivity are issued, either for different sections of track, or if a new provider is selected at the end of a contract period). On the other hand, the restrictive approach may provide more reassurance that only those with rail connectivity contracts can use the relevant spectrum access rights. The pros and cons of these options would need further assessment, but it should, in principle, be feasible to develop a licensing approach along the above lines.

5.12 Our preference, based on the information we have to date and our assumptions on the selection approaches being considered, would likely be to adopt the simpler non-restrictive approach. We have used this approach previously in a similar circumstance when authorising Smart Metering devices as part of the Department for Energy and Climate Change's contract awards.[92] This approach would likely allow the spectrum licensing process to operate in a relatively quick and more straightforward manner.

5.13 In contrast, a restrictive approach would likely require Ofcom to give careful thought to the eligibility criteria and how best to assess this. An approach that requires Ofcom to make a judgement is more complex (and, in the case of an award process, it can be very resource- and time-intensive as well as less flexible).

[91] An alternative version of the restrictive approach could be to hold a comparative selection award process, sometimes referred to as a "beauty contest", doing so after the rail connectivity solution procurement has taken place. The central criteria for choosing the winning applicant would be that they hold a contract to provide a rail connectivity solution along the relevant rail track.

[92] Ofcom, *Statement on 870-876 MHz and 915-921 MHz: Update and Way Forward*, 27 June 2013, https://www.ofcom.org.uk/__data/assets/pdf_file/0014/41405/statement.pdf

Authorisation for on-board equipment providing trackside connectivity

5.14 The discussion above focuses on the authorisation of base station equipment that would be installed on the trackside. Radio equipment would also need to be installed on the trains to form the other end of the track-to-train link. The most appropriate authorisation method for this on-board equipment is likely to depend on several factors including whether the equipment is under the control of the licensed trackside infrastructure and who operates the equipment. It may be appropriate to authorise the on-board equipment under the umbrella of the same licence that is used to authorise the trackside base stations (e.g. if the onboard equipment is owned and operated by the same company). Alternatively, if the onboard equipment is owned separately (e.g. by the TOC itself) but operates under the control of the base station (in an analogous manner to the way that a mobile phone works) then regulations exempting use from licensing (licence exemption) is likely to be the more appropriate method of authorisation (although a new separate but complementary licence product could also be considered).

5.15 The most appropriate authorisation approach will depend on the specific arrangements under which the trackside connectivity solution is installed and operated, and we can advise further once these become clear. However it should, in principle, be feasible to develop a suitable licensing approach when required.

Spectrum Fees

5.16 As per Ofcom's policy, any new licences issued would incur a fee which can be cost-based if there is little or no opportunity cost associated with the use of spectrum, or can reflect Administrative Incentive Pricing (AIP) if there is a material opportunity cost associated with the use of spectrum. The most appropriate basis for setting fees would need to be determined in light of the spectrum band in question. However, we think that an AIP-based approach is likely to be relevant for the bands considered in Section 4 where a new rail corridor licence is required. To calculate the fee level, we would need to consider the value of others uses that would be denied spectrum access along, and in the adjacent area around, the rail corridor (in order to avoid harmful interference to the rail use, or because of the impact of interference from the rail use into the alternate use near to the rail corridor). This will depend on the nature of potential alternate users of the spectrum, and on the geographical extent of any limitations on their use of this spectrum. This will not be possible to determine until we have carried out a technical evaluation of the interference risk for the relevant band so as to understand the size of any potential exclusion or coordination zones. However, if the rail connectivity solution involves a reasonably high degree of directionality along the rail corridor (which we would expect to be the case), we would expect this to limit the geographic impact of restrictions on alternate users of the spectrum (noting also that the rail corridors cover a limited area in themselves) and for this to be reflected in the level of fees.

Process, timescale and effort required to create licence product

5.17 Most of the candidate spectrum solutions discussed in Section 4 would likely require us to create a specific rail connectivity licence product to authorise use of spectrum along the relevant rail corridor(s) in the manner set out above. Exceptions to this would be the 5.4 GHz band where a licence exemption is already in place[93] and the 66-71 GHz band where we are currently consulting on the implementation of a new licence exemption regime.

5.18 Creating a new licence product for rail connectivity would, in effect, mean that we were allocating the spectrum access rights in places along the rail corridors to this particular use. In doing so we would need to be satisfied that this was likely to support optimal use of the spectrum, as required by our statutory duties. We would expect to carry out a consultation to support our assessment on this point.

5.19 In general, the work required to get a suitable licence product available for grant would involve the work areas, indicated in the table below.

[93] Which is covered by existing licence exemption regulations which support 1 W (30 dBm) use by mobile outdoors.

Table 8: Summary of work areas and indicative timing required to authorize spectrum for rail connectivity

Work area	Description	Indicative time required
Technical coexistence assessment	Requires detailed understanding of the technical characteristics of the planned rail connectivity spectrum use (where we are unable to use 3GPP standards) as well as of incumbent spectrum users that could suffer interference from, or cause interference to, the rail connectivity user. Results then define appropriate technical licence conditions to avoid risk of harmful interference. It may also result in coordination criteria and a process for dealing with inter-operator interference issues if they were to arise.	3-6 months (if issues are straightforward) 1-2 years (if bands involved require complex assessment with safety cases etc.)
Non-technical terms and conditions	The development of other non-technical terms and conditions for use of the spectrum (including spectrum fees). This would include considering provisions on what information the licensee needs to hold and report about their deployments, whether the licence would be tradable and the rules governing grounds to revoke the licence.	Part of preparation for consultation (included in elapsed time for Public Consultation below)
Licence grant process	The development of the appropriate process for granting the licence(s).	Included in elapsed time for Public Consultation below
Public consultation	Prior to us issuing a licence we would need to go through a process of consultation on the proposals which would ask for comment on the results of the main work areas detailed above. These proposals would be adopted taking into consideration any proposed changes based on the responses received.	6-9 months (although 1-2 months could be done in parallel with earlier work items)
Licensing system changes	Changes to internal processes and licensing system to support grant and subsequent maintenance of licence.	Can be carried out in parallel with other activities if simple Could take up to a year if significant enhancements are required (e.g. to support technical assignment tools in shared band)
Statutory instrument	The drafting and laying of any required Regulations (Statutory Instruments) necessary for us to grant the licence(s) (the extent of the Regulations required will depend on a number of factors including whether the licences are to be restricted or tradable) and notification of the technical regulations set out in the Interface Requirement to the European Commission.	5 months (though 2 months of this could be done in parallel with public consultation)

5.20 One of the critical elements of the authorisation process is the technical coexistence assessment. This specific work area is significantly dependent on the spectrum band being considered. If the technical coexistence issues are relatively straightforward, this process may take 3-6 months only (including appropriate engagement with interested parties).

5.21 However, if the issues are more complex, the assessment requires technical trials to be set up in order to provide empirical evidence on risks of interference or involve applications that have to go through safety cases with other regulators, then these can take considerably longer to resolve. It is hard to generalise, but we note that technical coexistence studies have taken up to two years in some cases. The coexistence work on the 2.7-2.9 GHz band could fall into this category if there was a need for trials with MOD and CAA applications, as noted in Section 4. If we were required to perform technical assignment work for individual deployments, this could also add to the time needed as a system to handle this would have to be designed.

5.22 In relation to the 26 GHz band, we note the following:

a) For the upper band (26.5-27.5 GHz), where there is very limited existing use, there is only limited work needed on technical coexistence with the few existing users and on determine the technical conditions for use of this band; this could take around 3-6 months. The overall process, including consultation and any statutory instruments could take around **9-12 months** from the point at which it was triggered.

b) For the lower band (24.25-27.5 GHz), the technical coexistence analysis would be more involved as it would require us to examine the conditions for coexistence with current users (fixed links), including an assessment of how much bandwidth could be made available at different locations along a rail corridor, and it may require us to design and implement changes to the existing technical assignment tool used for licensing fixed links in the band. We estimate the overall process could take **18 months to two years**.

Next Steps

5.23 This section has explained how, in principle, Ofcom would expect to approach the authorisation of these spectrum bands for trackside connectivity at the point that a clear decision was made to progress with a particular solution. However, it will not make sense for us to carry out a lot of speculative work towards making licence products available for individual spectrum bands in advance of this decision being taken.

5.24 We recognise that getting to a clear decision will involve other considerations in the choice of spectrum band(s) to support a track-to-train system for on-board passenger connectivity aside from their technical capability (as discussed in Section 4). In particular, the characteristics of different spectrum bands could impact on the business case for deploying any such system.

5.25 There are also other issues to be considered in the design of a network to provide track-to-train connectivity before being ready to progress, including the business model on which such a service would be run (taking account of the build and operating costs amongst other things), how such a service would be funded, ensuring access to the trackside, and potential interoperability of equipment used by different TOCs or on different routes.

5.26 These additional considerations are clearly issues for Government and industry rather than Ofcom (with our remit in this area limited to the management of UK spectrum resources).

5.27 We will, however, continue to work with Government as it further develops its plans for the enabling and deployment of any solutions to improve passenger connectivity on rail routes where these plans involve the use of radio spectrum. We will respond accordingly to requests by industry or Government to begin further work exploring authorisation of any given band in more detail, and we remain available for discussions with stakeholders with interests in this area.

6. Other potential solutions for improved rail connectivity

Summary

6.1 Section 4 focused on a number of spectrum options for supporting trackside connectivity solutions. We did not discuss the use of existing mobile spectrum, as there are a number of aspects to this which go beyond trackside connectivity solutions. This section therefore outlines the possible role of mobile spectrum in improving rail passenger connectivity.

6.2 In this section, we also comment briefly on possible satellite solutions.

MNO networks

6.3 Rail passengers do, of course, use the mobile network service today when the train they are on is in an area with mobile network coverage, the signal is strong enough to overcome the penetration losses associated with the rail carriage and the capacity on the serving cell is sufficient (taking account of the combined demand of the rail passengers passing through the sector as well as demand from other users in the surrounding area). The quality of service can be very poor, in large part because mobile networks are designed primarily to meet the demand of general customers in the surrounding area, rather than the large, transient load of a busy train passing through a cell.

6.4 There are several ways in which the spectrum licensed to MNOs could be used as part of a more deliberate policy to support rail passenger connectivity via on-board Wi-Fi:

a) **Via roof-mounted gateways on the trains with SIM cards for different MNOs, whereby on-board Wi-Fi is backhauled through the mobile network**. This approach overcomes the effect of attenuation losses associated with signals having to penetrate the rail carriage, and may make it possible for MNOs to prioritise the rail demand over other users (it is also possible to use on-board repeaters to support mobile services in the carriage instead of, or as well as, using on-board Wi-Fi). However, the mobile network still faces capacity constraints and, on many lines, passengers using the system for free can face tight usage caps on their on-board Wi-Fi.

b) **Through targeted investment in additional base stations to support Wi-Fi backhaul on a route**. As above, but with investment in additional base stations specifically designed to support increased rail connectivity, such as in the case of EE's partnership with Chiltern Railways.[94] Base stations could be either on or close to the trackside, but would have their own fibre backhaul (as opposed to using Network Rail's trackside fibre).

---

[94] Chiltern Railways, "Chiltern Railways and EE set to transform onboard Wi-Fi experience for thousands of commuters with revolutionary continuous connectivity", https://www.chilternrailways.co.uk/news/chiltern-railways-and-ee-set-transform-onboard-wi-fi-experience-thousands-commuters (accessed 25 July 2018)

c) **As a spectrum option for dedicated trackside connectivity**, i.e. as an alternative to the spectrum bands discussed in Section 4 for providing the link between trackside base stations and trains, where these trackside base stations are dedicated to serving the data demand of the passing trains.

6.5 Existing systems for providing on-train Wi-Fi in the UK are often based on having roof-mounted receiver units connected to Wi-Fi access points installed inside the train carriages. These systems contain multiple SIM cards typically from different MNOs to maximise coverage and capacity as the train travels through different areas. The backhaul connectivity to/from the train is therefore provided using the MNOs' networks and requires signal from at least one MNO to provide a connection to the on-board Wi-Fi system and ultimately to rail passengers.

6.6 Although having SIM cards for different MNOs helps to reduce the impact of the train passing through not-spots for individual operators, coverage from these systems can nonetheless be patchy, and is still limited by the presence of cuttings and tunnels. Moreover, the capacity is limited by that of the surrounding mobile cells, which, as noted above, are not usually designed to serve passing trains (in part, because large transient loads on the network are hard to manage and bring limited incremental revenue from the mobile consumers themselves).

6.7 The approach of building additional base stations and adding capacity and coverage to serve rail lines has an advantage over dedicated trackside solutions in that these new base stations do not need to be located on trackside land. From our discussions with stakeholders, we are aware that securing access to the trackside from the owner of the land (for most mainline routes, this is Network Rail) can add greatly to the complexity and cost of building and maintaining any connectivity solution, due to the safety and operational need for access to the trackside to be controlled.

6.8 However, the dedicated trackside connectivity approach does have the potential to maximise the capacity that can be provided to rail passengers using mobile spectrum for the backhaul link. This is because dedicated trackside antennas (or base stations) using MNO spectrum would not also have to share their capacity with other mobile users in the same cell, whereas this is likely to be the case for the previous two approaches, and trackside antennas would be positioned along the track at more regular intervals to optimise connectivity.

6.9 One model for a dedicated trackside connectivity solution using MNO spectrum could be to use a Distributed Antenna System (DAS). In such a model, an MNO's network would be plugged into a small number of 'base station hotels' located along the route and connected via fibre to trackside radio and antenna systems.[95] This could be more cost-efficient than deploying multiple traditional mobile base stations, each with their own base station

[95] According to an industry stakeholder designing these solutions, a 60-mile line such as the one going from London to Brighton would only need three base station hotels.

equipment, as in this model this equipment is placed at the base station hotel and used to support multiple trackside antennas.

6.10 The DAS can be comprised of both discrete trackside antennas and additional systems such as leaky feeders to provide coverage in tunnels.[96] This helps to overcome terrain obstacles such as tunnels and deep cuttings which can make improving coverage with traditional mobile base station deployments a challenge.

6.11 One version of this proposed approach involves a ‘neutral host’ in which a single infrastructure comprised of fibre connections, masts, antennas and base station hotels, is built and operated by a single third party. [97] This single infrastructure can then be used to support the use of mobile spectrum by more than one MNO and, potentially, to support hybrid approaches using both mobile and non-mobile spectrum to increase capacity.

6.12 Such a system would likely provide the most efficient means of supplying backhaul to on-train Wi-Fi using mobile spectrum. Spectrum which is already licensed to MNOs (or which is expected to be awarded in the next auction) is outlined in Table 9 below.

---

[96] Leaky feeders, also known as radiating cables, act like extended antennas. They are coaxial cables with small sections of copper shielding stripped away to allow radio frequency signals to “leak”.

[97] See for example the solutions offered by BAI Communications (www.baicommunications.com); Transport for London has also listed a tube DAS as one of its major infrastructure projects in its Connected London document (http://content.tfl.gov.uk/connected-london.pdf).

Table 9: MNO spectrum holdings and spectrum to be assigned in upcoming auctions

Band	BT/EE	Vodafone	O2	H3G	Unassigned	Total
700 MHz Paired					60	*60*
700 MHz Centre-gap					20	*20*
800 MHz	10	20	20	10		*60*
900 MHz		34.8	34.8			*70*
1400 MHz		20		20		*40*
1800 MHz	90	11.6	11.6	30		*143*
2100 MHz	40	29.6	20	29.5		*119*
2.3 GHz			40			*40*
2.6 GHz Paired	100	40				*140*
2.6 GHz Unpaired	15	20				*35*[98]
3.4 GHz	40	50	40	60		*190*
3.6-3.7 GHz				84	16	*100*[99]
3.7-3.8 GHz					100	*100*
Total MHz	*295*	*226*	*166.4*	*233.5*	*136*	*1117*

6.13 The total bandwidth of mobile spectrum in this table suggests that it has the potential to support significant data rates to trains. However, it would not be practical to exploit all of these spectrum bands at the same time in a trackside solution because there may be some significant challenges in accommodating multiple radio and antenna systems at the mast and on the train. But if, for example, 100 MHz of mobile spectrum were to be used for track-to-train connectivity using a combination of bands then this could provide in the

[98] We have not considered the entire 50 MHz in this band as it is not all considered "usable" due to EIRP restrictions. For more information, see Annex 3 of our document on the award of the 2.3 and 3.4 GHz spectrum bands from July 2017: https://www.ofcom.org.uk/__data/assets/pdf_file/0013/104305/Statement-annexes-Award-of-the-2.3-and-3.4-GHz-spectrum-bands.pdf

[99] Following a request from UK Broadband, which is owned by H3G, Ofcom is consulting on changes to UK Broadband's spectrum access licence in this band which would see it surrender the rights to use 4 MHz of spectrum in that band. If these changes are adopted this would reduce H3G's holding in the band to 80 MHz and leave 20 MHz unassigned: https://www.ofcom.org.uk/consultations-and-statements/category-2/variation-uk-broadbands-spectrum-access-licence-3.6-ghz

region of 200-400 Mbit/s to trains. This would be enough to meet our figure for current unconstrained passenger data demand set out in Section 3. It might be possible to increase this to several hundred Mbit/s by exploiting more mobile bandwidth in contracts with more than one MNO, but this would struggle to meet the 1 Gbit/s-plus scenarios in the mid-2020s without using mmWave spectrum.

Satellite options

6.14 For the sake of completeness, we note that satellite solutions could also provide mobile connectivity to trains but are more likely to be considered as a hybrid solution alongside trackside and mobile connectivity.

6.15 Satellite solutions are unlikely to provide the same level of capacity as could be provided by trackside solutions in the mmWave bands, particularly in urban areas. This is due, in large part, to the fact that an individual satellite spot beam would cover a much larger length of track than a single base station, and as such would have to supply all the trains in this area. They also face challenges from obstacles that block the path between the satellite and the antenna on the train (tunnels, gantrys, tall buildings etc). Satellites do, however, provide near-ubiquitous service across the geography of the UK and may be an attractive solution for flatter, less densely populated areas, allowing service providers to focus their infrastructure investment in other parts of the track and speeding up overall roll-out of the service. This was the approach chosen by Renfe in Spain and NTV in Italy.

6.16 Satellite solutions today for airline Wi-Fi, when paired with phased array antennas and modern modems, can provide speeds of between 100-400 Mbit/s per plane and up to 15 Mbit/s per passenger,[100] and so could be compatible with implied levels of unconstrained passenger data demand today. Looking forwards, the capacity of satellite services over Europe is expected to increase ten-fold from 2021 with the arrival of several Very High Throughput Satellites (VHTS) in Geostationary Orbit (GSO)[101] and the OneWeb Low Earth Orbit (LEO) constellation.[102]

6.17 In the short term, GSO satellites could be suitable in flatter rural areas where installing terrestrial base station infrastructure may be less cost-effective and/or a lower priority owing to lower passenger numbers. However, the relatively high latitude of the UK means GSO satellites are at low elevation angles above the horizon, which makes terrain obstacles such as buildings along the side of the track, trees and cuttings a barrier to delivering a consistent service. Additionally, the higher latency caused by communicating with a GSO

[100] Based on existing aeronautical and rail Wi-Fi systems; higher figure based on high throughput satellites and existing satellite modem technology (such as Hughes' JUPITER system) which is available on planes but may need to be adapted for UK rail use. Note that rail systems will by more affected by atmospheric/rain losses but less affected by Doppler compared to aeronautical systems, so performance will not be identical.

[101] VHTS arriving over Europe in the 2020s expect to have total capacity of 500 Gbit/s-1 Tbit/s as opposed to High Throughput Satellites (HTS) today, which have capacity of 50-60 Gbit/s: http://news.eutelsat.com/pressreleases/eutelsat-orders-konnect-vhts-a-new-generation-satellite-to-deliver-high-speed-broadband-across-europe-2469821

[102] OneWeb also expects a global capacity of 1 Tbit/s

satellite (due to the high orbital height of GSO satellites) would cause delays in making voice or video calls,[103] and would be problematic for some applications (though for others this would be less of an issue).[104]

6.18 Looking forwards, LEO satellite constellations and satellites operating on inclined orbits would overcome some of these disadvantages. Their lower orbital height would greatly reduce latency, and their higher angles of elevation would overcome many terrain obstacles. The fact that multiple satellites would be visible from any location at any one time would also make the service more reliable. However, LEO satellites would still face issues from the many tunnels and deep cuttings present on the British railway network, and so would need to be considered as part of a hybrid solution. Services from LEO constellations are not expected to be available before 2020.

6.19 High throughput satellite systems are also often highly asymmetric, and while we expect mobile broadband demand to follow this pattern, being much higher for downlink compared to uplink, any surges in uplink demand might exhaust the available satellite uplink resources.

6.20 Finally, as far as we are aware, there is no train-mounted satellite antenna system currently approved by Network Rail for use on UK rolling stock, although we note Renfe AGV has been using a roof-mounted antenna since 2015.[105] Installation of satellite antennas on existing rolling stock can also be expensive, although rail services may eventually benefit from the development of smaller, lighter, flatter antennas for the connected car market.

---

[103] Around 0.9 seconds based on current technology.

[104] Rail Safety and Standards Board, *Connected Train and Customer Communications: Rail and Digital Industry Roadmap*, January 2018, https://www.rssb.co.uk/Library/research-development-and-innovation/2018-01-T1138-Connected-Train-Customer-Communications.pdf, pp. 17-18

[105] HISPASAT, "HISPASAT carries out pilot project with Renfe to provide audiovisual and Internet services to AVE train fleet", 29 October 2015, https://www.hispasat.com/contenidos/notas-de-prensa-en/0/194-1.pdf

A1. Data demand methodology

Introduction

A1.1 This Annex sets out the methodology used to estimate the data demand of rail passengers. Our analysis is made up of two distinct parts:

a) **Assessment of unconstrained passenger demand**: this estimates the potential data demand per passenger in bits per second

b) **Assessment of passenger numbers**: this analyses the number of passengers along each mainline, taking into consideration all trains running along that line

A1.2 The average data speed requirement per passenger and the passenger and train numbers along sections of rail tracks are combined in order to calculate an overall data speed requirement per section of track across three mainline rail lines.

Part 1: Assessment of unconstrained passenger demand

Overview and General Assumptions

A1.3 Demand for data will vary considerably from passenger to passenger. However, any solution providing a track-to-train link will consider the demand for a train as a whole, aggregating the data of all passengers at any one point in time. We therefore consider it reasonable to assess an average data demand per passenger (without needing to consider the variations between individual passenger data use at any given time). This is appropriate when considering busy trains in peak hours with large numbers of passengers where aggregate demand smooths out the variability between passengers. It should be noted that on less busy trains at off-peak times, an average data demand figure may not necessarily be reflective of actual data usage at any point in time as this will be more dependent on individual passenger behaviour (however, we are less concerned with data demand at off-peak periods as this will not set the capacity requirement for the trackside infrastructure).

A1.4 We have considered two approaches for estimating average passenger data demand in order to ensure robustness of analysis:

a) **Bottom-up approach**: where we have looked at the typical online activity profile of a consumer and the average data download speeds required to conduct these online activities;[106]

b) **Top-down approach**: where we have looked at real consumer data usage over a month, the average time spent on devices and converted this into an average data speed per passenger.

[106] We consider download data only as this drives the vast majority of demand.

A1.5 We consider that both approaches are suitable for estimating present day demand. The bottom-up approach involves a detailed breakdown of passenger activities and therefore has an additional benefit of enabling us to build different activity profiles to account for different passenger types (business/commuter/leisure), as well as enabling us to look at demand across smartphones, tablets and laptops. The top-down approach considers actual measured data usage and therefore provides a view of average demand per passenger, but one that is based purely on use of mobile data (i.e. not including measured use of Wi-Fi data). To check the validity of these approaches, we have also obtained some real speed measurements from an organisation called LetsJoin which provides on-board Wi-Fi services over transport networks in the UK using connectivity from the MNOs' 4G networks.

A1.6 When assessing future demand, we have chosen to estimate demand levels up to 2025, but we also consider how these 2025 projections might inform our judgements on demand levels in the mid-late 2020s. A time horizon of around ten years is relevant because of the high capital expenditure involved, and because of the practical challenges in accessing trackside locations in upgrading trackside capacity if existing infrastructure is unable to meet rapidly growing demand over this time horizon. It is difficult to predict future demand with any degree of certainty, so each approach involves a series of assumptions. For future projections, we think it more appropriate to focus on the larger results of the top-down analysis in order to size a solution to be viable beyond 2025.

A1.7 Current connectivity on trains is limited by in-carriage Wi-Fi solutions backhauled over mobile networks which are subject to poor coverage along tracks, particularly in cuttings and tunnels. These solutions can offer a poor and often very inconsistent user experience, so we have chosen to assess general and unconstrained device usage rather than current device usage on trains, which is unlikely to reflect desired demand.

A1.8 As we are modelling unconstrained demand, we are also assuming that rail passengers are not expected to pay for connectivity. Charging customers for a service would constrain their demand.

A1.9 In the remainder of this section, we describe the main input assumptions, calculations and results for each of the bottom-up and top-down approaches.

Bottom-up approach: Main input assumptions, calculations and results

A1.10 The main inputs for the bottom-up approach are as follows:

a) **Time spent on activities.** This looks at how long an average user spends carrying out various online activities when using their mobile devices (phone, laptop, tablet).

b) **Different user profiles.** This considers the fact that time spent on activities may vary depending on the purpose of the user's journey.

c) **Average data speeds.** This considers the average data speed a single user would require to conduct the various online activities.

d) **Proportion of users connected.** This considers the proportion of users in a section of track who are assumed to be using data at the same time.

A1.11 In order to estimate future demand, we have changed the time spent on activities to reflect the fact that usage is likely to increase over time. We have also changed the average data speeds and the proportion of users connected to account for increases in user expectations and behaviour over time.

A1.12 Each of these inputs is described in more detail below.

a) Split of time spent on different activities when using mobiles, tablets and laptops

A1.13 We have used data from Ofcom's Digital Day Report 2016[107] to build a view of the types of activities a person carries out when using a mobile phone, tablet or laptop and the average length of time they spend on each activity.

A1.14 When looking at time spent on activities in the future, we consider it better to base our analysis on the current usage patterns of a younger demographic (as we think this is more likely to be representative of average usage patterns in the future than an assumption that there is no change in the overall pattern of activities). The Digital Day data enables us to split the data by age,[108] so we have used the activity split and overall time spent on devices of the current 11-34 age group as a proxy for what the activity split might look like in 2025 for the average user.[109]

A1.15 The table below lists the various activities alongside the proportion of an average user's time they make up:

[107] http://www.digitaldayresearch.co.uk
[108] The age ranges from the Digital Day data are 6-11, 11-15, 16-24, 25-34, 35-44, 45-54, 55-64, 65+. We combined the data from the 11-15, 16-24 and 25-34 age ranges to create a larger 11-34 age range.
[109] This is, of course, a simplifying assumption – and patterns of use may change as a cohort of users grows older.

Table A1.1: Activity split (average % of time on each application when using mobile, tablet or laptop)

CATEGORY	% of total time 2017	% of total time 2025
WATCHING		
Live TV	1%	1%
Free on-demand (iPlayer, All4 etc.)	2%	2%
Paid on-demand (Netflix, Amazon etc.)	3%	4%
Online video clips (YouTube, videos on social media)	5%	6%
WATCHING TOTAL	**10%**	**12%**
LISTENING		
Live radio	2%	2%
On-demand radio	1%	1%
Streamed music	3%	5%
Music videos	1%	2%
LISTENING TOTAL	**7%**	**9%**
COMMUNICATING		
Social networking (Twitter, Facebook excluding checking updates)	12%	14%
Instant messaging	12%	17%
Emailing	11%	6%
Texting	7%	9%
Photo or video messaging	1%	3%
Phone calls	3%	3%
Video calls	1%	2%
COMMUNICATING TOTAL	**48%**	**54%**
GAMING		
Gaming	4%	3%
GAMING TOTAL	**4%**	**3%**
READING/BROWSING/USING		
Newspapers (print or digital)	2%	1%
Magazines (print or digital)	0%	0%
Other online news	1%	1%
Sports news/updates	2%	1%
Online shopping/ticketing	2%	1%
Other websites or apps (incl. checking social media, online banking)	14%	12%
Other activities (creating office documents/spreadsheets, editing videos/music/audio)	8%	5%
READING/BROWSING/USING TOTAL	**30%**	**22%**
OVERALL TOTAL	**100%**	**100%**

A1.16 We do have some more recent data from TouchPoints[110] which was collated in a slightly different manner. This looks at information from over 6,000 people who detail their activities on a half-hourly basis over seven days. Our initial analysis of this data provides similar overall numbers to the Digital Day data, but with a different split of activities. However, it has some limitations for current purposes as compared to the Digital Day research. Firstly, it only records activities on a half-hourly basis, so if a respondent completed an activity at some point during that half hour, the activity is recorded as having been undertaken for the full half hour. Secondly, it records time spent on desktops and laptops as a combined figure and we therefore cannot separate out the laptop time. We have therefore chosen to base our analysis on the Digital Day data even though the data relates to 2016 (whereas we use 2017 data for other components of this analysis where this is the most recent full year for which we have the data).

b) Different user profiles

A1.17 We have developed three rail user profiles for Commuters, Business users and Leisure users to reflect the fact that users may conduct different types of activities depending on their reason for travel. We have used the same user profiles for our 2025 calculations as we have no reason to believe that these will change significantly over time.

A1.18 The table below shows the different activity make-up for each user type:

[110] http://www.ipa.co.uk/page/touchpoints-methodology#.W1reZ2yWywc, available via subscription

Table A1.2: Activity make-up by user type for 2017 (average % of time on each application when using mobile, tablet or laptop)

Category	Average % of total	Commuter % of total	Business % of total	Leisure % of total
WATCHING				
Live TV	1%	1%	0%	1%
Free on-demand (iPlayer, All4 etc.)	2%	2%	0%	2%
Paid on-demand (Netflix, Amazon etc.)	3%	2%	0%	3%
Online video clips (YouTube, videos on social media)	5%	4%	0%	5%
WATCHING TOTAL	**10%**	**9%**	**0%**	**12%**
LISTENING				
Live radio	2%	1%	0%	2%
On-demand radio	1%	1%	0%	1%
Streamed music	3%	3%	0%	4%
Music videos	1%	1%	0%	1%
LISTENING TOTAL	**7%**	**6%**	**0%**	**9%**
COMMUNICATING				
Social networking (Twitter, Facebook excluding checking updates)	12%	10%	17%	14%
Instant messaging	12%	10%	17%	14%
Emailing	11%	16%	21%	5%
Texting	7%	6%	10%	8%
Photo or video messaging	1%	1%	2%	2%
Phone calls	3%	5%	7%	4%
Video calls	1%	1%	0%	2%
COMMUNICATING TOTAL	**48%**	**50%**	**74%**	**49%**
GAMING				
Gaming	4%	4%	0%	5%
GAMING TOTAL	**4%**	**4%**	**0%**	**5%**
READING/BROWSING/USING				
Newspapers (print or digital)	2%	2%	3%	2%
Magazines (print or digital)	0%	0%	0%	0%
Other online news	1%	1%	2%	1%
Sports news/updates	2%	1%	2%	2%
Online shopping/ticketing	1%	2%	3%	2%
Other websites or apps (incl. checking social media, online banking)	14%	12%	0%	17%
Other activities (creating office documents/spreadsheets, editing videos/music/audio)	8%	12%	16%	0%
READING/BROWSING/USING TOTAL	**30%**	**31%**	**26%**	**25%**
OVERALL TOTAL	**100%**	**100%**	**100%**	**100%**

A1.19 The proportion of Commuters, Business users and Leisure users on a train will be influenced by a number of factors, for example the day of the week, time of travel and train route. The average split of the three user types is 56% commuting, 10% business and 33% leisure, as published by the Department for Transport in 2017[111] and we have applied this average split of users in our calculations.

c) Average data speeds

A1.20 Users will require different data speeds to conduct different activities, for example a user watching live TV on his mobile phone will require a higher data speed than a user reading an online magazine. We have therefore estimated an average data speed for each activity for the present day which would provide an acceptable experience for users. We have also estimated average data speeds for 2025 which account for the fact that expectations of quality and data speed are likely to increase over time and are therefore reflective of a better experience.

A1.21 For example, standard definition video would ideally require an average data speed of 1.5 Mbit/s today, but we have chosen to apply an acceptable data speed of 500 kbit/s, as this data speed would still enable the user to watch the video at an acceptable level of quality on their device. Looking forward to 2025, an acceptable data speed for standard definition video may be 1.5 Mbit/s but we consider that passengers' expectations would increase over time and we therefore apply a 3.2 Mbit/s ideal data speed for this activity, reflecting HD video quality. The average data speed requirements we have used for the various activities are displayed in Table A1.3 below.

[111] DfT, *Rail Factsheet*, November 2017, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/663116/rail-factsheet-2017.pdf

Table A1.3: Average data speed estimates per activity[112]

CATEGORY	Average data speed estimates (Mbit/s) 2017	2025
WATCHING		
Live TV	0.5	3.2
Free on-demand (iPlayer, All4 etc.)	0.5	3.2
Paid on-demand (Netflix, Amazon etc.)	0.5	3.2
Online video clips (YouTube, videos on social media)	0.5	3.2
LISTENING		
Live radio	0.096	0.32
On-demand radio	0.096	0.32
Streamed music	0.096	0.32
Music videos	0.5	3.2
COMMUNICATING		
Social networking (Twitter, Facebook excluding checking updates)	0.2	1
Instant messaging	0.1	0.1
Emailing	0.2	1.5
Texting	0	0
Photo or video messaging	0.5	1.5
Phone calls	0.013	0.013
Video calls	0.5	1.5
GAMING		
Gaming	1	4
READING/BROWSING/USING		
Newspapers (print or digital)	0.2	1
Magazines (print or digital)	0.2	1
Other online news	0.2	1
Sports news/updates	0.2	1
Online shopping/ticketing	0.2	1
Other websites or apps (incl. checking social media, online banking)	0.2	1
Other activities (creating office documents/spreadsheets, editing videos/music/audio)	0.2	1

A1.22 These data speeds reflect the *average* bit rates required by each service; in general, a much higher bit rate will be required from time to time (for example when a passenger initially starts to conduct a specific activity), but this will reduce once the initial connection has been established.

[112] These data speeds are based on publicly available sources such as https://www.bbc.co.uk/iplayer/help/how-to-guides/getting-started/3g_4g and https://en.wikipedia.org/wiki/Bit_rate#Audio, as well as internal Ofcom estimates and judgement

A1.23 Our analysis of 2025 speed requirements do not account for advancements in technology where we cannot sensibly predict the impact on the type of activities undertaken on mobile devices. Examples of this could be the increase in uptake of virtual reality gaming which would require higher constant data speeds, or new techniques or standards for encoding which could make applications more efficient and reduce data speed requirements (to the extent that they are not anticipated in the numbers above).

d) Proportion of passengers connected

A1.24 A key determinant of the data requirements of a busy train is the proportion of passengers which are using their mobile devices at any one time. There is significant uncertainty in our assumptions regarding this figure. In large part, this is because we are considering the hypothetical scenario in which there is no constraint on the ability of passengers to use their mobile devices on a train as they wish (i.e. that the train has good connectivity along the whole length of their journey, that they do not have to pay for on-board Wi-Fi access and that on-board Wi-Fi access does not constrain online activities in any way). Since this is not the case for many train journeys at present, empirical evidence on actual passenger behaviour today will not tell us about this hypothetical scenario.

A1.25 Nevertheless, a mobile connectivity research study[113] commissioned by the Department for Transport in 2016 stated that, on average, 65% of survey respondents had already used the internet or were planning to use the internet during their rail journey. TouchPoints data provides a very similar figure: 62.5% of survey respondents carried out online activities whilst travelling by rail.

A1.26 However, these numbers do not mean that passengers were connected for their entire journey. Whilst some might have been connected for the majority of their journey, others might have been connected only for a short period of time, for example to send an instant message. Therefore, it is not credible to assume that all of these 65% of passengers would be using their mobile device on the train at the same time. If the amount of time that these passengers were carrying out online activities amounted to half of their journey (when averaged across the 65% of passengers that did so at some point in their journey) then the average percentage of passengers connected at any one time would be 32.5% (50% x 65%). On the other hand, a greater proportion of passengers might use their mobile devices at some point in their journey if connectivity were unconstrained and free to use. For current purposes, we have assumed that the highest percentage of passengers connected to the internet at any one time would be 45% if they had good connectivity that they did not have to pay extra to access. We have made an assumption that this figure increases to 65% in 2025 to reflect an increase in the number of passengers using their devices and passengers using their devices for longer periods. There is clearly a high degree of judgement in choosing these assumptions, and other assumptions could reasonably be made.

---

[113] Steer Davies Gleave, *Mobile connectivity research study: Final report*, March 2016, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/518976/mobile-connectivity-research-study_SDG-report-with-appendices.pdf

Calculations and Results

A1.27 The blended average data speed requirements per passenger are derived by:

a) Multiplying the % time spent on each activity from Table A1.2 (selecting the relevant column as appropriate) by the relevant proportion of user types on a train, then by the average data speed estimates from Table A1.3 and totalling the results to get a blended average data speed requirement across all activities that take place when using mobiles, tablets and laptops; and then

b) Multiplying this total by the maximum proportion of passengers assumed to be connected at any one time.

A1.28 The resulting blended average data speed requirements per passenger are **102 kbit/s for 2017 and 689 kbit/s for 2025.** We note that the data speed requirement for 2017 may be an underestimate as we are only accounting for acceptable data speeds (as outlined in A1.20) rather than more desirable data speeds.

A1.29 The table below shows how each main category of activity contributes to these average data speed requirements. For example, the contribution of 'watching' to the overall average data requirement increases from 20% in 2017 to 33% in 2025, driven by an increase in the proportion of time spent watching videos, making video calls etc. and, more significantly, by the effect of the assumed increase in the quality of video stream (from today's typical mobile experience to HD video).

Table A1.4: Contribution of each activity category to overall data speed requirement

CATEGORY	Data speed requirement by category (as % of total)	
	2017	2025
WATCHING	20%	33%
LISTENING	5%	7%
COMMUNICATING	33%	32%
GAMING	18%	9%
READING/BROWSING/USING	25%	19%
TOTAL	**100%**	**100%**
Blended average data speed per passenger (kbit/s)	**102**	**689**

Top-down approach: Main input assumptions, calculations and results

A1.30 We have also considered a top-down approach which looks at the amount of data which is consumed by each passenger. This looks at the average consumer's monthly data usage and converts this into an average data rate during the times that rail passengers are actively using their devices (mobile phones, and potentially other devices which use SIM cards).

A1.31 Our starting point is the total monthly mobile data use in 2017 of 156 PB.[114] This translates into 2.99 GB per adult population per month based on a population of 52.1m people of 15 years old and above according to the 2011 UK census.[115] We have then uplifted this to account for Wi-Fi usage on the assumption that 25% of mobile usage was via mobile data.[116] This brings total monthly mobile data and Wi-Fi usage to 12 GB/month, or 399 MB/day over an average of 30 days per month. People are using data on their mobile phones for an average of 2.03 hours per day according to the Digital Day report,[117] which translates into an average data speed of 447 kbit/s. We then adjust this figure to reflect the assumption that the maximum percentage of passengers connected at any one time in 2017 is 45%, giving an estimate of 201 kbit/s per passenger.

A1.32 The exact calculation is as follows:

Monthly data consumption per user:	2.99 GB
Uplifting to include Wi-Fi data over handset:	2.99 GB/0.25 = **11.96 GB**
Daily consumption:	11.96 GB/30 = **399 MB/day**
Consumption per hour:	399/2.03 hours = **196 MB/hour**
Bit/s figure:	196 MB/3600*8*1024 = **447 kbit/s**
Scaling to 45% connected passengers:	447*45% = **201 kbit/s**

A1.33 Looking forward to 2025, we have amended the above factors as follows:

---

[114] Ofcom, *Connected Nations 2017 Report*, 15 December 2017, Annex 5, https://www.ofcom.org.uk/__data/assets/pdf_file/0018/108513/connected-nations-mobile-2017.pdf

[115] We have applied the same methodology to this calculation as outlined in 0 which explains that our future consumption figures were obtained from Ofcom's Mobile Data Strategy. A population of 52.1m people of 15 years old and above was used in these calculations. We recognise that this does not account for younger mobile users, a point that is addressed in A1.41.

[116] Ofcom, *The consumer mobile experience: Measuring the consumer experience of using Android mobile services*, 9 May 2018, https://www.ofcom.org.uk/__data/assets/pdf_file/0028/113689/consumer-mobile-experience-2018.pdf. Note that our research on consumer mobile experience finds that the surveyed mobile consumers spend 25% of their time on a mobile data connection and 75% using Wi-Fi. For simplicity, we assume this corresponds to 25% of mobile data and 75% of data sent over Wi-Fi. We are conscious this may underestimate the proportion of data sent via Wi-Fi as mobile users tend to use this technology for more data intensive applications, such as video streaming.

[117] Ofcom's 2018 Communications Market Report (https://www.ofcom.org.uk/research-and-data/multi-sector-research/cmr/cmr-2018) refers to an increased average time online of 2.47 hours per day. However this figure relates to March 2018 whereas the total monthly mobile data use relates to June 2017; we would also expect monthly mobile data use to have increased by March 2018 which would in some way offset the effect of the increased time spent online.

a) Firstly we have used low, medium and high estimates for future monthly data use per active connection. We have used estimates of 10 GB, 20 GB and 40 GB for monthly data consumption per person in 2025 based on future projections in Ofcom's Mobile Data Strategy update published in 2016.[118] We expect this growth in total data consumption to be driven by the introduction of new applications, more data-intensive use of current applications as well as more time spent connected to the Internet using a mobile phone. We have again uplifted these figures to reflect the fact that data is also consumed via Wi-Fi; we have used the same assumption of 25% of data consumption being via mobile data.

b) Secondly, in a similar vein to the bottom-up approach, we consider it reasonable to assume that the current usage patterns of a younger demographic would be representative of average usage patterns in the future. The current 11-34 age group spends an average of 3.17 hours actively using data on mobile phones, considerably more than the average figure across all age groups of 2.03 hours.

c) Thirdly, as with the bottom-up approach, we are assuming that more passengers are connected, and therefore use the figure of 65% for the maximum number of passengers connected at any one point in time in our calculations.

A1.34 The uplifting factor for Wi-Fi use is our most sensitive parameter and also the most difficult to predict. We keep the split (25:75) constant between now and 2025 but it is unlikely to remain at the same level over the next few years:

a) Today we use Wi-Fi more than mobile data because Wi-Fi has fewer constraints, namely no data caps (in the majority of cases) and more consistent user experience, e.g. higher indoor data speeds. This however may be subject to change:

   i) 5G (and in some cases 4G) may provide a more consistent user experience.

   ii) Pricing changes may relieve some of the current constraints, e.g. if data bundle sizes are increased significantly or unlimited data allowances are reintroduced in the market.

   iii) Increasing convergence and fixed-to-mobile substitution could increase the amount of mobile data we consume.

b) However, changes could also happen in the opposite direction:

   i) Fixed traffic could increase at a higher rate than mobile due to further penetration of superfast broadband and fibre to the premises products. If the mobile handset is used as the principal device to connect to the Internet, it will mean we spend more time on Wi-Fi than on mobile data.

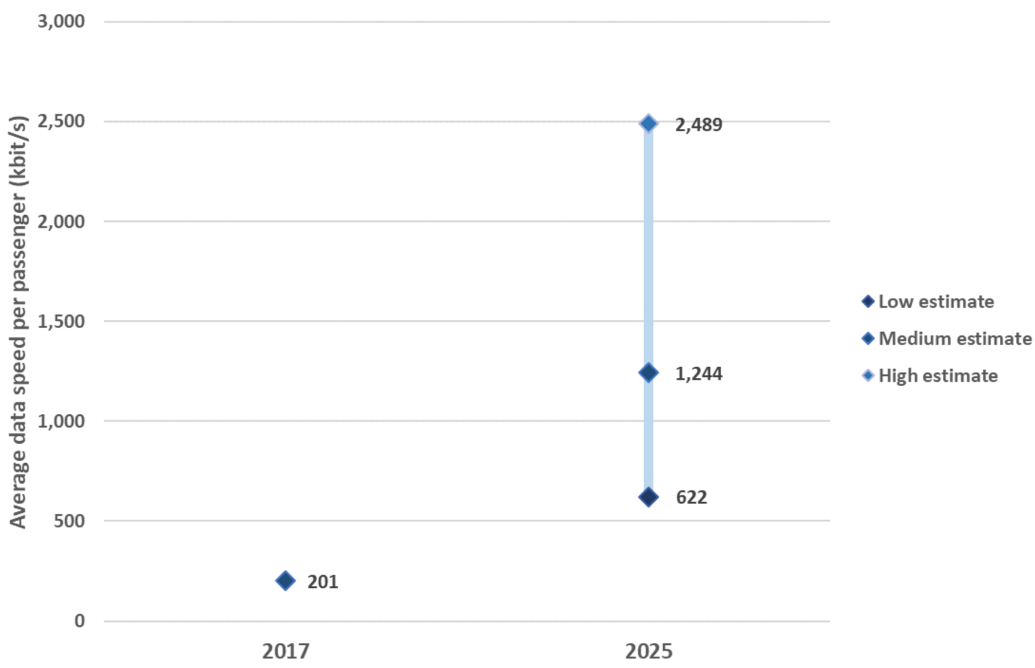
[118] Ofcom's Mobile Data Strategy update published in 2016 (https://www.ofcom.org.uk/__data/assets/pdf_file/0033/79584/update-strategy-mobile-spectrum.pdf) contains low, medium and high estimates of 10, 20 and 40 GB of monthly data consumption per population in 2025.

ii) Fixed prices could continue to offer unlimited data allowances, whereas mobile contracts may not.

iii) We have already seen the proportion of traffic over mobile data reduce to 25% in 2017 from 31% in 2016.

A1.35 The low, medium and high estimates for 2025 in Figure A1.1 below reflect the low, medium and high monthly data consumption estimates outlined above:

Figure A1.1: Top-down approach: Passenger data speed forecasts: 2017 and 2025



Comparison with real traffic measurements over a transport route

A1.36 To test the validity of our passenger demand analysis, we obtained some real measurements from an organisation called LetsJoin[119] which provides on-board Wi-Fi services over transport networks in the UK using connectivity from the MNOs' 4G networks. These measurements were taken in June 2018. We have deliberately chosen to compare today's demand predictions from our model with the average download throughput obtained over several bus routes with good 4G reception instead of a rail route, in order to reflect a good quality experience for passengers. As set out above, 4G coverage along rail tracks today is subject to several limitations, for example tunnels, cuttings and general coverage gaps, and Wi-Fi services on trains often forbid video-streaming and other data-intensive applications and limit free access to very low data usage (e.g. 15 MB on Great Western trains).

[119] LetsJoin works with transport operators (e.g. bus and train operators) to provide on-board Wi-Fi services. In providing passenger behavioural analytics services to operators, LetsJoin is able to monitor the use of Wi-Fi services and has shared some of its real-time measurements with us.

Table A1.5: LetsJoin analysis based on real measurement of user traffic

	Average download rate (MB/minute)	Sample size (user sessions)	Average download rate (kbit/s)
All	0.90	733,086	123
Upper quartile	2.85	183,271	321
50% - 75%	0.80	183,272	109
25% - 50%	0.36	183,271	49
Lower quartile	0.10	183,272	14

A1.37 Table A1.5 shows the average download rate obtained from a sample of around 733,000 different user sessions. For each session, it is possible to calculate the average download rate by dividing the data downloaded during each session by the duration of the session (typically a few minutes). The average of these averages is 123 kbit/s. The same analysis is then repeated for different quartiles of the sample.

A1.38 For our purposes, we consider it relevant to look at the throughput of the upper quartile (321 kbit/s) as well as the simple average throughput (123 kbit/s). This is because the average is subject to downward bias as it may include sessions where the MNOs' coverage or the network capacity of the cell serving the bus over a specific section of the route is limited; we would expect the sessions in the top quartile to be less affected by this. The top quartile however would also skew the sample towards sessions where more data-hungry applications like video streaming are being used by bus passengers.

A1.39 For a meaningful comparison with our average data user throughput, we also need to scale down the LetsJoin measured throughput to reflect the maximum proportion of users connected of 45% used in our two demand approaches. Considering all of the above, the current average throughput over a well-served bus route is therefore in the range of **55-145 kbit/s.**[120]

Overall demand estimates

A1.40 Table A1.6 summarises the results from the bottom-up approach, the top-down approach and the LetsJoin measurements. These results account for the fact that we have assumed a maximum of 45% of passengers connected at any one time in 2017 and a maximum of 65% in 2025. As an example, looking at the bottom-up approach, our average data demand figure for 2017 is 226 kbit/s per active user on the train. However, using the assumption

[120] This is obtained as 123*45% = c.55 kbit/s and 321*45% = c.145 kbit/s

that the maximum percentage of passengers connected at any one time is 45%, then the blended average data demand per passenger in 2017 is 102 kbit/s (226 x 45%). The numbers in Table A1.6 have been rounded.

Table A1.6: Indicative per-passenger data demand, 2017 and 2025

	2017	2025
Bottom-up (kbit/s)	**100**	**690**
Top-down (kbit/s) (low/medium/high figures for 2025)	**200**	620 / **1,240** / 2,500
LetsJoin figure (kbit/s)	**55-145**	**n/a**

A1.41 In relation to current passenger demand, we consider it appropriate to use an average demand of 150 kbit/s per passenger on the train, balancing the three information sources. We assume that the passengers' experience during the journey would be similar to the level of service they currently receive when using their mobile phone in a well-served area over a 4G network connection. We note that the results of the bottom-up approach may be lower as they reflect acceptable data speeds rather than more desirable data speeds. We also note that the results of the top-down approach may be higher as it uses an average online time per day of 2.03 hours from 2016 which is likely to be an underestimate of the equivalent figure for 2017 which the monthly data consumption relates to (more recent data relating to March 2018 from Ofcom's Communications Market Report refers to an equivalent figure of 2.28 hours). It also does not account for the younger population of 11-15 years (the inclusion of which would bring the figure down to 188 kbit/s per person) and it includes the use of multiple devices (e.g. tablet, mobile broadband or second mobile phone) which may overstate the single passenger's demand.

A1.42 In relation to the 2025 projections, we use the figures from the top-down approach to illustrate the range of demand scenarios. The bottom-up approach gives a result which is similar to the low scenario in the top-down approach – but the bottom-up approach does not make allowances for the impact of new types of application that we cannot currently predict.

A1.43 Table A1.7 presents rounded data requirements for a single passenger which we take forward to Part 2 of this Annex:

Table A1.7: Data requirement of a single connected passenger

	2017	2025		
		Low	Medium	High
Blended average rate for single passenger (kbit/s)	**150**	600	**1,200**	2,500

Part 2: Assessment of passenger numbers

Introduction

A1.44 We have used rail industry data supplied to Ofcom by the Rail Delivery Group (RDG)[121] to analyse numbers of trains and passengers across three UK mainline rail routes both in 2017 and looking forward to 2025:

1. **East Coast Main Line** (London Kings Cross-Edinburgh Waverley)
2. **Great Western Main Line** (London Paddington-Penzance)
3. **TransPennine Express** (Manchester Victoria-York)

A1.45 We explain how the train and passenger numbers along different sections of track have been estimated, and then present our findings for each of the three rail routes.

Assessment of passenger numbers

Passengers per train

A1.46 Table A1.8 below provides an example of the available passenger data from the MOIRA 2.2 dataset provided to us by the RDG. The MOIRA 2.2 dataset is a model and provides us with estimates of passenger numbers rather than data on actual passenger numbers. While the train is moving, the number of passengers on the train is represented by the passengers that departed from the last stop. When the train is stationary, we derive the number of passengers that were on the train while it was stopped from the number of passengers departing at that stop less the number of passengers that joined at that stop.

[121] The Rail Delivery Group (RDG) is a membership body for the rail industry which includes both Network Rail and all of the TOCs which provide passenger services on the UK rail network.

Table A1.8: Example data extract from MOIRA dataset[122]

Origin Name	Destination Name	Departure from origin	Arrival at destination	Location Name	Arrival at stop	Departure from stop	TOC Name	Total passengers arriving	Total passengers departing	Total passengers joining	Miles
Aberdeen	Edinburgh	05:46	08:23	Aberdeen	05:46	05:46	First ScotRail	✂	✂	✂	0
Aberdeen	Edinburgh	05:46	08:23	Dundee	06:57	06:58	First ScotRail	✂	✂	✂	71.2
Aberdeen	Edinburgh	05:46	08:23	Leuchars	07:11	07:12	First ScotRail	✂	✂	✂	79.5
Aberdeen	Edinburgh	05:46	08:23	Kirkcaldy	07:40	07:41	First ScotRail	✂	✂	✂	104.5
Aberdeen	Edinburgh	05:46	08:23	Edinburgh	08:23	08:23	First ScotRail	✂	✂	✂	130.4

A1.47 We derive new entries for this table for all the intermediate minutes between stops through a simple linear interpolation, assuming constant average speed for the train. We calculate the position of the train in miles from a fixed reference point (Kings Cross station for the East Coast Mainline, Paddington for the Great Western Main Line, Manchester Victoria for the TransPennine Express route).

[122] Real passenger numbers have been removed.

Figure A1.2: Zones along the East Coast Main Line

A1.48 The data for the TransPennine Express line includes all stations on the line with exact passenger changes at each station. The data for the East Coast and Great Western mainlines only contains stop times for larger stations (primary locations), with passenger changes for smaller stations aggregated into the passenger changes of the primary locations.[123] This adds uncertainty regarding stopping times, stopping duration and passenger numbers at these smaller stations. Our analysis therefore considers ‘zones’ which contain all of the stations which are linked to a primary location. Where the last station of one primary location and the first station of the adjacent primary location are far enough apart, we consider this a separate ‘interzonal’ zone.

A1.49 There are some cases when we can be certain of the number of passengers on a train; this is the case when a train has left the last stop of its departure zone and has not yet reached the first stop of its arrival zone or when there is only a single station in a zone. However, if a train stops within a zone which contains more than one station, we use whichever is the larger number of those passengers entering or exiting the zone.

---

[123] Data was produced for us by DfT and Rail Delivery Group using the OR02 zoning system on MOIRA 2.2

Segments of track

A1.50 In practice, we cannot consider passengers per single train in isolation as the trackside network may have to serve more than one train at any one time. We have therefore analysed the way that passenger numbers vary across different sections of track.

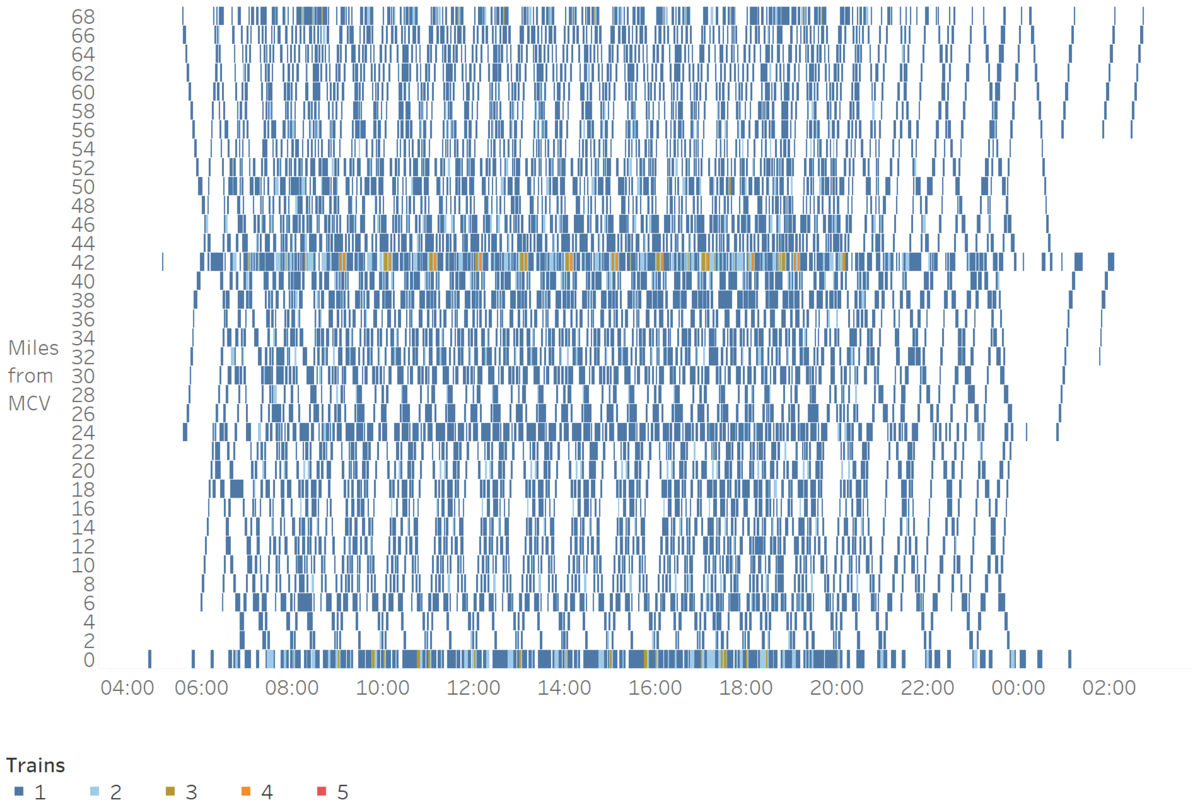
A1.51 The smallest length of track we can analyse is limited to approximately two miles (3.2km) because of the granularity of the MOIRA data, which defines a train's arrival to and departure from a station to the nearest minute. We interpolate the position of a train along the track for every minute and observe that the maximum distance travelled by fast trains in a minute is just under two miles (i.e. they travel at 120mph). We therefore consider this two-mile distance to be the basic unit of track, since the minimum increment of time used in the dataset is one minute and we are unable to make our assessment at a more granular level than this. We refer to this two-mile length as a 'segment of track'. We ensure that zones are longer than the distance travelled by the fastest train in a minute, so that there are no gaps in the data with trains skipping over certain zones.

Aggregation per minute per segment of track

A1.52 We sum all the passengers from all the trains for each minute and each segment of track. This gives us a view of how the number of passengers per minute changes over a 24-hour period.

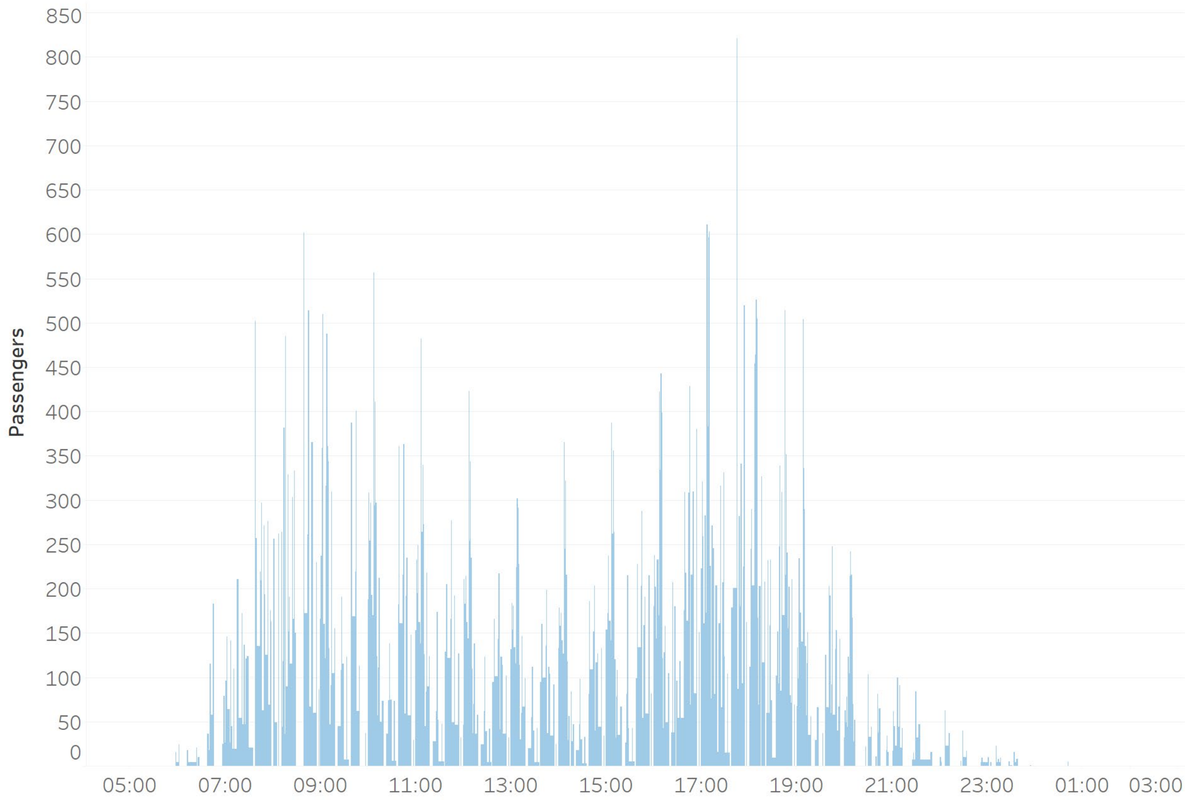
A1.53 Figure A1.3 below shows an example train heatmap for the TransPennine Express line. The dark blue coloured squares represent instances when there are only single trains within sections of track. However, the other coloured squares illustrate that there are a number of sections of track where more than one train is passing at that particular time.

Figure A1.3: Example train heatmap for the TransPennine Express line (Manchester Victoria to York)



A1.54 Figure A1.4 below provides an example to illustrate how passenger numbers change within a section of track over a 24-hour period. The morning and afternoon peaks are clearly visible, but there also a few times of the day when there are no passengers at all.

Figure A1.4: Sample 2-mile segment of track at Leeds showing number of passengers over a 24-hour period in 2017



A1.55 We have applied overall growth figures per Train Operating Company (TOC) per year shared with us by the Department for Transport (DfT).[124]

A1.56 These figures give a percentage growth rate compared to 2016 passenger numbers. As the passenger data we use is for the summer of 2017, we recalculate the growth per TOC per year from 2017. We do not incorporate changes in timetable into the forecast, we simply multiply the 2017 passenger numbers by the growth factor to find 2025 passenger numbers assuming the same timetable. Once growth factors are applied, we round the result to avoid fractional numbers of passengers on a train.

A1.57 While passengers are expected to grow by a factor of approximately 1.2 from 2017 to 2025, growth numbers are different for each TOC, and as different TOCs cover different parts of the line, the result of the forecast analysis is not simply a scaled-up version of the 2017 result. For example, the growth of Govia Thameslink/Great Northern passenger

[124] Growth numbers do not include a number of TOCs that are included in the passenger data: First Hull Trains, Merseyrail Electrics, Heathrow Connect, Caledonian Sleepers, TFL Rail (Crossrail), Tyne & Wear Metro. For First Hull trains we assume growth follows East Coast growth. For First Caledonian Sleepers we assume growth follows ScotRail growth (this TOC only affects the analysis for the Edinburgh zone). For local TOCs we assume the growth follows London Overground growth. Of those, Heathrow Connect only affects a small part of the Great Western Main Line, and Tyne & Wear Metro only affects a small part of ECML. The only local TOC for which we had no growth figures that affects a significant part of a mainline will be First Hull trains.

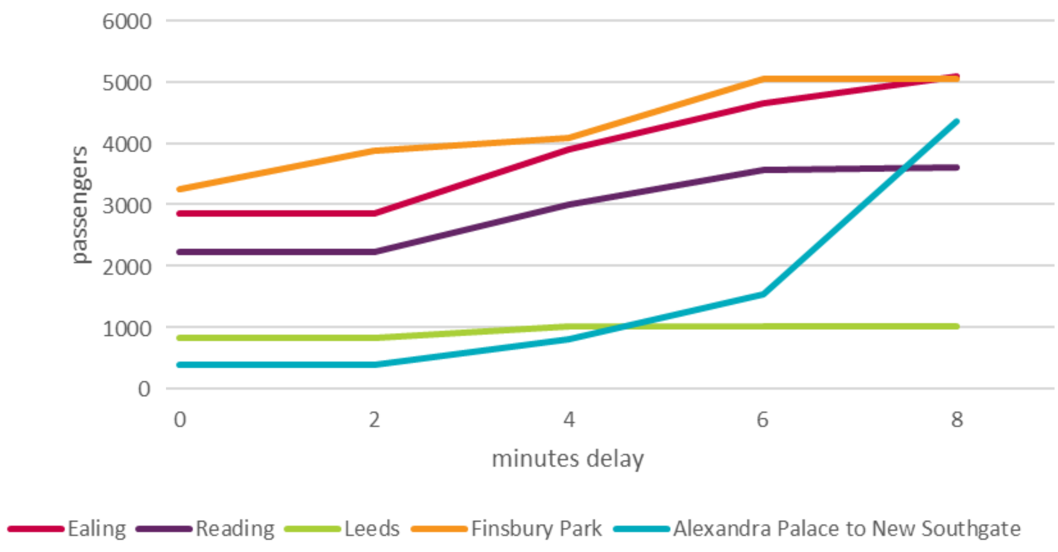
numbers will only affect the part of the East Coast Main Line south of Peterborough, and growth of Scotrail passenger numbers will only affect the part of the mainline in Scotland.

A1.58 We note that applying these growth rates to current passenger numbers (which have themselves been derived from a model) results in very high future passenger numbers in some cases. These are consistent with the most crowded trains today.[125] However we understand that there are likely to be measures to address high future passenger numbers, for example timetabling changes.

Sensitivity to delays

A1.59 We consider trains 2, 4, 6 and 8 consecutive minutes around a selected minute for the particular zone to investigate the effect of delays, and then sum the passenger numbers for each unique train that goes through the zone in that time. In this way, trains that would not normally be in the same zone at the same time have their passengers summed together to simulate the effects of delays. We observe that different zones have very different sensitivities to delays. The Leeds 2-mile segment is not affected much by even eight minutes' delay around its peak minute. On the other hand the Ealing, Reading and Finsbury Park zones see a significant increase in passengers with a few minutes' delay around their peak busy minute. For the Alexandra Park to New Southgate interzonal area we start from a time that is not so busy for the area, but with eight minutes' delay we get peak level passengers.

Figure A1.5: Increase in passengers for different delay scenarios for Ealing and Reading zones on the Great Western Main Line, Leeds zone on the TransPennine Express, and Finsbury Park zone and Alexandra Park to New Southgate interzonal area on East Coast Main Line



[125] DfT, "'Top 10' overcrowded train services: England and Wales, spring and autumn 2017, 24 July 2018", https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728105/top-10-overcrowded-trains-2017.pdf

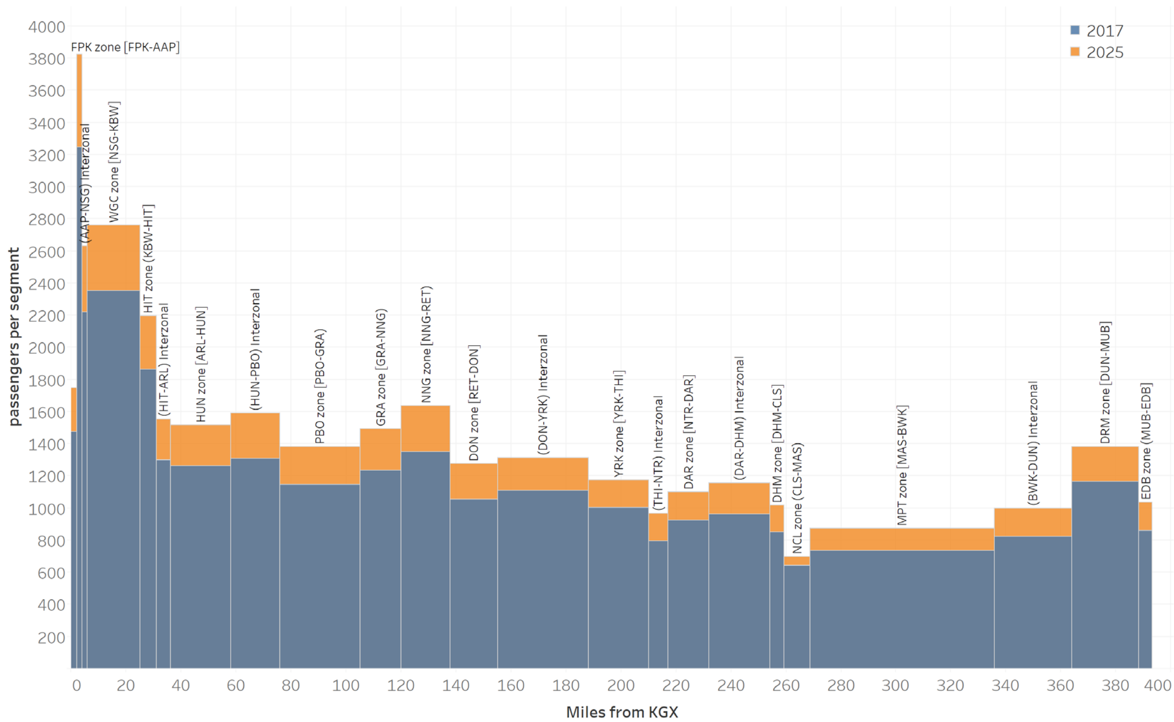
Findings

A1.60 We are able to estimate a total data speed requirement for individual sections of track by combining the average data speed requirement per passenger from Part 1 of this Annex with the overall number of passengers per section of track. Our findings for each of the three train lines are presented below.

East Coast Main Line

A1.61 Figure A1.6 below shows passenger numbers along the various segments of track on the ECML[126] from London Kings Cross to Edinburgh Waverley in 2017 and 2025.

Figure A1.6: Peak passengers per segment in 2017 and 2025, East Coast Main Line



A1.62 The busiest part of this line (both in 2017 and 2025) is the roughly 30 miles between London Kings Cross and Hitchin in Hertfordshire. This is due to high numbers of commuter trains and passengers using this section of track, as well as converging tracks which serve other mainline routes. In particular, the mainline heading south from Kings Lynn and Cambridge joins the ECML just north of Hitchin. This area could require around 330 Mbit/s per mile to meet current levels of demand, and around 3.2 Gbit/s in 2025 (based on our medium future scenario for per-passenger data use of 1.2 Mbit/s).

[126] We use a square bracket where the station is included in the zone, and a round bracket where it isn't. Thus the King's Cross zone [KGX-FPK] includes King's Cross station and covers the length of line up to but not including the Finsbury Park station. [FPK-AAP] starts from Finsbury Park station itself up to and including the Alexandra Palace station. The interzonal area (AAP-NSG) starts just after Alexandra Palace station and stops just before the New Southgate station.

A1.63 However, as can be seen on the graph above, the 2-mile segment from Finsbury Park to Alexandra Palace is substantially busier than the rest of this 30-mile section. This area could require around 490 Mbit/s to meet current levels of demand, and 4.6 Gbit/s in 2025. The route map below shows why this particular segment is so much busier than its neighbouring segments: the line into Moorgate station in the City of London splits off from the ECML south of Finsbury Park, and the Hertford Line splits off north of Alexandra Palace, running via Bowes Park to the east of the ECML, which runs via New Southgate. In addition to this, Finsbury Park is the first interchange with the London Underground for many commuters coming into London.

Figure A1.7: Route map showing ECML (stations highlighted green) and other rail routes passing through Finsbury Park

Source: Thameslink Railway website; Produced by FWT London 16/05/18 (GTR All Brands Diagram)

A1.64 Other busy areas on the line are the sections from Hitchin to Peterborough and Grantham to Retford (approximately 75 miles in total); these could require around 200 Mbit/s per segment now, and around 2 Gbit/s in 2025. The fact that these areas are busier is due to a combination of having larger hub or interchange stations in these areas, having a higher number of commuter rail services, or having several rail lines converge in these areas (and therefore taking into account trains and passengers which are only on this line for part of their overall journey). An example would be the branch line from Lincoln which connects with Newark North Gate, or the line from Ely which joins the ECML just south of Peterborough.

A1.65 Across the remainder of the line, a level of 175 Mbit/s per segment should suffice at present, although this could rise to around 1.7 Gbit/s by 2025.

A1.66 The table below shows estimated demand figures for the East Coast Main Line across the busiest segments, moderately busy segments and the rest of the line:

Table A1.9: Estimated passenger data requirement per segment across East Coast Main Line, ranked from busiest areas to least busy areas

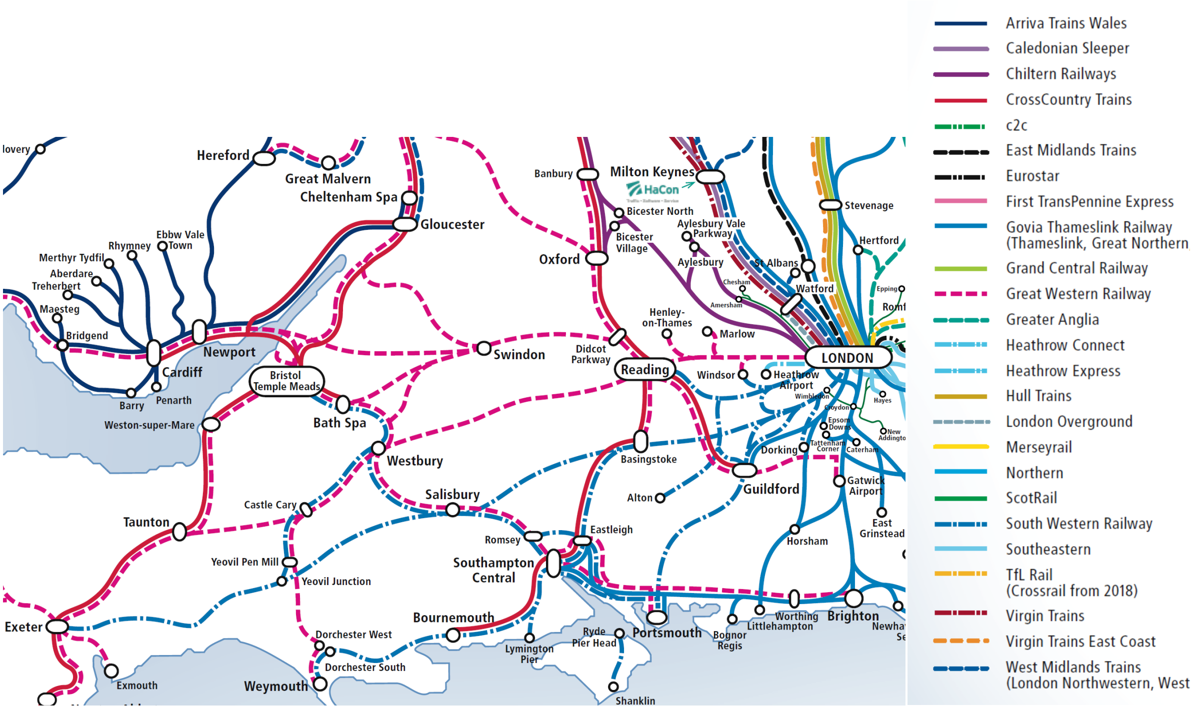
		2017		*2025*			
Area	**Miles of track**	**Max passengers per segment**	**Data demand per segment**	**Max passengers per segment**	**Data demand per segment**		
					Low	*Medium*	*High*
Finsbury Park Zone	*2*	3247	**490 Mbit/s**	3822	2.3 Gbit/s	**4.6 Gbit/s**	9.6 Gbit/s
London Kings Cross-Hitchin area, excluding Finsbury Park Zone (uses Alexandra Palace-New Southgate figures)	*30*	2220	**330 Mbit/s**	2630	1.6 Gbit/s	**3.2 Gbit/s**	6.6 Gbit/s
Hitchin-Peterborough and Grantham-Retford areas (uses Newark North Gate Zone figures)	*75*	1348	**200 Mbit/s**	1635	980 Mbit/s	**2 Gbit/s**	4.1 Gbit/s
Rest of line: Peterborough-Grantham, Retford-Edinburgh (uses Drem Zone figures)	*285*	1164	**175 Mbit/s**	1384	830 Mbit/s	**1.7 Gbit/s**	3.5 Gbit/s

Great Western Main Line

A1.67 Figure A1.9 below shows passenger numbers along the various segments of track on the Great Western Main Line from London Paddington to Penzance in 2017 and 2025. Note that the Penzance and St Erth zones were merged, in order to avoid a zone smaller than the distance travelled by the fastest train in a minute.

A1.68 Reading is a busy junction where CrossCountry and SouthWestern trains contribute considerably to the passenger total, along with Great Western trains. While the approach to London is not as busy on this mainline as it is on the ECML, the part of the line that requires less than 2 Gbit/s in the future is smaller both in absolute number of miles and as a percentage of the total mainline length (approximately 40%). This is somewhat expected, as this line serves commuter areas beyond central London such as Heathrow Airport and Reading, Bath and Bristol and is used by several TOCs.

Figure A1.8: Route map showing some Great Western routes and other operators whose routes pass through Reading, Bath and Bristol



Source: https://www.raildeliverygroup.com/files/Publications/2017-12_BDrailmap39.pdf

Figure A1.9: Peak passengers per segment in 2017 and 2025, Great Western Main Line

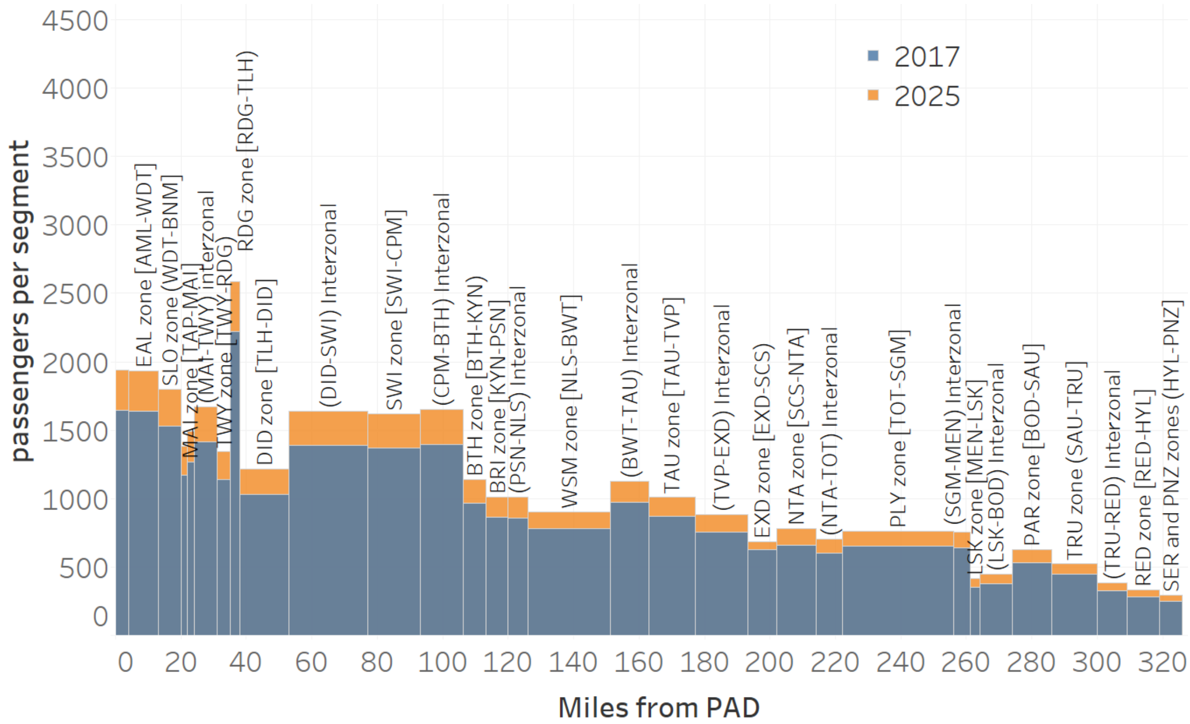


Table A1.10: Estimated passenger data requirement per segment across the Great Western Main Line, ranked from busiest areas to least busy areas

		2017		*2025*			
Area	**Miles of track**	**Max passengers per segment**	**Data demand per segment**	**Max passengers per segment**	**Data demand per segment**		
					Low	***Medium***	***High***
Reading Zone	*3*	2220	**330 Mbit/s**	2600	1.6 Gbit/s	**3.1 Gbit/s**	6.5 Gbit/s
London Paddington to Reading, Didcot to Bath (uses Paddington Zone figures)	*88*	1650	**250 Mbit/s**	1950	1.2 Gbit/s	**2.3 Gbit/s**	4.9 Gbit/s
Tilehurst to Didcot, Bath to Exeter St Davids areas (uses Didcot Zone figures)	*102*	1050	**160 Mbit/s**	1650	990 Mbit/s	**2 Gbit/s**	4.1 Gbit/s
Rest of line: Exeter St Davids to Penzance (uses Plymouth Zone figures)	*125*	660	**100 Mbit/s**	750	450 Mbit/s	**900 Mbit/s**	1.9 Gbit/s

TransPennine Express

A1.69 Figure A1.11 below shows passenger numbers along the various segments of track on the TransPennine Express route from Manchester Victoria to York in 2017 and 2025. The TransPennine Express route is a special case as we have the full detail of timetable and passengers, therefore we use a uniform two-mile section width.

A1.70 We do not have per-TOC passenger growth information for this line so we apply an overall growth factor of 1.20 (i.e. add 20% growth) to obtain 2025 passenger number projections.

A1.71 The section of the mainline from Huddersfield to Leeds is the busiest, together with isolated busy segments elsewhere. The rest of the line has much lower requirements, compared to the less busy areas of other mainlines.

Figure A1.10: Map showing TransPennine Express (blue) and other rail routes (grey), including section from Manchester Victoria to York (stations highlighted green)

Source: http://www.projectmapping.co.uk/Reviews/Resources/tpe_map_geo_oct2016.pdf

Figure A1.11: Peak passengers per segment in 2017 and 2025, TransPennine Express

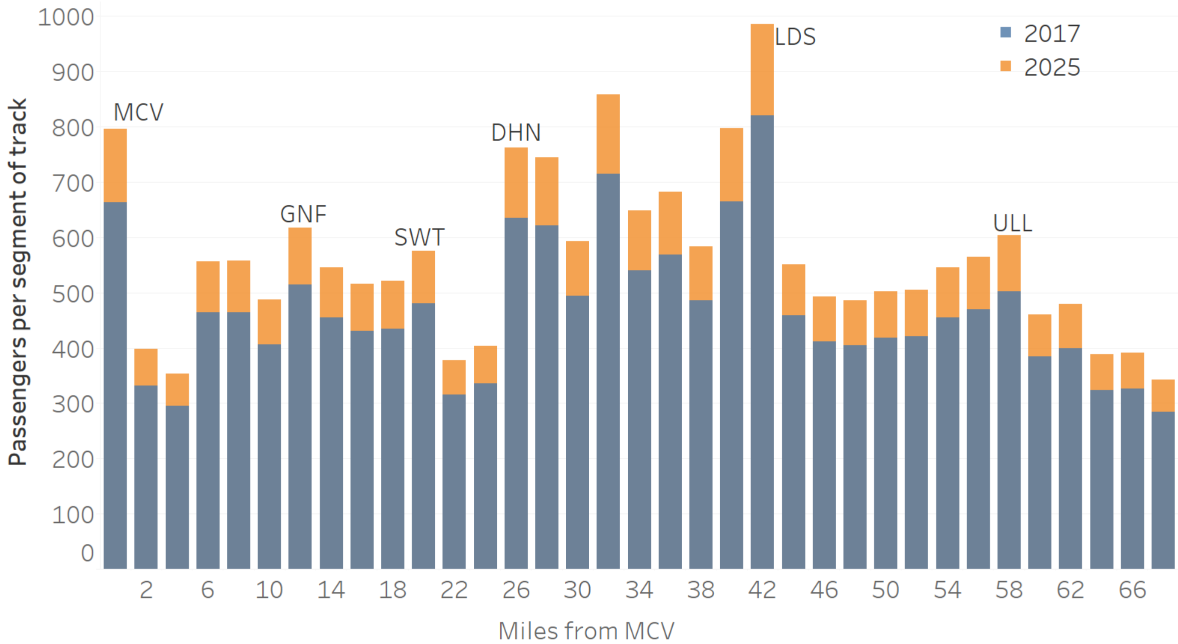


Table A1.11: Estimated passenger data requirement per segment across the TransPennine Main Line, ranked from busiest areas to least busy areas

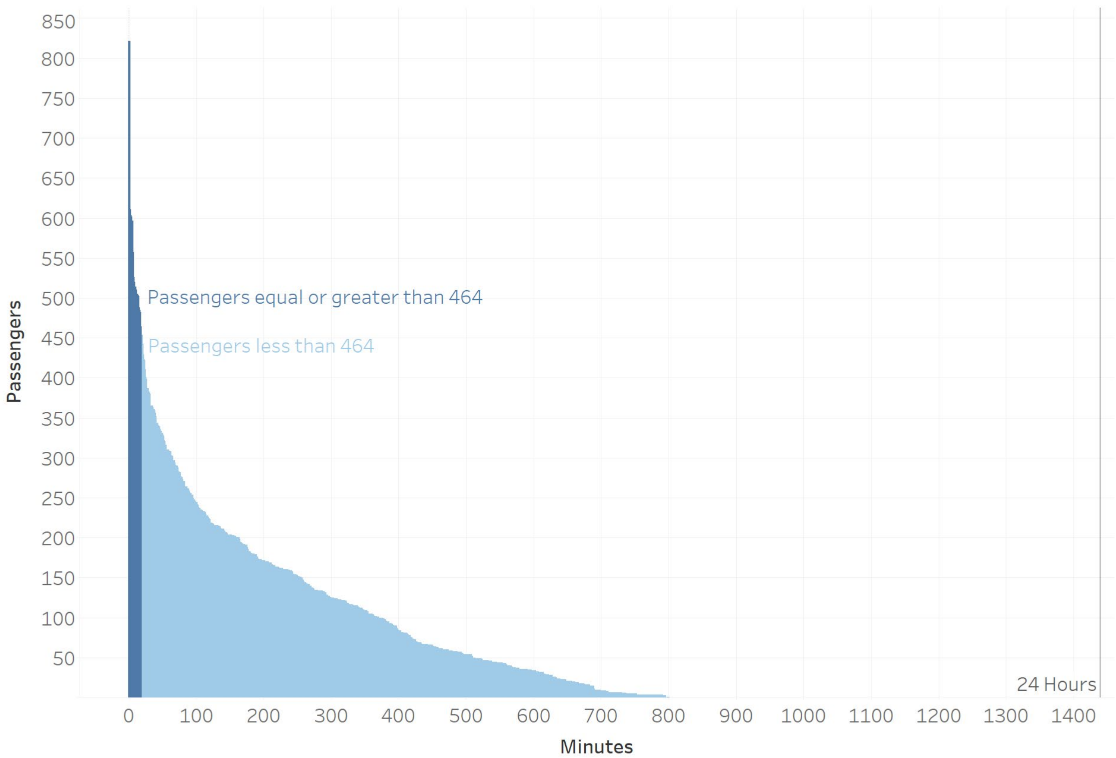
		2017		*2025*			
Area	**Miles of track**	**Max passengers per segment**	**Data demand per segment**	**Max passengers per segment**	**Data demand per segment**		
					Low	***Medium***	***High***
Manchester Victoria, Greenfield, Slaithwaite 2-mile segments, Deighton to Leeds, Ulleskelf 2-mile segment: (uses Leeds figures)	*26*	820	**330 Mbit/s**	985	590 Mbit/s	**1.2 Gbit/s**	2.5 Gbit/s
Rest of line: (uses Church Fenton figures)	*44*	470	**250 Mbit/s**	565	340 Mbit/s	**680 Mbit/s**	1.4 Gbit/s

Implications of varying passenger load during the day

A1.72 The results presented above relate to the peak passenger numbers (and associated peak data rate demand). In the case of the track segment illustrated in Figure A1.4 above, for example, the peak passenger numbers occur for a very short time around 8am in the morning. For many other times of day the number of passengers (and hence the associated passenger data demand) will be considerably less than this. This section considers the possible implications of the varying passenger loads for the sizing of rail connectivity solutions.

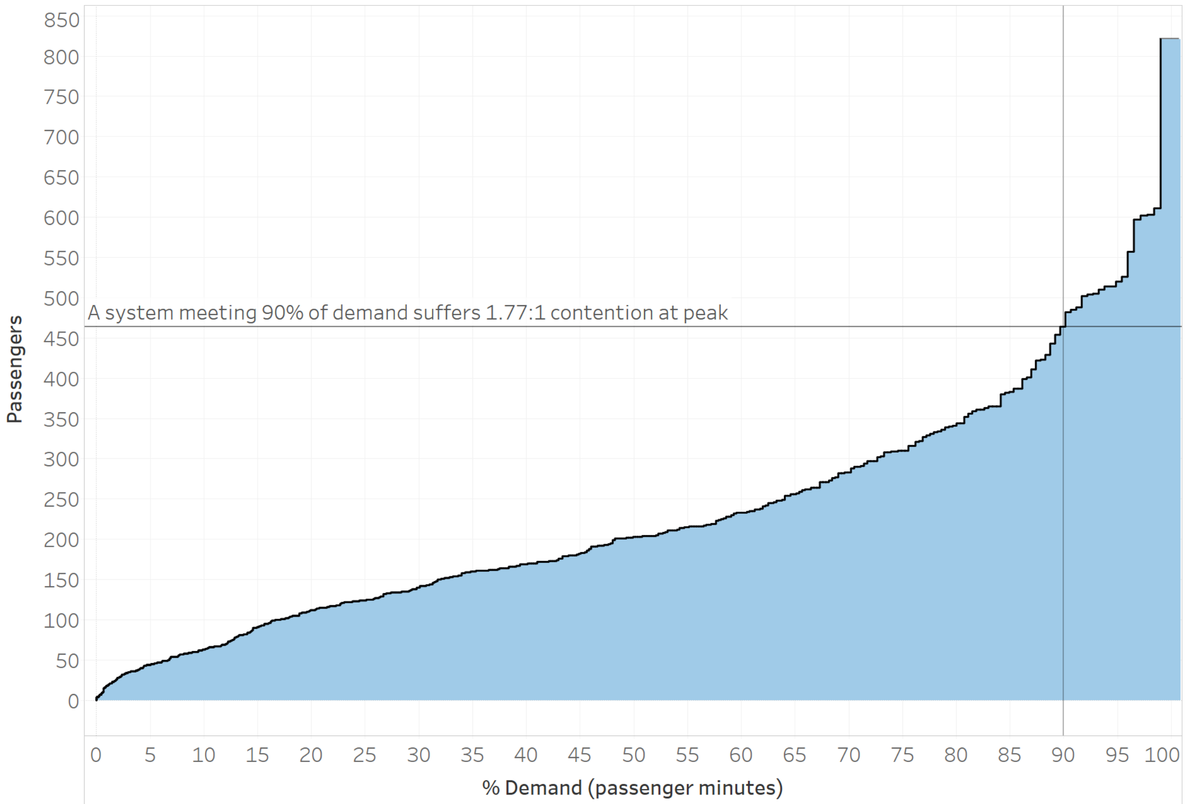
A1.73 Figure A1.12 takes the same information as presented in Figure A1.4, but reorganises it so that the bars representing passenger numbers run from largest to smallest. The minutes with no passengers in the section are at the right-hand side of the chart between the 800th minute and the 1440th minute (1440 minutes corresponds to 24 hours). The total area under this graph represents 'passenger minutes' and is a proxy measurement of overall mobile broadband demand (the product of total passenger minutes times the 'average data rate per passenger minute' will give the overall data demand across the 24-hour period). We shade the area of this graph from the origin to 18mins, which corresponds to 464 passengers on the y axis. The dark blue shaded area represents 10% of the total area under the full curve – in other words, 10% of overall demand takes place when the number of passengers in the segment at the same time is above or equal to 464 and the other 90% takes place when the number of passengers in the segment at the same time is below 464 (light blue area).

Figure A1.12: Sample 2-mile segment of track at Leeds showing number of passengers per minute, arranged in descending order, over a 24-hour period in 2017



A1.74 The same analysis can be carried out for every point along the x axis in Figure A1.12 with the results represented as a cumulative load duration curve as in Figure A1.13 below. In this curve, cumulative demand (as represented by passenger minutes) is shown along the x axis, expressed as a % of total demand. The same 90% point is marked in this figure to show that 90% of demand occurs when the total number of passengers in the segment is at 464 or less (note also that the ratio of peak demand to the level of demand at this 90% point is around 1.8; in other words, if the capability of a trackside connectivity system was limited to being able to serve a train with 464 passengers on board, then the level of excess demand at the peak would be 80%, and the average speed to the individual passenger at this peak time would have to be reduced accordingly).

Figure A1.13: Cumulative load-duration curve of 2-mile segment of track including Leeds, showing overall demand profile in 2017

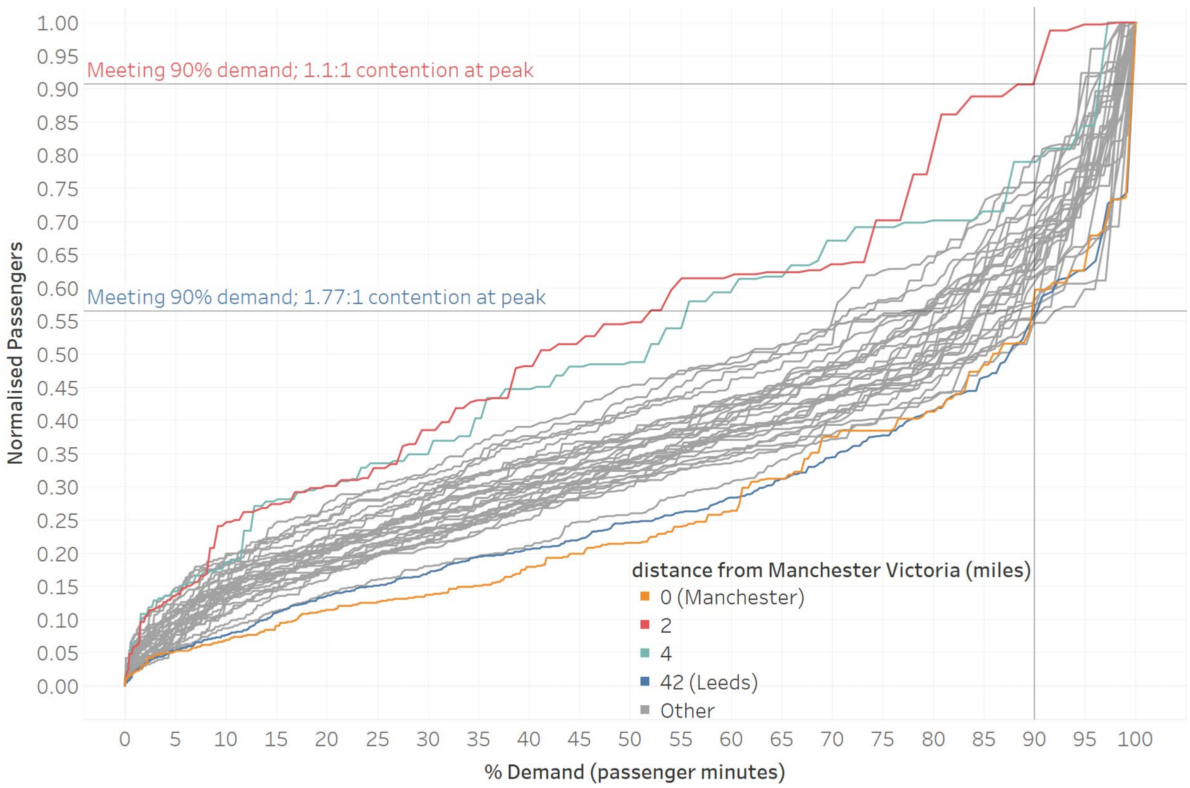


A1.75 Figure A1.13 shows that the maximum number of passengers in the segment at any time is 821 (as represented by the top of the curve on the very right of the graph). But this situation reflects only 2% of the total demand across the day (as represented by the width of the bar under the cumulative load duration curve at this peak demand point). It would clearly be desirable to design the trackside connectivity solution so as to meet all demand at the absolute peak. But there could be a case for a commercial deployment to be sized in a way that does not meet all demand at this absolute peak if doing so were to trigger the need for a much more expensive solution (compared to sizing it to meet the 90% or 95% point in the above figure). In this case, a significant proportion of demand could still be served at the right-hand end of this figure. But this would require a reduction in average speed to individual users on the train at these times. The impact on these users might be mitigated by appropriate traffic management mechanisms that deal with temporary excess demand (noting also that certain applications automatically adjust in these situations; for example some video streaming services drop down automatically to a lower resolution so that the user continues to get service, albeit at a lower quality). The black outline envelope in this figure will be used instead of the shaded area in the subsequent plots that present load duration for different parts of a mainline in the same figure.

A1.76 The following figures present the shape of this cumulative load duration curve for different segments along the various rail lines we have analysed (without shading in the bars under the curve). To be able to compare their shapes, we normalise the passenger numbers on the y axis (by dividing the passenger numbers by the maximum number for that segment so that the peak is always represented by 1.00). The significance of these curves depends on how fast they drop away from the high point on the right-hand side (where y=1 and x = 100%). If they drop steeply, then the consequences of a trackside connectivity solution that doesn't meet the absolute peak will be more modest (than if the slope is more shallow).

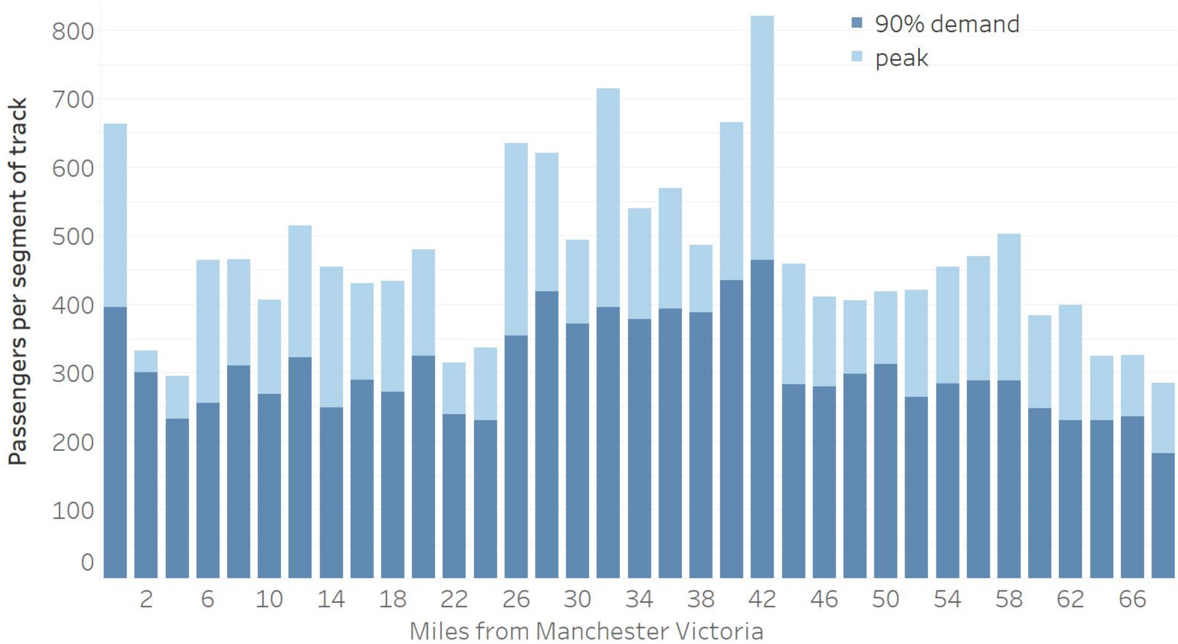
TransPennine Express line

Figure A1.14: Cumulative distribution of normalised passengers for all two-mile segments of the TransPennine Express route



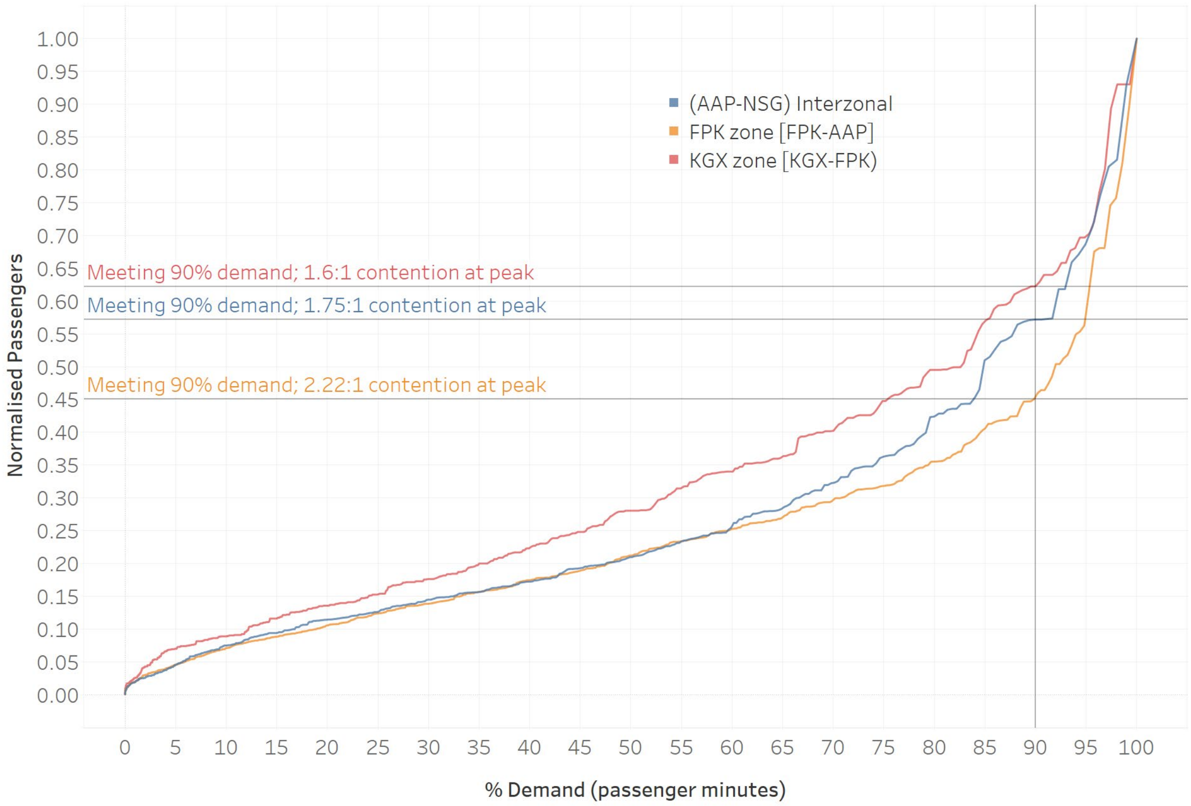
A1.77 On the TransPennine Express line, the busy urban segments (Manchester, orange line and Leeds, blue line) have a very sharp fall off from the peak down to 90%, whereas the rural zones (e.g. the red and green line for segments 2 and 4 miles from Manchester) decrease more steadily. Figure A1.15 below shows how the demand profile changes over the length of the TransPennine Express line (broken into 35 segments of 2 miles each), taking two different measures of demand: the peak demand in each segment: and the 90% point on the cumulative load duration curve in each segment. This shows that there is less variability along the track in the '90%' point than there is in the peak demand.

Figure A1.15: Passengers per TransPennine Express mainline route segment, 2017 figures



East Coast Main Line

Figure A1.16: Cumulative distribution of passengers for small zones on the East Coast Main Line[127]

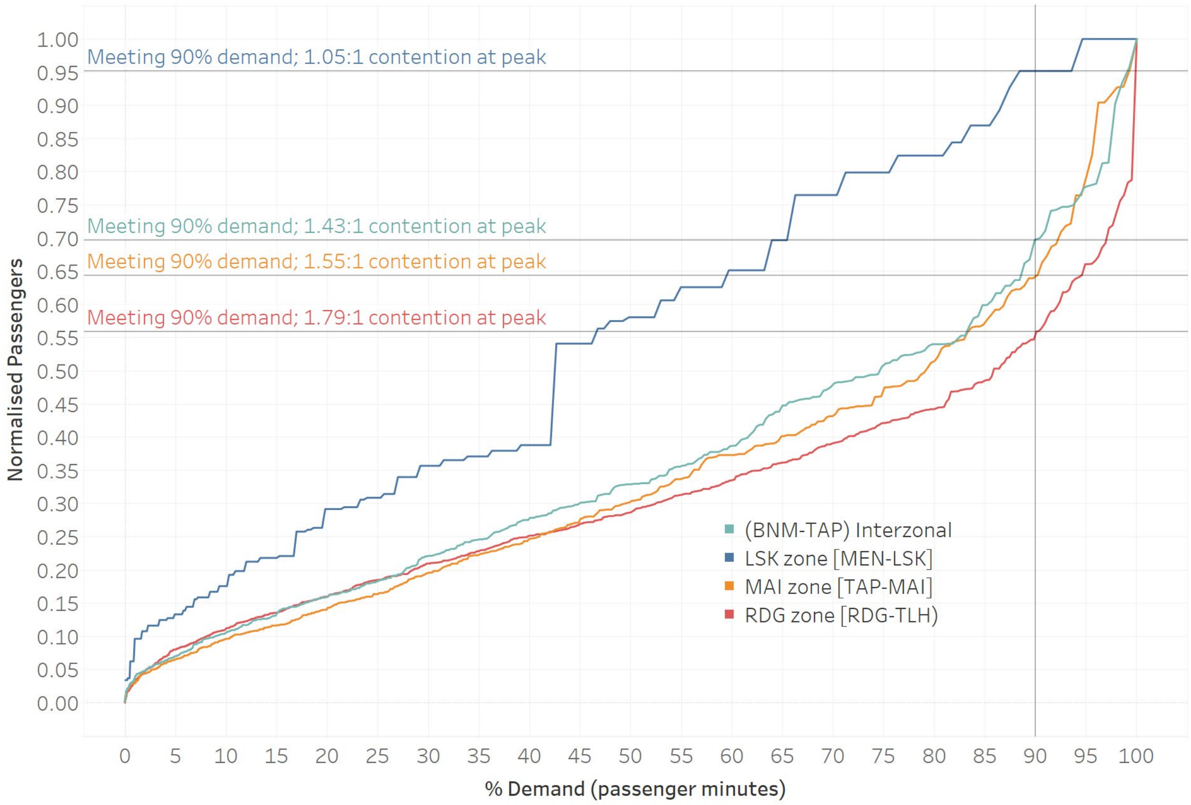


A1.78 The East Coast Main Line has highly variable zone lengths. It is only meaningful to show the curves for small zones that correspond to one segment of track. The small zones of the East Coast Main Line are all on the approach to the London terminal. The slope of this curve is particularly steep for the Finsbury Park zone which has the highest peak demand (demonstrating again that the highest passenger numbers persist for a short time only).

[127] Contention at peak is estimated as the ratio between demand at peak and demand at 90% point on cumulative load duration curve

Great Western Main Line

Figure A1.17: Cumulative distribution of passengers for small zones on the Great Western Main Line



A1.79 The Great Western Main Line also has variable zone lengths. Looking at the smaller, single segment zones, they include both rural areas such as Liskeard in Cornwall, that have a ratio near 1 for peak passengers to 90% demand passengers, and busy junctions such as Reading where the number of passengers nearly doubles because of the steep rise from 90% to 100% of demand. As with the above cases, the busiest segments with the highest demand also have the peakiest shape (i.e. the peak demands are much greater at these busy points, but these peaks are short and represent a small percentage of overall demand).

A2. Spectrum efficiency estimation

A2.1 This annex provides a brief review of a sample of relevant wireless technologies that could be used to implement a track-to-train mobile backhaul link to carry passenger broadband traffic. This purpose of this review is to develop a range of spectrum efficiency to help estimate data rates that might be achieved in the bands outlined in Section 4.

Technologies available today and in the future

A2.2 The spectrum required to deliver a given data rate is dependent upon the specific technology chosen for radio transmission and is mainly characterised by spectrum efficiency (expressed in bits/s/Hz).

A2.3 Growing data use means that spectrum efficiency is a key criterion which has driven technology design to the point that many contemporary radio system technologies employ the same underlying techniques thereby achieving similar spectrum efficiencies.

A2.4 These underlying techniques include Adaptive Modulation and Coding (AMC) whereby the data rate drops to a rate that can be sustained for deteriorating link conditions; Orthogonal Frequency Division Multiplexing (OFDM) which supports efficient wideband transmission; Multiple Input Multiple Output (MIMO) antenna arrays that can support multiple spatial data streams or beam-forming which can enhance range; Multi User MIMO (MU-MIMO), which can improve delivery efficiency to multiple users; and massive MIMO antenna arrays which can enhance many of the aforementioned techniques.

A2.5 Broadly, there are three families of technology considered here:

a) **3GPP** (4G LTE, 5G NR etc.);

b) **IEEE 802.11** (Wi-Fi/WiGig); and

c) **proprietary technologies** (often based on enhanced versions of standardised technologies).

A2.6 We review the maximum data rates quoted and associated figures regarding spectrum efficiency where available, before concluding what efficiencies may be practicable in a rail environment.

3GPP technologies

A2.7 The 3GPP Long-Term Evolution (LTE) family, commonly referred to as 4G, dominates the provision of mobile broadband. LTE should be considered the baseline 3GPP mobile technology as 2G and 3G based systems would not deliver significant data rates economically. LTE technology is mostly implemented below 3 GHz, but custom solutions leveraging the ecosystem may be available up to about 6 GHz.

A2.8 Basic 4G LTE is often quoted as delivering a headline rate of 150 Mbit/s in a 20 MHz channel, and later evolutions of this technology can in theory achieve a headline rate of

3 Gbit/s by aggregating five 20 MHz channels using Carrier Aggregation (CA). With this advanced form of 4G, peak spectral efficiency is quoted as 30 bits/s/Hz,[128] but this figure is the maximum achievable and is not representative of the average a user may experience. Deployed LTE technology typically achieves average spectral efficiencies circa 2 bit/s/Hz,[129] but that can further increase if higher order MIMO and MU-MIMO technologies are used. Accordingly, when 100 MHz is aggregated using the latest release of LTE, a user average of 200 Mbit/s should be achievable in an appropriately dimensioned cell.

A2.9 Forthcoming 5G mobile systems satisfy various new requirements, including enhanced mobile broadband. The 5G New Radio (NR) specification facilitates broadband by being highly flexible in using bandwidth and supports single channel widths up to 100 MHz below 6 GHz and 400 MHz in mmWave spectrum above 20 GHz. In addition, there is also some support for 800 MHz-wide blocks of spectrum,[130] and it may become possible to aggregate separate channels in similar ways that can be achieved in 4G today.

A2.10 Compared to 4G, 5G NR gives a straight-forward increase in spectrum efficiency of 10-30% by eliminating unnecessary guard blocks and by leaner use of control signals, along with other efficiency gains (dependent upon configuration).

A2.11 5G used in bands below 6 GHz can benefit from the use of massive MIMO antenna technologies that can improve capacity to multiple users in a cell. These new MIMO techniques can realise huge benefits compared to basic 4G that is currently deployed, with at least double the overall spectral efficiency.[131] This is likely to be very effective in the 3.4-4.2 GHz bands, but in the lower bands where Frequency Division Duplexing (FDD) frequency plans are common, the technology is less effective, and furthermore lower frequencies imply larger antenna arrays which could be limiting.

A2.12 When 5G is deployed in mmWave bands above about 15 GHz, massive MIMO arrays are generally used to provide beamforming gain to overcome propagation losses (which are generally much higher than below 6 GHz), and these beams can also help serve multiple users efficiently by minimising interference.

A2.13 5G mmWave trials have shown cell throughputs of 20 Gbit/s[132] and spectral efficiencies of more than 70 bits/s/Hz have been reported,[133] but typical user average figures are probably much more modest. Various 5G simulation scenarios make more realistic

[128] See http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced
[129] Amitava Ghosh, “5G New Radio – Technology and Performance”, Nokia Bell Labs, presented 20 July 2017, slide 5, http://mmwrcn.ece.wisc.edu/wp-uploads/2017/05/5G-NR-Ghosh-Nokia-Keynote.pdf
[130] Huawei, *5G Spectrum: Public Policy Position*, http://www-file.huawei.com/-/media/CORPORATE/PDF/public-policy/public_policy_position_5g_spectrum.pdf (accessed 8 August 2018)
[131] 4G in later releases can also take advantage of these new MIMO technologies although not as efficiently as 5G.
[132] NTT Docomo, “Next-generation Mobile Communications System: 5G”, https://www.nttdocomo.co.jp/english/info/media_center/event/mwc2017/pdf/about_5g.pdf (accessed 17 August 2018)
[133] Amy Nordrum “5G Researchers Set New World Record For Spectrum Efficiency”, *IEEE Spectrum*, 12 May 2016, https://spectrum.ieee.org/tech-talk/telecom/wireless/5g-researchers-achieve-new-spectrum-efficiency-record

estimates of the average efficiency experienced by a single user in the range of 3-5 bits/s/Hz.[134]

Wi-Fi (802.11) technologies

A2.14 Whilst Wi-Fi is not strictly a mobile technology, but with careful network design it can be deployed for mobile and reliable delivery in a high-speed rail context may be achieved with proprietary technology additions.

A2.15 For outdoor operation in a mobile environment, the only spectrum that is currently authorised is the 5470-5725 (5730) MHz band.[135] This band supports a single 160 MHz channel, although use of smaller channels (20/40/80 MHz) will be more likely as the band has to be shared amongst all licence exempt users. Furthermore, Wi-Fi operating in this part of the spectrum must support Dynamic Frequency Selection (DFS) to protect radar systems in this band, and in the event of radar being detected it must avoid that channel.

A2.16 The current standard 802.11ac supports MU-MIMO, which can deliver peak data rates up to 867 Mbit/s (MIMO with two streams) in an 80 MHz channel. The forthcoming 802.11ax standard should deliver higher rates through various improvements upon the current standard, some of which are implemented by some vendors today. The peak single user spectral efficiency may be circa 7.5 bits/s/Hz, but whilst certainly lower, it is not clear what a realistic single user average would be.

A2.17 For greater data rates WiGig (802.11ad) operates in the 57-71 GHz mmWave spectrum and offers the prospect of multi-Gbit/s throughput today as it employs large bandwidths and includes beam-forming gain to overcome propagation losses. WiGig can deliver a maximum data rate of 6.8 Gbit/s, and whilst not really created as a technology for infrastructure to a moving platform, it has been demonstrated in a rail environment with throughputs quoted around 1 Gbit/s. The next iteration of the WiGig standard 802.11ay due next year is more efficient and may deliver many tens of gigabits per second depending upon configuration.

A2.18 Overall it is unclear what a single user average spectral efficiency would be, but with evolving needs for broadband, and with many common underlying elements of the technology, it is reasonable to assume that efficiencies similar to 3GPP can be achieved.

Other proprietary technologies

A2.19 There are various mobile products targeting the transport market using proprietary technology. Taking Radwin's Fiber-in-Motion product as an example, it has a headline data rate of 750 Mbit/s (so the user average in a cell is likely to be significantly lower). The Radwin technology can be deployed in spectrum from 4.9 GHz to 6 GHz, so could be deployed in the same licence exempt spectrum as Wi-Fi assuming it complies with current

---

[134] Amitava Ghosh, "5G New Radio – Technology and Performance", Nokia Bell Labs, presented 20 July 2017, slide 14, http://mmwrcn.ece.wisc.edu/wp-uploads/2017/05/5G-NR-Ghosh-Nokia-Keynote.pdf

[135] Ofcom, *IR 2030 – UK Interface Requirements 2030: Licence Exempt Short Range Devices*, 27 February 2018, https://www.ofcom.org.uk/__data/assets/pdf_file/0028/84970/ir-2030-july-2017.pdf

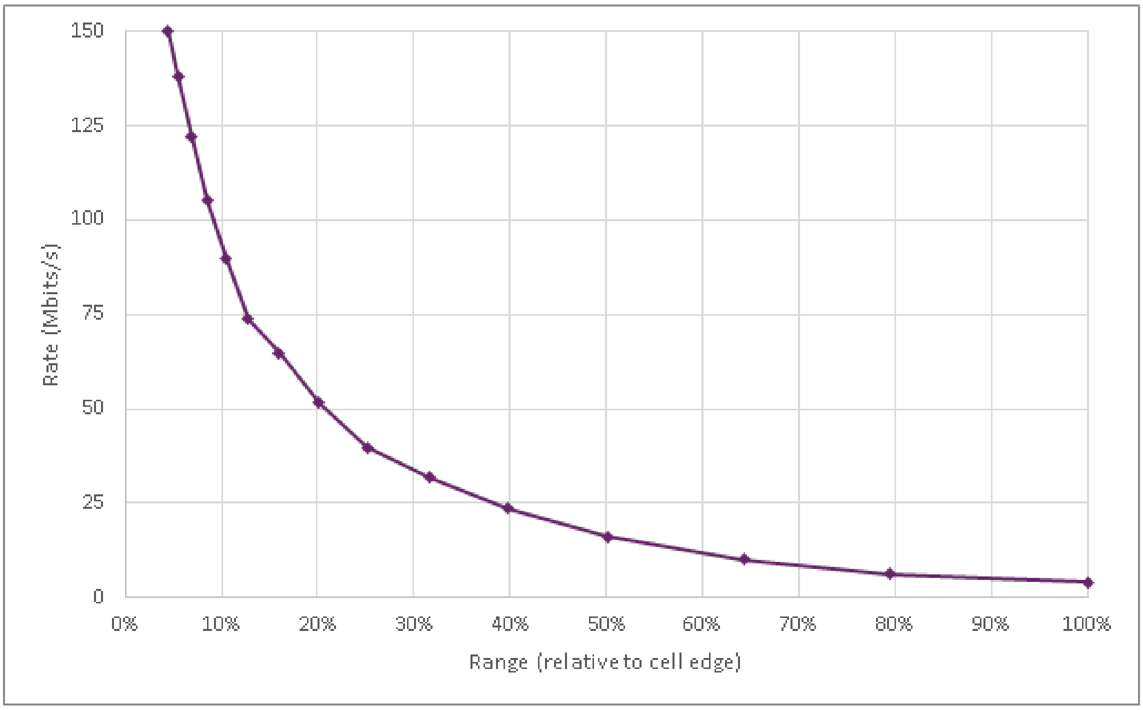
regulations. Transport solutions from FluidMesh can operate in the 5GHz Wi-Fi band and a throughput up to 500 Mbit/s is quoted (so again the user average is likely to be considerably lower). This equipment can operate in the 5 GHz Wi-Fi bands and various others too (4.94-4.99 GHz, 2.35-2.7 GHz).

A2.20 In terms of spectral efficiency, it is likely that these proprietary technologies can achieve similar figures to Wi-Fi, as they may use many of the same underlying technologies.

Average user data rates in a cell are much lower than the peak

A2.21 The data rates discussed in the previous section correspond to the maximum rate attainable and since most modern technologies implement adaptive modulation and coding, the rate will reduce as the user in a cell ranges from the centre to the edge, which is illustrated in a hypothetical scenario in Figure A2.1.

Figure A2.1: Hypothetical data rate to a user along a radial from a 4G LTE base station



A2.22 This plot shows a hypothetical case of the data rate achievable to a user in free space from a 4G LTE base station, with the power at the cell edge being only just enough to allow the system to usefully communicate data (absent other users and interference). The maximum data rate achievable is 150 Mbit/s, which is the maximum rate supported (physical layer), however, to achieve it, the user would have to be very close to the base station so that there would be sufficient power at the receiver for the highest order modulation and coding. In this illustration this would be at 5% of the distance from the base station to the cell edge. In contrast the rate at the cell edge may only be circa 4 Mbit/s, because the lower signal received would only support the lowest modulation and coding.

A2.23 In reality, cells radiate at sufficient power to allow for signal degradation due to terrain and clutter obstacles and may also be limited by interference from neighbouring cells. This means that the higher data rates may be achievable at greater distances within the cell, however, the rates at the cell edge may be even lower (compared to the illustration). In both theory and reality, the same principle applies; the average rate will be much lower than the peak.

Spectrum efficiency as a tool to estimate spectrum needs

A2.24 The data rates referred to in the previous sections are those achieved for the given technology employing a block of spectrum (usually in channelised form). Given that different technologies can be employed in different bands, and that channel widths may be different, it is useful to consider typical spectral efficiencies that are achievable across all technologies. This then permits typical data rates to be estimated by multiplying the size of the spectrum block available by the efficiency.

A2.25 Whilst there are many factors to consider, we estimate that the modern technologies discussed above are likely to deliver a usable *average* efficiency to a single train (i.e. 'the user') in the range of 2-4 bits/s/Hz.

A2.26 The upper end of this range is relatively low compared to the higher user average figures often quoted, because these figures mostly apply to multiple users benefitting from the use of MIMO technology. MIMO technology exploits the properties of the user environment which can provide huge throughput gains under certain conditions. However, when the antenna systems are line-of-sight, which is mostly the case when considering a train communicating with trackside equipment, the gains can be much less significant. This situation is compounded for mmWave where the high frequencies mean higher propagation losses and so paths are likely to be much shorter.

A2.27 Another aspect of MIMO is the ability to handle multiple users efficiently (via MU-MIMO techniques), however, in the context of rail, most cells will usually only have one train at any one time (depending on the size of the cell), so again this efficiency is unlikely to be realised, except perhaps with particular deployments at large railway stations where there are many trains and the antenna is in an optimum position.

A2.28 Most 4G systems deployed below 3 GHz employ FDD, meaning that separate but equal bandwidth is employed in the uplink and downlink. Usually the system can be dimensioned according limits of the downlink, so the minimum channel bandwidth required is the product of the spectral efficiency and the data rate required. We note that 5G NR generally targets Time Division Duplexing (TDD), partly because some of the technologies employed do not work as well with FDD, but also because better spectrum utilisation can be achieved compared to FDD where data requirements up and down are asymmetric.

A2.29 Taking for example a case where the downlink rate requirement is ten times the uplink requirement, and accounting for relative inefficiencies in the uplink, a design with a 3:1 TDD structure could be considered as satisfactory. The size of bandwidth required would be calculated from the sum of the uplink and downlink rates achievable within this TDD structure. In this example. estimating the bandwidth from the downlink rate alone implies a that the spectral efficiency would effectively be reduced by about 40%.

A2.30 We also note that the spectral efficiency estimations above consider over-the-air throughput. When comparing over-the-air spectral efficiencies with demand requirements we need to account for the protocol overhead. Given the low contention ratio and the line-of-sight conditions, we believe protocol overhead is of the order of 20% or less, leading to a further spectral efficiency reduction of about 20%.

A2.31 Taken altogether, 2-4 bits/s/Hz seems to be a sensible estimate of the range of spectral efficiency, which means the amount of spectrum required to deliver 1 Gbit/s would be between 250 and 500 MHz.

A2.32 Delivering gigabit rates based on current mobile technology has significant implications in relation to spectrum availability and choice of spectrum band. Contiguous bandwidths in the range of 250 MHz to 500 MHz are generally not available in sub-6 GHz spectrum used for mobile today, but plans suggest that this would be available in the higher mmWave bands. Considering carrier aggregation techniques, it is possible to combine spectrum in multiple low frequency bands to achieve higher rates, but this is still likely to provide much less than mmWave bands and to be less efficient in doing so.

A2.33 In summary, we have made an assumption of a spectral efficiency of the order of 2-4 bits/s/Hz for the purposes or our analysis, although any practical plan should be mindful of the principles outlined above.

A3. Glossary

3GPP: The 3rd Generation Partnership Project. A collaboration between groups of telecommunications standards associations, initially formed with the aim of making a globally applicable third-generation (3G) mobile phone. Since enlarged and expanded to include the development and maintenance of 2G, 4G and 5G standards.

AIP: Administrative Incentive Pricing. A fee charged to users of spectrum to encourage them to make economically efficient use of the spectrum. The fee is usually based on the opportunity costs of the use of spectrum.

B(F)WA: Broadband (Fixed) Wireless Access. Radio link to the home or the office from a cell site or base station for the purpose of providing broadband internet access, replacing the traditional local loop.

CAA: Civil Aviation Authority

CEPT: European Conference of Postal and Telecommunications Administrations. Coordinating body for European state telecommunications and postal organisations and regulators.

CMU: Spectrum Central Management Unit, part of UK Government Investments (a government company wholly owned by HM Treasury). Identifies opportunities to manage public sector spectrum more efficiently, and where possible make this available as part of the Public Sector Spectrum Release (PSSR) programme through Ofcom.

dBm: A unit of level used to indicate that a power ratio is expressed in deci-Bels relative to one milliwatt. A measurement of power used in radio communications.

DCMS: Department for Digital, Culture Media & Sport

DFS: Dynamic Frequency Selection. A system that causes Wi-Fi routers to change frequency when a radar using the same frequency is near.

DfT: Department for Transport

DEFRA: Department for Environment, Food & Rural Affairs

Earth station: A station located either on the Earth's surface or within the major portion of the Earth's atmosphere and intended for radio communication with one or more satellites or space stations.

EIRP: Equivalent Isotopically Radiated Power. This is the product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna (absolute or isotropic gain).

ETSI: European Telecommunications Standards Institute

FDD: Frequency Division Duplex. The concept that uplink and downlink may be split into separate frequency channels.

Fixed link: A terrestrial-based wireless system operating between two or more fixed points

Frequency band: A defined range of frequencies that may be allocated for a particular radio service, or shared between radio services

GHz: Gigahertz. A unit of frequency of one billion cycles per second.

GSO: Geostationary Satellite Orbit. The orbit of a satellite whose circular and direct orbit lies in the plane of the Earth's equator and which remains fixed relative to the Earth's surface.

Harmonisation: The identification of common frequency bands throughout a region (e.g. Europe) for the same particular application and, in some cases, technology.

Hz: Hertz, basic unit of frequency. One Hertz is equivalent to one cycle per second.

IEEE: Institute of Electrical and Electronics Engineers

IMT: International Mobile Telecommunications. The ITU term that encompasses 3G, 4G and 5G wireless broadband systems.

Interference: Unwanted disturbance caused in a radio receiver or other electrical circuit by electromagnetic radiation emitted from an external source.

ITU: International Telecommunications Union. Part of the United Nations with a membership of 193 countries and over 700 private-sector entities and academic institutions. The ITU is headquartered in Geneva, Switzerland.

kHz: Kilohertz. A unit of frequency of one thousand cycles per second.

LEO: Low Earth Orbit. LEO satellites orbit the Earth at heights between typically a few hundred kilometres to one or two thousand kilometres above the Earth's surface.

Licence exemption: Exemption regulations are made by Ofcom allow anyone to use specified radio equipment without the need to hold a WT Act licence.

LTE: Long-Term Evolution. A standard for communication of high-speed data for mobile phones and data terminals.

LTE-Advanced: A mobile communication standard representing an enhanced form of LTE.

Massive MIMO: MU-MIMO using large antenna arrays to further enhance performance.

MCA: Maritime and Coastguard Agency

MHz: Megahertz. A unit of frequency of one million cycles per second.

MIMO: Multiple Input Multiple Output. The use of multiple antennas at both the transmitter and receiver to improve communication performance.

mmWave: Millimetre-wave. Generally refers to radio spectrum with frequencies above around 10 GHz.

MNO: Mobile Network Operator

MOD: Ministry of Defence

MOIRA: Rail industry dataset used to model and forecast UK rail passenger numbers and journeys.

MU-MIMO: Multi-user MIMO, a form of MIMO that enhances performance with multiple users.

NR: 3GPP New Radio specification

Network Rail: Owner and infrastructure manager for most of the rail network in England, Scotland and Wales.

Ofcom: The Office of Communications. Independent regulator and competition authority for the UK communications industries.

PES: Permanent Earth Station. A satellite Earth station operating from a permanent, specified location to one or more satellites in space

Radio Spectrum: The portion of the electromagnetic spectrum below 3 THz used for radiocommunications.

ROES: Receive-Only Earth Station. A satellite Earth station which receives radio signals but does not transmit.

RSA: Recognised spectrum access. A method of recognising the use of radio spectrum by an operator which is not covered by a Wireless Telegraphy Act licence or licence exemption.

RSPG: Radio Spectrum Policy Group. High-level advisory group that assists the European Commission in the development of radio spectrum policy.

SARG: Safety and Airspace Regulation Group. Part of the Civil Aviation Authority responsible for setting civil aviation standards and ensuring that these are maintained.

SI: Statutory Instrument. Also referred to as secondary legislation, Statutory Instruments are a form of legislation which allow the provisions of an Act of Parliament to be subsequently brought into force or altered without Parliament having to pass a new Act.

SRD: Short Range Device. A general term, applied to various radio devices designed to operate usually on a license exempt basis, over short range and at low power levels.

TDD: Time Division Duplex. The concept that a channel may be split in time to serve both uplink and downlink.

TES: Transportable Earth Station. A satellite Earth station that can be transported to a fixed location where it then is able to communicate via satellites in space.

TOC: Train Operating Company

VSAT: Very Small Aperture Terminal. A satellite Earth station equipped with an antenna of relatively small size.

WiGig: Used to refer to the IEEE 802.11ad technical specification for wireless data transmission.

Wi-Fi: Commonly used to refer to wireless local area network (WLAN) technology, specifically that conforming to the IEEE 802.11 family of standards. Such systems typically use one or more access points connected to wired Ethernet networks which communicate with wireless network adapters in end devices such as computers or smartphones.

WT Act: The Wireless Telegraphy Act 2006

WTR: Wireless Telegraphy Register. Ofcom's online register which provides information about individual licences.