The impacts of historic shocks on infrastructure demand

FINAL VERSION

This report was commissioned as part of the evidence base for the work on Behaviour Change and Infrastructure Beyond Covid-19. The views expressed and recommendations set out in this report are the authors' own and do not necessarily reflect the position of the National infrastructure Commission.

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January 11, 2021

Executive Summary

The lockdown measures implemented in response to the COVID-19 pandemic triggered significant changes in demand for infrastructure services across 2020. Infrastructure services support everyday *practices* that are required to meet our fundamental needs, such as access to work or education, heating, sanitation or washing. After lockdown measures were introduced, demand for infrastructure services was transformed as large numbers of workers shifted to remote work, schools closed temporarily and many non-essential shops were forced to close.

This report analyses a series of historical case studies of shocks to infrastructure demand, including *infrastructure failure*, *technological or economic shocks*, or behaviour changes triggered by external events, to inform the development of scenarios to support infrastructure planning and decision-making in coming years.

The case studies include:

- Auckland power blackout, 1998
- Hurricane Sandy, New York City, 2012
- Broadband internet rollout, South Korea, 1998
- Oil crisis, United Kingdom, 1973
- Fukushima nuclear disaster, 2011
- SARS epidemic, Taiwan, 2003
- 9/11 terrorist attack, New York City, 2001

Comparative analysis of a range of cases showed how the impacts of a shock on infrastructure demand are determined by its impacts on specific practices. These practices either adapt to use an alternative technology or means of meeting the fundamental need, or the practices are suppressed and the fundamental need is not met. The long-term impact on demand depends on whether practices adapt to, or are suppressed by the shock. When practices adapt to use different technologies to meet the fundamental need, this significantly reduces demand for a specific technology and concurrently increases demand for the new adapted practice. This is clearly illustrated by the large reduction in demand for public transport for commuting, and increased demand for internet access and technologies to support remote work.

Shocks can cause long-term changes in the level of demand if they trigger adaptation of routines or practices. These changes depend on the degree of flexibility of established practices, and whether the shock has impacts for an extended period. Where the shock prevents certain practices, there is a reduction in demand and the fundamental needs supported by infrastructure provision (mobility, heat, sustenance, sanitation) are not met.

Policy interventions can either reinforce or reduce a shock's impact on demand, by increasing or decreasing flexibility of alternative practices. For multiple cases, such as the rollout of broadband internet in South Korea, the 1973 oil crisis, and the Fukushima nuclear disaster, policy decisions were significant in shaping the ultimate impact of the shock on infrastructure demand. The impacts of external events such as pandemics or terrorist attacks only had a short-term impact on willingness to travel by public transport, as long as there were no further events to suggest that the risk would persist over time.

Introduction

Why was this report commissioned?
The COVID-19 pandemic is unparalleled in terms of the nature and extent of its impacts. The rapid global outbreak of the virus in early 2020 and introduction of widespread lockdown measures profoundly transformed the way that economies and societies function, and in turn, rapidly changed the extent and patterns of demand for infrastructure services. This change presents a challenge for infrastructure decision-making as previous forecasts or projections for future demand may no longer hold true. A more nuanced understanding of the potential impacts of shocks on infrastructure demand is needed to support the development of plausible scenarios of behaviour change. The scenarios will be used to estimate the impacts on infrastructure demand.

While there is no historical precedent for such an extreme change, much can be learnt from comparative analysis of historical shocks and the corresponding impacts on infrastructure demand. The analysis is also an opportunity to advance understanding of the drivers of demand, and improve planning for different future scenarios.

What does it contain?
This report outlines a conceptual framework to understand the nature of infrastructure demand, and its drivers, followed by seven case studies of the impacts of historic shocks on infrastructure demand. The findings outline generalisable conclusions that explain:

- How historic shocks affected infrastructure demand, including the scale of impact on demand across different sectors, the timings and duration of impacts, and recovery
- Characteristics of the shocks, policy responses, or wider factors influencing the impacts
- Factors causing behaviour changes to be permanent or temporary
- Similarities and differences between historic shocks and COVID-19

Scope of the analysis
Infrastructure services are defined as water, waste water, solid waste, transport, energy, telecommunications and digital infrastructures. Cases are selected based on the suitability of the case to represent different types of shocks and infrastructure sectors, and the availability of data to characterise the extent and nature of the shock's impacts. Following these selection criteria, the case studies span between 1973 – 2019.

Background

What is infrastructure demand?
Understanding the drivers of demand for specific infrastructure services is essential to inform future planning, design and prioritisation of infrastructure investments. Since demand is the aggregated total of a large number of individual, household-level or firm-level decisions to consume the infrastructure services that are available to them, there are challenges to robustly theorising the drivers of demand, or how it may respond to external shocks. Theories of demand from economics are useful to capture how individuals respond to changes in the price or supply of certain services. However, it provides less insight into precisely how demand is transformed in response to disruptions or unanticipated shocks[1]. Since this report aims to capture how shocks induce qualitative changes in demand, as well as the aggregate

[1] Rinkinen, J., Shove, E. & Marsden, G. (2020). *Conceptualising Demand: A Distinctive Approach to Consumption and Practice*. Routledge.

impacts, it draws from practice theory and science and technology studies. These disciplines conceive of demand as the outcome of activities or practices that are enabled and realised across physical infrastructures, governance institutions, and individual practices[2]. This approach is useful to capture how policy responses can shape or mediate the impacts of a shock, alongside the initial effects of the shock event. In light of the many questions raised by the COVID-19 pandemic, such as whether public transport demand will return to previous levels[3], this joint consideration of infrastructures, governance institutions and practices allows a holistic analysis of the potential outcomes.

What is a shock?

A shock is any form of disruptive event that causes an impact on a system that is serious enough to warrant consideration within planning or operational management of the system, to mitigate harmful impacts. Shocks or disruptions have been theorised in various ways to understand their nature and impacts on social, economic or engineering systems. This section provides a brief overview of how different disciplines conceptualise shocks, before setting out the conceptual framework selected for this report.

Shocks in economic analysis

Within economic theory, shocks are defined as unexpected events that are caused by factors external to economic models, with a widespread impact on key economic variables. Since economic models often assume that economic systems tend towards equilibrium, shocks are important insofar as they put the system into disequilibrium, before it reverts to the initial equilibrium state or shifts to a new equilibrium[4]. Shocks are conceived as either demand- or supply-side shocks. In a demand-side shock, the impact of the unexpected event directly affects consumer or business demand for certain goods or services. A supply-side shock affects economic systems through the production side, such as a fuel shortage or natural disaster that disrupts supply[5]. Economic theories capture the aggregate impacts of shocks on demand, but have less detailed exploration of how these aggregate impacts are realised beyond individual responses to changes in price or supply.

Shocks in studies of system resilience

In studies of the resilience of systems, shocks are characterised as a diverse set of threats, each with a distinct profile of disruption resulting from direct impacts such as damage to property and infrastructure systems, as well as indirect impacts such as behavioural responses to the initial event[6]. Within this body of literature, shocks are distinguished by the *nature* of their impacts. For example, the impacts of terrorist attacks were shaped by their motivation to 'disrupt urban life by increasing fear'[7], which often created more far-reaching impacts on behaviour than the physical damage or loss of life resulting from the attack itself. Conversely, shocks like the bushfires in Australia in 2020 created widespread destruction of the natural environment and affected communities primarily through the direct impacts on their livelihoods and damage to the built environment[8]. The following section outlines the conceptual framework selected for the case study analysis in this report.

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[2] Ibid.
[3] Marsden, G. (2020). Potential impacts of the COVID-19 pandemic on the future of travel demand. *Proceedings of the Institution of Civil Engineers* 173(3), 99.
[4] Hoover, K. (2014). The ontological status of shocks and trends in macroeconomics. *Synthese* 192, 3509–3532
[5] Brinca, P., Duarte, J.B. & Castro, M.F. (2020). *Is the COVID-19 pandemic a supply or demand shock?* Federal Reserve Bank of St. Louis. Research Paper No. 31.
[6] Della Bosca, H., Schlosberg, D. & Craven, L. (2020). Shock and place: reorienting resilience thinking. *Local Environment* 25(3), 228-242.
[7] Siman-Tov, M., Bodas, M. & Peleg, K. (2016). The social impact of terrorism on civilian populations: Lessons learned from decades of terrorism in Israel and abroad. *Social Science Quarterly* 97(1), 75-85.
[8] Della Bosca, H., Schlosberg, D. & Craven, L. (2020). Shock and place: reorienting resilience thinking. *Local Environment* 25(3), 228-242.

Conceptual framework for the impact of shocks on infrastructure demand

A flexible conceptual framework for infrastructure demand is needed to analyse the diverse cases covered in this report. The framework outlined in Table 1 is adapted from Rinkinen et al.[9] and Shove et al.[10], drawing from practice theory to conceptualise how demand to meet specific fundamental needs is the result of interdependent *practices*, *material infrastructures*, and *policies and institutions*. Together, these components form a system of provision for specific human or societal needs, underpinned by specific energy or natural resources.

The fundamental needs are fixed in this framework: they include needs or expectations for an adequate level of provision to enable communication, illumination, hygiene, sustenance or nourishment, mobility or transport, shelter, thermal comfort[11]. These needs can be met through diverse configurations of practices, infrastructures and appliances, and policy and regulation, which change over time or in response to shocks. The framework separates out the different components of infrastructure demand so that the impacts of shocks can be analysed as they propagates through individual behaviours (practices), networked infrastructures and the built environment (material infrastructures), underlying resources, as well as the policies and institutions that govern the use of infrastructures and specific practices.

Table 1 - Conceptual framework for infrastructure demand

<table>
<tr><td colspan="3">Fundamental needs
Communication, illumination, hygiene, sustenance, mobility, shelter, thermal comfort</td><td>Fundamental needs remain fixed</td></tr>
<tr><td>Practices
Culture
Behaviour or preferences</td><td>Material infrastructures
Networked systems
Mobile appliances</td><td>Policies & institutions
Policy and regulation
Taxation or charges</td><td rowspan="2">Shocks propagate through one of these four components, influencing the way they work together to meet fundamental needs.</td></tr>
<tr><td colspan="3">Resources
Fuel, water, wind, sunlight</td></tr>
</table>

[9] Rinkinen, J., Shove, E. & Marsden, G. (2020). *Conceptualising Demand: A Distinctive Approach to Consumption and Practice*. Routledge.
[10] Shove, E., Pantzar, M. & Watson, M. (2012). *The Dynamics of Social Practice: Everyday Life and How it Changes*. London: Sage.
[11] Morley, J. (2018). Rethinking energy services: the concept of 'meta-service' and implications for demand reduction and servicizing policy. *Energy Policy* 122, 563-569.

Examples of fundamental needs, related practices, and ways of measuring demand are provided in Table 2, below.

Table 2 - Components of infrastructure demand

Fundamental need	Practices required to meet the fundamental need	Potential metrics for demand
Access (to information, goods and services, employment, education, recreation)	Travel (mode-specific) Commuting Using the internet	Internet subscription, bandwidth and traffic Transport patronage by mode Commuting patterns
Warmth and cooling	Heating, air-conditioning	Energy usage, by type
Light	Electric lighting systems	Energy usage
Sustenance	Cooking, access to water and food services or supplies	Energy usage or consumption of services or supplies
Cleaning and sanitation	Sewage and water supply, use of appliances (i.e. washing machine, toilet, shower)	Water and waste water volumes, energy usage by activity

To illustrate the impact of shocks, studies on the impacts of London Tube strikes in 2015[12] showed how even a one-day strike action triggered long-term changes in travel demand. The disruption forced commuters to find alternative routes and travel modes as Tube lines stopped running or operated on severely reduced service frequencies. Around 5% of commuters made long-term changes to regular travel routes, following this event. This illustrates a change in practices that is triggered by a brief shock to the operations of material infrastructures.

A shock typically enters the system through one particular component – such as an unanticipated shortage reducing the supply of fuel, changes in the technologies of material infrastructures, or major policy changes that affect how infrastructures can be used or the cost of doing so. Each component has a distinct temporal and spatial scale. For example, policies and regulations are applied across specific jurisdictions and time scales. Infrastructures often have fixed limits across space and uneven coverage between cities and rural areas, or even within cities. For any given situation where infrastructures are subject to an external shock or disruption, this framework can be used to identify how the shock impact, and then analyse the secondary impacts and interdependencies between the different dimensions. The framework can also capture how the behavioural or policy responses to shocks also have a strong influence on the medium to long-term impact on demand. Using this framework, the comparative analysis will illustrate how different types of historical shocks affected infrastructure demand.

[12] Larcom, S., Rauch, F. & Willems, T. (2017). The benefits of forced experimentation: Striking evidence from the London Underground network. *The Quarterly Journal of Economics* 132(4), 2019-2055.

Comparative case studies

Seven historic cases were selected to capture a variety of types of shocks and infrastructure sectors, summarised below in Table 3.

Case studies are grouped into three types:

Infrastructure failure:
Major failure of a physical system or systems, causing it to lose functionality for a short or extended period.

Technological or economic shock:
Technological innovation that disrupts the existing system of infrastructure provision by displacing existing technologies or creating demand for new types of services, or an economic shock that disrupts the system through a significant change in costs or prices, or change in demand resulting from economic expansion or downturn.

Behavioural change triggered by an event that is external to the infrastructure system:
Where behaviour is influenced by non-infrastructural factors that influence the safety or sustainability of certain behaviours, such as public health crises, terrorist attacks, or major environmental disasters.

Table 3 - Overview of selected cases

Infrastructure failure	Power outage, Auckland 1998	Hurricane Sandy New York, 2012	
Technological or economic change	1973 oil crisis, impact on transport in the United Kingdom	Innovations in broadband technology, South Korea, 1998-2019	
Behaviour change in response to external drivers	SARS pandemic, Hong Kong, 2003	9/11 terrorist attack, New York, 2001	Fukushima Daiichi nuclear disaster, 2011

To derive generalisable findings about the impact of historic shocks on demand, each case responds to the following questions.

1. What was the fundamental need that was affected by the shock?
2. What practices were required to meet that need, and the subsequent changes for routines that determine demand?
3. What was the impact on demand for infrastructure services, and persistence of the impact?

INFRASTRUCTURE FAILURE

Auckland power blackout, 1998

A significant electricity network failure in the city of Auckland, New Zealand. The failure caused a power outage for most of the city's Central Business District (CBD), including 6,000 residents and 70,000 workers. The power outage extended for 5-10 weeks, as substantial upgrades and reconstruction of the network were required to restore reliable power supply[13].

Fundamental need/s affected by the shock: Disruption to networks caused widespread impacts to all areas – access, warmth and air conditioning, light, food, cleaning and sanitation

Intermediate practices affected

- Shoppers relocated to other areas of the city, including smaller centres and shopping malls
- Large firms relocated to other offices where possible, or remote work
- Some hotels and essential services switched temporarily to generators
- Retail and services businesses did not have the flexibility to adapt, many stopped operating temporarily or closed down

Impact on demand and persistence over time

- Temporary displacement of shoppers, residents and businesses during blackout.
- As larger corporate firms could relocate temporarily to other regional offices or procure temporary facilities outside the CBD, demand for office space returned after the end of the blackout. This demand was reinforced by the challenges of working remotely when many firms relied on paper-based systems and documents stored in their offices.
- Many small firms, particularly in retail and hospitality, could not operate nor relocate during the blackout and either went out of business. This created a permanent reduction in demand for retail space, although the broader growth patterns in the CBD counteracted this effect.
- Residents returned following the end of the blackout. Any impact of the blackout on the CBD population was contacted by the broader growth of residential populations in the area: between 1996-2001, all wards of CBD increased in population[14] (Statistics New Zealand, 2018)
- There was a persistent negative impact on demand for retail shopping in the CBD. This resulted from two factors: first, many shops could not open nor relocate during the blackout and went out of business, and second, shoppers opted to visit suburban malls instead of the CBD and did not return after the blackout ended. Retail shopping activities returned only after a significant publicity campaign and the introduction of competitions to attract shoppers to the CBD[15].

[13] Newlove, L., Stern, E. & Svedin, L. (2005). *Auckland Unplugged: Coping with Critical Infrastructure Failure*. Lexington Books.
[14] Statistics New Zealand (2018).
[15] Ibid.

A critical question in the aftermath of the Auckland power blackout was whether residential and employment populations would return to the CBD after an extended disruption that displaced most businesses and required residents to evacuate. Population statistics across a broader time period show that the blackout generated no significant, persistent impacts on the growth of the CBD. This demonstrates that prolonged disruption to a specific area in a city does not necessarily lead to permanent changes to residential and commercial activities, once the disruption is resolved.

Figure 1 illustrates the population of Auckland's Central Business District between 1996-2018, showing that both residential and employment population continued to grow significantly following the 1998 blackout.

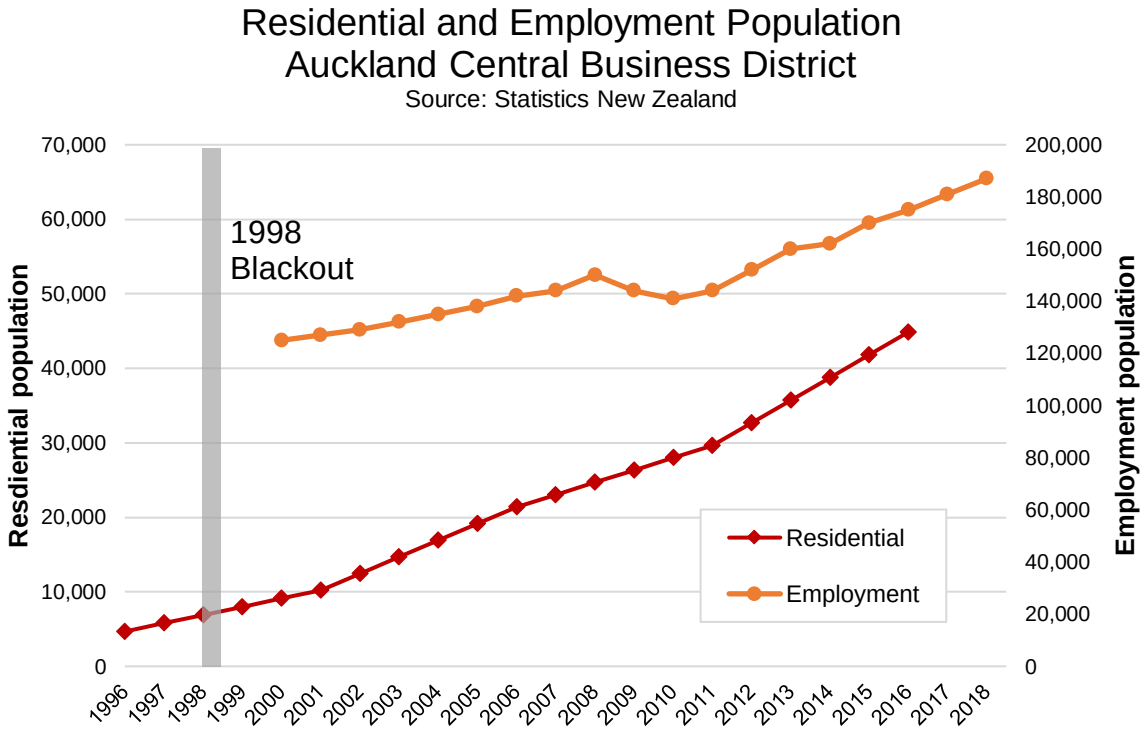

Figure 1 – Population growth in Auckland's Central Business District, 1996-2018. Note: Employment data not available prior to 2000.

Hurricane Sandy, New York City, 2012

Hurricane Sandy was one of the most intense and destructive hurricanes to hit New York City, causing 43 deaths and US$50 billion worth of damage in New York City and New Jersey in October 2012[16]. The storm caused widespread disruption to the city's infrastructure systems, as the storm surge flooded the Subway and most road tunnels entering Manhattan, and high winds caused damage to telecommunications, utilities, water and waste water networks. Electricity outages caused substantial indirect impacts on the operation of transport, water and utility systems.

Fundamental need/s affected by the shock: Disruption to networks caused widespread impacts to access, warmth, light, food, cleaning and sanitation.

Intermediate practices affected

- Physical damage and electrical outages affected most infrastructure networks across the metropolitan area. Table 4 summarises the direct and indirect impacts across different sectors. This disrupted commuters travelling to work and stopped households and businesses from operating temporarily until power was restored.

Impact on demand and persistence over time

- Demand for essential services returned, as alternative means of provision were not available for water, waste water, energy and telecommunications
- No significant long-term impact on remote working, as it was not feasible for many jobs and the disruption was not long enough to trigger more persistent changes. However, it did raise business concerns over the need for improved business continuity management[17]

Table 4 summarises how the cascading impacts of infrastructure failures affected different sectors. Importantly, this shows how electrical outages temporarily affected the availability of most other infrastructure sectors.

Table 4 - Direct and indirect impacts of Hurricane Sandy, adapted from Cimellaro et al.[18]

Direct damage	**Sectors affected**	**Indirect damage**	**Sectors affected**
Physical damages to facilities	*Transport (tunnels, subways, bridges), telecommunication, utilities (substations, distribution, transmission lines), water, waste water*	Stopped operations due to electrical outage or lack of fuels	*Transport, telecommunication, water, waste water, solid waste, utilities*

[16] Kaufman, S., Qing, C., Levenson, N. & Hanson, M. (2012). *Transportation During and After Hurricane Sandy*. Rudin Center for Transportation, NYU Wagner Graduate School of Public Service.
[17] Folkers, A. (2017). Continuity and catastrophe: business continuity management and the security of financial operations. *Economy and Society* 46(1), 103-127.
[18] Cimellaro, G.P., Crupi, P., Uk Kim, H. & Agrawal, A. (2019). Modeling interdependencies of critical infrastructures after Hurricane Sandy. *International Journal of Disaster Risk Reduction* 38, 101191.

Figure 2 illustrates the impacts of Hurricane Sandy on electricity supply across New York and New Jersey, alongside the probability of remote working across a shorter period. These graphs show the significant impact of the storm on electricity supply. However, the prolonged outages in New York did not result in substantial levels of remote working after the first three days.

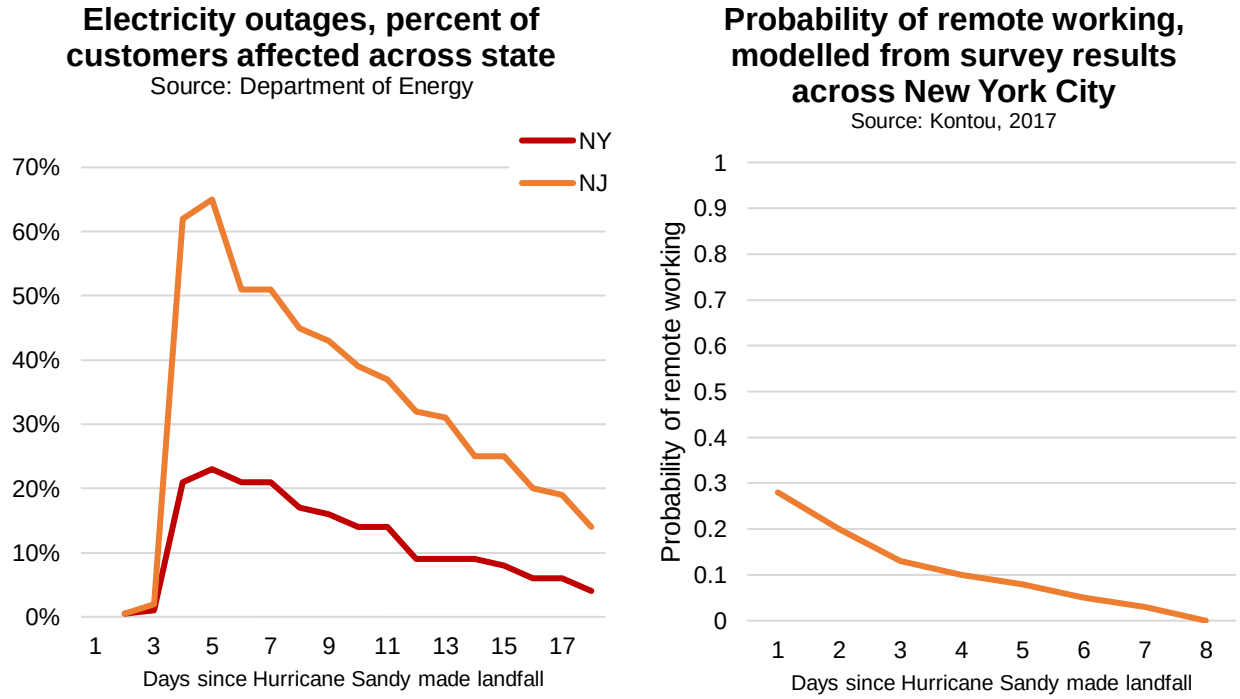

Figure 2 – Impact of electricity outages and probability of remote working, for the days following Hurricane Sandy

Table 5 summarises the changes in trends as a result of the shock. The impacts of energy outages took a short time to reach their peak, however the time taken to resolve the outages was extended across two weeks for both New York and New Jersey.

Table 5 - Impact on trends

Variable	Trend before	Trend after	Longevity of impact
Customers affected by energy outages	Near 0	8%/day, NY 22%/day, NJ	Four days to peak impact, then declining across the following 13 days to 4% (NY) and 14% (NJ).

TECHNOLOGICAL OR ECONOMIC SHOCK

Broadband internet, South Korea, 1998

In response to innovations in internet technologies that substantially increased network capacity, South Korea initiated a drive to increase internet connectivity as part of a wider economic and social policy to develop a knowledge-based economy and improve public services through e-government. Since demand for broadband internet is heavily influenced by the supply and quality of internet access, the case of South Korea as an early-mover is valuable to understand how technological shocks impact on demand, in the context of supportive policy measures.

Figure 3 shows the rapid growth in internet usage across South Korea, in response to the policy changes enabling this transition to new internet technologies. Subsequent policy changes, including the IT829 Strategy to shift to VDSL and broadband network rollout, generated further growth in internet usage to reach over 90%.

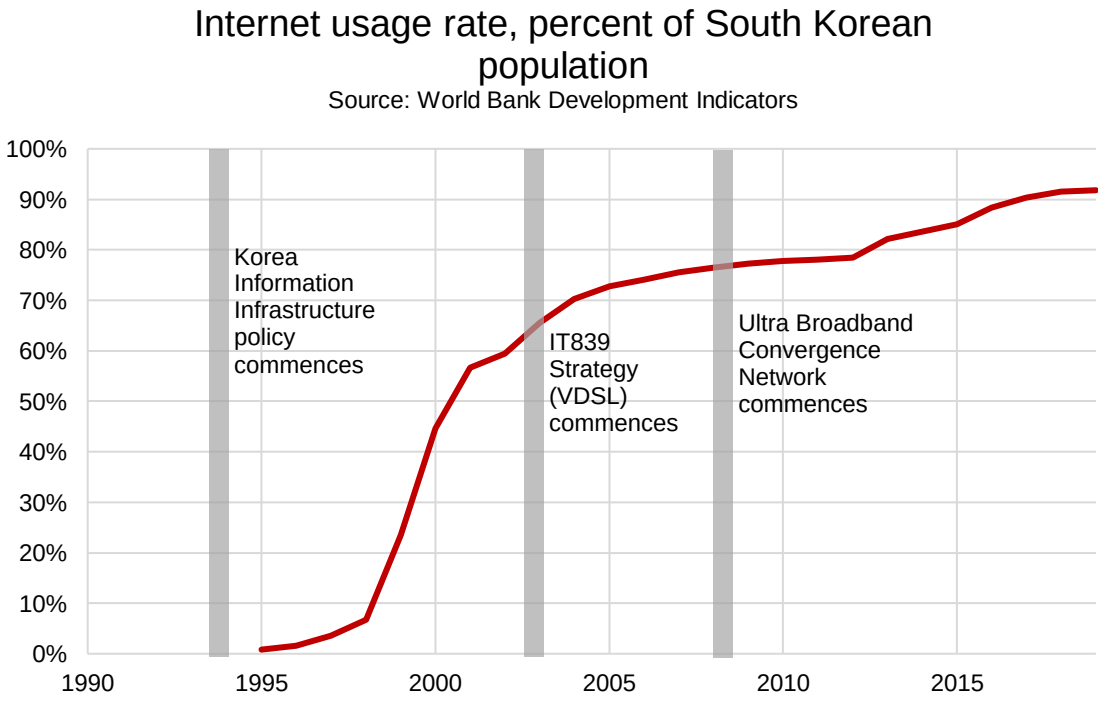

Figure 3 - Internet usage rate in South Korea, 1995-2019

Fundamental need/s affected by the shock: Access to information and other people, for work, education, goods and services, and recreation

Intermediate practices affected

- Public services: Public service provision transitioned online, with the introduction of e-government services
- Education and office work: Education and office-based organisations integrated online tools and platforms
- Teleworking: The government policy promotes remote work, however by 2016 only 3% of firms had adopted telecommuting[19]. The ability to work remotely expanded the activities of workers in South Korea, many of whom operated on an 'always on, always available' basis for their employers[20]. In this way, extending workers' activities beyond the usual working day negatively impacted satisfaction, as remote work emerged as a complement, not a substitute for working at an office[21]. Remote work was also linked with social isolation, lack of visibility in the workplace affecting opportunities for promotion, and social isolation[22].
- Commuting: Evidence from Seoul showed that teleworkers tended to live in peripheral areas of the city. Since firms that allowed telecommuting were also more likely to be based in peripheral areas, teleworkers had shorter, not longer commutes than other workers[23]. This challenges the claim that telecommuting enables geographic dispersal of workers, or that it is necessarily triggered by a long commute before shifting to telework.
- Leisure: Recreational activities were possible online, with the rise in popularity of gaming at LAN gaming centres

Impact on demand and persistence over time

- Supply- and demand-side policies that made broadband commercially available and trained people to use the internet induced new demand for a range of online services including e-government, digitalisation of office work, education, social activities and entertainment
- Broadband enabled teleworking, although this was more commonly used a way to extend the working day beyond office hours, than a substitute for travelling to the office. Only 3% of firms adopted teleworking by 2016.
- Teleworking does not necessarily result from, or lead to, longer commutes: Evidence showed that telecommuters in Seoul tended to live in peripheral areas but had shorter commutes, because firms allowing telecommuting were also based in the periphery[24].

[19] Hankyoreh (2016). Adoption of flexible work policies show early signs of success. *The Hankyoreh*.
[20] Wirth, M. (2006). Broadband convergence: Future directions and societal impacts. *International Journal of Media Management* 8(1), 19-28.
[21] Reynolds, T. & Jin-Kyu, J. (2004). *Shaping the future mobile information society: The case of the Republic of Korea*. International Telecommunication Union.
[22] Leung, L. (2004). Societal, organisational and individual factors in the adoption of telework. In P.S.N. Lee, L.Leung, & C Y K. So (Eds.) *Impact and issues in New Media: Toward intelligent Societies.* Creskill, NJ: Hampton.
[23] Kim, S.N. (2012). The Seoul of Alonso: New perspectives on telecommuting. *Urban Geography* 33(8), 1163-1191.
[24] Kim, S.-N., Mokhtarian, P.L. & Ahn, K.-H. (2012). The Seoul of Alonso: New perspectives on telecommuting and residential location from South Korea. *Urban Geography* 33(8), 1163-1191.

Oil crisis, 1973

The 1973 oil crisis saw energy prices increase dramatically, as crude oil prices increased fourfold between 1971-1974. In the United Kingdom, this shock produced distinct impacts on demand for transport, in conjunction with policy changes triggered by the oil crisis. Figure 4 illustrates the sharp increase in the retail price of fuel, which was partially exacerbated by an increase in VAT, followed by a reduction in both VAT and fuel duty.

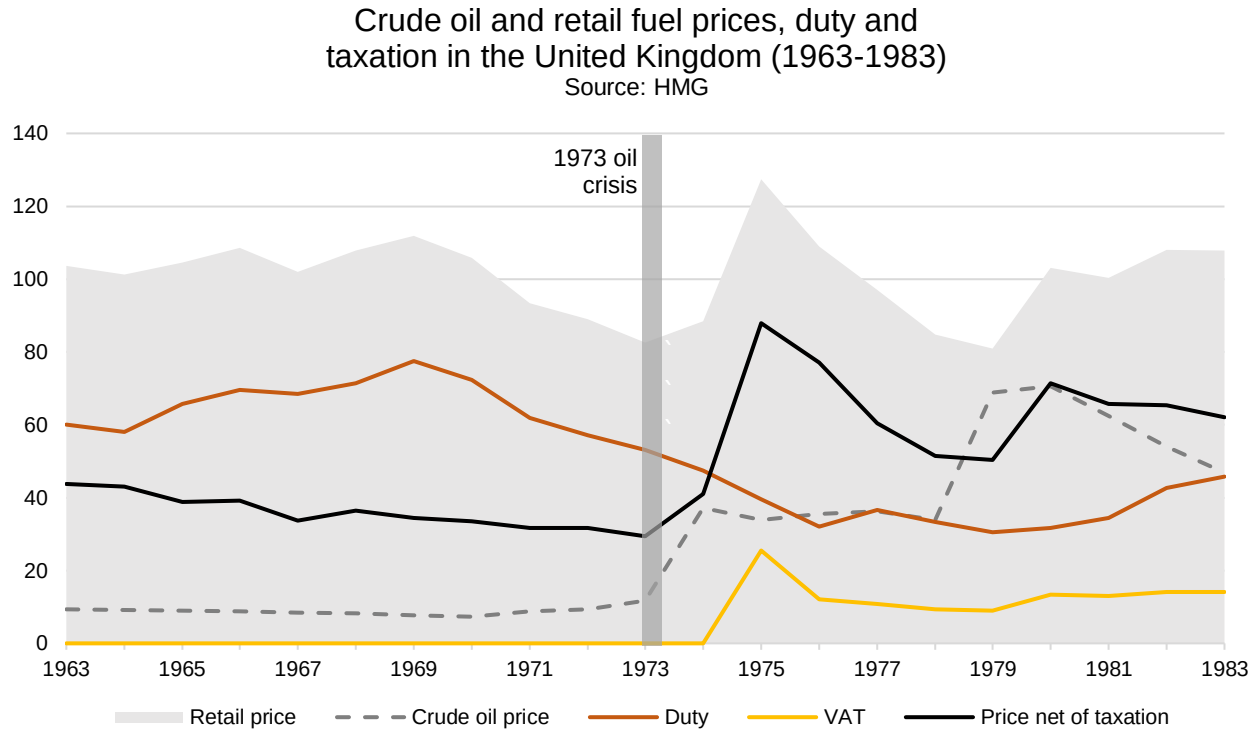

Figure 4 – Fuel price in the United Kingdoms, decomposed into crude oil price, duty and taxation, 1963-1983.

Fundamental need/s affected by the shock: Access to work, education, public services and recreation.

Intermediate practices affected

- The price shock spurred a re-allocation of household transport spending: Households spent less on new vehicles, or delayed new purchases to upgrade their motor vehicle, to compensate for the increased costs due to higher fuel prices[25]
- Research shows that policy responses to the crisis sought to reduce oil-dependence by encouraging greater energy efficiency, improving public transport and intensifying land use. In practice, the latter two measures were not implemented comprehensively: the resulting decline of public transport service provision and continuation of low-density, automobile-dependent land use patterns restricted individuals' ability to adapt their travel habits in response to the crisis[26].

[25] Mogridge, M.J.H. (1978). The effect of the oil crisis on the growth in the ownership and use of cars. *Transportation* 7, 45-67.
[26] Ibid.

Impact on demand and persistence over time

- Public transport use, which was decreasing up until 1973, continued to fall however the rate of decline fell slightly[27]
- Motor vehicle traffic fell between 1973-4, in response to the crisis, reversing the trend of continuous growth between 1958 – 1973. However, this impact was short-lived as positive traffic growth returned in 1975 and continued throughout the 1970s, apart from another one-year reduction in traffic during the 1979 price increases[28].
- Following 1973, a minor reduction in energy use for transport was followed by a gradual increase in energy use for transport[29]. This correlates with the continued growth of motor vehicle traffic after 1974, as shown in Figure 5.
- Cycling increased sharply after the crisis, reversing the downward trend in cycling vehicle-miles travelled up until 1973. This short recovery in cycling activity saw an increase from 2.25bn vehicle miles in 1973 to 4bn in 1980. From 1983, the downward trend continued and total vehicle-miles fell to 3bn by 1990[30]

Figure 5 shows how the crisis triggered a temporary reduction in road traffic, growth in cycling, and reduction in the decline of public transport use compared with the previous decade.

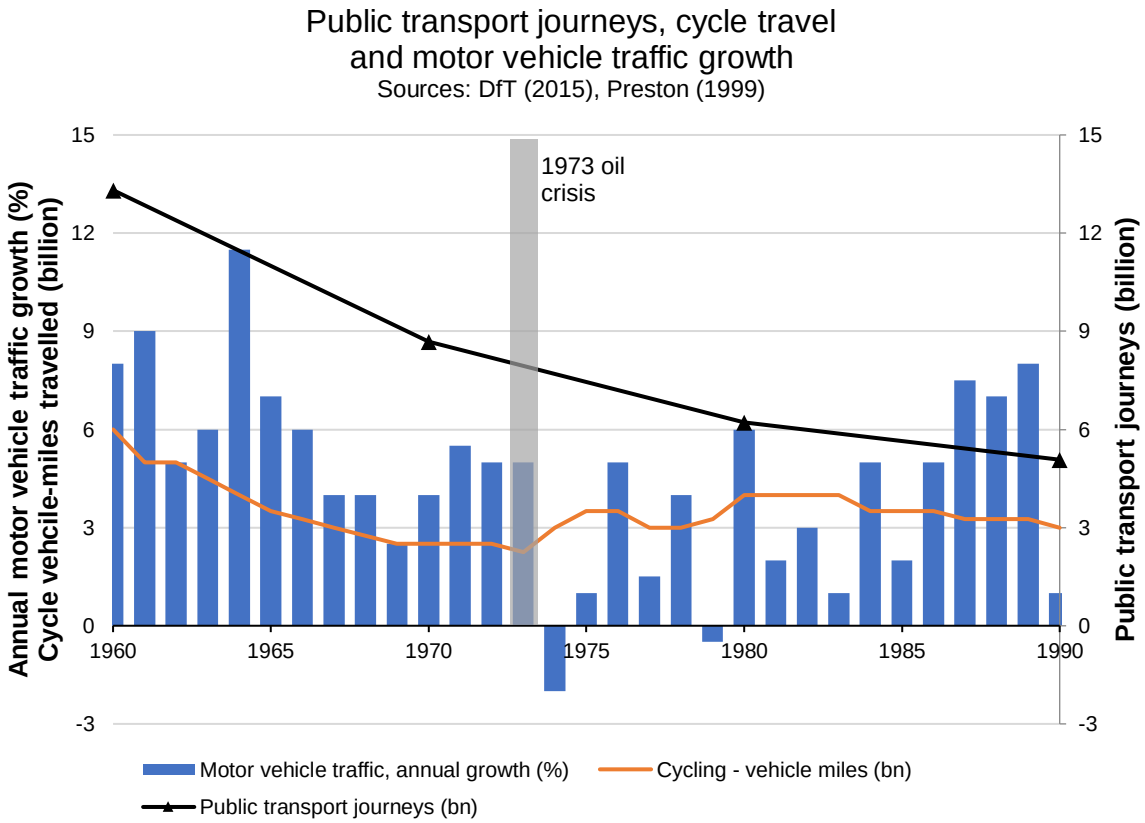

Figure 5 - Public transport journeys, cycle travel and growth of motor vehicle traffic

[27] Preston, J. (1999). An overview of public transport in the United Kingdom and forecasts for the new millennium. Sixth International Conference on Competition and Ownership in Land Passenger Transport. Cape Town, South Africa.
[28] Parish, D. (2009). *The 1973-1975 Energy Crisis and its Impact on Transport*. RAC Foundation, Report 09/107.
[29] Banister, C. & Banister, D. (1983). Transport, travel and energy in the UK: Trend analysis of published statistics. *Energy Policy* 11(1), 39-51.
[30] DfT (2018). *Road Traffic Estimates: Great Britain 2017*. Department for Transport, HMG.

The impact on road traffic was not persistent, as positive growth rates returned after one year of decline. The impact on cycling activity was longer-lasting, as the total level of vehicle-kilometres travelled increased with some fluctuation to 4 billion by 1980, remaining at this level for three years, before declining from 1984 onwards.

Table 6 summarises the impacts on the trends in key variables.

Table 6 - Overview of impacts on demand

Variable	Trend before	Trend after	Longevity of impact
Public transport journeys	-462.6m journeys/year, 1960-1970	-246.3m journeys/year, 1970-1980	Persistent impact to weaken rate of decline in journeys, for at least 10 years
Cycle travel (vehicle-kilometres)	-175m vehicle-miles/year	100m vehicle-miles/year	Persistent for ten years, then previous negative trend returns
Motor vehicle traffic	5.5%/year growth in traffic	2.2%/year growth in traffic	Persistent for one year, trend returns to previous positive growth rate (except for 1979 price disruption)

Fukushima nuclear disaster, 2011

The major disaster at Fukushima-Daiichi nuclear plant in 2011 triggered a global response as many countries, including Japan, changed their risk assessment of nuclear energy. This case examines the impact of this event on energy policy settings and consumption behaviours.

Fundamental need/s affected by the shock: Access to electricity for heating, transportation and industrial use

Intermediate practices affected

- Policy agendas: The Fukushima-Daiichi disaster impacted on intermediate activities at a higher level, as it rapidly changed governments' risk perceptions of nuclear energy
- While the crisis established the increased risks of nuclear power, this did not induce a ban or restriction on the energy source for most countries. A key barrier to stronger policy measures was the underlying need for nuclear as a source of energy to support decarbonisation as part of climate change policy. Table 8 itemises policy changes for each country.
- Public attitudes and energy conservation: The disaster also influenced public perceptions of nuclear energy, with public support for nuclear power falling from 25% to 17% between 2007-2011[31]. Following the earthquake in March 11, the Japanese government asked households to make voluntary energy savings to manage the disruption to the energy supply network. The effects of these voluntary changes were evident, with a 2011 survey reporting that 82% of residents would raise the temperature on air-conditioning units, 54% would reduce the cooling intensity of refrigerators and 66% would unplug appliances when not in use[32]. A 2012 follow-up to the survey showed

[31] Poortinga, W., Aoyagi, M. & Pidgeon, N.F. (2013). Public perceptions of climate change and energy futures before and after the Fukushima accident: A comparison between Britain and Japan. *Energy Policy* 62, 1204-1211.
[32] Tanaka, M. & Ida, T. (2013). Voluntary electricity conservation of households after the Great East Japan Earthquake: A stated preference analysis. *Energy Economics* 39, 296-304. Findings based on Tokyo area households.

that 81% of households followed through on these claims, and their intent to continue the practices in subsequent years was slightly lower[33].

- Out-migration from the area: The disaster caused 164,000 local residents to evacuate, and by 2017 around 77,000 (47%) of those evacuated still had not returned to the area, illustrating the persistent impact. The lack of returning residents was attributed to ongoing concerns about radiation from the disaster, the lack of employment opportunities in the area, and poor living conditions compared to their evacuation location[34].

Impact on demand and persistence over time

Temporary reduction in nuclear production at the global scale, reduced from the previous peak of 2,803 TWh in 2007 to 2,471 in 2012. This has subsequently increased to 2,796 TWh by 2019 (BP Statistical Review of World Energy).

Figure 6 illustrates the diverging trends across countries: Supplies initially fell in Germany and Japan and then stayed constant or recovered to around 20% of previous levels. Across the same period, Supply in India and the UK increased initially, and the UK supply fluctuated across this period.

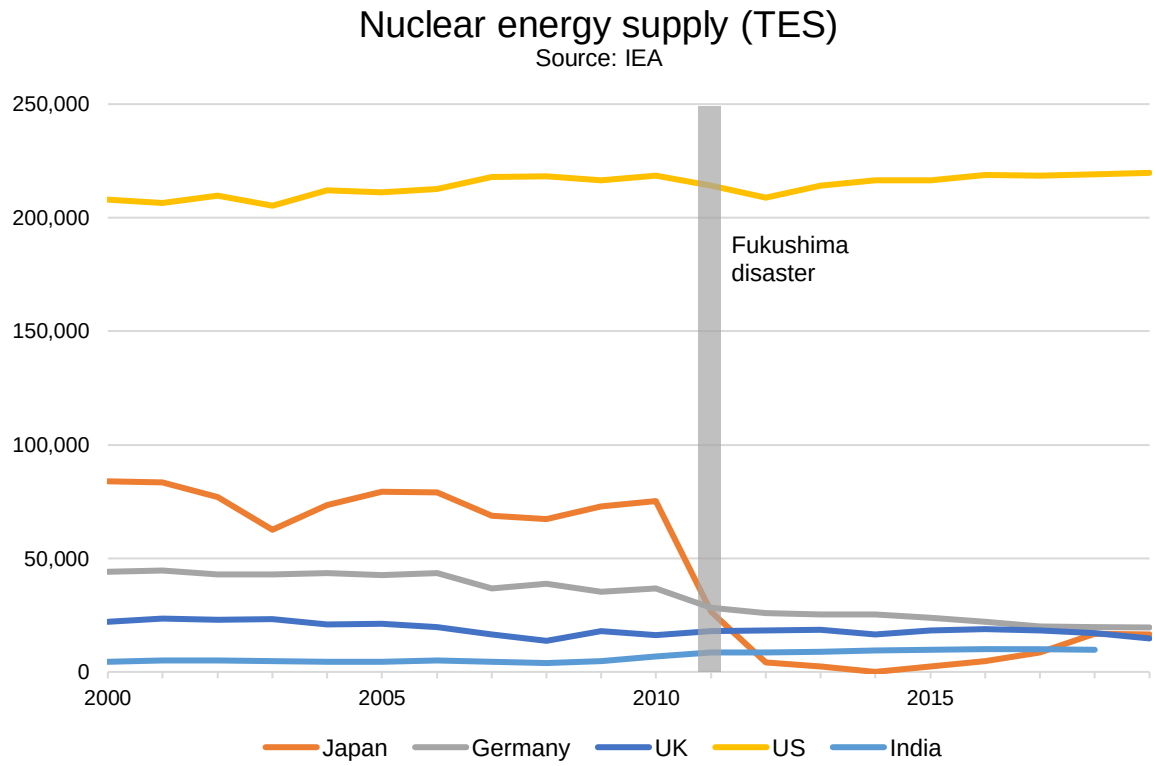

Figure 6 - Nuclear energy supply in selected countries, 2000-2019 (Source: IEA).

[33] Tanaka, M. & Ida, T. (2013). Voluntary electricity conservation of households after the Great East Japan Earthquake: A stated preference analysis. *Energy Economics* 39, 296-304. Findings based on Tokyo area households.
[34] Do, X.B. (2019). Return migration after the Fukushima Daiichi nuclear disaster: the impact of institutional and individual factors. *Disasters* 44(3), 569-595.

Table 7 summarises the impacts on the trends in nuclear energy supply.

Table 7 - Impact on trends

Variable	Trend before	Trend after	Longevity of impact
Nuclear energy supply (Japan)	1,396 TES/year	-18,775 TES/year	Persisted for 3 years, before recovering to 21% of 2010 peak

Figure 7 shows the intended and actual changes in energy conservation practices by Tokyo area residents, after the 2011 disaster and in the following year. This shows that households made higher savings than intended by reducing energy consumption from air-conditioning, and lower savings through decreasing the consumption from refrigerators and appliances on standby. These impacts on conservation behaviours showed persistence across refrigerators and appliances, as households indicated that they would continue the practice in subsequent years.

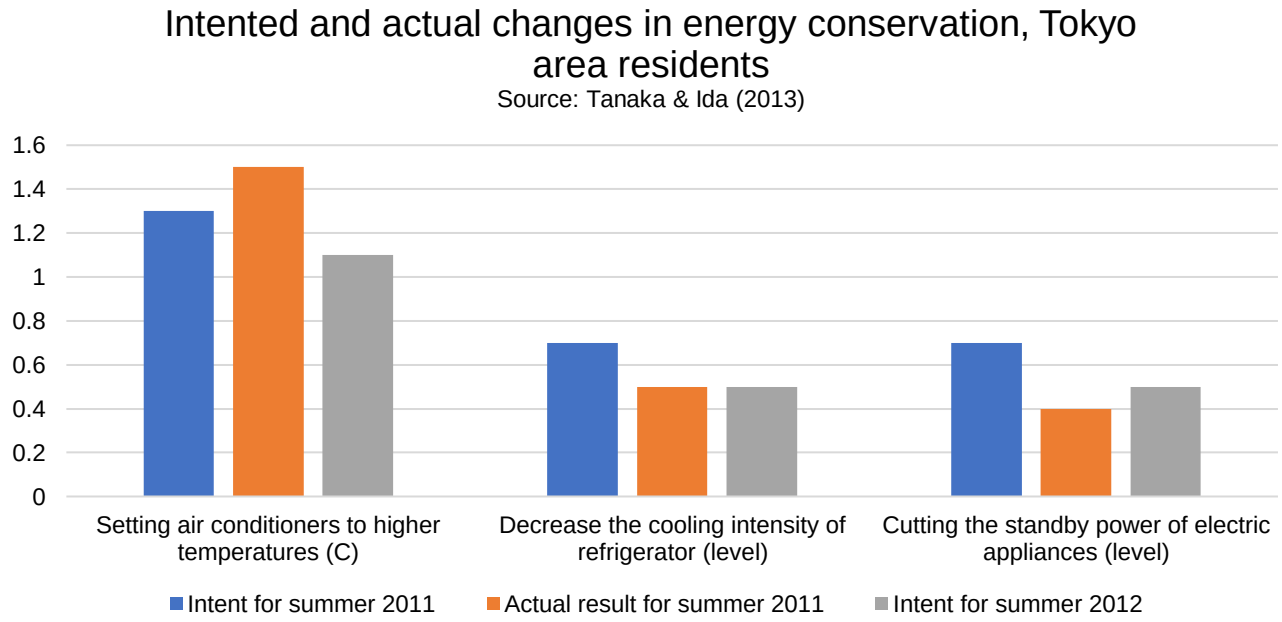

Figure 7 - Intended and actual changes in energy conservation

Table 8 - Key policy changes, adapted from Ming et al.[35], IEA Policy Database

	Japan	**USA**	**UK**	**India**	**Switzerland**
2011	Implemented new safety audits to determine whether to commission further nuclear operations.	Continued with planned construction of new nuclear plants. Comprehensive evaluation of domestic plans to ensure safety and reliability.	Continued with planned renewal to decommission some plants and construct others, and enhance safety management.	Carried out safety evaluation of all facilities, otherwise continued with planned development of nuclear facilities.	Performed 'stress tests' on existing nuclear plants, ceased plans to renovate nuclear plants. Plan to phase out nuclear by 2034.
2012	Publish *Innovation Strategy for Energy and the Environment*, plan to phase out nuclear power			*National Electricity Policy* outlines need to significantly increase share of nuclear energy	
2013			*Nuclear Industrial Strategy*, 12 nuclear reactors planned across five sites.	*Twelfth Five Year Plan* identifies nuclear as essential for adequate energy supply	
2014	Government reverse decision to close nuclear plants				
2015		Government pass *Clean Power Plan*, targeting 19% nuclear energy by 2030			
2016					Government passed *Energy Strategy 2050*, prohibiting new nuclear plants or basic changes to existing plants.
2017					
2018	*Fifth Basic Environment Plan* aims to restart nuclear power plants where safety standards are met	Government pass *Nuclear Energy Innovation Capabilities Act* to support nuclear development.			
2019	*Long Term Strategy under the Paris Agreement* aims to reduce nuclear dependency 'as much as possible'				

[35] Ming, Z., Yingxin, L., Shaojie, O., Hui, S., Chunxue, L. (2016). Nuclear energy in the Post-Fukushima Era: Research on the developments of the Chinese and worldwide nuclear power industries. *Renewable and Sustainable Energy Reviews* 58, 147-156.

BEHAVIOURAL CHANGE TRIGGERED BY EXTERNAL DRIVERS

SARS epidemic, Taipei, 2003

Between November 2002 – 2004, the SARS coronavirus spread to more than 30 countries worldwide, with significant outbreaks in China, Hong Kong, Canada, Taiwan and Singapore. Fears of the spread of the disease through person-to-person contact caused many individuals to adjust their daily behaviours, including the use of public transport systems, in response to the epidemic. In Taiwan, the first known case emerged on 14 March 2003, after which the government adopted a strict policy to isolate suspected cases and their contacts. Amidst this public health emergency, there were significant changes in travel behaviour as the population perceived higher risks and sought to avoid or minimise the risk of infection. There were 3,032 suspected or probable cases of SARS reported in Taiwan before July 2003.

Fundamental need/s affected by the shock: Access to work, education, recreation, goods and services.

Intermediate practices affected

Awareness of the SARS risk caused travellers to avoid taking the underground

Impact on demand and persistence over time

- The pandemic caused a temporary reduction in patronage, shown to be correlated with publicity about SARS cases. The reduction equated to a loss of 50% of patronage at the peak of the pandemic[36].
- After the last SARS case was reported on June 15 2003, reduced ridership was evident for a further 111 days, reflecting the persistent perceptions of risk even after no further cases were reported. Demand recovered completely to previous levels in 3.5 months, and continued to grow in subsequent years.
- Since offices and schools were not closed throughout the pandemic, the data shows that ridership was responsive to newly-reported cases, with an immediate loss of approximately 1200 riders for each new reported case[37]
- The impacts of the pandemic on individual behaviours were significant, as it established the regular habit of wearing masks on public transport for many riders, beyond the 2003 pandemic[38]. This may account for the rebound in ridership and minimal long-term impacts on transit ridership, in conjunction with the low car ownership rate[39] restricting alternative travel options for those reliant on public transport.

[36] Wang, K.-Y. (2014). How change of public transportation usage reveals fear of the SARS virus in a city. *PLoS ONE* 9(3):e89405.
[37] Ibid.
[38] Blumgart, J. (2020). Mass transit ridership didn't snap back after the 2003 SARS outbreaks. *CityMonitor*. December 18.
[39] 260 vehicles per 1000 population, 2002. Dargay, J., Gately, D. & Sommer, M. (2007). Vehicle ownership and income growth, worldwide: 1960-2030. *The Energy Journal* 28(4), 143-170.

Figure 8 shows the changes in patronage on the Taipei Underground between March – August, across the 2003 outbreak. The 2003 figures are shown in black, with previous years' patronage in pink and later years' patronage in blue.

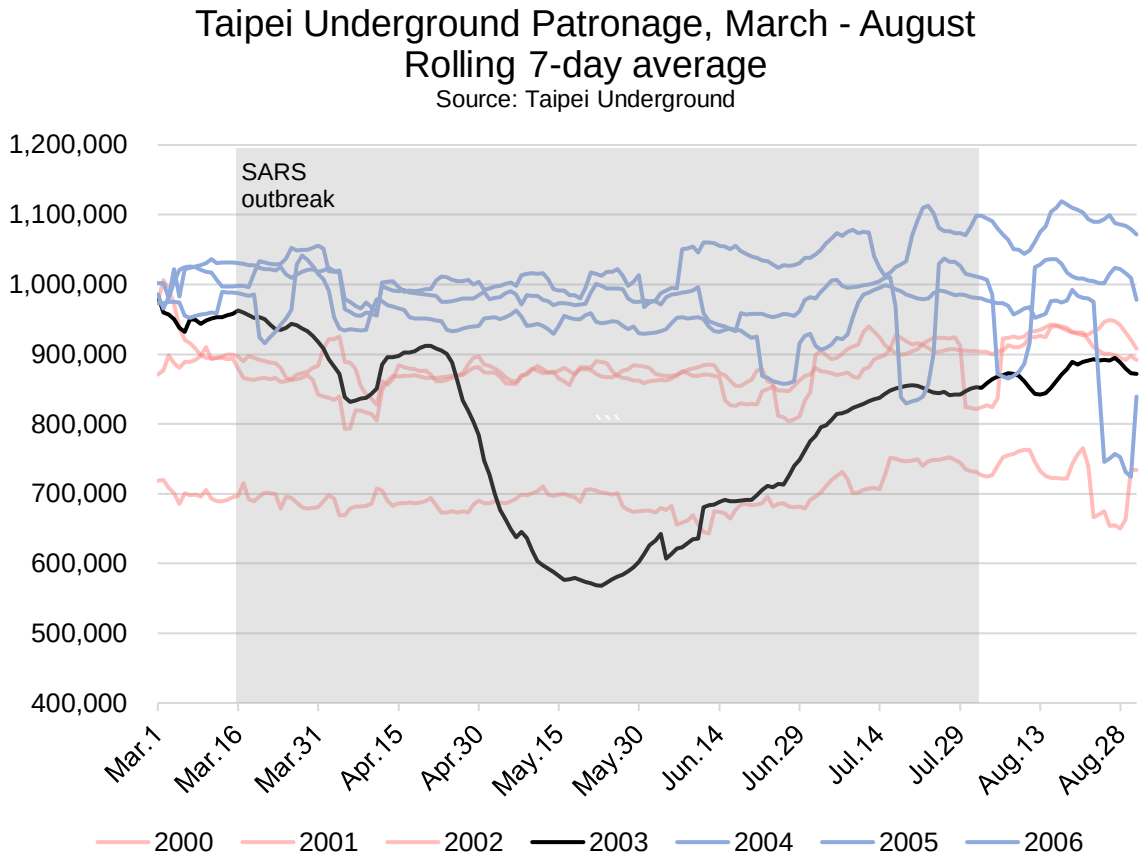

Figure 8 - Patronage on the Taipei Underground throughout the 2003 SARS outbreak

Table 9 summarises the changes in trends, as a result of the shock. This shows the strong increase in the rate of change in journeys/day, and the persistence of the impact across the 3 ½ month period.

Table 9 - Impact on trends

Variable	Trend before	Trend after	Longevity of impact
Underground ridership	-1,921 journeys/day	-5,798 journeys/day	Persisted for 3½ months to return to previous levels of ridership

9/11 terrorist attack, New York City, 2001

The September 11 terrorist attack in New York City caused the collapse of the twin towers of the World Trade Center, with a substantial number of fatalities, injuries, as well as damage to lower Manhattan and New York's road and rail networks. The attack also generated significant medium-term effects on travel behaviour as residents became more aware of the heightened risk of attacks targeting air travel or public transport systems.

Fundamental need/s affected by the shock: Access to information, employment, goods and services

Intermediate practices affected

Commuting to work, and travel for recreation and to access goods and services

Impact on demand and persistence over time

- Temporary reduction in transit demand on commuter rail as workers seek to reduce commuting into Manhattan, or change working location altogether
- The impacts of economic expansions and downturns are more significant drivers of change in in the longer term

Figure 9 shows the annual ridership of Subway and commuter rail services in New York between 1991-2015. This shows a small reduction after the 9/11 attacks, followed by a strong recovery in demand until the 2008 crisis caused another temporary downturn.

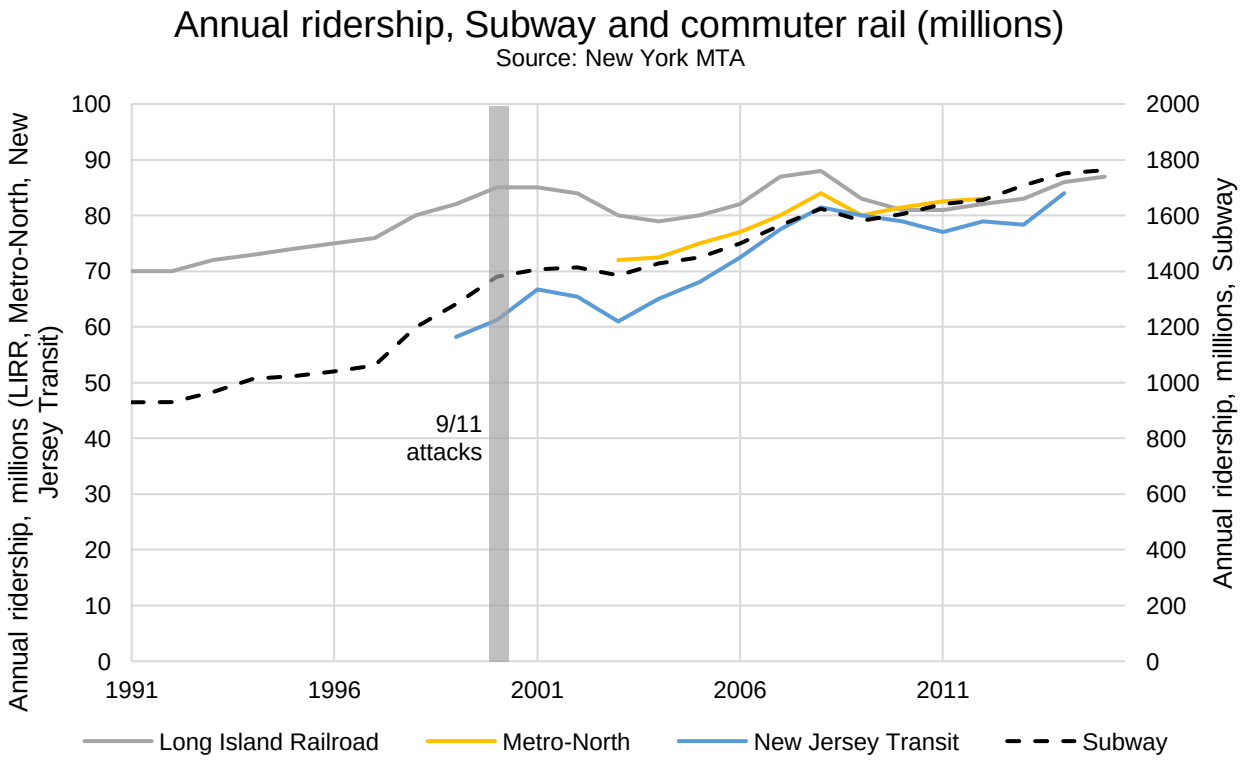

Figure 9 - Annual ridership on Subway and commuter rail services in New York, 1991-2015

Table 11 summarises the impacts of the shock on trends in public transport ridership. This shows how the rate of change in journeys per year after the shock was reduced. It also indicates that the long-term impacts were shaped by a subsequent shock, the Global Financial Crisis.

Table 10 - Impact on trends

Variable	**Trend before**	**Trend after**	**Longevity of impact**
Subway ridership	48m journeys/year	27.3m journeys/year	Seven years, until Global Financial Crisis triggered another downturn.
Commuter rail ridership (Long Island Railroad)	1.5m journeys/year	0.4m journeys/year	

Key findings

Table 12 summarises the findings of each case study, itemised by the fundamental needs affected, direct impacts and subsequent changes to practices or routines. The following section synthesises these findings into a set of conclusions.

Table 11 - Summary of findings

	Fundamental need/s affected by the shock	**Direct and long term impact of the shock**	**Changes to practices or routines in response to the impact**
Auckland Blackout, 1998	Cooling, light, cleaning and sanitation, food, access to information	Blackout disrupted air conditioning, lighting, internet access, sewerage. Minimal long-term impacts on growth and behaviours within the affected area.	Residents relocated temporarily Firms shifted to remote work or satellite offices Retail or services businesses failed or closed temporarily
Hurricane Sandy, 2012	Access (transport and digital), heat, cooling, light, food, cleaning, sanitation	Damage disrupted networked infrastructures – cascading impacts. Prolonged period required to restore networks, however, no significant long-term impacts on behaviour.	Temporary shift to remote work Closure of many firms and schools Fundamental needs not met during disruption
South Korea broadband, 1999	Access to work, education, recreation, goods and services	Enabled online access to information for a range of activities. Significant long-term impacts, transferring a large portion of work, social, administrative and recreational activities online.	Switch to online e-government services, recreation and social interactions, internet access for knowledge work
Oil crisis, 1973	Access (transport) to work, education, recreation, goods and services	Increased prices made it costlier to travel by car or other activities that rely on petrol. Long-term impacts to reduce motor vehicle traffic were minimal, as the impacts of oil crisis were outweighed by policies encouraging motorisation.	Compensatory consumption habits Travel routines didn't changed; elasticity limited by policy measures reinforcing longer travel distances and the absence of public transport improvements
SARS pandemic, 2003	Access to work, education, recreation, goods and services	Decreased attractiveness of travelling by underground – contagion risk. Long term impacts on behaviour, as travellers continued to wear masks. Transport demand returned to previous levels.	Temporary quarantine – prohibited going outdoors, and removed need to access work and education
9/11 attacks, 2001	Access to work, education, recreation, goods and services	Perceived risk of terrorist attack affected commuting by rail. Long term impacts were minimal, as the perceived risk did not remain after the threat of another attack subsided.	Switch to remote working or changing residential location No persistent impacts on public transport usage
Fukushima 2011	Warmth and cooling, light, food, cleaning and sanitation	Disaster triggered change in the preferences for energy sources. Long term impacts evident in policy changes, energy-saving behaviours and outmigration from the affected region.	Decommissioning of Fukushima caused switch to other energy sources; all plants went offline for maintenance.

Conclusions

How have historic shocks have affected infrastructure demand?

The impacts of shocks on infrastructure demand are determined by their specific effects on the *intermediate practices* (i.e. commuting, using heating appliances, washing) that meet fundamental needs such as mobility, access to information, heat, sanitation or sustenance. These practices either adapt to an alternative technology or means of meeting the fundamental need, or the need is not met. The ultimate impact on demand depends on whether practices adapt, or are suppressed by the shock. For example:

- During the 1998 Auckland Blackout, most large firms or public authorities were flexible to relocate to other regional offices, allowing them to temporarily relocate until the power outage was resolved and return to the area. Contrastingly, many small firms, retail and hospitality services did not have this flexibility and the outage prevented them from operating, suppressing demand and in some cases causing the business to fail.

The relationship between quantitative factors of the shocks and the impacts on infrastructure demand

The quantitative measures of demand captured for each case showed the variable impacts of shocks on aggregate demand. Importantly, not all shocks result in changes in aggregate demand, because they can be counteracted or mitigated by other trends or policy interventions. In cases like the Auckland power outage, the temporary displacement of residential and employment populations from the Central Business District does not affect infrastructure demand in the area, as both residential and employment populations increased significantly in the following years.

Characteristics of the shocks, policy responses or wider influences that led to changes

Policy measures have a significant role in mitigating or reinforcing the impacts of shocks.

- The policy response to the 1973 oil crisis in the United Kingdom focused on improving energy efficiency, which improved the efficiency of fuel use, but without complementary policies to reduce travel distances and support public transport use, the elasticity of demand was low and many travellers were locked into higher demand for fuel.

The impacts of technological shocks on individual behaviours are weakened when behaviours also generate negative effects that outweigh the positive benefits. For example

- The initial promotion of telecommuting for South Korean workers had limited uptake, as remote work caused workers to become socially isolated, and miss out on important face-to-face interactions within the office. The relative benefits of remote work may improve if incentives for working at the office were diminished.

Cascading failures across interdependent infrastructure networks increase the length of disruption

- The impacts of Hurricane Sandy were prolonged because the simultaneous failure of energy, water, telecommunication and transport networks slowed efforts to restore each individual system. The severity of the impacts across different sectors created high barriers to adopting new practices or forms of demand that may have

emerged if fewer sectors were affected, such as telecommunications or transport only.

What caused behaviour changes to be permanent or temporary?

Shocks can cause long-term changes in the level of demand if they trigger adaptation of intermediate practices. This depends on the degree of flexibility of these practices:

- During the 1998 Auckland Blackout, shoppers could go to alternative shopping areas in the suburbs, and did not immediately return to shop in the city without strong incentives.
- During Hurricane Sandy in 2012, disruption to commuting caused by the cascading failure of energy and transport systems temporarily suppressed travel demand as many workers could not get to work. This travel demand returned relatively soon afterwards because many jobs could not be done remotely.
- During the 2003 SARS outbreak in Taipei, there was a temporary reduction in transit demand as riders avoided taking the underground because of the risk of contagion. However with no established alternative way to access work, education, goods and services and recreation, in conjunction with the reduced risk as the number of reported SARS cases fell, ridership returned to previous levels.

Similarities and differences between historic shocks and COVID-19

There were distinct similarities between many of the cases and the current COVID-19 situation. First, Hurricane Sandy and the Auckland power blackout both triggered urgent shifts to remote working. However, these took place at a time when internet infrastructures and business systems were not adequate to support productive home working.

- Hurricane Sandy in New York City in 2012 triggered a significant shift to remote working, however this was short-lived as workers could not work effectively without access to on-site systems in the city's commercial areas
- The 1998 Auckland blackout required the sudden relocation of many office workers to remote work or alternative locations, for an extended period of time. Most office workers returned to the Central Business District after 5-10 weeks, as larger firms had the flexibility to relocate to regional offices on a temporary basis and smaller firms relied on temporary rental spaces in other parts of the city.
- The 2003 SARS outbreak in Taiwan and 9/11 attacks in New York triggered a fall in public transport use, although the impact was not as severe as the 2020 COVID-19 lockdowns. The impact of the pandemic and terrorist attacks on travel behaviour was not long-lasting, as patronage levels returned within 1-2 years.

Lessons that can be drawn on the conditions which make long term behaviour change more or less likely

Disruptive shocks that are prolonged over time are more likely to generate long-term impacts on behaviour change, as individuals or firms are forced to find alternative practices or services to meet their needs for an extended period.

- The extended impacts and risks of the Fukushima-Daiichi disaster caused many evacuated residents to re-settle in the areas they were evacuated to, and not return at all.

Perceived risks to health or safety appear to dissipate over time if there are no further events that reinforce the perceived or actual risk.

- After a brief drop in ridership directly after the 9/11 Terrorist Attacks in New York, subway and commuter rail ridership continued to grow significantly.

For shocks to result in new practices, the individuals or firms that demand infrastructure must have sufficient flexibility to change their behaviour.

- In Taipei, the absence of long-term impacts of the SARS pandemic on public transport ridership was influenced by riders' flexibility to wear masks that mitigated the risk of contagion, as well as their inflexibility to shift to other transport modes, due to the country's low car-ownership rate.

Policy interventions can influence the impacts of shocks on demand, by either increasing or decreasing flexibility of alternative activities or routines. For example:

- Policies to educate the general population about the internet in South Korea acted to catalyse changes in work and education activities, recreation and social interaction, and access to government services that were made possible by the rollout of broadband internet
- In the aftermath of the 1973 oil crisis, policies in the United Kingdom that failed to support public transport improvements and urban intensification decreased flexibility to change to alternative travel behaviours and locked in automobile dependence.
- Policy responses to the 2011 Fukushima Daiichi nuclear disaster showed contrasting effects: moves to ban nuclear energy in Switzerland shortly after the disaster locked in the impacts on demand by forcing alternative energy sources, while policies reinforcing safety audits and standards in the UK, USA and India mitigated the likelihood of moving to alternative energy sources