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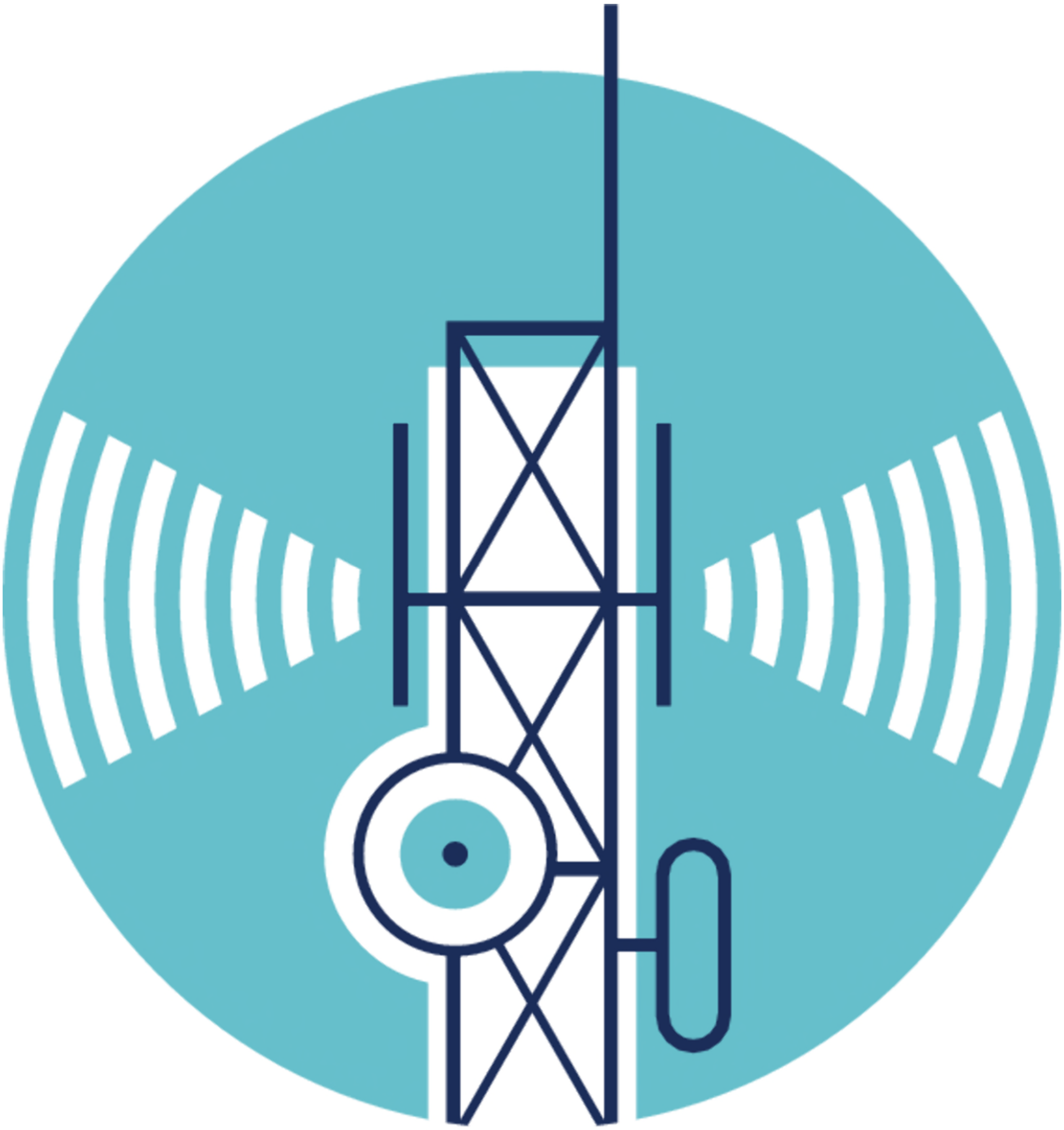

The impacts of mobile broadband and 5G

A literature review for DCMS

June 2018

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Executive summary

The Department for Digital, Culture, Media & Sport (DCMS) has commissioned Deloitte to undertake a focused literature review on the economic and social impacts of mobile broadband generally, and the potential impacts of 5G specifically. The purpose of this review is to provide DCMS with a view of the body of evidence as to the economic and social impacts of 5G in the context of the ongoing 5G Testbeds and Trials Programme. This report presents findings in relation to three specific areas of research:

- A review of international evidence to understand the impact of mobile broadband on consumer value, productivity and efficiency, drawing from evidence on 3G, 4G and Wi-Fi in particular;
- A review of international evidence to understand the potential macroeconomic impacts of 5G technology; and
- A review of international evidence to understand the economic impacts of a selection of specific use cases likely to be delivered by 5G technology.

There is a clear consensus that mobile broadband technologies have brought significant benefits for consumers, businesses and the wider economy

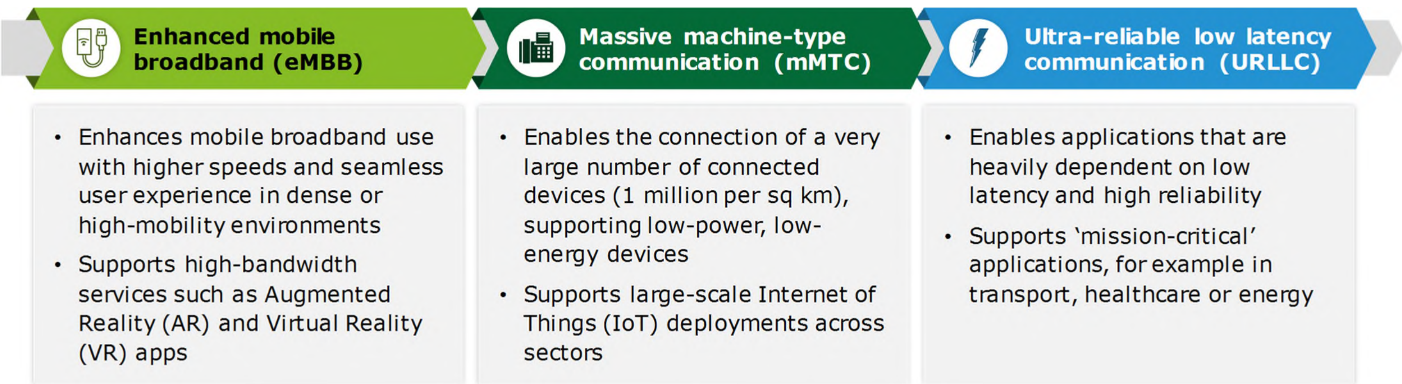
Studies show that mobile broadband is associated with positive impacts for the economy, such as higher GDP and employment. Underlying this effect are the investments made by mobile network operators and the impacts these investments have had throughout the supply chain, as well as productivity improvements from employees having access to more advanced mobile connectivity. Additional impacts on consumers include benefits from access to a range of innovative apps and services powered by mobile broadband.

Notwithstanding this consensus, the literature on the economic impact of mobile broadband specifically is more limited than for fixed broadband or broadband in general. There is also a lack of conclusive evidence on the impact of specific generations of mobile broadband technologies or the particular features of each generation. Studies often face data measurement issues and challenges in establishing causality rather than mere correlation.

5G technology is still nascent but promises a range of new and enhanced capabilities

Though technical standards have yet to be finalised, 5G has the clear potential to offer a variety of new and enhanced capabilities over existing mobile technologies, including higher data rates, lower latency, higher energy efficiency and improved performance in challenging environments. 5G networks may also make use of ‘network slicing’, which optimises physical infrastructure by providing multiple virtual networks tailored to different end-users or user classes, facilitating the simultaneous delivery of diverse uses. The three key usage scenarios identified by the International Telecommunications Union (ITU) and discussed in the literature are set out below.

Figure 1: Key usage scenarios for 5G



Source: Deloitte based on ITU (2015).

The capabilities of 5G have the potential to deliver transformative impacts for key sectors of the UK economy. However, attempts to quantify potential impacts remain limited and vary significantly according to underlying assumptions. The nature of impacts, including in wider areas such as research and development, foreign direct investment, digital skills or international competitiveness, has not been explored in depth in the literature. Further development of the technology, deployment scenarios and potential use cases will help aid precision in the quantification of these impacts.

In the long term, 5G has the potential to deliver transformative impacts in key sectors

Equipment vendors, mobile network operators, standardisation groups, EU projects and industry associations have all contributed to a wide literature on potential 5G use cases. In general, these use cases are currently in the early stages of development, particularly where they rely on mMTC or URLLC capabilities, the benefits of which are more likely to be realised in the long term. However, the literature suggests a diverse set of potential benefits could ultimately be realised for consumers and businesses across key sectors of the UK economy.

Figure 2: Examples of potential benefits arising from 5G

Improved connectivity: Faster and more reliable 5G connectivity for users in a range of environments, including on road and rail networks, in dense areas and even at home

- *Potential benefits:* Increased consumer value and productivity gains

New consumer devices and services: Smart devices and services enabled by 5G, from immersive media and entertainment through new healthcare wearables to connected and autonomous vehicles

- *Potential benefits:* A variety of consumer and business benefits driven by innovation

New IoT solutions: Opportunities for more advanced asset tracking, remote control, predictive maintenance and sensor-enabled optimisation of processes across sectors

- *Potential benefits:* Increased productivity

Smarter infrastructure and public services: Street lighting, traffic management systems, energy grids and other areas could be enhanced by 5G connectivity

- *Potential benefits:* More efficient and secure service delivery, environmental benefits

Source: Deloitte analysis

The scale of potential benefits has yet to be defined precisely

The literature tends to define potential use cases by reference to solutions or trials already implemented using existing technologies, or based on uncertain assumptions that will require further development. Overall, evidence is often inconclusive on whether 5G will be critical for the deployment of specific use cases, or whether there may be similar approaches that are viable using existing network technologies.

As definitive standards for 5G technology are established and commercial deployments begin to materialise, tangible use cases with quantifiable benefits will become clearer. The availability of 5G technology, alongside associated technologies and devices, will allow for testing of use cases and proofs-of-concept on a much wider scale. Further clarity on deployment plans and business cases for specific uses will provide greater certainty and enable further research to estimate the potential impacts of 5G more accurately.

The UK Government's 5G Trials and Testbeds Programme will play a critical role in accelerating this process, bringing forward the potential benefits and keeping the UK at the forefront of 5G-enabled use cases. Supporting real-world demonstrations, particularly in those areas where the business case and potential benefits appear most compelling, could bring material benefits to UK businesses and consumers.

1 Introduction

The advent of mobile broadband has brought sweeping changes to UK consumers and organisations alike. Looking ahead, the UK Government has recognised the development of the next generation of mobile technology, 5G, as a key economic opportunity. The Government's 5G Strategy, published in 2017, aims to "*ensure that the UK is a world leader in the development of 5G networks and services*" by accelerating deployment, maximising productivity and efficiency benefits and creating new opportunities for UK businesses (DCMS, 2017a).

However, 5G is still a nascent technology. Technical standards are still being finalised and commercial deployments on a large scale are unlikely to take place until around 2020. There remains a need for extensive further testing of applications and products that can make use of 5G technology and for the engagement of different stakeholders across a number of sectors and expertise areas. Future business models may also need to be explored within the wider context of the future telecoms market, as there may be different investment incentives between mobile network operators (MNOs) investing in 5G infrastructure and downstream industries originating new 5G use cases.

In this respect, the UK Government's 5G Testbeds and Trials Programme is an important component of the 5G Strategy, providing funding to "*stimulate trials by many different future 5G users designed to address some of society's biggest challenges*" (DCMS, 2017c). Research and collaboration networks such as the UK5G innovation network are also tasked with ensuring engagement and collaboration between stakeholders on building the economic and commercial evidence base. Further, wider Government initiatives such as the Future Telecoms Infrastructure Review, which seeks to articulate MNOs' *"incentives for investment in new digital infrastructure*", may aid in establishing a *"a clear evidence base to determine what, if any, additional policy interventions may be needed"* (DCMS, 2017d). This may, as a result, enable the development of new commercial models and opportunities required for deployment and use of 5G.

The literature related to 5G is expanding rapidly as stakeholders increasingly focus attention on understanding its potential use cases and impacts. Nevertheless, there are still substantial areas of uncertainty. This study provides a review of literature related to the impacts of mobile broadband technologies, including future impacts of 5G, summarising the current state of the evidence base for the economic case and potential benefits of these technologies.

The report is structured around three key research questions:

Section 2	Section 3	Section 4
Reviews the international evidence related to the impacts of mobile broadband, focusing on macroeconomic impacts and on the relation to consumer value and productivity or efficiency.	Summarises current expectations of 5G and reviews the international evidence related to the macroeconomic impacts of 5G.	Focuses on specific potential use cases for 5G and reviews the international evidence related to these, including potential economic and social impacts.

The literature review employed a systematic approach using a large number of search terms related to each research question across multiple sources and applied techniques such as snowballing. However, the literature review is not exhaustive, given the wide breadth of related literature available. Efforts have been made to include evidence from a variety of sources, including material published by equipment vendors, MNOs, consultants, academics, public bodies and international organisations. Emphasis has been placed on areas where the evidence base appears stronger, with a focus on literature that is most directly relevant to the research questions and to the UK context.

2 Impacts of mobile broadband

There is a general consensus on the **positive impact of mobile broadband on the wider economy, through GDP and employment impacts**. Approaches to measurement differ widely however; for example, some studies consider the impacts of faster speeds, while others focus on the benefits of increased penetration.

Evidence indicates material benefits for **businesses** in the form of enhanced **productivity**, and for **consumers** from enhanced access to **innovative services and apps**.

There remains uncertainty over the magnitude and nature of some impacts, given the relatively limited literature on mobile broadband specifically and the variety of different methodological approaches used.

This section reviews existing evidence on the impacts of mobile broadband, covering the following areas:

- Background information, including wider evidence on the impacts of Information Communication Technologies (ICTs);
- Macroeconomic impacts of mobile broadband;
- Relationship between mobile broadband and productivity;
- Relationship between mobile broadband and consumer value;
- Economic impacts generated through the mobile industry supply chain;
- The role of WiFi in relation to mobile broadband; and
- Conclusions and limitations.

2.1 Background and impacts of ICTs related to mobile broadband

There is a wide literature describing **positive economic impacts of broadband** in general, though the literature on mobile broadband specifically is more limited.

Over time, a wide body of literature has developed examining the macroeconomic impacts of different ICTs, including academic and non-academic studies. Most commonly, researchers have sought to estimate the extent to which ICTs are associated with higher levels of GDP or economic growth.

With regard to mobile broadband specifically, in the UK the transition from 2G to 3G began in 2003, when the first 3G-enabled handsets went on sale (BBC, 2003). However, many of the most material economic impacts may have come later, as the combination of 3G networks and capabilities offered by new consumer devices (such as the iPhone, launched in 2007) "*created a platform for the development of new software services and advanced high-bandwidth applications*" (Shapiro and Hasset, 2012). Subsequently, the first 4G network was launched in the UK in 2012. Users switching to 4G typically experienced download speeds around 5-7 times higher than with 3G, using services such as video streaming, mapping and social networking (Ofcom, 2012).[1]

Within the broader literature looking at the economic impacts of ICTs, the evidence base relating to mobile broadband specifically is more limited. The need for further research has been identified in recent years by previous studies. For example, a study published by the World Bank notes that "*much more research is needed on the nature of [mobile broadband's] impact and use*" (Minges, 2015), while an evidence review by the Institute of Development Studies finds that "*there is a lack of studies that measure the impact of switching mobile phone network speeds (from 2G to 3G or from 3G to 4G, for example)*" (IDS, 2016). Among those studies that focus on

[1] While each generation may sometimes be thought of as distinct and creating a 'step change' in connectivity, it should be noted that mobile network technology development may still occur gradually. This is due to the continuous process of new technology deployment and consumer transition, which may take several years, as well as the release of updated technology standards within the same generation of mobile technologies, such as so-called 2.5G or 3.5G technologies.

the impact of mobile broadband specifically, studies differ according to whether they examine specific technologies such as 3G or 4G, or instead consider mobile broadband in general.

Box 1: Overview of wider literature on the impacts of ICTs

- Several studies have focused on fixed broadband penetration, or broadband connectivity in general. A previous literature review commissioned by DCMS finds that "*there is a strong consensus in the literature that broadband has material positive impacts for national economies*" (SQW, 2013). Estimates of the magnitude of these impacts vary, with different studies finding that a 10% increase in broadband penetration is associated with an increase in the GDP growth rate of between 0.02 and 0.15 percentage points (Plum, 2011, Table B-1).
- Other studies focus on the impacts of faster broadband speeds. While findings mostly point to a positive incremental economic impact (SQW, 2013), there are examples of studies finding small impacts or no impacts (Briglauer and Gugler, 2017; Bai, 2017), suggesting that the relation between faster speeds could be non-linear or dependent on other factors.
- The impacts of mobile telephony have also received significant attention. For example, a 2009 study published by the World Bank found that a 10% increase in mobile penetration is associated with an increase of 0.6 percentage points in the GDP per capita growth rate for high income countries (Qiang et al, 2009); Scott (2012) updated this analysis with more recent data, finding a coefficient equal to 0.2. A separate study by Deloitte for the GSMA (2012) finds a coefficient of 0.65 for a sample including low- and high-income countries.

Nevertheless, the evidence base on mobile broadband specifically is sufficient to identify several key areas of consensus. The following sections provide an overview of the existing literature examining different impacts of mobile broadband, with emphasis on studies that analyse impacts in the UK or other developed countries.

2.2 Macroeconomic impact of mobile broadband

The literature suggests mobile broadband may have positive impacts on **GDP and employment**, although there are differences in measurement approaches. For example, a 2014 study finds that **faster mobile speeds** delivered by 4G could increase GDP by 0.7% per annum, while a 2017 study finds that a 10% **increase in mobile penetration** could increase GDP by 0.6% to 2.8%.

There is a clear agreement in the literature that mobile broadband is associated with significant positive impacts on national economies. Though the extent of evidence available remains relatively limited to date, it encompasses research papers commissioned by industry players and regulators, as well as academic analyses.

A study for the global association of mobile operators, GSMA, examines the impact of transitioning from 2G to 3G, based on an econometric analysis using cross-country data. The study finds that, for a given level of mobile penetration, a 10% substitution from 2G to 3G is expected to increase the GDP per capita growth rate by 0.15 percentage points (Deloitte, 2012). Similarly, Shapiro and Hassett (2012) conduct econometric analysis of US data to estimate the impacts of the transition from 2G to 3G, using detailed data that distinguishes technologies at a granular level (2.5G, GPRS and 3G). The study finds that increases in new technology penetration are associated with employment creation, estimating that the transition to 3G "*spurred the creation of some 1,585,000 new jobs from April 2007 to June 2011*" in the US.

Other studies have attempted to isolate the impact of 4G on GDP. Focusing on the UK specifically, a study commissioned by EE estimates that 4G technology adds 0.5% per annum to GDP (Capital Economics, 2012), arising from time savings alone as a result of the faster speeds offered by 4G. A subsequent study by the same researchers uses updated assumptions and finds that gains could be in the order of up to 0.7% of GDP per annum (Capital Economics, 2014).

A final category of studies examines the impacts of mobile broadband in general, without attempting to distinguish between 3G and 4G technologies. Most recently, Imperial College Business School (2017) estimates that a 10% increase in mobile broadband penetration causes a 0.6%–2.8% increase in GDP, based on an econometric analysis across countries. A previous study commissioned by the Australian telecommunications regulator ACMA finds that mobile broadband added 0.28% to Australia's GDP growth rate each year from 2007-2013 (Centre for International Economics, 2014), where the impact is estimated as the sum of benefits for the mobile sector itself, business mobile users and consumers. Other studies focusing on developing countries find comparable results, suggesting that a 10% increase in mobile broadband penetration may yield an increase of between 1.0% and 1.8% in GDP (Qualcomm, 2012), though these results should not necessarily be assumed to apply to developed countries such as the UK.[2]

A distinct approach to examining the impacts of mobile broadband is to consider the volume of mobile data usage, as opposed to adoption of or access to mobile broadband. This is an approach taken by Deloitte (2012) using cross-country data on gigabytes used per connection. The study shows that a doubling of mobile data use is associated with an increase in GDP per capita growth of 0.5 percentage points, with more pronounced effects for countries such as the UK that have higher average levels of data consumption.

2.3 Mobile broadband and productivity

Mobile broadband can enhance **productivity** by saving time, facilitating more efficient ways of working and increasing opportunities for working on the move, although these impacts can be difficult to quantify.

A key mechanism underlying the analysis of overall macroeconomic impacts is the contribution of mobile broadband to increased efficiency of workers and productivity of businesses. This is particularly relevant for the UK in the context of weak productivity growth since the financial crisis (UK Government, 2017). Measurement of productivity and changes in productivity is challenging, and research efforts have often focused on examining the impacts of fixed-line internet, or of mobile telephony on enterprises in developing countries (Bertschek and Niebel, 2016). Nevertheless, there is sufficient evidence to support the notion that the productivity impacts on the UK economy are material.

One approach to estimating productivity impacts is to consider the time saved as a result of the availability of mobile broadband. One study used 2011 mobile internet traffic data and average download rates for 3G and 4G respectively, to estimate on a bottom-up basis the download time that UK businesses could save as a result of using 4G. On this basis it is estimated that over 37 million business hours per year could be saved, valued at over £730 million per annum using an average cost to employers of £19.60 per hour (Firth and Lazanski, 2011).

The actual download time saved may have increased significantly since the Fritz and Lazanski study, in line with rapid growth of internet traffic per user. Analysis by Capital Economics for EE (2014) provided new survey evidence showing that business users saved an estimated thirteen minutes per day as a result of using 4G. Based on this result, Capital Economics estimated that the value of these time savings could reach more than £11 billion with a full transition of existing mobile data users to 4G, not taking into account potential new users.

International evidence lends support to these findings. A separate study commissioned by EE finds that 67% of businesses using 4G in the US report productivity increases, and that this is the most frequently mentioned benefit of using 4G by survey respondents. Similarly, 86% of respondents stated that 4G allows them to get more work done on the move (Arthur D Little, 2012). A more recent academic study has provided the first microeconometric evidence on the productivity impact of mobile internet using firm-level data from Germany. The study finds a significant and positive impact, noting that "*the positive aspects of mobile internet, like the improved information flows and the support for a more flexible organisation of work, seem to outweigh the increased difficulty of monitoring the employees or of employees getting distracted because of permanent connectivity*" (Bertschek and Niebel, 2016).

Looking beyond the productivity impacts on existing firms, one academic study has found that mobile broadband is also associated with an increase in entrepreneurship, measured as the number of adults per 100 involved in nascent or young firms (Alderete, 2017). The findings are based on econometric analysis across a wide panel of developed and developing countries. While evidence in this area remains limited, this suggests that mobile

[2] In many developing countries mobile broadband represents the only way to access broadband services for large parts of the population, which is not the case in the UK where fixed broadband networks are more developed.

broadband supports the creation of new businesses; for example, innovative app-based business models represent another mechanism by which the overall productivity of the economy may increase.

It should be noted that there is not a complete consensus on productivity impacts in the literature. One example is an academic study using cross-country data to examine the impacts of fixed and mobile broadband separately. The findings suggest that mobile broadband penetration is actually associated with lower productivity, potentially due to a "*time wasting element*" and "*non-productive temptations*" offered by mobile broadband (Thompson and Garbacz, 2011a). However, aspects of this study's approach have been subject to debate, including the reliability of the input data used and a possible model misspecification (Minges, 2015). A separate study published by the same authors indicates that mobile broadband can reduce inefficiency, though this effect is largely observed in lower-income countries (Thompson and Garbacz, 2011b).

2.4 Mobile broadband and consumer value

Evidence suggests that the availability of mobile broadband unlocks new forms of **consumer value**, for example by enabling **innovative apps and services**.

Consumers may also realise significant value from mobile broadband. As bandwidths have increased, a high-level analysis of price developments alone is suggestive of increased value. Ofcom data shows that UK mobile users in 2016 paid around £16 per month for an average basket of mobile services including 1.3GB of data; this is around 30% cheaper than the price paid in 2012 for an average basket including only 0.2GB of data, meaning that consumers are effectively getting more for less (Ofcom, 2017d).

In economic terms, the value to consumers may be thought of as consumer surplus, which is the value they would be willing to pay above the price actually paid for the services. Consumer surplus would not be captured in any estimated GDP impacts, so it could represent an additional benefit. However, the robust estimation of consumer surplus can be problematic; Capital Economics (2012) reviews the evidence on consumer surplus from the internet and broadband, noting that "*overall, the evidence on surpluses is patchy, variable and at times implausible*".

In the UK, Analysys Mason (2012) provides a direct estimate of total consumer value. Based on a model of the UK telecom market, the consumer surplus from use of mobile data services in 2011 is estimated at approximately £5 billion, compared to a significantly larger consumer surplus of £19 billion to £23 billion for voice services. The balance between consumer surplus from data and from voice may have shifted significantly since then, as usage of data has increased relative to voice (including use of data for voice and video calls).

More broadly, BCG (2015) estimates that consumer surplus from mobile internet across 13 countries including the UK is approximately $4,000 per user per year, though the study's methodology is not explained in detail. A key driver of this value appears to be the vast variety of mobile apps that are available to use for free or at low cost. The study finds that the most valued uses for smartphones include browsing, search, email, maps, social network, financial, news and weather; such uses are generally reliant on mobile broadband or significantly enhanced by mobile broadband. Similarly, Ghose and Han (2014) build a demand model for mobile apps and estimate that mobile apps have enhanced consumer surplus in the US by around $33.6 billion annually.

Another approach to understanding consumer value is to attempt to measure consumers' willingness to pay (WTP). A study commissioned by the UK Government finds that the average WTP for 3G services is higher than 2G for UK consumers (by £1.40 per month) and businesses (by £8.70 per month), though perhaps surprisingly WTP for 4G was not higher than 3G (RAND Europe, 2014). Possible explanations for this may include relatively low awareness of 4G and its benefits at the time of the survey and the use of a rural consumer sample which is not necessarily representative of the UK population as a whole. A separate study for the Department for Transport surveyed train users and shows the importance to consumers of high-speed internet access (SDG, 2016). Respondents were willing to pay between 7% and 26% of the one-way train fare for improved internet service (speed) and reliability, with speed apparently valued more highly than reliability.

The evidence of consumer WTP for mobile broadband remains relatively limited and somewhat inconclusive. Further survey evidence suggests that 60% of 4G users would not consider returning to 3G (Capital Economics, 2014); this could indicate that the benefits of 4G may not be compelling for the remaining share of users. An academic study in Cyprus finds that consumers will pay for improved data rates but are indifferent between 30 Mbps and 300 Mbps mobile services (Dagli and Jenkins, 2015), though these results may not translate to the UK market and could again be limited by consumer awareness and understanding.

Overall, despite limitations in the extent of the evidence base, the literature reviewed suggests that mobile broadband delivers significant consumer benefits in addition to its macroeconomic impacts and productivity enhancements.

2.5 Economic impacts through the supply chain

Another source of economic benefit stems from the **network investments** made by mobile operators, which generate increased economic activity throughout the **mobile supply chain and the wider economy**. For example, a 2015 study estimates that direct investments in the UK by one network equipment vendor of £230 million over 2012-2014 led to wider impacts of **£725 million**.

Aside from the impact of mobile broadband on end users, whether consumers or businesses, there is a separate route through which mobile broadband may affect the wider economy. As with any other large-scale investment, the investments made by operators in upgrading networks and rolling out new technology standards have economic ramifications. Specifically, the impacts on GDP or employment are often classified as follows:[3]

Direct impact	**Indirect impact**	**Induced impact**
Associated with the operators undertaking the investment.	Associated with the operators' supply chains, in terms of businesses from which they purchase goods or services, and in turn the supply chains of those businesses.[3]	Induced impacts associated with increased employment and economic activity, which then generates higher spending by both consumers and businesses.

The investments made may also represent inward foreign direct investment in the case of non-UK owned MNOs.

However, estimating the magnitude of additional investments brought about by new mobile technologies is problematic, as this should take into account the investment that would have taken place in a counterfactual scenario where operators may have continued to invest in networks using existing technologies, such that an incremental investment due to new technologies can be calculated. Capital Economics (2014) attempts to do this, finding that "*mobile network operators are currently [as of 2014] investing around £5.5 billion to upgrade the mobile network to 4G LTE spread over three or four years, in addition to routine maintenance and upgrade work*", based on information provided by EE.

A study commissioned by Huawei illustrates the potential indirect and induced impacts from such investment. From an estimated direct investment in the UK of around £230 million over 2012-2014, the study estimates indirect impacts of around £435 million and induced impacts of around £290 million, leading to a total economic impact of more than £950 million, with 7,400 jobs supported (Oxford Economics, 2015). Similarly, a Deloitte study estimates that investment in 4G networks in the US could fall in the range of $25-$53 billion between 2012 and 2016, leading to a total impact of $73-$151 billion on GDP and the creation of 371,000-771,000 new jobs (Deloitte, 2011).

[3] Linkages between different economic sectors are based on 'Input-Output' tables produced at national level by statistics agencies.

2.6 The role of WiFi

WiFi enhances the benefits of mobile broadband by **reducing congestion** on mobile networks, lowering costs for MNOs and supporting **quality and availability** of services for consumers.

The increasingly widespread availability of WiFi internet access, at home and elsewhere, has been another major development in wireless connectivity in the UK as in other countries. Only a few studies have examined the economic impacts of WiFi to date, but an important effect that has been identified relates to 'offloading'. Essentially, when mobile devices connect to WiFi networks they reduce the amount of data being carried on mobile networks. This may benefit MNOs through lower congestion on mobile networks and consumers may benefit if using WiFI is cheaper than mobile data or offers better service quality.

Analysys Mason (2012) estimates the benefits to the UK resulting from WiFi offloading as £1.8 billion in 2011, rising to a net present value of £31 billion over the ten subsequent years, with 90% of the benefit accruing to consumers. The findings are derived from an economic model that estimates consumer benefits based on assumptions about the volume of traffic offloaded to WiFi (95% by 2021), applying a benchmark cost per Megabyte to calculate the resulting cost saving.

Separately, WIK and Aegis (2013) focuses on cost savings to MNOs, estimating that these could reach £19 billion in the UK in 2016. This estimate is larger than Analysys Mason's (2012) estimates and the authors recognise the result is likely to be an overestimate, as overall data use on mobile devices would be lower if WiFi were not available.

Finally, Katz (2014) provides an estimate of benefits for the US, seeking to estimate a range of impacts including consumer surplus, producer surplus (i.e. the producer value obtained over and above the cost of providing services), and additional contributions to GDP where WiFi allows the use of faster speeds and the development of new business models, for example for WiFi hotspot provision. The value of WiFi offloading in public areas in the US is estimated to be around $15 billion in 2013, rising to around $30 billion in 2017. The benefits from residential WiFi are estimated to be much larger, in the order $36 billion; this is projected to rise to around $270 billion in 2017, assuming that all traffic would be served by cellular networks in the absence of WiFi. As with WIK and Aegis (2012), this assumption may entail a risk of overestimation.

Overall, there is a clear consensus that WiFi offloading leads to significant benefits for both consumers and operators, though in general these studies face challenges in estimating the size of benefits accurately, due to uncertainty around the counterfactual in terms of likely consumer behavior if WiFi offloading were not possible.

2.7 Conclusions and limitations

The evidence on the impact of existing mobile broadband technologies shows a general consensus that mobile broadband provides a range of benefits:

- There is clear evidence of positive impacts at overall economy level (for example on GDP and employment), which is likely to result from a combination of network investment-related economic impacts and end-user benefits in the form of improved productivity.
- Significant additional benefits appear highly likely for consumers, from being able to benefit from a range of innovative apps and services enabled by mobile broadband.
- Evidence on specific technologies is not extensive, though some studies suggest that the incremental benefits from 4G may be less than the benefits from 3G.

There is remaining uncertainty over the magnitude and nature of some impacts, reflecting the relatively limited literature on impacts of mobile broadband specifically, compared to other ICTs (such as fixed broadband, or broadband in general), but also the methodological issues that should be taken into account when interpreting results:

- A variety of methodological approaches are taken to examine these impacts, each with different challenges and limitations, with little consensus over the most appropriate methods in different contexts.
- Many studies establish correlation rather than causality. While steps can be taken to mitigate risks of spurious correlation or reverse causality, there usually remains a risk of overestimation.
- There are some significant data measurement issues that are specific to mobile broadband. For example, subscription figures may overstate the number of unique active users;[4] measuring volumes of usage is difficult; factors such as device used and network coverage can affect impacts but are not easily accounted for.

These limitations and challenges will remain relevant when considering the evidence base for 5G, especially if studies rely on previous estimates or methodological approaches. Additional factors to consider for forward-looking 5G studies are set out in Section 3.2.

[4] For example due to some individuals using multiple subscriptions. See ICT Data (2013) for a discussion.

3 Potential impacts of 5G

5G is expected to offer **unique new capabilities**, with the potential for economic impacts that match or exceed those of previous mobile broadband generations. However, due to the nascent state of 5G technology, there is still uncertainty around specific **capabilities, deployment scenarios and timeframes**.

As a consequence, the **literature on potential impacts is limited** at this stage and inevitably relies on **uncertain assumptions**. Estimates vary widely and are not directly comparable, ranging from impacts in the order of €113 billion in the EU by 2025 to $12 trillion globally by 2035.

Further development of potential 5G use cases from a technical and commercial perspective will be essential for a better assessment of 5G's potential impacts.

This section reviews evidence on the potential impacts of 5G, covering the following areas:

- Expectations around the capabilities and deployment of 5G;
- Current challenges in estimating potential impacts of 5G; and
- Evidence of the potential macroeconomic impacts of 5G.

3.1 What can be expected from 5G?

Overview

'5G' refers to the next generation of mobile technologies that are currently under development. Though a first set of common standards was approved in December 2017 by the 3rd Generation Partnership Project (3GPP), the complete set of standards have yet to be defined fully (3GPP, 2017), meaning that the technology remains in its early stages. A number of trials are being carried out in the UK and internationally, with large-scale commercial deployments and widespread availability of compatible devices expected from 2020 (Ofcom, 2017b).

At a high level, 5G differs from previous generations in that it is expected to integrate different mobile technologies, rather than simply replacing previous generations. For this reason, 5G is sometimes referred to as a 'network of networks' or 'system of systems', with the potential to encompass a variety of technologies and access modes. As well as entailing a new radio access network, 5G is envisioned to require a new core network that can support a wide range of services (Deloitte Insights, 2017).

Expected capabilities

Whereas the central innovation offered by 4G largely consisted of increased capacity and achievable bandwidths, 5G offers a potentially broader range of new or enhanced capabilities.

As well as benefits associated with these enhanced capabilities, 5G networks may bring further benefits through the expected use of 'network slicing', which involves providing distinct virtual networks to different users or classes of users, over a common network infrastructure (Ofcom, 2018).[5] Separate virtual networks could be dedicated and tailored to specific end-user requirements, leading to a better quality user experience overall.

While the industry is working towards delivering on these targets and potential features, there remains uncertainty over the extent to which these capabilities will be realised in practice in different environments and the timeframes involved. In the short and medium term, developments may be evolutionary rather than revolutionary (DotEcon and Axon, 2018).

[5] Under net neutrality rules, network slicing practices may be subject to certain restrictions, for example only being used when objectively necessary given the end-user requirements (Analysys Mason, 2017a).

Figure 3: Summary of expected minimum requirements for 5G

- **Data rates:** Peak data rates of 20Gbit/s (20x higher compared to 4G), with user experienced rates of 100Mbit/s (10x higher compared to 4G).
- **Latency and reliability:** Delays of 1ms (10x lower compared to 4G), with 99.999% reliability.
- **Connection density:** 1,000,000 devices per square km (10x higher compared to 4G).
- **Mobility:** Support for high mobility up to 500 km/h, with low interruption time.
- **Energy efficiency:** Increased network efficiency so that energy consumption of mobile networks does not increase, despite the enhanced capabilities.

Source: ITU (2015), ITU (2017a). Further requirements include higher spectral efficiency and area traffic capacity.

Key usage scenarios

The ITU (2015) defines three broad usage scenarios for 5G. This framework has been widely adopted in the literature.

Figure 4: Key usage scenarios for 5G

Enhanced mobile broadband (eMBB)

- Enhances mobile broadband use with higher speeds and seamless user experience in dense or high-mobility environments
- Supports high-bandwidth services such as Augmented Reality (AR) and Virtual Reality (VR) apps

Massive machine-type communication (mMTC)

- Enables the connection of a very large number of connected devices (1 million per sq km), supporting low-power, low-energy devices
- Supports large-scale IoT deployments across sectors

Ultra-reliable low latency communication (URLLC)

- Enables applications that are heavily dependent on low latency and high reliability
- Supports 'mission-critical' applications, for example in transport, healthcare or energy

Source: Deloitte based on ITU (2015).

Initially, 5G may be used primarily in eMBB scenarios (GSMA, 2017), delivering an evolutionary improvement of user experience for existing services. The use of 5G in mMTC scenarios for the development of more advanced IoT applications, or the use of URLLC to facilitate new mission-critical applications, are considered to be longer-term prospects (Ofcom, 2018; Mobile World Live, 2018).

Use of spectrum

At a European level, three key spectrum bands have been identified for the use of 5G, as well as existing mobile broadband spectrum that could be repurposed for 5G (Ofcom, 2017b):

Low-bandwidth

700MHz spectrum, which could be used to provide coverage over large geographic areas, similarly to the 800MHz band currently used for 4G.

Medium-bandwidth

Spectrum at 3.4 – 3.8GHz, seen as a 'primary' band to provide capacity on 5G networks.

High-bandwidth or 'mmWave'

24.25 – 27.5GHz spectrum, identified as a 'pioneer' band for 5G.

The current literature focuses particularly on the use of mmWave spectrum, which is markedly higher frequency than any spectrum currently used for mobile. This spectrum could deliver ultra-high capacity for innovative services. Due to this spectrum band's propagation characteristics, which limit the geographic range of signals transmitted, this band favours deployment using a large number of 'small cell' base stations, which are particularly suited to dense urban areas.

Potential deployment scenarios

5G is expected to be deployed in the UK by the current MNOs initially, but there appears to be potential for new types of providers to emerge, including sector-specific private networks or new types of intermediaries (Ofcom, 2018). As the business case for 5G deployment is still at a nascent stage, there is significant uncertainty over how and where network infrastructure will be deployed and the timeframe for this.

Regarding mobile connectivity, current studies and activities are focused primarily on use cases of potential urban deployments of 5G, rather than nationwide networks. A number of studies highlight the potential obstacles to delivering rural coverage using 5G, where lower population density renders the business case particularly challenging (EPRS, 2016; Oughton and Frias, 2016; Chiaraviglio et al, 2017).

Despite these challenges, some studies suggest that 5G does offer technical capabilities that make rural network expansion and upgrades more economical than with current technologies (Yu, 2016), even if initial deployments focus on dense urban areas. Even with 5G, rural deployments may require compromises in terms of lower levels of bandwidth or higher latency than would be available in urban areas (Oughton and Frias, 2016), or a phased approach where performance improvement takes place progressively (Khalil et al, 2017). Real-world trials and deployments such as the 5G Testbeds in rural areas across the UK may therefore aid in investigating the use of 5G for rural connectivity (DCMS, 2018a; Office of the Secretary of State for Wales, 2018).

This notwithstanding, even in urban areas, 5G deployment is considered to be significantly reliant on the extent of fibre connectivity that is available (Deloitte, 2017a; WIK 2018), as well as other factors such as operators' ability to access suitable sites for small cell deployments (Ofcom, 2018). Such factors create uncertainty over urban 5G deployment.

Finally, the possibility of 5G being used to deliver fixed wireless access in urban areas is receiving attention, particularly in the US, in contrast to the UK where wireless-only home internet is currently rare (Deloitte, 2018). A study for Ofcom found that "*5G at a fixed location might … be a relevant solution in areas which could not otherwise be reached by a fixed network*" (WIK, 2018). Other studies for the National Infrastructure Commission found that the potential costs and benefits of using 5G to provide home broadband in urban areas (for example '5G to the lamp-post') may make it a viable commercial proposition (Tactis and Prism, 2017; Frontier Economics, 2017).

3.2 Challenges for estimating the potential impacts of 5G

The current early stage of development of 5G, together with some of its inherent characteristics, present significant challenges for any estimation of the potential macroeconomic impacts of 5G.

Relying on uncertain forward-looking assumptions

The majority of studies discussed in section 2 relied on observed data in order to estimate the actual impact of mobile broadband in different contexts. By definition, any study of the potential impacts of 5G at this point in time is forward-looking and therefore relies on assumptions that are uncertain and subject to change. As noted above, particular areas of uncertainty range from the standardisation of 5G itself, its precise capabilities, deployment scenarios, timeframes and related factors that can influence these.

Where methodologies are based on estimated 5G investment levels, these are subject to particular uncertainty in addition to the issues set out in section 2.5. The GSMA notes that "*there is little guidance on 5G operator mobile capex around the globe. Ultimately, it will depend on a number of factors including the model (standalone, non-standalone or phased approach) selected for 5G network deployments, the targeted network coverage, the range of spectrum bands in use and the availability of fibre infrastructure and nationwide LTE networks*" (GSMA, 2018).

Accounting for new capabilities and features of 5G

5G's three distinct usage scenarios and the notion of 5G as an overarching system of diverse network technologies means that estimating its impacts is a complex exercise. For example, BT has suggested that "*5G benefits cannot easily be separated from benefits of mobile services in general given that 5G is a 'system of systems' and will, in the long-term, encompass 4G capabilities, Wi-Fi and fixed networks (for backhaul and wireless access, as well as end user services)*" (BT, 2018a). While some previous studies provide estimates for the impacts associated with increased data speeds, 5G promises a range of potential benefits beyond data speeds that have not been documented or examined in detail in the existing mobile broadband literature, meaning there is a limited evidence base upon which to build any new analysis.

Separating the impacts of 5G and other technologies

5G is often associated, either explicitly or implicitly, with other technologies that can enable innovative use cases. Technologies which overlap with 5G in this way include:

IoT

Advances in this area are already rapidly expanding the number of connected devices and creating use cases that these support (Cambridge Consultants, 2017). 5G technology is seen as complementary to IoT devices and may augment their potential, particularly through mMTC use cases.

Cloud computing and big data analytics

These technologies already benefit consumers and businesses alike (Deloitte, 2017; McKinsey, 2011), and 5G technology may enhance these benefits by allowing more data to be transmitted more quickly and more reliably to the cloud.

AR and VR

Due to high-bandwidth and low-latency requirements, more advanced applications of these technologies may be facilitated by 5G, in parallel with the development of new consumer devices that support more advanced AR and VR apps.

The above examples illustrate how potential benefits may be brought about by various technologies that can be deployed and used in combination with 5G. If all such benefits were solely attributed to 5G this could be misleading; however, isolating the incremental impact of 5G specifically is inherently challenging.

3.3 Current evidence on the potential macroeconomic impact of 5G

Notwithstanding the challenges in measuring the impact of 5G on the economy, a few studies have attempted to assess the macroeconomic impact. A report, by Development Economics for O2, predicts that "*national 5G infrastructure will directly contribute an additional £7 billion a year to the UK economy*" by 2026, with an additional £3 billion per annum through indirect impacts through the supply chain (O2, 2017). It is claimed that this benefit will be realised more quickly from 5G than from fibre broadband. However, the full report is not publicly available, meaning that the basis for these findings remains unclear.

Internationally, the most widely cited and comprehensive studies are those by IHS Markit and by Tech4i2 et al, which cover the global and European economies respectively. The widely-cited study by IHS Markit for Qualcomm provides the most sophisticated assessment to date of the economic potential of 5G. It estimates that the global 5G value chain will generate $3.5 trillion in output (of which $76 billion is in the UK) and will support 22 million jobs in 2035, of which 600k in the UK (IHS Markit, 2017). When taking into account the economic activity supported in other sectors of the economy, the total economic output enabled globally by 5G by 2035 is estimated as $12.3 trillion.

The methodology used has several steps:

- Input-output techniques[6] are used to estimate value chain impacts, based on IHS Markit forecasts of 5G-related capex.

[6] Based on 'Input-Output' tables which show the economic linkages between different sectors of the economy.

- The effect on other industries is estimated based on a selection of 21 5G use cases, with a calculation dependent on IHS Markit's assessment of the potential impact of each use case on sales in other industries (net of any impact achievable from implementing the use cases using 4G).
- The global economic impact is calculated using a proprietary Computable General Equilibrium (CGE) model.[7]

The IHS Markit study provides a useful reference point of the potential magnitude of benefits. However, as well as the inherent uncertainty in relying on estimates of 5G capex (as noted in section 3.2), specific aspects of the approach should be taken into account when interpreting the results:

- The timeframe over which impacts are estimated, with results obtained for 2035, means that these estimates are highly uncertain, particularly given the dynamic nature of the telecommunication sector and the current cycle of new mobile technologies typically being introduced roughly every ten years.
- The study may not capture the net contribution made by 5G, as the estimate is based on expected future investments that are 5G-related. It is not clear whether the study accounts for the possibility that this projected investment includes a level of activity that would in any case have been observed in the absence of 5G, if operators continued to invest in network infrastructure based on 4G technology.
- The study does not mention any steps to take into account the potential costs associated with developing, implementing and transitioning to 5G-enabled use cases in each sector, such that the estimates may represent gross benefits rather than net benefits.

Another oft-cited study was commissioned by the European Commission to assist strategic planning for the introduction of 5G in Europe (Tech4i2 et al, 2016). The study considers specifically how the introduction of 5G capabilities will affect four 'verticals' (Automotive, Healthcare, Transport, Utilities) and four 'environments' (Smart Cities, Non-urban areas, Smart Homes, Smart Workplaces) that are often associated with 5G in the literature. Aggregating across these areas, the study finds total benefits to the EU economy of €113 billion per annum in 2025.

The estimated benefits are again material, but are lower than IHS Markit's estimates. This may reflect a more conservative approach taken by Tech4i2 et al, though the two results are not directly comparable due to the difference in timeframes and methodologies used. When interpreting the findings, some factors should be noted in considering the results:

- Most impact estimates within each vertical or environment rely on a variety of estimated results from previous studies, conducted using different methodologies and without a specific focus on 5G. The impact estimates rely on assumptions made about the share of benefits that is attributable to 5G, with the basis for assumptions not detailed in the study.
- By having selected only a subset of verticals and environments, the study might underestimate the total impacts across all parts of the economy. On the other hand, if there is any overlap between verticals and environments that is not accounted for, there may be a degree of overestimation.
- As with the IHS Markit study, this study does not mention any measures to take into account the potential costs associated with developing, implementing and transitioning to 5G-enabled use cases in each sector, such that the estimates may represent gross benefits rather than net benefits.

The study by Tech4i2 et al. also produces a separate economic impact estimate using an investment-based multiplier approach. First, 5G deployment costs are forecast based on a historic analysis of deployment costs per subscriber, projecting that these will be higher for 5G than for previous generations, leading to total expected deployment costs of €56 billion in 2020. Using input-output analysis, 'trickle down' effects across the wider economy are estimated, leading to a total impact of around €140 billion.[8] This type of analysis provides a useful benchmark of potential impacts, subject to the issues previously discussed in relation to investment-based methodologies, though it does not account for the potential capabilities that are unique to 5G and could lead to different impact mechanisms compared to previous generations.

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[7] CGE models are relatively complex models of an entire economy, often used to assess the potential impact of policy changes.
[8] This appears to be an annual estimate though it is not specified whether this impact would be sustained over several years at the same level or otherwise.

A study commissioned by US telecommunication trade association CTIA follows a similar approach, again estimating economic impacts on the basis of expected network investment (Accenture, 2017a). The study projects that operators will invest $275 billion over seven years to deploy 5G technology in the US; this is then estimated to lead to the creation of 3 million jobs, with an associated impact on GDP of $500 billion over that time period. However, the authors note that uncertainty over deployment means the impacts may vary, and the economic impact relies on estimates from a previous study examining 3G technology. A separate study uses Accenture's estimate of 5G investment levels as an input and finds a $533 billion potential GDP impact based on input-output analysis (The Lost Economy, 2017).[9]

Finally, a report estimates the economic impact of 5G in China, finding that "*6.3 trillion yuan ($925 billion) of economic output and 8 million jobs will be created by 2030*", though details on the impact mechanisms examined and the methodology used do not appear to have been published (China Daily, 2017).

As noted in section 3.2, 5G may have the effect of enhancing other complementary technologies or amplifying their benefits. Therefore, studies that look at the potential impacts of such technologies may be relevant, even if they do not consider the role of 5G specifically.

Box 2: Overview of wider literature on economic impacts of complementary technologies

Various studies have estimated the economic impacts of technologies that could be enhanced by 5G, without considering specifically the role of 5G. For example:

- Cebr (2016) estimates the cumulative value of big data and IoT to the UK economy from 2015-2020 as £322 billion. The study finds that benefits primarily consist of increased efficiency and are particularly pronounced in Manufacturing, Telecoms, Professional Services, Healthcare, Retail and Energy & Utilities.
- McKinsey (2015) considers the role of IoT across nine settings and estimates total potential impacts of $3.9 trillion to $11.1 trillion globally in 2025.
- Deloitte (2016) estimates that cloud computing could add €449 billion to EU28 GDP over five years, as well as employment and business creation impacts.

3.4 Conclusions and limitations

Existing evidence, though limited, suggests that 5G could have macroeconomic impacts that are comparable to previous generations (e.g. 3G, 4G). 5G has the potential to offer a range of unique new capabilities with impacts on the UK economy that could be greater than previous generations, but at present this remains a theoretical prediction to be validated as the technology develops and starts to be deployed commercially. The nascent state of 5G and the uncertainty around its precise capabilities in different environments, its actual deployment scenarios, the timeframes for this and other related factors mean that any future projections of its impact entail a degree of speculation.

Equally, it may be that countries or regions that lag behind in the deployment of 5G networks could suffer disadvantages in terms of international competitiveness, trade or inward investment. References to these types of impact are relatively common as part of current industry and policy debates (Euractiv 2018a; Euractiv 2018b), but the likely magnitude of these effects has not been established by the wider literature.

Given that 5G is in the early stages of development, the limited extent of available literature is to be expected. There are very few studies at present that attempt to estimate the potential macroeconomic impacts of 5G robustly and comprehensively. Among these studies, the magnitude of estimates varies greatly, reflecting different underlying assumptions and methodological approaches taken. As the uncertainty around 5G is gradually resolved, additional research may be produced to define expectations more clearly and objectively.

[9] The study additionally estimates long-run consumer benefits of $1.2 trillion, but these are based on historic spectrum auction revenues and therefore do not appear related to 5G specifically.

Further development of potential 5G use cases is likely to be a key prerequisite for a more detailed and precise understanding of 5G’s macroeconomic potential. The current state of development of a range of potential 5G use cases is examined in the next section.

4 Potential 5G use cases

Literature on 5G use cases identifies a **range of potential applications across many sectors** of the economy, with potential benefits arising primarily from the ability of 5G to offer higher bandwidths, reliable low-latency service and IoT connectivity on a large scale.

Businesses stand to benefit from innovative ways to **enhance productivity and optimise processes**, while **consumers** could gain access to **new and improved services** in sectors such as transport, healthcare, media and entertainment, and public services. A range of **social benefits** may also be achievable, from improvements in **public safety** to **environment**.

Given the **early stage** of 5G's development, literature on use cases is not yet mature; indeed, the discussion of many use cases and their associated benefits remains largely theoretical. Further work is needed to better demonstrate the real-world capabilities of 5G and to articulate specific 5G use cases. Initiatives such as the UK Government's **5G Testbeds and Trials Programme** should play an important role in **accelerating the process** of use case discovery and definition, bringing forward the realisation of social and economic benefits across key sectors where 5G shows significant promise.

Ongoing research programmes should clarify the viability of different use cases, the demand for these and the associated costs, and will **enable a better understanding of 5G's impact** in practice.

This section focuses on frequently discussed use cases across six broadly defined economic sectors. For each use case, the evidence reviewed covers:

- An overview of the use case;
- The role that 5G could play in enabling or enhancing the use case;
- The potential social and economic impacts; and
- Any other factors or conditions that may play a role in enabling the use case.

4.1 Overview

There is significant variation in the breadth and depth of the literature on potential 5G use cases and expected economic and social impacts. Equipment vendors and mobile operators in particular have published a large volume of material, while work on defining and developing use cases is also ongoing at the European level and among some industry bodies. At least eight EU projects have conducted work on 5G use cases, while standardisation bodies and industry fora such as NGMN, 3GPP, ITU and 4G Americas, among others, have all made separate contributions (METIS II, 2015).

Given the breadth of literature, this literature review focuses on use cases that are relatively developed and that together illustrate diverse applications of 5G technology and types of impacts. It does not necessarily reflect all possible use cases in each sector. Sectors and use cases in each sector are summarised below in Figure 5.

Figure 5: Summary of sectors and use cases analysed

Transport	Healthcare	Media and Entertainment	Public Services and Utilities	Agriculture	Manufacturing
• Connected and autonomous vehicles • Passenger connectivity on road and rail	• Remote monitoring • Remote surgery	• High fidelity and immersive entertainment at home • Mobile dynamic and immersive media	• Smart public infrastructure • Smart energy grids	• Agri-sensor networks	• Remote control and monitoring

Source: Deloitte analysis

The literature suggests a diverse set of potential benefits could be realised for consumers and businesses across virtually every sector of the economy. These are explored further in the following sections.

Figure 6: Examples of potential benefits arising from 5G

Improved connectivity: Faster and more reliable 5G connectivity for users in a range of environments, including on road and rail networks, in dense areas and even at home

- *Potential benefits:* Increased consumer value and productivity gains

New consumer devices and services: Smart devices and services enabled by 5G, from immersive media and entertainment through new healthcare wearables to connected and autonomous vehicles

- *Potential benefits:* A variety of consumer and business benefits driven by innovation

New IoT solutions: Opportunities for more advanced asset tracking, remote control, predictive maintenance and sensor-enabled optimisation of processes across sectors

- *Potential benefits:* Increased productivity

Smarter infrastructure and public services: Street lighting, traffic management systems, energy grids and other areas could be enhanced by 5G connectivity

- *Potential benefits:* More efficient and secure service delivery, environmental benefits

Source: Deloitte analysis

At this early stage of 5G's development, the evidence base regarding specific use cases is not yet mature. Stakeholders in some industries are just beginning to focus on potential applications of 5G, and academic literature mainly considers technical aspects rather than potential costs and benefits.

As the technical and commercial opportunities become better understood, the range of viable use cases should become clearer, with new use cases potentially still to be discovered. In parallel with this progress, further research can be expected to produce more robust evidence on social and economic impacts. It is likely that governments, working groups and multi-stakeholder partnerships will need to play a key role in supporting this evidence development through a collaborative approach.

Building on existing international evidence, the UK Government's 5G Testbeds and Trials Programme is helping to create conditions for collaboration across industries and academia. Projects selected by the Programme should produce tangible demonstrations of 5G's potential in different sectors where significant potential exists, supporting the discovery and definition of 5G use cases. In doing so, the Programme has the potential to accelerate progress in the UK and bring forward a range of potential economic and social benefits.

The remainder of this report examines use cases in each sector in more detail.

4.2 Transport

Significant attention is being devoted to developing **autonomous vehicles**, with potential improvements for **fuel efficiency, safety, access and mobility and the environment**. There is some uncertainty regarding the role of connectivity and 5G for autonomy, but further research, including through the **5G CAV testbed** at Millbrook, should help to identify opportunities to exploit enhanced autonomy, co-ordination and redundancy.

5G's high-mobility capabilities will likely play an important role in meeting demand **for faster and more reliable connectivity on road and rail**, potentially increasing **productivity** and **consumer value**. Analysis to quantify these benefits will help to identify commercial models for investments in road and rail mobile infrastructure.

5G-enabled digitalisation of railways and vehicle infotainment may have wider productivity benefits and consumer value benefits, although further analysis is needed to understand the specific role and benefits of 5G in particular.

Transport is oft-cited as an area where 5G capabilities are expected to enable transformative change. Studies note 5G's high-mobility, mMTC and URLLC capabilities as being important for connected and autonomous vehicles (CAVs), with a large evidence base developed on whether 5G is essential for full autonomy and on potential social and economic impacts. High mobility is also noted as being important for meeting future passenger connectivity demand on both rail and road, with potential consumer value and productivity benefits. The literature also discusses operational benefits from investment in 5G-enabled rail networks, as well as the possibility for 5G to enhance vehicle infotainment capabilities, although the literature on the latter is more limited.

4.2.1 CAVs

Overview of use case

The use of 5G technology in relation to CAVs is the most widely discussed use case in the literature. CAVs are vehicles that are, to varying extents:

- **Connected:** able to communicate with the surrounding environment, for example with other vehicles (V2V communication) or infrastructure (V2I communication); and
- **Autonomous:** able to operate with reduced or no driver input.

There are different degrees of vehicle automation that road vehicles could achieve (see Figure 7). Discussion in the literature notes 5G's importance to enabling higher levels of automation through connectivity, allowing for the interaction and communication between a vehicle's sensors and other vehicles, infrastructure and connected devices more generally to support automated driving capabilities.

Figure 7: Levels of road vehicle automation

Level 0 No automation	Level 1 Driver assistance	Level 2 Partial automation	Level 3 Conditional automation	Level 4 High automation	Level 5 Full automation
Driver performs all steering and acceleration.	System can perform either steering or acceleration, with driver performing main driving tasks.	System can perform both steering and acceleration, with close driver monitoring of driving conditions.	System performs full driving tasks in defined environments, requiring driver intervention if requested.	Full automation without need for driver intervention in defined environments (e.g. urban)	Full automation in all driving modes without need for driver intervention in all environments.

Source: Deloitte based on SAE (2016).

Level 1 and 2 vehicles are already commercially available, while extensive testing is being carried out on higher levels of automation and the first Level 3 autonomous car was recently launched commercially (Audi, 2017). In the UK, several trials of autonomous vehicles have taken place and testing on public roads has been permitted (Department for Transport, 2015).[10]

CAVs have been identified as potentially having important applications in a number of sectors, such as agricultural and marine environments (Science and Technology Select Committee, 2017). However, there is recognition that widespread use of fully autonomous vehicles remains a longer-term prospect, with some predictions that the technology could become available after 2025 (KPMG, 2015) or after 2030 (Science and Technology Select Committee, 2017).

Role of 5G

Testing thus far has focused on autonomous vehicles (AVs) that do not rely on connectivity, but rather operate based on data from a combination of on-board sensors including cameras, radar and LIDAR[11], high-precision maps and advanced software incorporating Artificial Intelligence (AI) elements. There are alternative schools of thought regarding the role of 5G in the development and deployment of CAVs, with uncertainty about the extent to which advanced connectivity is a prerequisite for the realisation of higher automation levels. The view of the Society of Motor Manufacturers and Traders (SMMT) is that "*vehicles with some levels of automation do not necessarily need to be connected, and vice versa, although the two technologies can be complementary*" (SMMT, 2017).

Nevertheless, a common view is that 5G has the potential to at least complement or enhance automation capabilities. Sensor-based automation may be largely limited to line-of-sight awareness, whereas connectivity provides 360-degree data, which may be particularly valuable in situations such as blind junctions or very busy urban environments. Analysys Mason (2017b) identifies a range of safety use cases, including warning, information and actuation services that may rely on advanced connectivity between the vehicle and the surrounding environment. Connectivity could also serve to provide redundancy in cases of sensor failure or inability to function accurately, for example in extreme weather conditions (SMMT, 2017).

5G PPP (2015c) suggests other areas where 5G connectivity can enhance autonomous driving technologies. The underlying principle is that, in the absence of connectivity, the actions of other road users have an element of unpredictability, which can be reduced by sharing data between vehicles. With this 'cooperative' approach, vehicles may be able to drive closer together, react more quickly to prevent collisions and potentially engage in other activities that benefit from greater coordination, such as automated overtaking and platooning (5G PPP, 2015c).

For features and services such as those mentioned above, the potential of 5G to connect a very large number of devices and sensors while ensuring high reliability and low latency is highly relevant. Until 5G standards are finalised and the technology is widely available, some uncertainty around the role of 5G is likely to remain, with some industry players potentially still considering relying on alternative ITS-G5[12] technology for short-range communications (SMMT, 2017). However, steps are being taken to develop the evidence base in this area. Most recently, the UK Government's first independent 5G Testbed for CAV testing was launched in March 2018, providing an environment where CAVs can be tested using high-speed, low latency connectivity (Millbrook, 2018).

Potential socio-economic impacts

There is relatively extensive literature examining the potential impacts of CAVs compared to most other use cases. The majority of this has been conducted or commissioned by the automotive industry or related industries. A range of quantitative impact estimates have been produced, though typically these do not seek to account for the potential costs involved in developing and deploying CAVs, or the specific effects attributable to 5G.

[10] For example, the LUTZ Pathfinder project demonstrated AV technology in Milton Keynes in the UK (ORI, 2016). Testing is also on-going in other countries, such Uber's testing of AVs in certain urban driving conditions in Pittsburgh in the US (Uber, 2016).
[11] A technique that uses pulses of light to build a high-resolution 3D map of the surrounding environment.
[12] ITS-G5 refers to the European standard for vehicle communications as set by the European Telecommunications Standards Institute (ETSI).

Box 3: Overview of potential benefits from CAVs

A review of evidence by the Science and Technology Select Committee (2017) identified the key potential benefits of CAVs as follows:

- Increased accessibility and mobility, for example for the elderly or disabled who would otherwise be unable to operate road vehicles.
- Improved road safety, including the potential to reduce the number of fatalities, as a result of new safety features and the reduction of human error.
- Transporting freight by platooning, which could improve efficiency and fuel economy. Efficiencies through platooning may be achievable without 5G, but "*the low latency, higher reliability and network prioritisation features could make 5G a secondary system or part of a redundancy for vehicle-to-vehicle or vehicle-to infrastructure communications in the context of platooning*" (Arthur D Little, 2017).
- Reduced congestion from fewer accidents, reduced headway between vehicles and improved traffic management, though there could also be negative impacts on congestion during a transition to fully autonomous vehicles, when different classes of vehicles coexist on the road (HERE, 2016).
- Wider economic impacts through increased output and employment, though it should be noted that driverless cars could also lead to job losses in some instances (Science and Technology Select Committee, 2017). For the UK, "*being among the leaders in the future of mobility could offer a significant source of domestic revenue and act as a boost to companies that can compete globally*" (Deloitte, 2018).

Productivity impacts may also be realised as a result of time freed up from not having to drive, as well as potentially shorter commutes. The evidence on such impacts is more limited, but it may be that 5G plays a role both by supporting automation and providing connectivity to enable productive online activities in-vehicle (Strategy Analytics, 2017). Finally, several studies note that reduced congestion and increased fuel efficiency associated with CAVs, including electric vehicles, could lead to environmental benefits (KPMG, 2015).

Notwithstanding the range of studies produced in this area, the Committee expressed the view that "*there is little hard evidence to substantiate the potential benefits and disadvantages of CAV because most of them are at a prototype or testing stage*". Moreover, as discussed below, studies generally do not consider specifically the potential impacts from 5G-enabled CAVs.

In a study for the Society of Motor Manufacturers and Traders (SMMT), KPMG (2015) provides estimates of the macroeconomic impact for the UK, with a £51 billion impact projected by 2030 from the development of higher-level CAVs. Estimated benefits consist largely of time savings and increased productivity; associated costs are also estimated as £11 billion. The study does not address the extent to which connectivity or 5G specifically may be responsible for a share of these benefits or whether 5G could extend these benefits.

Several other international studies have examined the economic impact of AVs or CAVs in general. In the US, Clements and Kockelman (2017) estimate that, once CAVs capture a large share of the market, they will generate economic impacts in the order of $1.2 trillion per year. Morgan Stanley (2014) finds a similar estimate of potential savings of $1.3 trillion per year from autonomous cars in the US, without considering the role of connectivity; the benefits consist primarily of productivity gains, accident avoidance, congestion reduction and fuel efficiency.

A recent study by Analysys Mason (2017b) considers specifically the potential benefits of cellular technology to enable CAVs to communicate with any other relevant entities (C-V2X). Net benefits are estimated to reach more than €39 billion in 2035 in a base case that assumes automotive manufacturers adopt 5G technology gradually as it matures, though again the specific benefits from 5G are not estimated. Based on the model used, which reflects a combination of primary and secondary research, the majority of benefits consists of increased road safety and traffic efficiency, accounting for 80% and 17% of total benefits respectively. Tech4i2 et al (2016) attempt to isolate impacts in the automotive sector that are attributable to 5G, estimating these as €42 billion in 2025.

Some studies attempt to quantify social impacts, such as lives saved. KPMG (2015) estimates that CAVs can lead to 2,500 additional lives saved between 2014 and 2030, while Strategy Analytics (2017) estimates that globally "*585,000 lives can be saved due to pilotless vehicles in the era of the Passenger Economy from 2035 to 2045*".

Environmental benefits have also been the subject of research, but estimates vary widely and depend on assumptions about how CAVs are deployed (DRISI, 2018).

Enablers

Widespread deployment of CAVs will depend on a range of factors, in addition to the development of key technologies such as sophisticated sensors, software and communications. The UK Government has taken steps to facilitate testing and create an enabling environment. A number of further issues may need to be addresses both at national level and internationally to support future development and deployment of CAVs. These include but are not limited to:

- **Regulatory and legal issues**. The use of CAVs at Level 3 and above may require regulatory and legal frameworks to evolve in order to deal with issues ranging from liability in case of accidents, through the potential monetisation of driver data, to standardisation of technical parameters (Allen & Overy, 2017).
- **Cyber security risks**. CAVs could introduce a number of new vulnerabilities, including the possibility of cyber-attacks to steal data, hack into communications and potentially even hijack vehicle controls and sensors (Deloitte, 2017c). The growing phenomenon of sophisticated cyber-attacks on critical infrastructure, including transport, is a concern for industry, governments and regulators, who will face the challenge of mitigating new risks as the large-scale deployment of fully autonomous vehicles grows near.
- **Consumer trust.** Widespread adoption of higher-level CAVs will rely on consumer acceptance, which currently appears to be limited. A survey of UK consumers in 2016 suggested that 73% of consumers think that fully self-driving cars will not be safe (Deloitte, 2017).
- **Availability of spectrum**. A number of studies have suggested a need for dedicated spectrum to be used for vehicle communications (LS Telcom, 2016; 5G PPP, 2015c; KPMG, 2015).
- **Connectivity on road networks**. If 5G connectivity is to be a key feature of CAVs, this will require adequate network coverage across the road network. This is discussed further below.

4.2.2 Passenger connectivity on road and rail

Overview of use case

The provision of reliable and fast connectivity in high-mobility situations, such as on road and rail, is an oft-cited potential use case for 5G. Deployment of 5G cells on road and rail networks is expected to allow passengers to take advantage of 5G's enhanced capabilities, which are expected to be more reliable than existing technologies in high mobility situations (5G PPP, 2017).

The National Infrastructure Commission (NIC) has raised the need to address current shortcomings in connectivity along road and rail routes (NIC, 2016); similarly Ofcom states that "*coverage on roads will need to improve significantly to adequately support*" mobile connectivity services such as entertainment and navigation in connected cars (Ofcom, 2017). The Government's 5G Strategy responds to this need and sets out an expectation that "*trackside infrastructure will be required to deliver high quality, reliable coverage in areas of high passenger demand*", while for the road network further work will be conducted to inform the business case for deployment of 5G-ready roadside infrastructure (DCMS, 2017b).

Role of 5G

Currently, connectivity on the road network is provided through road-adjacent infrastructure on public or privately owned land (LS Telcom, 2016). While this allows for data connectivity on 91% of UK motorways, only 58% of A and B roads have data coverage (Ofcom, 2017a). Similarly, coverage on rail is currently provided through existing telecom infrastructure near railways (LS Telcom, 2016). Ofcom (2017a) notes that some train operators have sought to meet consumer demand for connectivity by installing repeaters to boost in-carriage mobile signals or by installing WiFi systems, which rely on 3G or 4G mobile connectivity (Arthur D Little, 2017).

A common expectation across studies is that alternative approaches will need to be applied to meet future passenger demand. On both road and rail, the NIC (2016) and other studies therefore predict that 5G is likely to have a large role in providing the required connectivity. This is expected to involve dense deployment of 5G cells on road and rail networks such as signage, bridges, overhead gantries and poles (LS Telcom, 2016).

5G is expected to reduce service interruptions such as high latency and transmission errors in high mobility situations relative to 4G. 5G PPP (2017) suggests that would be enabled through 5G's ability for simultaneous connection and seamless handover between several base stations. Oughton and Frias (2016) suggest that 5G might enable user throughput of 50 Mbps download and 25 Mbps upload on high-speed trains up to 500 kmph. To date, testing has demonstrated the ability of 5G to provide higher bandwidths, up to 1.7 Gbps, on high-speed trains traveling at 100 kmph (Samsung, 2017).

However, while there is a consensus that 5G could facilitate the provision of improved coverage to passengers, the business case and commercial model for this is still to be developed. Specific challenges that have limited deployment using existing technologies, such as the influence of trees and foliage, tunnels and anti-glare windows may continue to apply with 5G (Cisco, 2017).

Potential socio-economic impacts

Studies have noted the importance of increased mobile coverage on transport networks for a number of other use cases, including CAVs and vehicle infotainment. As such, the potential benefits from better passenger connectivity are likely to overlap with other use cases.

Some studies estimate the benefits of passenger connectivity in AVs through access to infotainment and productivity gains from the ability to work in-transit (Strategy Analytics, 2017; KPMG, 2015). Other studies note the potential for productivity gains from enabling commuters to more reliably work while on trains (NIC, 2016; RealWireless, 2016); survey evidence suggests up to 40% of train commuters are prevented from working on trains at least half the time with existing connectivity (YouGov, 2016).

Regardless of how the connectivity is used, evidence suggests the potential for substantial value to consumers from addressing current connectivity limitations, which could in turn result in the development of new commercialisation opportunities and business models (Digital Railway, 2017). For example, Steer Davies Gleave (2016) find that train passengers are willing to pay an uplift to their fare for an improved internet service, with business travellers in particular valuing 100% connection reliability. The NIC (2016) notes the possibility for the road network to "*be a commercial asset selling connectivity services to drivers, MNOs and the public sector*".

Enablers

Commercially viable deployment models will be needed to ensure passenger 5G connectivity on road and rail. LS Telcom (2016) estimates deployment costs as £1.75 billion to £7.79 billion for full UK road network coverage depending on deployment models,[13] and £495 million to £595 million for rail.

Studies identify the following key enablers to deploying a 5G road and/or rail network. These are also considered in the Government's 5G Strategy (DCMS, 2017a):

- **Access to existing telecoms infrastructure** such as spare duct and fibre capacity in Highway England's National Roads Telecommunications Service to support the backhaul network. Currently, only 20% of capacity is used to serve the needs of the Strategic Road Network (LS Telcom, 2016).[14]
- **Access to physical infrastructure** such as gantries, poles, bridges, signage, etc. for installation of 5G telecommunications equipment. This would require consideration of health and safety requirements for engineering work, particularly on the rail network, but also considering the possibility of disruptions on roads.
- **Supporting infrastructure sharing** through a regulatory regime optimised for new business models, particularly for rail where safety requirements will limit the amount of infrastructure possible. For both road

[13] Two different models of deployment of 5G on road networks are considered in LS Telcom's study for the NIC (2016). These are (i) use and expansion of Highway England's existing fibre capacity to support the backhaul network for 5G cells installed on road infrastructure and (ii) MNOs upgrading roadside telecommunication infrastructure and adding new sites to meet 5G cell density requirements.
[14] The National Roads Telecommunications Service is a fibre optic network used by Highway England for traffic management and monitoring of the Strategic Road Network, comprised of motorways and major A roads.

and rail 5G networks, the NIC (2016) notes that the Government would need to consider "*who is best placed to install, manage, fund and own the network, noting the potential for private sector funding*".

4.2.3 Other use cases in the literature

The literature points to operational benefits to rail operators from investment in digitalised railways. 5G connectivity is expected to enable more sophisticated command and control of rolling stock; advanced detection of obstacles; and predictive maintenance, increasing network efficiency and reducing transport delays from out-of-commission rolling stock. Given the nature of fast-moving trains and safety considerations, 5G's eMBB and URLLC capabilities could lead to significant improvements.

To enable 5G investment for operational purposes, Digital Railway (2017) suggests that partnerships and new business models may be required to commercialise demand for passenger connectivity. However, while there are some attempts to estimate wider economic impacts including on productivity, there appears to be limited evidence of attempts to develop a complete business case including investment costs, operational benefits and commercialisation benefits. Juniper Research's recent study for O2 (2018) suggests that installing 5G-enabled sensors in UK trains could reduce train delays and cancellations through predictive maintenance, recovering 2.6 hours per rail commuter per year and £440 million in lost productivity, but does not consider the potential costs of network deployment and implementation of new sensor based solutions.

The literature also points to other use cases related to connected vehicles, including vehicle infotainment and 'digital cockpits'. Examples include high-bandwidth vehicle entertainment for passengers as well as display of real-time information to drivers such as AR navigation displays on windshields. However, this has been highlighted more frequently as a demonstration of 5G capabilities by vendors (Samsung, 2018), and material related to economic or social impacts of these types of services tends to consider them within the context of CAVs. There are some considerations of potential commercialisation opportunities of these services (5G PPP, 2015c), but a business case for this is yet to be developed by content producers.

4.3 Healthcare

Reliable and low cost 5G-enabled **wearable or implanted health monitoring devices**, taking advantage of 5G's mMTC capabilities, are expected to support transitions to **out-of-hospital care** models. While evidence on net cost savings remains limited, real-world testing such as through the **Liverpool 5G Testbed** could help provide demonstrable evidence on both cost and care impacts.

5G's URLLC capabilities are expected to enable innovative **tactile internet** applications in healthcare through use of **robotics for remote surgery**, potentially increasing **access to specialised care**, although benefits in the UK may be more limited due to broad availability of specialists. In addition, there remain some significant non-5G technological challenges as well as **regulatory and liability considerations**.

5G's ability to meet specific technical requirements for other potential IoT applications, such as in hospital asset management and precision medicine using real-time data analytics, is also articulated in the literature. However, further research is still necessary to identify and quantify potential impacts.

The literature on healthcare focuses primarily on 5G's capabilities in decentralising and optimising healthcare. 5G is expected to play a large role in enabling IoT in this sector, with eMBB and possibly mMTC capabilities enabling complex sensor networks interacting and sending patients' biological data for remote monitoring. In addition, some studies note the importance of URLLC in healthcare within the wider context of tactile applications, noting the possibility of remote surgical robotics. Use cases in this sector centre on delivering care efficiently and increasing access to quality care, although there is limited quantitative analysis of these impacts.

4.3.1 Remote monitoring

Overview of use case

5G is expected to enable remote monitoring of patients' health data by healthcare professionals (or by AI software) utilising wearable medical devices or implanted bio-medical devices. This allows for the real-time collection and analysis to support a variety of applications such as assisted living, chronically-ill patients and preventive care.

Remote monitoring may form part of a wider trend of digitalisation and virtualisation of healthcare, transitioning from costly hospital-based care towards decentralised remote care. Some studies therefore predict that remote monitoring will be a key part of national health strategies, particularly as a means of cost reduction as well as a shift to treating root causes of health problems such as lifestyle and wellness (5G PPP, 2015a).

Role of 5G

The use of fitness wearables is common in the UK and some nascent remote monitoring technologies have already being deployed for some time using existing technologies, such as 4G and Bluetooth connections between smartphones and wearables. For example, in 2012 University Hospital Southampton became the first Trust in the country to monitor 1,000 heart patients remotely: the second highest number in Europe (NHS, 2012).

Literature suggests that 5G could enable remote monitoring on a much larger scale, with an increase in the number of connected devices that would otherwise cause network congestion (5G PPP, 2015a). Monitoring solutions such as those being developed for dementia could benefit from the improved bandwidth, reliability and device-to-device connectivity offered by 5G, bringing together data from different devices (Arthur D Little, 2017). Further enhancements from 5G could come in the form of more reliable coverage when patients are in specific environments, such as densely-populated areas or on high-speed trains (5G PPP, 2015a). Reliability and low latency will become particularly important if remote monitoring is paired with other use cases, such as automated intervention with precision medicine and remote management of artificial organs (Thuemmler et al, 2017).

The literature does not currently draw a clear distinction between use cases that are enabled or greatly enhanced by 5G and others which may be possible using existing technologies. Many cases of remote monitoring may not require high bandwidths, low latency or other 5G capabilities, although proliferation in the number of devices would potentially require mMTC capabilities (Thuemmler et al, 2017). Real-life testing of 5G applications in this area, such as tangible measurements of the impact on patient monitoring and support from the Liverpool 5G Testbed consortium funded by the UK Government, will be essential in providing evidence on the importance and distinctive impacts of 5G (DCMS, 2018a).

Potential socio-economic impacts

Key impacts suggested by the literature focus on the savings in healthcare costs due to preventive care and a 'decentralised' healthcare system with more care delivered outside of hospitals. From a patient perspective, there may be benefits in terms of improved patient experience and better health outcomes, for example due to early intervention, leading to increased longevity and quality of life.

In terms of quantification, the literature focuses predominantly on cost savings. For example, Tech4i2 et al (2016) estimate that 5G data capabilities will provide operational and strategic benefits of €4.15 billion and €1.1 billion respectively in public healthcare costs per year in the EU, though these estimates are based on uncertain assumptions about the share of potential benefits attributable to 5G directly.[15] PwC (2013) notes that remote monitoring reduces doctor shortfalls and Morgan Stanley (2014) similarly argues that the reduced need for human capital could result in 1-2% cost savings for healthcare providers.

For the UK specifically, Juniper Research (2018) suggests that 5G will enable the widespread adoption of wearable monitoring devices, reducing NHS hospital re-admissions by 30% through aftercare monitoring, though the basis for this finding is not specified. Frontier Economics (2017) looks instead at the impact of 'telehealth' in general,

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[15] For example, the study estimates that healthy living and disease preventative initiatives could create a saving of €21.5 billion per annum and assumes that 5G will contribute 5% of these savings.

including types of remote monitoring as well as other solutions, such as remote consultations. It finds that "*while there are potential benefits to telehealth and telecare, these functions can largely be delivered over existing networks*". In a high-adoption scenario, 5G technology is estimated to generate around £800 million in cumulative cost savings over a 30 year period, though the majority of these savings are estimated to also be achievable through wired broadband solutions.

Overall, Trueman (2009) finds that quantitative evidence of benefits from current remote monitoring systems is generally not robust. While this might change in the future, estimates of potential benefits from 5G-enabled remote monitoring currently rely on potentially subjective assumptions. Deloitte (2015a) examines digital technology in healthcare and finds that, in the UK, "*one of the biggest concerns identified by doctors is the limited evidence on outcomes, including cost savings*", reflecting that a previous pilot[16] had not been deemed cost-effective.

Enablers

Further expansion of remote monitoring in healthcare will be closely tied to commercial considerations. The widespread use of advanced remote monitoring devices may entail large investments, not only to purchase and install devices, but to develop the required supporting IT and data management systems and staff capability. The European Commission (2012) cites the challenges of high start-up costs for eHealth systems and the limited large-scale evidence of the cost-effectiveness of eHealth tools and services. These may be significant barriers for a capex-constrained NHS, where deployment of new remote monitoring systems may be challenging given that "*digital capability in NHS hospitals is variable, with most hospitals having a large number of separate and unconnected systems*" (Deloitte, 2015a).

There may be other challenges that any new technological solution would need to overcome (Deloitte, 2015a). It will be necessary to ensure compliance with patient data confidentiality and broader GDPR requirements, while cultural resistance to technological change among healthcare providers may also slow adoption.

4.3.2 Remote surgery

Overview of use case

The literature identifies remote control of robotics in healthcare settings most frequently in relation to 5G's tactile internet applications. This involves the use of 5G connectivity to "*allow the remote transfer of haptic, tactile, audio and visual technologies. This enables a surgeon or doctor to perform a diagnosis or even surgery on a patient anywhere in the world*." (Ericsson, 2018d)[17]

Remotely controlled advanced surgical robotics could have a number of applications. For example, 5G PPP (2015a) notes that 5G could enable specialists who may not be available locally to support local surgeons in complex procedures, and surgeons may be able to save on the time and costs of preparing for the operating theatre by remotely operating on patients.

Role of 5G

Given the patient safety considerations for this use case, a number of studies note that a key pre-requisite for remote surgery is ultra-low latency with ultra-reliability, availability and no interference. 5G PPP (2015a) notes that "*the continuity of a remote surgery intervention must be preserved in all cases in order to avoid losing lives*."

This low latency is required to enable haptic feedback allowing the surgeon to 'feel' stiffness of different organs through two-way communication with the robotic arm. Studies suggest latency requirements between 10 and 30ms (Lema et al, 2017; 5G PPP, 2015a), with 1ms being required to have 'on site'-like haptic feedback (Saracco, 2017; Oughton and Frias, 2016). Previous remote robotic surgery demonstrations with no haptic feedback suggest surgery with higher latency is still possible as surgeons are able to adapt to delays (Challacombe et al, 2003); however, this risks limiting surgeons' accuracy and skill (Lema et al, 2017). In addition, ultra-low latency is required to control for intrinsic latency in robotics technology (5G PPP, 2015a).

[16] 2010 Whole System Demonstrator remote monitoring telehealth pilots.
[17] Haptic feedback is technology simulating the sense of touch. This requires two-way communication between sensors and the user interface to allow for pressure to be 'applied' and 'felt'.

At this stage, there is limited discussion of how 5G as an enabler of this use case may compare to other connectivity technologies such as fibre. A recent study suggests that many remote surgery use cases would rely on fixed networks (DotEcon and Axon, 2018) and Saracco (2017) notes that latency requirements may mean that communications need to be local and that further analysis is needed to identify the necessary service architecture.

Potential socio-economic impacts

Social benefits in terms of increased access to specialist care is most cited in studies discussing this 5G use case. Thuemmler et al (2017) note that specialists may assist local generalist surgeons in peripheral locations and therefore improve the quality of care delivered through real-time expert availability. Other studies reiterate this, although there is limited evidence of attempts to quantify the impact. In countries such as the UK, where there is good availability of surgical expertise nationwide, benefits could be more limited than elsewhere (Real Wireless, 2016).

Ofcom (2018) notes that 5G could be used by medical students to allow them to practice surgery in a safe, virtual setting through hyper-realistic simulation and haptic feedback. These examples of tactile internet use cases remain largely theoretical, but they could lead to improved outcomes. Given the necessity for advances in robotics technology as well as uncertainty related to 5G, further study is needed to understand potential impacts.

Enablers

Discussion and analysis of remote surgery and its necessary enablers remain at an early stage of development. Some literature notes areas where significant challenges remain to realisation of this use case, although academic literature is at this stage limited. Areas highlighted to be important include:

- **Consumer trust:** A survey of consumers by Ericsson found that 61% consider remote robotic surgery to be 'risky' (Business Insider Intelligence, 2017). This suggests that consumers will need be convinced of the merits of this use case through real-world demonstrations of its safety.
- **Advances in other technologies:** Surgery robotics technology remains at a relatively early stage, and further development to ensure intrinsic reliability and lower latency will be required (Business Insider Intelligence, 2017; Saracco, 2017). In addition, advances in real-time high resolution imaging and AR are likely to be required to provide visual information for the remote surgeon and instructions for the local surgeon (Thuemmler et al, 2017).
- **Liability:** DotEcon and Axon (2018) note that issues in terms of allocation of liability for connected devices in healthcare may slow adoption. Given the number of stakeholders involved in remote surgeries, a regulatory framework for liability allocation will likely be required (Business Insider Intelligence, 2017).

4.3.3 Other use cases in the literature

The literature highlights a number of other use cases to manage healthcare resources more efficiently and deliver care to clients through 5G's IoT capabilities. This includes allowing hospitals to manage a high number of valuable assets, including wheelchairs, ECG (electrocardiogram) monitors and infusion pumps, as well as using data to develop personalised pharmaceutical dosages that may be administered remotely (5G PPP, 2015a; DotEcon and Axon, 2018).

Studies suggest 5G is particularly valuable for IoT solutions due to network slicing abilities, which could support a highly reliable and secure network; the scalability of its low-bandwidth connectivity; precision of positioning information; seamless handover across access technologies; and support for mobile assets (5G PPP, 2015a; Thuemmler, 2017). These studies suggest that the ability to track and manage assets more accurately is expected to have a number of operational benefits for healthcare systems, and that precision medicine could help deliver better quality of life for chronically ill patients. However, while these use cases are relatively well articulated, and there are some examples of existing precision medicine development, the literature remains less developed than for other healthcare use cases.

4.4 Media and entertainment

Future media formats, such as **AR and VR**, are expected to require both high bandwidth and low-latency and will therefore make significant use of 5G's capabilities to drive wider adoption for both **at-home and mobile consumption**. Stakeholders, including equipment vendors, MNOS and sector analysts, highlight demand for high fidelity and immersive content, suggesting potential for increased **consumer value**.

Given the importance of the UK's domestic markets in content production and consumption, the UK is likely to be **well-positioned to innovate** in this area as demonstrated by existing academia-industry collaboration. However, while there is general consensus on market potential, there are varying expectations on adoption timelines and **gaps remain** in impacts analysis despite significant potential for consumer and producer value in the UK.

Several other use cases utilising 5G-enabled AR and VR are also outlined in the literature, including **live on-site entertainment applications, tactile gaming and tourism**. These may have **potential consumer value** benefits as well as **wider social impacts** through 'serious tactile gaming', although further articulation and testing of these will be necessary. Trials such as the **5G Smart Tourism Testbed** may therefore aid in demonstrating the capabilities of 5G to identify additional use cases in the sector.

Media and entertainment sector use cases focus on the ability to consume higher fidelity and more immersive content. 5G is identified in the literature as an enabler for meeting consumer demand for content both at home and on the go. Relevant trends in entertainment consumption include:

- Increased demand for higher-resolution viewing, such as UHD 4K, 8K, etc.
- Evolution in content delivery from traditional broadcast media and physical media to video streaming over broadband networks.
- Development in AR and VR immersive entertainment as well as sub-applications of VR such as tactile gaming with advanced haptic functionality.

Generally, these use cases are discussed in the context of increased consumer value rather than productivity. However, there is limited quantitative analysis of consumer surplus. In addition, while the UK holds a competitive advantage in sectors such as gaming, where companies are already looking to capitalise on the UK's technological innovation and research in 5G (University of Surrey, 2017b), the full significance of 5G for the UK's media and entertainment industry has not yet been explored in detail.

4.4.1 High fidelity and immersive entertainment at home

Overview of use case

Trends in at-home entertainment suggest a future need for significantly more bandwidth than is available today, potentially in combination with low latency. Alongside fibre, 5G is identified in the literature as capable of supporting the delivery of superfast or ultrafast broadband at home (see section 3.1), helping to meet latent demand for high fidelity and immersive media through high-bandwidth and low-latency capabilities. Key examples of high fidelity or immersive content include higher-resolution content, immersive sports entertainment and immersive gaming through technologies such as AR and VR (Frontier Economics, 2017; Huawei, 2017).

Role of 5G

High fidelity and immersive entertainment are expected to demand higher bandwidth than is required currently for HD content streaming. Consumers are already beginning to use services such as 4K UHD streaming, which in some cases may require download speeds of 44 Mbps or more (BT, 2018c). In Ofcom's tests of existing home broadband technologies, it finds that 'up to 50 Mbps cable' services are 90% reliable in streaming 4K videos from Netflix during peak time[18], while 'up to 38 Mbps FTTC' services are 93% reliable during peak time (Ofcom, 2017c).

[18] Defined by Ofcom to be between 8 and 10 PM.

Studies suggest that future generations of viewing technologies will demand greater bandwidths for streaming, which 5G could address if used as a means of delivering fixed broadband (see section 3.1). For example, Frontier Economics (2017) suggests that 8K would require 50 Mbps for non-sports content and 90 Mbps for sports content, based on figures from Netflix and BT. Studies cite varying bandwidth requirements for VR depending on the quality of the VR experience. Quoted bandwidth requirements for AR- and VR-based services include 398 Mbps to 3.28 Gbps (Huawei, 2016), 4 Gbps to 28 Gbps (Oughton and Frias, 2016), 200 Mbps to 1 Gbps (ABI Research, 2017a) and 50 Mbps to 5 Gbps (Qualcomm, 2017).

In addition to bandwidth, VR technologies require low latency to ensure that movements correspond to stimulation, whether visual or in more advanced haptic VR applications such as tactile gaming. AR may have similar requirements. Lema et al (2017) note that "*for virtual reality and augmented reality 15 ms to 7 ms application to application delay, i.e., action to reaction, is the threshold to provide a smooth action-reaction experience*". A higher latency would result in delays between actions and rendering of the virtual reactions, leading to bad user experiences and possible motion sickness (Qualcomm, 2017; Oughton and Frias, 2016; ABI Research, 2017a).

The literature points to the inability of existing wireless technologies to meet these technical requirements, leading to the requirement for VR games to be locally pre-installed and rendered on expensive hardware (Arthur D Little, 2017; Intel, 2017). The studies note that 5G is therefore likely to be a key driver of higher adoption of AR and VR technologies through enablement of cloud processing. This ability will have further gaming applications as well, where end-users frequently require expensive PC or console hardware to process high-quality games. Huawei (2017) notes that 5G's capabilities to deliver at least 75 Mbps with less than 10 ms latency would improve the quality of cloud-processed games from 720p to 4K at 90 frames-per-second (fps).

Some studies note uncertainty about whether 5G may enable wide access to future high fidelity and immersive media content. Studies on deployment scenarios note that provision of 50 Mbps using 5G in rural areas could be prohibitively expensive in the short or medium term (Eriksson and van de Beek, 2015; Oughton and Frias, 2016). Newly-announced trials to test the potential of 5G to support less-connected and rural communities in the UK, such as the 5G Rural Integrated Testbed and the 5G RuralFirst Testbed (DCMS, 2018a), may aid in demonstrating the possibility for 5G to enable wider high-bandwidth access to future media.

Potential socio-economic impacts

It may be expected that high fidelity and immersive media would generate consumer value as well as supply chain impacts for content production in the UK. However, while this use case is widely discussed, limited evidence has been produced to date on its social or economic benefits.

A study by Frontier Economics for the NIC (2017) provides analysis of this use case, looking at the impact of mixed fibre and 5G broadband deployment compared to other possible broadband deployments and to current technology. It estimates that compared to current technology, a 'fibre to 5G' scenario is able to meet technological requirements for high fidelity viewing, AR and VR through all years in its analysis (2020 to 2050).[19] Frontier Economics' study estimates that, compared to current connectivity, the rollout of 'fibre to 5G would enable a cumulative £8.9 billion in additional demand for AR and VR, and a cumulative £0.9 billion in additional demand for high fidelity viewing to be met. However, similar figures are also estimated for rollout of 100% FTTP.

Enablers

Consumer adoption of the relevant devices (AR and VR headsets, 8K TVs, etc.) will be a significant enabling factor. There is uncertainty about which devices might be adopted as some highly-marketed technologies, such as 3D TVs, have not been accepted widely by consumers (Frontier Economics, 2017), and Analysis Group (2016) notes high variance in AR and VR adoption forecasts. Increasing device affordability from scale and having more content available may drive adoption of devices (Frontier Economics, 2017; Business Insider Intelligence, 2015).

[19] The study's 'fibre to 5G' scenario assumes FTTC with 5G as a 'last-mile' connection is rolled out to 63% of UK premises, particularly urban geography types, while FTTP is rolled out to 37% of UK premises, particularly rural geography types. In an 'ambitious evolution' scenario, where technology development and adoption increases faster than expected, fibre to 5G is estimated to be sufficient only until 2041. 100% FTTP is expected to be sufficient in all years.

4.4.2 Mobile dynamic and immersive media

Overview of use case

In addition to at-home consumption, 5G is expected to help meet demand for mobile consumption of high fidelity and immersive media, including gaming. Bandwidth requirements are likely to increase in particular due to the use of mobile devices for AR and VR, with developments in AR and VR technology and cloud processing further driving bandwidth demand (Intel, 2017; ABI Research, 2017a).

Role of 5G

Mobile streaming of UHD 4K and higher resolutions is expected to require higher bandwidth than existing 4G capabilities. In 2016, the average 4G download speed in the UK was 21 Mbps across seven urban areas (Ofcom, 2016); this suggests that current networks are unable to meet bandwidth demands for 4K or VR, though speeds are increasing over time. Seam et al (2017) state that 4G's technical limitations have restricted development of AR and VR content, requiring content to be pre-downloaded for local rendering.

5G's technical capabilities are therefore expected to be necessary for future mobile entertainment (Seam et al, 2017; University of Surrey, 2017a; ABI Research, 2017a; Huawei, 2017). This is particularly important for applications such as gaming, where two-way communication for AR, VR and multiplayer games require ultra-low latency. Demonstrating 5G's capabilities through testing of these and similar applications, such as in mobile high fidelity AR and VR at the University of Surrey (2017a) and mobile AR and VR-enhanced tourism at Bath and Bristol tourist sites as part of the 5G Smart Tourism Testbed (DCMS, 2018a), is therefore likely to be essential to enabling increased and innovative content production.

Finally, an important aspect of 5G will be increased network coverage, reliability and capacity to support a greater number of mobile devices requiring high bandwidth and low latency (University of Surrey, 2017a). In a study for Qualcomm, ABI Research (2017a) notes that "*the vision for AR is the mass adoption of an all-day wearable device that is constantly connected, uploading and downloading vast amounts of data throughout the day*", and forecasts sales of 48 million AR smart glasses in 2021 and 200 million VR devices globally, although forecasts related to AR and VR tend to vary significantly (Analysis Group, 2016).

Potential socio-economic impacts

The literature focuses on the benefits of 5G from the perspective of greater consumer value. For example, Lema et al (2017) highlight user demand for more realistic gaming experiences, particularly in terms of mobile immersive entertainment. They also suggest that, outside of consumer demand for more content, this may present an opportunity for telecoms operators to create new business models such as becoming platforms for immersive entertainment. This would develop an entertainment brand with seamless integration of at-home and mobile entertainment and offer opportunities for innovative in-game advertising.

Others note the potential for unanticipated transformation in how consumers interact with businesses more broadly. For example, while AR and VR are likely to focus initially on gaming and other forms of entertainment, this may lead to innovative transformation in how society interacts with technology in general. This would echo the transformation of how mobile technologies led to current app-centric transformations in the way consumers interact with banks, retailers and other businesses (Seam et al, 2017).

While the need for 5G to deliver mobile high fidelity and immersive experiences is clear, discussion and quantitative analysis of the social and economic benefits are less developed. No study has attempted to estimate gross consumer benefits or net consumer surpluses generated accounting for the costs of investment and deployment, likely due to the inherent uncertainty in forecasting future demand.

Enablers

The literature highlights trends in other technologies as important for realisation of this use case.

ABI Research (2017a) notes that "*there is much progress to be made for both AR and VR, most of which will also have an impact on network performance requirements*". The study notes key hardware issues including battery life, pixel density and field of view. It also suggests that standalone VR devices may be needed, which may also act as a competitor for mobile AR and VR.

Other studies highlight the importance of investment in edge cloud computing (Lema et al, 2017; Seam et al, 2017),[20] which has been demonstrated by researchers to be important to enabling more advanced AR and VR at minimum 4K quality (University of Surrey, 2017a). Seam et al (2017) note that investment by cloud providers in distributed edge cloud computing servers to enable wider AR and VR adoption is already ongoing.

4.4.3 Other use cases in the literature

The literature identifies a number of other use cases within the media and entertainment sector, although as these are specific to certain applications evidence around their social and economic benefits remains limited.

For example, 5G could deliver more immersive experiences during live events (Lema et al, 2017; ABI Research, 2017a). Arthur D Little (2017) highlights a case study of how this may be implemented using "*IoT sensors to re-create a 3D digital version of a real-life sport event*", utilising 5G's eMBB and URLLC capabilities combined with its ability to handle high device densities in both download and upload. This, and similar on-site media, could enhance audience experiences through control of replays, AR and other interactive features (Lema et al, 2017). ABI Research (2017) suggests that 5G could help drive economic activity through live event attendance to counter growing at-home media consumption, although it does not attempt to estimate impacts and, despite this competition, research by Deloitte (2018) suggests that live event attendance is likely to increase due to a variety of factors. In addition, pricing and business models for delivering necessary stadium connectivity levels would need to be better understood in order to estimate the economic impact of 5G for live event usage.

Other use cases for 5G remain at early stages of definition. Tactile gaming has been mentioned as an example of tactile internet applications requiring 5G connections due to ultra-reliable and ultra-low latency requirements (Accenture, 2017b; Simsek et al, 2016; Braun et al, 2017). ITU (2014) predicts that tactile gaming could have social implications through 'serious games' with regard to education, healthcare and training simulations. Despite its potential for wider social impacts, this use case remains relatively undeveloped compared to other 5G use cases in the media and entertainment sector.

4.5 Public services and utilities

Significant attention has been devoted to **'smart cities'**, with many cities establishing smart city strategies. 5G is expected to be a key enabler of **low-cost, mMTC-capable smart public infrastructure**. This is expected to lead to a number of wider impacts, such as **increased public safety, lower costs, higher revenues and environmental benefits**, although further analysis is needed to quantify net benefits for municipalities. Real-world deployments such as the **UK Government's Urban Connected Communities Project** are therefore likely to be essential for testing and analysis of impacts.

5G's mMTC and URLLC capabilities are expected to be important for the development of **smart grids**, although further research is still needed to articulate the role of 5G. Studies have considered the impacts of smart grids overall, including **energy grid security and efficiency and consumer savings**, but more analysis is needed to identify the specific role to be played by 5G.

5G's **network slicing** capabilities are expected to have a significant impact in supporting the provision of **emergency services** through a number of use cases. Further research and testing is needed to identify specific impacts, and the **UK Government's 5G Testbed in Bristol and Bath** may aid in demonstrating the precise impacts of this capability on emergency services.

[20] Edge cloud computing refers to non-centralised cloud processing nearer to data sources through distributed processing networks, reducing latency requirements for real-time applications.

Many UK and global municipalities have formulated 'smart city' strategies, seeking to develop city infrastructure to deliver more efficient and higher quality public services through greater connectivity.[21] Smart cities are often discussed in the literature in the context of IoT, and discussion of 5G has focussed on its role as an enabler of previously-developed IoT use cases. As such, the deployment of sensors in public infrastructure is most often discussed as an enabler of a family of use cases, leading to greater public safety, more efficient services, larger municipal revenues and less congestion. The use of 5G's IoT capabilities to develop optimised utilities grids is also frequently referenced in the literature. Finally, some literature provides brief discussion of 5G's eMBB and URLLC capabilities in highlighting non-IoT use cases for smart cities.

4.5.1 Smart public infrastructure

Overview of use case

A key focus of 5G's role in enabling smart cities is its use to deploy smart public infrastructure, with sensors installed in street furniture such as signage, street lamps, waste bins, traffic lights and parking meters to collect and send data and allow for intelligent management of city resources.

There are significant overlaps between literature on 5G use cases and general smart city IoT use cases. Specific applications of smart public infrastructure discussed in the literature include traffic and route management, dynamic public transport optimisation, city energy consumption management and threat and crime detection (Arthur D Little, 2017; Accenture, 2017a; Zanella et al, 2014; ABI Research, 2017b).

Role of 5G

Smart city strategies already exist in major cities across the globe (Future Cities Catapult, 2018). However, studies note the importance of 5G to delivering new smart city IoT use cases, arguing that the technical requirements of a massive urban IoT network can only be delivered through 5G's mMTC capabilities. Cited requirements include energy efficiency, reliability, scalability and quality of service (IHS Markit, 2017; Oughton and Frias, 2016; Accenture, 2017a; Tech4i2 et al, 2016; Palattella et al, 2016). However, a significant amount of smart city literature makes reference to IoT, but not to 5G's role. Studies tend to assume the proliferation of multi-function, high-quality sensors in city infrastructure to create massive IoT networks, with less discussion of the underlying enabling technologies or the role of 5G.

The literature suggests that it may be possible to deploy sensors in some cases using current technologies, for example using sensors deploying Narrowband IoT (NB-IoT). However, more advanced examples of use cases with interaction between different sensor networks and centralised data analytics have required large-scale rollout of dedicated fibre infrastructure, which may not be feasible for most cities (ZTEsoft, 2018; 5G UK Ltd, 2018). Therefore, the literature suggests that 5G's mMTC capabilities, paired with eMBB, URLLC and other specific capabilities such as more accurate geolocation for particular use cases (IHS Markit, 2017; 5G PPP, 2017), may be essential to wider deployment of smart public infrastructure. Studies also point to 5G's ability to integrate with other access technologies to form a continuous network as a key enabler for IoT in general and particularly for urban environments (Palattella et al, 2016).

Key to demonstrating the unique capabilities of 5G compared alternative technologies as well as measuring 5G's wider impacts will be real-world trials in urban environments. Initiatives such as the 5G Testbeds and Trials Programme's Urban Connected Communities Project to develop a large-scale, city-wide test bed for wireless 5G infrastructure (DCMS, 2018b) are therefore likely to be essential to demonstrating the impact of 5G deployments and identifying further use cases for connected public infrastructure.

Potential socio-economic impacts

Estimates of the socio-economic impacts of deploying smart public infrastructure have been developed as part of wider estimates of the impacts of smart cities. However, quantitative evidence focusing on the net impact of 5G

[21] The UK's national standards body, the British Standards Institution (BSI), defines 'smart city' as the "effective integration of physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens" (BSI, 2014).

sensors specifically, and accounting for costs of network and sensor investment, is more limited. As part of its wider analysis of the macroeconomic impact of 5G, IHS Markit (2016) estimates the impact of the widely-defined 'smart city' use case on global governments' economic output to be $1,066 billion in 2035, but do not consider the cost of 5G infrastructure or sensor deployment. Other studies by ABI Research (2017b; 2018) look at the economic impacts and cost-savings opportunities of smart cities generally, but not 5G specifically.

The literature outlines a number of other specific socio-economic impacts, with some studies attempting to quantify them. Expected socio-economic impacts of different applications of smart public infrastructure networks include:

- **Increased public safety** through notifications on digital signs of oncoming emergency vehicles, route guidance using sensors to monitor flooding and threat and crime detection using sensors combined with high quality CCTV video. Accenture (2017a) notes that San Francisco's implementation of real-time, location-tracking gunshot detection sensors helped reduce gun crime in neighbourhoods by up to 50%.
- **Lower costs** through auto-dimming street lights based on use and optimised heating and cooling of public buildings. Accenture (2017a) uses San Diego's estimated savings of $1.9 million annually from auto-dimming street lights to estimate potential savings of $1 billion across the US.
- **Higher revenue** through optimised use of parking spaces by integrating street lamp and sign sensors with smart parking meters. Accenture (2017a) suggests that 'smart parking' solutions could increase municipal parking revenues by 27% based on a previous estimate of the increase in revenue from Columbus, Ohio's installation of smart parking meters.
- **Lower traffic congestion and environmental pollution** through efficient public transport passenger loading and dynamic bus routing using real-time information on utilisation, smart parking solutions and traffic management systems paired with autonomous vehicles through V2I communications. Tech4i2 et al (2016) estimate an economic benefit of €8.1 billion and environmental benefit of €22.4 million in 2030 across the EU from reduced congestion. Juniper Research (2018) estimates that 5G-enabled traffic management would reduce time spent in traffic for private vehicle commuters by 10% and recover £880 million in lost productivity across the UK.

As 5G sensors are not yet implemented, most estimated impacts are extrapolations from existing deployments of sensors in public infrastructure. As such, evidence for the incremental impact of 5G through the proliferation of 5G sensors remains uncertain.

Enablers

A number of studies point to regulatory considerations in enabling the deployment and realisation of smart public infrastructure, particularly as dense small cell deployment is likely to be key to advanced 5G-enabled smart city solutions. Accenture (2017a) points to the importance of streamlining approval processes for installations of network small cells and public bodies such as Ofcom (2018) have acknowledged the importance of ensuring that access to sites is not a barrier. Arthur D Little (2017) also notes the importance of data encryption standards for the protection of public privacy, particularly with regard to security and surveillance applications. Finally, other literature notes the need to ensure adequate spectrum allocation and sharing to meet critical public service needs such as emergency services (Tech4i2 et al, 2016; IHS Markit, 2017).

4.5.2 Smart energy grids

Overview of use case

5G PPP identifies smart grids as the primary use case for 5G in the energy sector (5G PPP, 2015d). Though there is not a universally accepted definition of smart grids, the European Commission describes these as "*energy networks that can automatically monitor energy flows and adjust to changes in energy supply and demand*" (EC, 2018).

A smart grid encompasses a range of technical features and functions that promote energy network efficiency and flexibility; it "*uses information and communications technology to monitor and actively control generation and demand in near real-time, which provides a more reliable and cost effective system for transporting electricity from generators to homes, businesses and industry*" (DECC, 2014). Though the concept of a smart grid has existed since at least 2007 (US Government, 2007), smart grid requirements and technologies are still at an early stage of development and standardisation (Future Cities Catapult, 2017).

Role of 5G

The availability of adequate communications technology is a key prerequisite for the development of smart grids. Though energy grids are already becoming 'smarter' using existing technologies, the potential capabilities of 5G may deliver significant enhancements. In particular, the current international literature highlights:

- The need for low latency and reliability that is "*orders of magnitude higher than in current wireless access networks*" (5G PPP, 2015d) for mission-critical applications (URLLC), for which 4G was not designed.
- Support for a massive number of connected devices, such as smart meters (mMTC).
- The potential role of network slicing in adequately meeting these diverse requirements (China Telecom et al, 2018).

However, the literature on smart grids in the UK has yet to develop a clear and detailed analysis of 5G's role in delivering smart grids.

Potential socio-economic impacts

By making grids smarter, a range of benefits may be possible for consumers and the wider economy:

- For consumers, greater efficiency may translate to cost savings on energy bills. Consumer participation and engagement may also be enhanced, for example by providing surplus energy generated or stored at home to be supplied to the grid.
- The energy system as a whole may be more secure, reliable and better able to transition towards low-carbon solutions (DECC, 2014).
- The wider economy may benefit: in the UK the development of smart grids could lead to approximately £13 billion of Gross Value Added between now and 2050 (EY, 2012).

The extent to which 5G will contribute to these impacts has yet to be defined clearly. For example, a recent report commissioned by O2 predicts that 5G-connected smart grids will reduce household energy consumption by 12%, leading to savings of £3.9 billion per year, though the precise mechanism behind this is not provided (Juniper Research, 2018).

Enablers

Smart grids remain at a relatively early stage of development. From a technical perspective, challenges remain and further work is required in providing the required standardisation (5G PPP, 2015d), while regulatory frameworks may need to evolve to provide appropriate incentives. In the UK, regulatory price controls have evolved to include innovation incentives that promote more efficient smart solutions (DECC, 2014).

The UK Government has also highlighted smart meters as a key enabler of a smart grid, as these provide data to support efficient network management, demand shifting and distributed renewable energy generation. Smart meters are being rolled out to UK households over the next few years, though currently these rely on existing 2G networks (Science and Technology Committee, 2016), highlighting the uncertainty around the role that 5G can be expected to play in smart grids.

The UK smart meter rollout also illustrates that large-scale investments may be required to deliver a smarter energy grid. In addition to equipment and installation costs borne by energy retailers, the annual costs of Smart DCC, the company created to deliver the smart meter communications infrastructure and manage the data generated, are expected to exceed £400 million by 2020/21 (Smart DCC, 2017). Other future developments of the smart grid may require substantial upfront investment in order to realise longer-term efficiency benefits.

4.5.3 Other use cases in the literature

The literature highlights that 5G's eMBB and URLLC capabilities, in combination with smart public infrastructure, could help to improve the quality of emergency services delivery. Examples include supporting emergency responders with high-resolution imagery and video streaming and AR/VR-integrated visors or helmets (Ericsson, 2018a), integrating smart routing systems with hospital networks to guide ambulances to the most suitable hospital (Nokia, 2017) and delivering advanced disaster response using UHD imaging-equipped drones (BT, 2018b).

5G network slicing is identified as a key capability for emergency services, providing ultra-reliable and, where relevant, ultra-low latency for first responders, emergency medical personnel and disaster recovery personnel through a dedicated virtual instance of the network (Nokia, 2017; BT, 2018b; Zhang et al, 2017; GSA, 2017). Real-world demonstrations of this capability, such as with the UK 5G Testbed in Bath and Bristol, may aid in providing data to demonstrate and measure the impacts of 5G in emergency services (DCMS, 2018a).

4.6 Agriculture

5G's IoT capabilities may enhance existing **'smart farming'** applications and enable new use cases through the integration of **sensor networks** with other technologies. Evidence suggests there is significant potential for smart farming to have **operational benefits** and to increase agricultural **sector output**, although articulation of specific use case and 5G's impacts is needed. Other agricultural use cases include the use of **aerial drones** and **autonomous tractors**, although these use cases remain less articulated.

Discussion of agricultural 5G use cases tends to assume widespread, high specification 5G coverage. However, the literature highlights concerns around the **economic viability of rural deployment**. Ongoing **5G Testbeds in rural areas** may therefore aid in providing support to the business case for rural deployment of 5G.

In highlighting use cases in the agricultural sector, the literature has focused mostly on 5G's enablement of IoT through wider deployment of agricultural sensors. Other use cases include aerial monitoring through non-line-of-site drones and autonomous tractors for seeding and harvesting (Lanner, 2017; IHS Markit, 2017). Agricultural use cases are described in the literature as 'smart agriculture' or 'precision farming', with many studies describing operational benefits to farmers when considering impacts. It is notable that a key theme across all agricultural use cases is the need to ensure adequate rural 5G coverage at or near headline technical specifications. This is discussed further in Section 3.1.

4.6.1 Agri-sensor networks

Overview of use case

Agri-sensors are a family of use cases that focus on massive IoT in an agricultural context. Specific use cases include remote monitoring of soil temperature or moisture, crop development and livestock, with more advanced use cases pairing IoT capabilities with other technologies to provide remote intervention and automation to deliver optimised 'precision farming'. Examples of the latter include optimised and automated irrigation and pesticide spraying, real-time aerial monitoring of crops and livestock through the use of drones with sophisticated cameras and sensors and smart routing of livestock.

Role of 5G

In highlighting the importance of 5G to agricultural IoT and agri-sensor networks, the literature has focused on 5G's energy-efficiency and battery life, enablement of connectivity between different types of machinery and sensors and geo-location accuracy for precision farming (Ericsson, 2018a; EPRS, 2016). This suggests that a key capability of 5G for the agricultural sector is the potential to accommodate a very large number of low-cost sensors.

Some sources also reference the ability of 5G to improve the volume and quality of data available to farmers when paired with other technologies, such as Big Data analytics, cloud and edge processing, drones and automation. For example, 5G agri-sensors could enable the collection of high-quality imagery or information for real-time optimisation through automation (Arthur D Little, 2017).

However, there remains room for further technical analysis of how 5G-enabled agri-sensors might compare to 4G or other access types. DotEcon and Axon (2018) find that dependence on 5G may be a longer-term prospect in the agriculture sector as current technologies may provide sufficient capabilities in the medium term. While there is some reference to sensors potentially requiring high bandwidth or speed (Carritech, 2018), there is less evidence on specific bandwidth, device density, reliability or latency requirements. There are examples of current deployments of sensors and NB-IoT technology to support agricultural activities (Arthur D Little, 2017), suggesting that 5G may not be extended to all agri-sensor use cases. For example, sensors are already used to support blueberry irrigation in Chile, help to fight crop diseases in India and provide pest tracking and management systems in Slovenia (Lanner, 2017).

Real-world testing of 5G rural use cases and deployments is likely to be crucial in this area, particularly in considering how sensors may interact with other technologies to deliver distinctive 5G use cases. Evidence provided by real-world trials on smart farming as part of the 5G RuralFirst Testbed and the 5G Rural Integrated Testbed are likely to be crucial in identifying these (DCMS, 2018a).

Potential socio-economic impacts

Several sources describe operational benefits of using 5G to deploy massive IoT and agricultural sensors, defining the impacts in terms of what it delivers for farms. Examples of operational benefits of agricultural IoT include efficient use of resources such pesticide, water and fertiliser, optimisation of supply chain logistics, reduced costs including from less manual labour, higher crop yields and quality and increased margins. EPRS (2016) considers non-quantified benefits attributed to the wider deployment of agri-sensors including business development and higher revenues for sensor manufacturers in the agri-food chains and higher food security and food safety enabled through higher-quality information from sensor-based monitoring systems. However, analysis to quantify operational benefits is limited, particularly in the context of potential costs of deployment of sensors and wider supporting infrastructure.

In terms of wider economic analysis, IHS Markit (2017) considers impacts within the agricultural sector, estimating an impact of $510 billion on agriculture, forestry and fishing in 2035. The analysis uses a wider definition of a ‘smart agriculture’ use case, however, with a macroeconomic modelling approach to estimate the sectoral impact. The study also defines qualitative social benefits that may be attributed to agri-sensors, such as assurance and transparency for consumers due to accurate recording and reporting of data on ‘farm to market’ produce.

Other studies do not focus on 5G specifically but are indirectly relevant. For example, a study for the European Commission constructed a hypothetical business case for investing in ‘future internet’ technology, defined as future internet-based smart farming technology such as 'smart greenhousing' and 'smart spraying' (FI-PPP, 2013). The study finds that minor decreases in operating expenditure combined with increases in earnings enabled by the use of technologies significantly improved farms’ economic outcomes, while also providing environmental benefits in terms of water, pesticide and energy use and social benefits in terms of developing farmers’ technological skills.

Enablers

An important enabler of agricultural use cases is better mobile coverage through 5G. In its assessment for Vodafone of 5G use cases across the entire agricultural sector, Arthur D Little (2017) suggests the need for extensive rural coverage, presumably at headline or close-to-headline 5G technical specifications, in order for the technology to deliver the outlined use cases. Arthur D Little suggests that, while relatively simple agri-sensors may be feasible using current technology, development of smart precision farming through agri-sensor networks paired with other innovations such as autonomous equipment and vehicles may not be possible without adequate 5G coverage.

Other considerations that may impact the deployment of IoT in agriculture generally also include the ability to predict return on investment, access to financial resources for investment, access to and diffusion of knowledge and training in IoT technology and data analytics among farmers and compatibility between different agri-sensor equipment software (Parliamentary Office of Science and Technology, 2015; Libelium, 2017).

4.6.2 Other use cases in the literature

Other use cases are discussed as supplements to agri-sensor networks to deliver 'precision farming'. Most prevalent in the literature is the use of improved agricultural drones, using 5G's ultra-reliability to remove the need for operator line-of-sight conditions (IHS Markit, 2017) and 5G's eMBB capabilities to deliver higher quality imagery and information with more sophisticated cameras and sensor when surveying fields and livestock aerially (Arthur D Little, 2017). However, a quantitative assessment of the benefits of 5G-enabled agricultural drones has yet to be developed in the literature, with some studies referencing benefits and enablers of drones more generally outside of agriculture. Similarly, some literature references the use of 5G to deploy autonomous tractors performing field tasks such as seeding and harvesting as an example of CAVs deployed in contexts other than road transport.

4.7 Manufacturing

5G-enabled **remote control and monitoring of factory equipment** is expected to utilise URLLC and mMTC capabilities, enhancing existing applications and allowing for **operational benefits and increased productivity** in a wider number of factories **at a lower cost**.

Some attempts have been made to **demonstrate operational impacts**, although further research is needed to provide demonstrable evidence for industrial decision makers. Trials such as **5G-Enabled Manufacturing research project** and the **UK Government's 5G Testbed in Worcester** may therefore support for cross-sector collaboration to demonstrate 5G capabilities and impacts in the sector.

Other use cases focus on IoT capabilities and are expected to provide similar impacts through **seamless supply chain integration** and M2M communication for **automation**. Others may allow for new commercial models through **connected goods**. In general, however, these use cases remain less developed either due to lack of existing deployment on current technologies or commercial obstacles to testing.

The primary focus in the literature on industrial and manufacturing use cases is on 5G's URLLC and mMTC capabilities. URLLC is expected to play a key role in enabling remotely controlled and monitored equipment in industrial settings, with mMTC capabilities and advances in robotics and AI allowing for densely-connected, fully-automated factories and warehouses. Other uses of 5G sensors may occur across the value chain, from suppliers through to end-products. While the former use cases are expected to reduce costs and improve operational processes, the latter are expected to offer opportunities for new business services and models.

4.7.1 Remote control and monitoring of equipment

Overview of use case

The ability to remotely control and monitor factory and warehouse equipment is a key use case of 5G in manufacturing (5G PPP, 2015b; Arthur D Little, 2017). Examples include real-time control of assembly, welding, drilling and advanced robotic equipment, as well as monitoring of diagnostics for predictive maintenance to prevent machinery down-time and life-cycle engineering to improve and update existing operations (Mäntylä, 2017).

5G-enabled remote control and monitoring capabilities may integrate other technological innovations, such as AI and ML, automation and AR to deliver further sub-use cases. For example, AR devices can be used to create 'virtual back office teams' performing diagnostic functions from anywhere using smart devices as well as reduce training requirements by displaying real-time information and operational guidance (5G PPP, 2015b).

Role of 5G

5G is expected to play an important role in the transformation and proliferation of advanced manufacturing methods such as remote control and monitoring. URLLC and mMTC capabilities are likely to be necessary as future factory configurations are expected to involve more connected equipment transmitting data within the factory (Arthur D Little, 2017).

Current applications of remote control and monitoring do exist using current access technologies, with some firms using proprietary network setups to deliver more advanced control. For example, Ocado, an online supermarket, invested in creating a bespoke system based on 4G technology to connect and control over 1,000 robots in its warehouse with low latency, which would not have been possible using standard wireless protocols (Silicon, 2016). In contrast, 5G is expected to provide 1 ms latency and highly resilient and secure connectivity using the network slicing capabilities to ensure reliable control and monitoring of production machinery.

Potential socio-economic impacts

Several studies have described the potential benefits of proliferating remote control and monitoring processes in industrial settings. These studies generally focus on the benefits of optimised production and operational efficiencies, with a focus on cost savings. For example, Ludgren et al (2017) quantify the impact of 5G-enabled maintenance in manufacturing using Discrete Event Simulation (DES) techniques. They estimate a 3% increase in production output, with variation in output quality decreasing from 3.1% to 1.7%. While results are not found to be statistically significant, the paper highlights a method for quantifying technological impacts on manufacturing utilising 5G as an example.

Some studies have also attempted to quantify operational benefits of 'Industry 4.0' processes generally, noting 5G as an enabling technology. Arthur D Little (2016) notes that IoT, 'cyber-physical systems' and 'additive manufacturing' can result in savings of 15% to 50% on the operations processes. In a separate study, Arthur D Little (2017) suggests that a 5G connectivity layer is a key enabler for these new technologies.

Other studies also outline operational impacts of 5G in manufacturing in general, such as increased product quality, better worker safety and satisfaction and less training (5G PPP, 2015b). An Ericsson (2018a) survey of decision makers in the industrial sectors finds 79% plan to make investments in 5G to improve efficiency and 75% expect to create value for customers respectively. However, while these impacts may be related to industrial remote control and monitoring, this connection is not made directly in the literature. Additionally, evidence of analysis and estimation of wider social and economic benefits of these investments is more limited.

Enablers

The literature refers to key technical and safety considerations for use cases of 5G in industrial applications in general. For example, Arthur D Little (2017) notes that radio frequency interference in the factory floor may be an issue as "*several objects on the factory floor are already using radio communications*", while "*hundreds of connected automated devices on a factory floor can create a hazardous environment for humans*". Therefore, pilots such as the 5G-Enabled Manufacturing research project[22] and the UK Government's funding of the Worcestershire 5G Consortium as a 5G Testbed for industrial 5G use cases can be enablers by demonstrating how 5G can improve production processes and providing actionable evidence for manufacturing decision makers.

Another key enabler may be further research and evidence on the cost-effectiveness of 5G manufacturing processes. Arthur D Little (2017) notes that "*the manufacturing industry has high cost reduction requirements and will only implement new applications if these have been proven to ultimately reduce costs*". Further evidence similar to Lundgren et al (2017) quantification of 5G-enabled maintenance use cases' impacts is therefore likely to be necessary to convince manufacturing decision makers to invest in 5G-enabled manufacturing process.

4.7.2 Other use cases in the literature

The literature describes other 5G industrial use cases primarily related to IoT, although some likely relate to sensor cost rather than density as being key enablers. Examples include:

- Enabling seamless intra- and inter-enterprise communication (5G PPP, 2015b), with tracking of goods across the value chain and industrial premises and exchange of data for simulation and design;
- Allowing M2M communication for automation and asset tracking purposes (Mehmood et al, 2017); and

[22] See https://www.chalmers.se/en/projects/Pages/5GEM.aspx

- Connecting goods sold to manufacturers (5G PPP, 2015b), allowing manufacturers to sell Products-as-a-Service, e.g. charging by hours of use, rather than as a physical good or part.

5G PPP (2015b) notes the opportunity of new business models for manufacturers and/or service providers in the value chain, particularly through connected goods, and gives examples of new industrial roles or services that may be offered, but there is more limited evidence of quantification of social or economic impacts. Real-world trials, such as by the Worcestershire 5G Consortium (DCMS, 2018a), may therefore support the development of evidence on distinctive 5G industrial use cases.

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