THE IMPACT OF TECHNOLOGICAL CHANGE ON FUTURE INFRASTRUCTURE SUPPLY AND DEMAND

NATIONAL
INFRASTRUCTURE
COMMISSION

CONTENTS

1. INTRODUCTION

The National Infrastructure Commission has been tasked with putting together a National Infrastructure Assessment (NIA) once a parliament. This paper, focussing on technology, forms part of a series looking at the drivers of future infrastructure supply and demand in the UK. Its conclusions are designed to aid the Commission in putting together plausible scenarios out to 2050. It will also form part of the evidence base for the Commission's new study, which will look at using new technology to improve infrastructure productivity.

The National Infrastructure Assessment will analyse the UK's long-term economic infrastructure needs, outline a strategic vision over a 30-year time horizon and set out recommendations for how identified needs should begin to be met. It will cover transport, digital, energy, water and wastewater, flood risk and solid waste, assessing the infrastructure system as a whole. It will look across sectors, identifying and exploring the most important interdependencies and cross-cutting themes.

This raises significant forecasting challenges. The Assessment will consider a range of scenarios to help understand how the UK's infrastructure requirements could change in response to different assumptions about the future. Scenarios are a widely-used approach to addressing uncertainty. Quantifying scenarios also allows modelling of policy options.

In the absence of a known probability distribution for future outcomes, the scenarios will be based on available empirical evidence about past trends and quantitative and qualitative forecasts of changes in four key drivers of infrastructure services: the economy, population and demography, climate and environment, and technology. Understanding trends and discontinuities in the past can help identify where variation in the set of scenarios may be most helpful. The drivers should not be thought of in isolation: readers might also wish to consider the related discussion papers on the other drivers.

Technology enables us to live a lifestyle that our predecessors would have struggled to conceptualise. People now live longer than ever before, in greater levels of comfort and with ever-increasing amounts of information at their fingertips.

This paper considers first the effects of technology on existing infrastructure, where it can enable increases in effective capacity, create demand for an expanded system or lead to a decrease in demand. When it comes to new infrastructure, technology can both reduce the cost of supply and create demand for a new way to provide an infrastructure service. As the UK moves towards more connected infrastructure systems, the impact of system failure becomes more significant. The risk of technology being used to reduce our infrastructure supply through a cyber-attack also increases.

This paper considers these cross-cutting trends across the sectors under the Commission's remit and their potential impacts over the next thirty years, examining how technology can:

1. Reduce the need to build new infrastructure
2. Create demand for additional infrastructure
3. Lower the cost of supplying infrastructure
4. Create demand for a new infrastructure system
5. Drive a decrease in demand for an infrastructure system
6. Lead to more vulnerable infrastructure systems

Based on the analysis in this paper, the Commission is developing three scenarios based on varying rates of technological change as inputs into its broader scenario development for the NIA. These will assume different rates of change across key technologies which could have an impact on infrastructure supply and demand over the next thirty years.

The Commission would welcome comments on this discussion paper. In particular, references to further sources of evidence on these issues would be helpful. Please send any comments to **nicdiscussionpapers@nic.gsi.gov.uk** by 10 February 2017.

Further information on the scope and methodology of the National Infrastructure Assessment is available **here**.

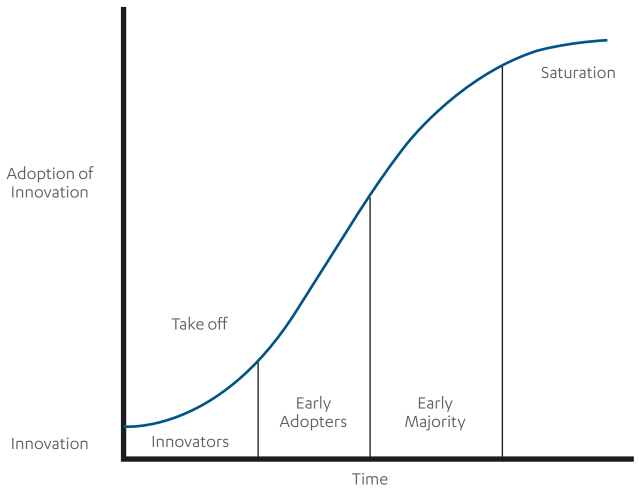
2. THE PROCESS OF TECHNOLOGICAL CHANGE

There is a wide body of literature examining the process of technological change, or innovation. This developed significantly during the twentieth century, from early perspectives which viewed it as a linear, one-directional process to more complicated theories which aim to take into account the wider context, acknowledging the complexity and interdependencies which exist.[1]

In his book about the diffusion of innovations, Everett Rogers set out six stages in the innovation development process: recognising a problem or need, basic and applied research, development, commercialisation, diffusion and adoption and finally the changes which occur to an individual or to as social system as a result of the adoption or rejection of an innovation (which he terms "consequences"). Whilst the diffusion of new technologies has been an area of focus for some economic historians, much of the wider research into innovation development focuses on the research and development stages rather than the later phases.[2] However, it is at this point that new technologies begin to interact with infrastructure systems.[3]

This paper uses the term "technology" to refer to both technologies and their applications, or products. Most products combine multiple technologies in order to solve problems. The adoption of most new technologies follows a similar "S-shaped" curve. This represents slow take-up to begin with, followed by a period of much more rapid growth which then slows down as the saturation point is reached.[4]

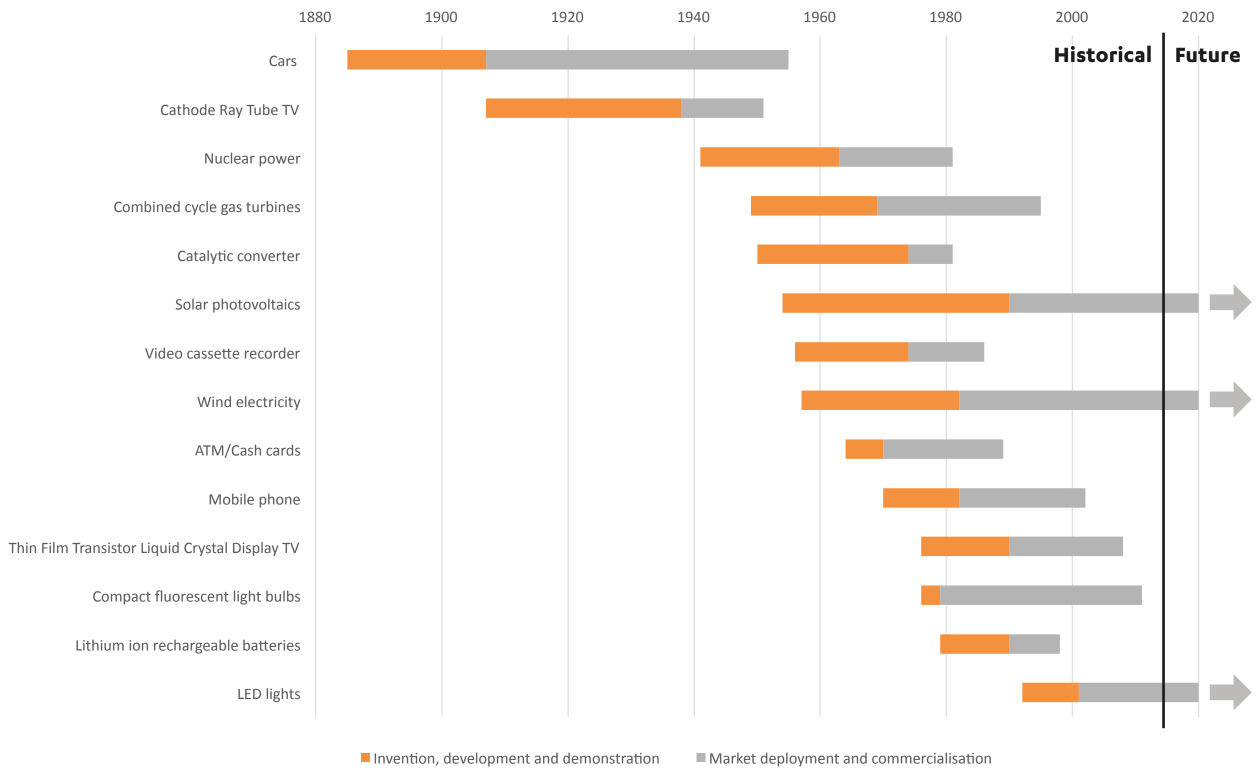
Figure 1: A typical S-shaped curve of innovation diffusion



However, the time this process takes varies widely. Whilst some consumer innovations may diffuse very quickly, other new ideas can take decades to spread and reach complete use. This rate of adoption depends on the perceived characteristics of a new technology, its price (or change in profitability it enables) and the system into which it is diffusing. Involving additional people in decisions about whether to adopt an innovation slows it down, whilst promotion by "change agents" or opinion leaders can speed it up.[5, 6]

A recent review which looked at the time from invention to widespread commercialisation of fourteen technologies found the average time this process took was 39 years (although this ranged from 19 to 70 years).[7]

Figure 2: Historical timeline and duration of innovation for different technologies



Everett Rogers also identified five attributes of any given innovation that affect the rate of adoption:

1. **Relative advantage**

   The new idea must be better than the technology it is replacing. This may be because it is less expensive or because it is linked to greater social status. The level of relative advantage can change over time, either as a technology becomes cheaper, or due to network effects which come into play once a certain number of people have adopted it.

2. **Compatibility**

   A technology which fits with existing values, previous experiences or client needs is more likely to be adopted. Radical and disruptive innovations which are not compatible with existing practices are unlikely to rapidly diffuse.

3. **Complexity**

   Technologies which are perceived as complex will be adopted more slowly. This can be an important barrier to adoption.

4. **Trialability**

   People (or organisations) need to see how an innovation works under their own conditions. Being able to test or try out a new idea speeds up the rate of adoption of an innovation, particularly for early adopters who act as triallers for later ones.

5. **Observability**

   The more visible the results of an innovation are, the faster it will be adopted. A good example of this is the mobile phone, or genetically modified crops in India.[8]

According to the OECD, government policy plays a large role in shaping both the level of development of new technologies and their rate of diffusion across an economy. Technology research and development is largely concentrated in a handful of countries, therefore it's critical for others to be able to capture the benefits of new innovations through focussing on adoption and diffusion.[9]

Measuring the rate of diffusion of different technologies across different countries is not straight-forward due to the difficulty in both developing indicators and collecting data to assess performance. In 2004, the OECD ranked the UK 15th out of 27 countries for technology diffusion, with Sweden, Ireland and Finland at the top of the table. They looked at indicators such as: the import of technology and patents; franchising and purchase of research and technical consulting; business' assessment of the application of new technology and the share of firms collaborating with others on innovation and technology.[10]

3. TECHNOLOGICAL CHANGE WITHIN INFRASTRUCTURE SYSTEMS

Infrastructure sectors tend to have certain features in common which mean they can be considered in the same way. In addition to being a group of physical assets, they also consist of people, organisations, knowledge, economic and legal conditions that together provide essential services to society.[11] Often, they are network based. As infrastructure services have become increasingly convenient, reliable and cheap, our dependence on them has increased, with the result that it is now very difficult to substitute for them.[12]

There are also specific characteristics of infrastructure sectors that affect how transformation takes place within them. Many sectors have high capital costs due to the physical networks on which they are based (for example, about 80% of the cost of treating wastewater is fixed).[13] Infrastructure assets also tend to be built to last several decades, which reduces capital intensity but increases the uncertainty at the time of construction. Due to these sunk costs, older forms of technology remain competitive for longer.[14]

Strategic decisions concerning infrastructure services are likely to be influenced by public authorities and policy makers in order to achieve their wider objectives, such as eliminating regional price disparities or cross-subsidising of other public services. Regulation is often also put in place to try and meet these aims, as well as to mitigate environmental impacts and to prevent overcharging by the natural monopolies which are often created by high capital costs.[15]

Finally, competition is likely to be low due to high barriers to market entry. In some sectors (such as telecommunications and electricity supply) operation of the capital intensive network has been unbundled from the rest of the value chain to enable more competition to be introduced across the rest of the sector.

The components of an infrastructure system are interconnected, and therefore dependent on each other to function effectively. This means that new technologies that are introduced must either have a high level of compatibility with the existing network structure, or that all the other elements of the system must adapt and change. This creates a significant barrier to transformation.[16]

Where several competing technologies emerge, historical or chance events can give one of them an initial advantage, particularly where there are increasing returns to scale. Positive feedback loops can magnify the impact of an insignificant event and tip the system. This effect was demonstrated by W. Brian Arthur in his paper entitled "Competing Technologies, Increasing Returns, and Lock-In by Historical Events". He showed that increasing returns can cause gradual lock-into an outcome not necessarily superior to alternatives, which is not easily altered and not entirely predictable in advance.[17] However, as an industry develops, superior technologies can re-emerge.[18]

To increase the compatibility of an innovation with a complex system, gateway technologies may be developed which can make it technically and economically feasible to introduce it. Aside to adding to the size of the investment, this may have other knock-on effects such as slowing down the development of other potentially radical improvements, or impacting competition between contending variants of a technology.[19]

Expensive assets with long lifetimes can lead to inertia and resistance to change, as there are limited opportunities to introduce new technologies and significant sunk costs. Organisational structures also tend to adapt to existing technical configurations. These factors combined mean that existing infrastructure systems tend to evolve gradually and incrementally.[20]

Technology can act as a direct driver of infrastructure supply and demand. However, it is also deployed to help achieve other infrastructure-related objectives. In the UK, our ambitious climate change targets and resulting policies present an opportunity to drive the diffusion of new innovations across our infrastructure systems. Since the 1980's, the UK has spent less public money on infrastructure than other OECD countries, which has only been partly offset by the private sector.[21] Re-investment and new sources of finance may also drive transformation.[22]

Policies, frameworks and incentives all contribute to enabling the UK's infrastructure sectors to both respond to the changes in expectations and demand which technological change can present and take advantage of the opportunities that it offers.

4. TECHNOLOGY CAN REDUCE THE NEED TO BUILD NEW INFRASTRUCTURE

One important use of technology over the next 30 years will be to integrate with our existing infrastructure, enabling us to make best use of what we already have. Managing our infrastructure systems in a smarter way could reduce the need to construct new assets in the face of increasing demand. Instead, technology can increase the effective capacity of our infrastructure, reduce maintenance and operating costs and improve reliability and safety.

Strategies which use technology to manage systems are an effective way to get the most out of the UK's current infrastructure stock. Innovations such as these do not depend on a particular product being diffused, but rather the application of a new technology which increases the overall efficiency of the system.

For example, demand management allows an operator to reduce the overall demand peak by shifting consumers' usage of the infrastructure to times where demand is lower. This can significantly reduce costs. Demand management has reduced peak demand for electricity by up to 15% in parts of the USA. In the Pennsylvania, Maryland and New Jersey electricity market this has resulted in a reduction of the average wholesale price of electricity by 5-8%, alongside a much larger drop in peak wholesale prices.[23]

Other innovations allow operators to maximise system capacity. Technology can enable suppliers to gain an increased understanding of demand patterns, including real time data on consumer usage, allowing them to only deliver the required amount of infrastructure service to match demand.

Smart motorway schemes use technology to read traffic flows and adjust speed limits in real time to help manage traffic. The net result is an increase in the capacity of the motorway, without the need for work to physically widen it, as well as reductions in journey time variability, pollution and fuel consumption.[24] The recent upgrade of part of the M62 to a smart motorway in 2013 has resulted in commuters saving an average 30 minutes a week.[25]

Another use of embedded technology is to measure, monitor and improve the performance of an asset itself, by providing asset owners with information in real-time about the condition and use of the asset. Used effectively, this can lead to condition-based maintenance, reduced down time and greater operational efficiency of the infrastructure overall.

Increasingly, technology can provide information about how infrastructure is performing. Using technology to monitor or map the health of infrastructure can enable the quantification of the extent of ageing and remaining design life.

One recent project by Cambridge University used highly-accurate sensing technologies to identify and prioritise defects on a stretch of three-lane road. Not only was the data collected more cheaply and quickly than using conventional methods, it provided a ten-fold increase in spatial resolution. Moreover, there was no need to close the road or impose speed restrictions. This resulted in significant cost savings and meant that a more effective, risk-based maintenance and repair programme could be prepared.[26]

In Staffordshire, fibre-optic sensors have been installed during the construction of new railway bridges as part of a trial. These allow the structure to be monitored during the manufacturing, construction and operational phases of the project. Combining this with building information modelling (BIM) to visualise the captured data can allow savings to be realised at every stage and contribute to an improved understanding of how structures behave.

The effect of deploying technologies such as these is generally an incremental improvement in capacity or efficiency. It is therefore relatively straightforward to predict the impact of these interventions for any given system. Estimating the likely scale of these impacts in the future is more difficult, as the deployment of these technologies depends as much on policies, regulations, consumer behaviour and the culture of different organisations as on their technical potential.

There may also be secondary effects – it is well-established that an increased supply can lead to higher demand. For instance, in the 1960's researchers started to look into the potential of telecommunications for reducing travel. Yet, even though innovation in this area has exceeded expectations, we see no sign of congestion reducing. One researcher concluded: "It is difficult to improve technologies and services for the purposes of reducing travel, without having those same technologies and services used to stimulate travel".[27]

5. TECHNOLOGY CAN CREATE DEMAND FOR ADDITIONAL INFRASTRUCTURE

Technological innovations constantly provide us with more ways to connect with people, goods, services and opportunities.[28] This can lead to an increase in infrastructure demand, redefine how we use and interact with the infrastructure around us or even lead to an entirely new infrastructure system.

The information and communications sector is currently undergoing the most rapid changes and growth in response to technological change.[29] Demand for internet services and mobile communication infrastructure has risen dramatically over the past few decades, driven by demand from businesses and consumers to make the most of new technologies. Another driver of this has been the application of new technologies to other infrastructure sectors e.g. smart meters and smart motorways.

As users have been given access to faster data speeds and lower latency rates, the way they access and use the internet has changed. For example, mobile phone operators report that 4G customers consume around double the monthly amount of data of non-4G users, and in some cases three times as much.[30] This suggests that demand may currently be constrained by supply. Based on current trends and analysis of devices and user mobility, work carried out for Ofcom projected that the demand for mobile broadband could increase between 23 and 297 times between 2012 and 2030 (with 80 times as a mid case scenario).[31]

Patterns of usage are also changing. For example, growing numbers of people are watching TV over broadband or mobile internet connections rather than over the broadcast network, particularly amongst younger viewers. The number of homes with no conventional TV but with a broadband connection has risen, trebling between 2009 and 2014 to over 1.1 million homes.[32]

Increased demand for ICT has also led to increased energy consumption and greenhouse gas emissions associated with the sector. The ICT sector currently contributes 4% to the UK's overall emissions. Three-quarters of these emissions are from end-user devices, while networks and data centres make up the rest. Whilst the energy requirements of individual devices are predicted to decrease, their overall number will continue to grow. Data centres meanwhile, will continue to consume increasing amounts of energy. It is still unclear whether any technological solution will be able to make a material difference to this.[33]

Case study: The impacts of autonomous and electric vehicles on travel and energy demand

Autonomous vehicles are those where at least some of the essential safety control procedures such as steering and breaking are not implemented by direct human control. The US government has defined five different levels of autonomous driving, ranging from specific functions being automated to the driver being no longer required. Car manufacturers today are already implementing some degree of automation to their vehicles, with features such as automatic braking and adaptive cruise control representing incremental steps on the road to fully autonomous vehicles.

A number of countries, including the UK, are already testing driverless cars on their roads. A 2014 survey of self-selected experts provided 2019 as a median estimate of a time when cars could operate autonomously on motorways, 2025 as the year that driving tasks on urban and rural surface roads could be automated and 2030 as the year that full automation could be achieved. Elon Musk of Tesla has publically stated that he expects fully autonomous vehicles to be ready by 2018, although regulatory approval may take 1 to 3 more years.[34]

Autonomous vehicles could impact demand for car travel, opening it up to new sections of the population, such as the elderly, those with physical disabilities and even children. Driving demand could also increase as drivers become free to spend travel time in more productive or entertaining ways. This could result in passengers requiring more space during the journey and a knock-on increase in the size and weight of vehicles, causing them to become less fuel efficient, even compared with today.

Automation in itself is unlikely to significantly affect energy consumption, but it could facilitate changes in the road transportation system which could reduce it, such as energy-saving driving practices.[35]

However, the increased take-up of electric vehicles could have a more significant effect on the UK's infrastructure needs. It is possible that electric vehicles may increase travel demand through reducing the marginal cost of a journey. In any case, widespread adoption would also impact the demand for electricity. Under a high uptake scenario and assuming no demand management policies, the use of electric vehicles could increase peak demand for electricity by around 50% (28 GW) by 2050.[36]

This would need to be supported by a comprehensive charging infrastructure system, including a public network and millions of charging points at homes, workplaces and depots. This will have an impact on the electricity distribution networks. Research funded by Ofgem found that in a scenario where 40% - 70% of customers have electric vehicles, over 30% of local electricity networks would require intervention.[37]

Technology can also be used to mitigate the impact of electric vehicles. Improvements to battery technology will allow them to travel further distances between charges, lowering the need to provide a large-scale public network and smart technologies can protect power networks from potential overload through managing demand.[38, 39] The development of storage would also increase the possibility for consumers to sell back electricity stored in their vehicles back into the grid.[40]

6. TECHNOLOGY CAN LOWER THE COST OF SUPPLYING INFRASTRUCTURE

Technology has the potential to lower the cost of constructing new infrastructure projects. A review of thirteen studies looking at the future of construction identified the technological developments that were most frequently mentioned as having the biggest potential impact on the construction sector. These were:

- Increased standardisation and offsite construction
- Increased use of common ICT and information sharing platforms
- Increased automation and use of robotics
- Increased use of 3D technology (virtual reality, CAD)
- New/smart construction materials[41]

3D printing is one technology which could bring down the cost of building new infrastructure. Winsun, a Chinese firm, is using 3D printing to build houses more quickly and cheaply than with more conventional methods. The company claims to have built 10 houses in less than 24 hours at a cost of less than $5,000 per house. They have also worked to 3D print a five storey apartment block.[42] Earlier this year in Dubai, the first 3D printed office was opened. The basic building structure took 17 days to print, with labour costs roughly half of what would be expected for a building of the same size made using traditional methods.[43] To date, 3D printing has been focused on the construction of residential buildings and offices. However this trend could spread to large scale infrastructure projects. MX3D, a Dutch startup company, is currently working to 3D print a fully functional pedestrian steel bridge across the Oudezijds Achterburgwal canal in Amsterdam.[44]

New materials are also being created. Examples include: topmix permeable, an alternative to cement that will allow the absorption of 4000 litres of water a minute; aerogel, a material made of 99.98% air which is transparent and super-insulating; and concrete canvas, a concrete cloth that can be used to build drains and passages.

New processes are breaking through into the sector, such as building information modelling and 5D project planning, which allows for a project's cost and potential schedule to be included with the traditional 3D modelling of the project site. These techniques help to promote collaboration throughout all stages of the construction process and are already being used on large infrastructure projects, such as Hinkley Point C and Crossrail.[45]

Cost reduction is dependent on adoption, and the construction industry has a reputation for being slow to innovate with new technologies, materials or processes.[46] Against average growth in research and development expenditure of 35% across all UK sectors since 2000, spending in construction has declined over the same period. In 2011, just £22 million of research and development spending was registered.[47]

Many arguments have been put forward to explain why this might be the case. Government reports have identified issues such as poor rates of investment in research and development, fragmented supply chains and lack of coordination between academia and industry in research activities. In addition, most construction projects are developed on an individual basis. This means that learning may not be carried forward from one project to the next.[48]

These factors, combined with the large numbers of actors who are typically involved in construction projects and preferences for tried and tested techniques, may contribute to why rates of innovation lag behind many other sectors.[49] However, the most common reason that construction firms themselves give for not innovating is that market conditions do not require them to.[50] Without demand for more innovative solutions, the rate of change in the construction sector is likely be low.

Increased demand for cleaner technologies has led to falls in the cost of supplying infrastructure. Renewable energy technologies are an often-cited example of this. From 2010-15, the average cost of new utility-scale solar PV declined by two-thirds and is predicted to decline by an additional quarter between 2015 and 2020.[51]

The falling cost of energy storage technologies could have huge implications across multiple infrastructure sectors, but particularly in energy and transport. The cost of lithium ion batteries has fallen to 15% of their cost in 1990 (from $3000/kWh to $200/kWh). In the electricity sector, it is estimated that the deployment of storage, alongside smart solutions such as demand management and the construction of interconnectors which allow the UK to import and export more electricity from the continent, could lead to savings of £8 billion a year by 2030. This is primarily because of the reduced need to construct capital-intensive power stations.[52]

7. DISRUPTIVE TECHNOLOGY CAN CREATE DEMAND FOR A NEW INFRASTRUCTURE SYSTEM

Technological innovations which provide a better, cheaper way of accessing infrastructure services can give rise to demand for new infrastructure systems to support them. In some instances, when technology and infrastructure development combine, new infrastructure systems can take off which can have impacts on the economy beyond the sum of their parts.[53]

Trains are an example of technological change creating demand for new infrastructure. Before the advent of the railway, economic growth and passenger travel were constrained by expensive and slow methods of travel, including the canal system and a poor quality road network. The cheap, fast, safe and comfortable journeys that railways enabled meant that demand grew rapidly throughout the 19th century. This created incentives for the private sector to roll out an increasingly extensive network, which grew from around 2,400 miles in 1845 to around 24,000 miles at its peak in the early 1920s.[54]

By the end of the 19th century the railways accounted for almost 90% of all passenger-km travelled. In addition, cheaper transportation meant that the price of goods also fell. Demand for coal, steel and construction rose. The profitability of water transport sharply declined.[55]

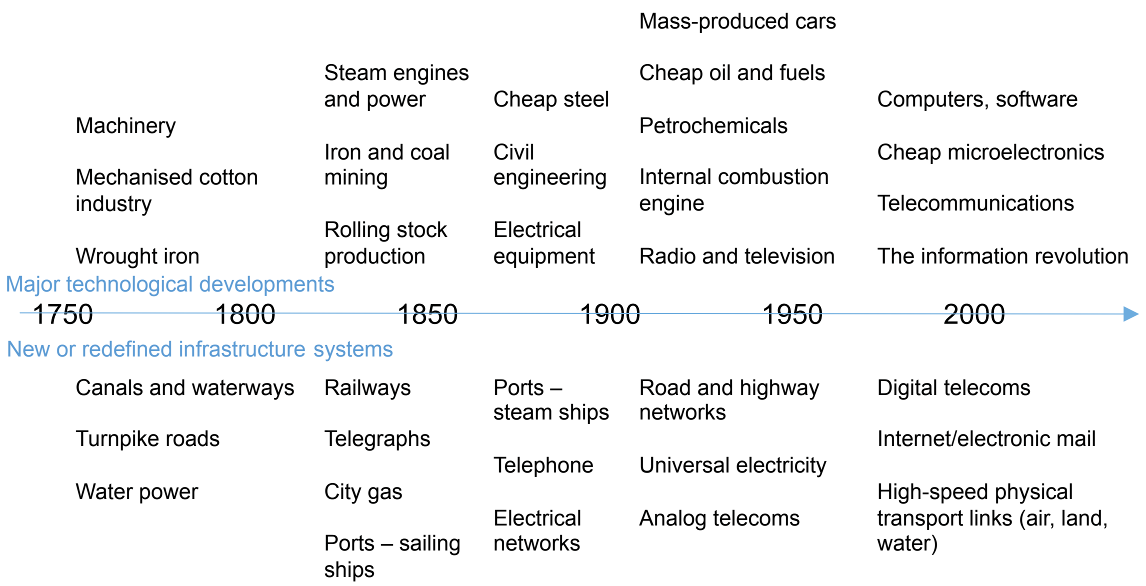
In the transport sector, this phenomenon has occurred on a regular basis over the last 200 years. Older forms of transport are replaced by newer transport modes which are faster and offer a wider human activity range, according to a characteristic pattern of change. We observe similar trends in the energy sector, where more efficient ways of generating energy have led to the rise and decline of different infrastructure systems.[56]

It is unclear whether this pattern will continue. Some argue that big transport breakthroughs in particular are unlikely to be seen again, as they could only represent an improved good, not a new good.[57] In terms of cost-benefit analysis, the benefits of investing in one method of transport are generally much lower when another already exists. Take for example, maglev trains. Even though they may be able to cut intercity journey times radically, if average end-to-end journeys are not radically shorter the business case is unlikely to stack up. A new technology in the wrong location, or without the supporting city infrastructure that helps deliver sizeable benefits is unlikely to be worth investing in.

The trend of technological changes accompanying or driving new forms of infrastructure has also been looked at more widely across the whole economy. Figure 4 shows some of the most notable technological developments which have been linked with the creation of new infrastructure systems over the past 250 years.

It is interesting to note that, with the exception of our strategic roads, many infrastructure networks have been initially funded and developed by private companies, sometimes sometimes offered as concessions or monopolies by the state. During the 20th century, many systems were nationalised, a trend that began to be reversed during the 1980's under Margaret Thatcher.

Figure 4: Major technological developments and infrastructures since 1750[58]



Case study: The potential impact of drones on UK infrastructure

Drones combine three technologies that are predicted to have significant impacts on our lives: the internet of things, through embedded sensors which collect information and send it over the internet to be analysed; advanced battery technology, which will allow drones to operate for increasingly long periods of time and cognitive computing, which will enable drones to carry out tasks autonomously.

The online retailer Amazon recently announced that they, in partnership with the CAA and other government bodies, were to start testing the delivery by drone of small parcels which make up 80% of their sales.[59] Swiss Post and Posti, the national postal service of Finland, have started to use drones as a useful method of delivery in both rural and urban areas.[60]

In spite of increasingly high expectations to the contrary, economic, logistical and security concerns mean that deliveries made by drone may never result in any significant decrease in demand for road freight. Even if drones were to replace a quarter of all deliveries currently made by van, this would only reduce overall traffic levels by 1%. As a drone's productivity is around 94% lower than that of a delivery van, fifteen drones would be needed to replace one vehicle.[61]

Alongside delivery, there is a huge range of additional potential uses for drones. Hundreds of companies in the UK alone are already using drones to offer services, including photography, land surveying, building inspection and crop analysis. Drones are especially suited to monitoring the integrity of large, distant infrastructure, such as oil and gas installations and wind farms, which they can do with more accuracy than the naked eye. A drone inspection of a wind farm is already half the cost of sending a human to carry out the task.[62]

As drones will be primarily used for commercial purposes in the UK, it is unlikely that significant new public infrastructure would be required to support their adoption. Drones are already demonstrating how they can reduce the cost of maintaining infrastructure. However at present, they are likely to be employed as a complement to other fleets rather than as a substitution.

For the UK to make the most of the economic opportunities that drones will offer and to ensure any safety risks are managed, the development of a robust and forward-looking regulatory framework would be essential.[63]

8. TECHNOLOGY CAN REDUCE DEMAND FOR AN INFRASTRUCTURE SYSTEM

New technologies can impact on demand for infrastructure systems in unforeseen ways. In the 1950's, the increasing numbers of televisions in people's homes meant that cinema attendance fell sharply. This had a knock-on effect on bus usage in the evenings and weekends. The commercial viability of many bus operations was undermined.[64]

In extreme cases, changes in technology can represent one of the drivers of infrastructure systems becoming obsolete – in other words, failing to meet a changing performance requirement – amongst other factors such as regulatory, economic or social change, or changes in the values or behaviour of people who use and own the infrastructure. This is consistent with Schumpeter's theory of creative destruction, which says that constant reinvention is an inherent feature of any capitalist system.[65]

This has been observed over time, as entire infrastructure systems, which, due to a change in technology are no longer considered to meet consumers' expectations, have gradually lost their market share. The pattern of different infrastructure systems rising and then declining as a superior technology emerges has been observed in many countries.

New technologies do not usually start off by disrupting entire systems. More often they provide a solution to a particular problem, or do well in a specific niche.[66] It is only once they are established that this process begins. For example, the growth of cars in the UK can be characterised by two periods. The first, between 1900 and 1930, represented the car replacing horse-drawn carriages. This substitution proceeded quickly, as cars hold a large, direct comparative advantage to this mode of transport. The second phase, between 1930 and 1985 was a longer period of steady growth, where the car started to diffuse into areas of the market that were either previously held by railways, or were new, such as leisure and weekend travel.[67] Between 1991 and 1996, road travel peaked at 94% of passenger-km travelled, comparable to the peak of the railways at the end of the nineteenth century.[68]

The decline of an infrastructure system tends to occur fairly gradually. In some cases, obsolete systems continue to exist, but serve a much-reduced economic purpose. For example, canals are now primarily used for leisure activities such as recreational boating. In others, a superior technological solution results in a system being completely displaced. In 2012, analogue terrestrial TV services in the UK were switched off and replaced by digital services. These offer better picture quality and enable the transmission of a greater number of channels while using less radio spectrum.[69]

Whether or not we will be required to decommission existing infrastructure systems in the future depends on what technologies come forward, the scale of the benefits they offer and whether or not they successfully diffuse. However, a large decrease in demand for an infrastructure system is unlikely to occur overnight.

9. TECHNOLOGY CAN CREATE MORE VULNERABLE INFRASTRUCTURE SYSTEMS

Perrow argues that the more complex and tightly coupled systems become, the greater the likelihood of "normal accidents". He defines these as unavoidable events which occur due to multiple and unexpected failures, which cannot be foreseen and therefore cannot be designed around. Modern, high-risk systems may be prone to failure however well they are managed. Where the consequences of this are potentially catastrophic, a radical redesign of the system may be required.

It may be worth considering how Perrow's theory applies to our present and future infrastructure systems. The majority of emerging technologies for enhancing our management of existing assets are IT enabled. Take three of the current major innovations - the internet of things, cloud-based services and cognitive computing – they are all information and communications technologies. In the same way that all infrastructure services have come to rely on uninterrupted power to operate, many will also become increasingly dependent on our digital communications infrastructure. We are moving towards networks of connected systems rather than unconnected physical assets.

This creates both the challenges of increased demand for the telecoms sector to accommodate and increased risks for organisations as they become more exposed to potential vulnerabilities in the system. Modelling by the Cambridge Centre for Risk Studies of a successful cyber-attack against the energy system highlights the impacts of cascading effects on other infrastructure systems such as transportation and public health, which in an extreme scenario could lead to large losses to the UK economy.[70]

In turn, these risks could be mitigated by new levels of resilience within connected systems, especially with the use of machine learning technology to predict and pre-empt failure. In his book "Adapt", Tim Harford uses the example of the financial sector, suggesting that complex and coupled systems need to learn lessons from the field of industrial safety by putting in place reliable indicators which enable operators and regulators to anticipate and react to crises. Near-misses should be recorded and those individuals who raise concerns should be rewarded. Most importantly, connections should be decoupled where possible, to ensure that failures are survivable.[71]

The Commission will be looking at the risks and opportunities associated with more connected infrastructure as part of the National Infrastructure Assessment.

10. CONCLUSION

This paper has explored some of the ways in which changes in technology could affect the UK's infrastructure in the future. However, trying to quantify the potential scale of these impacts is challenging.

There is no consensus about the likely pace and impact of innovation over the coming decades. Some argue that technological change is likely to accelerate, while others suggest that the pace of innovation has already slowed.[72] This means we need to accept a level of uncertainty when thinking about the future. In building scenarios out to 2050, the Commission will attempt to capture the range of the possible.

However, there are technology trends which we can acknowledge and try to cater for. We can consider how technology is likely to interact with our existing stock of infrastructure, how it could enhance it and how technology itself may drive demand for more. Whilst it is relatively easy to model how technology may lead to incremental improvements or future efficiencies, innovations which change the way we interact with infrastructure or create new demand are more difficult to conceptualise.

The Commission is exploring how to capture these trends as part of the modelling for the National Infrastructure Assessment. The table set out at the end of this document is an initial attempt to identify the most important technologies and trends in each sector in relation to the themes identified in this paper.

Alongside considering what infrastructure the UK needs to foster sustainable economic growth, remain competitive and to improve quality of life, the Commission will consider how to maximise the opportunities that technology can play in shaping it. Emerging technologies have the potential to radically improve the way we manage our infrastructure. In recognition of this and to complement the work underway on the National Infrastructure Assessment, the Commission's next study will look at how the UK can make best use of technology to improve infrastructure productivity. This project will report by the end of 2017.

The Commission would welcome comments on this discussion paper. In particular, references to further sources of evidence on these issues would be helpful. Please send any comments to **nicdiscussionpapers@nic.gsi.gov.uk** by 10 February 2017.

Further information on the scope and methodology of the National Infrastructure Assessment is available **here**.

Table 1: The potential impact of current technological trends across infrastructure sectors

Technological change can...	...reduce the need to build new infrastructure	...create demand for additional infrastructure	...lower the cost of supplying infrastructure	...create demand for a new infrastructure system	...reduce demand for an infrastructure system
Energy	Energy storage can enable more efficient matching of supply and demand. Demand flexibility technologies shift load from system at peak times. Smart grid management.	More energy-consuming devices, more cloud-based services. Electric or fuel cell vehicles will require more widespread refuelling infrastructure.	Continuing falls in the cost of storage and renewable energy technologies.	Deployment of carbon capture and storage technology. Increased demand for hydrogen would require production facilities and adapted gas grid.	Low carbon vehicles could result in a decrease in demand for petrol infrastructure. Microgrids could reduce demand for electricity networks. Ultra energy efficient buildings could reduce demand for heating infrastructure.
Transport	Demand management technologies (smart ticketing, road pricing GPS). Autonomous vehicles could allow us to use existing capacity more effectively. 3-D printing could reduce the movement of goods. Real-time traffic management could increase capacity. Digital management of the railway would increase capacity.	More deliveries create extra demand for freight. Autonomous vehicles could create demand for extra journeys. Increased amount of energy from biomass would drive up rail freight. Electric vehicles could reduce marginal cost of journeys, driving up demand.	Technologies which enable discontinuous electrification of railways could lower their cost. Offsite and advanced manufacturing could reduce costs but all change patterns of movement. Predictive asset maintenance.	If drones take off significantly, we might require a network of hubs. If the hyperloop concept is proven this may create demand in the UK.	Reduced rail freight demand due to phase out of coal.
Water	Smart metering could be used to manage demand. Predictive asset maintenance. Technology could enable increased leakage detection.	High levels of carbon capture and storage and nuclear will increase the demand for water abstraction.	Technological change (or cheaper energy) could increase attractiveness of desalination or reverse osmosis technologies.		
Waste	Resource efficient product design. Sharing economy.	Decommissioning of existing infrastructure.	Internet of things – better product data and knowledge of material content. New energy from waste technologies. Robotics and photonics provide opportunities to increase productivity and value extraction.	New materials will create new waste streams (e.g. batteries, permanent magnet materials).	Increased offsite construction could reduce waste. Novel biodegradeable packaging materials.

Technological change can...	...reduce the need to build new infrastructure	...create demand for additional infrastructure	...lower the cost of supplying infrastructure	...create demand for a new infrastructure system	...reduce demand for an infrastructure system
Flood risk management	Better asset management through drones, sensors, inspection techniques. Integrated catchment management - working out what can be done in each part of the catchment to minimise flooding.	Integrated catchment management. Internet of things enables risk assessment at property level.	More advance warning of flooding, more time to prepare appropriate response.		
Telecoms	Efficiency gains in mobile spectrum usage reduces the need to build telecom towers. Other innovations to improve usage of existing infrastructure e.g. copper, can reduce the need to build new broadband infrastructure. Alternative means of provision, such as satellites could reduce the need for building other traditional infrastructure.	More phone masts and faster internet speed (5G or FTTC/ FTTP) are demanded due to the increasing data usage of new technologies e.g. the desire to stream HD videos in any location.		Increasing demand of higher quality technologies e.g. to stream HD videos in any location creates a business case for 5G so supply can meet demand.	Further improvements in Cloud data services could reduce demand for traditional, physical data centre infrastructure. Further developments in wireless technology could reduce the need to connect all houses and install fibre to the premises (FTTP) for broadband.

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