CLIMATE CHANGE ADAPTATION WITHIN NEW ZEALAND'S TRANSPORT SYSTEM

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SUMMARY HAIKU

Climate change threatens
our transport system. We need
clear rules and signals.

FOREWORD

This note was initially drafted as background information for the Deep South Dialogue on Climate Change and Transport, which comprised two facilitated workshops hosted by Motu in July and August 2018 as part of the Deep South National Science Challenge. This final document incorporates material from participants' presentations at the workshops, research recommendations, and direct feedback.

Dialogue participants did not attend as representatives of their organisations. Opinions expressed in this note are those of the authors, and not necessarily those of all dialogue participants, authors' employers, or the Deep South National Science Challenge.

INTRODUCTION

New Zealand's transport system is inter-dependent. It comprises a network for which demand is derived from local communities and the wider economy. People use this network for economic and social purposes, such as commuting, shifting freight, and visiting friends and family. Transport also provides critical links during emergencies.

Climate change affects the transport network itself. It causes damage, accidents and network disruption (Koetse & Rietveld, 2009). These have wider effects on communities and the economy. Climate change also alters the spatial allocation of activities and consequently leads to changes in derived demand for transport infrastructure. Climate change is important to consider in transport planning because transport assets are long-lived, and because the transport system is inter-twined with the wider economic and social systems. There are opportunities for adaptation in the normal cycle of infrastructure build and renewal. However, there are also many challenges due to the costs involved, the uncertainties[1] ahead and the need to coordinate the different institutions that make up the transport system.

This note discusses climate change impacts and adaptation within New Zealand's transport sector. First, we describe the physical and institutional structure of New Zealand's transport system.[2] Second, we review the science behind, and impacts of, climate change related events that disrupt the transport network. Third, we discuss issues around climate change adaptation and the many questions that are still to be addressed. Finally, we conclude by identifying opportunities for further research.

1. This note uses the word "uncertainty" to capture the general inability to know the future, and in reference to events that can and cannot be ascribed a probability distribution.

2. The Ministry of Transport (2017) provides a supplementary reference.

The key messages of this note are fourfold. First, climate change will impact the transport network both directly by damaging infrastructure and indirectly by changing network use. Second, the scale of this impact is determined by components' relative criticality, but there is currently no system-wide measure of criticality that allows us to efficiently allocate adaptation effort. Third, a systems approach to adaptation is necessary to account for the inter-dependencies between transport and other sectors. Finally, this inter-dependency means that delaying adaptation decisions also delays investments and decisions made in other parts of the economy, and may therefore lead to poor placement of new infrastructure.

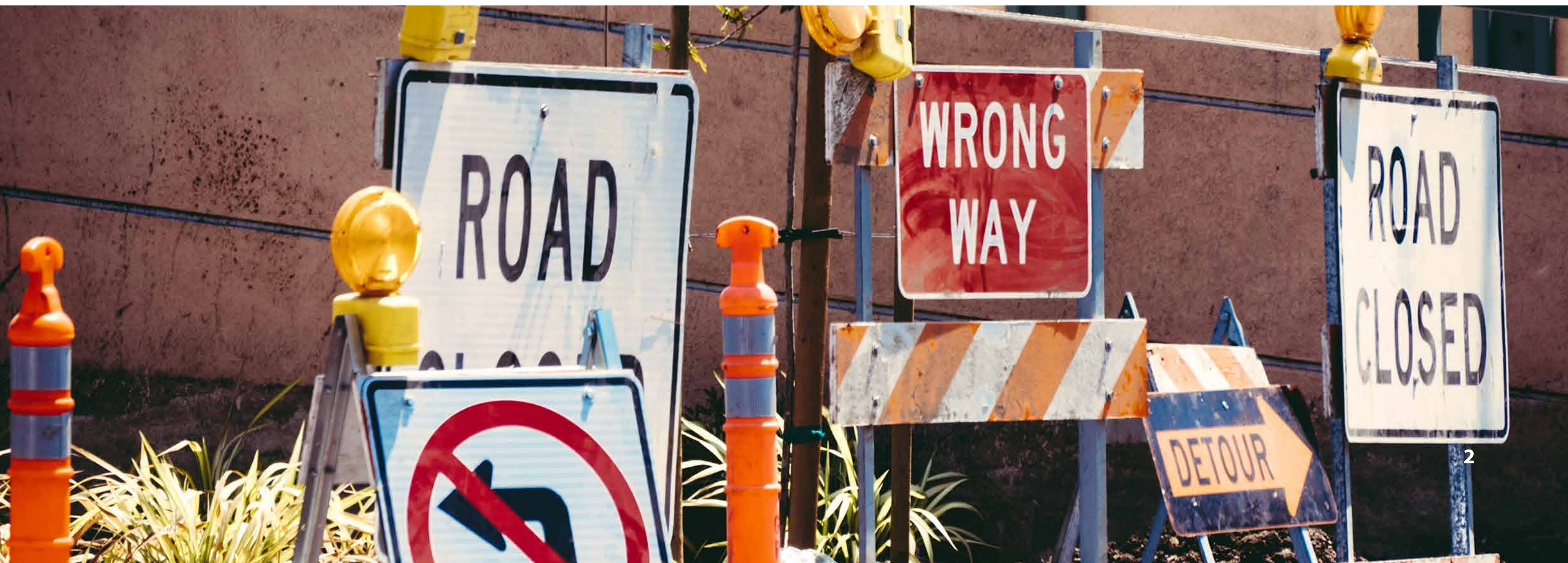
NEW ZEALAND'S TRANSPORT NETWORK

Our transport network captures five inter-connected modes of travel: air, sea, rail, road and active (i.e., walking and cycling). On average, New Zealanders spend just under one hour travelling each day. A full 78% of trip legs and 93% of distance travelled by households are as a car driver or passenger (Ministry of Transport, 2017). Other usage statistics for recent years include 0.96 million flight hours in New Zealand (NZ) airspace in 2015 (Ministry of Transport, 2016), 1.9 million shipping container movements across NZ sea ports in 2017 (Ministry of Transport, 2018), and 183 million tonnes of freight moved within regions and 53 million tonnes moved between regions in 2012 (Ministry of Transport, 2014).

The transport sector is infrastructure intensive. Gardiner et al. (2009) lists the road infrastructure as about 94,000km roads (around 13% of which comprises state highways), 15,000 bridges and an unspecified number of tunnels, and the rail infrastructure as about 4,000km rail, 2,200 bridges and 150 tunnels. Deloitte (2018) lists the sea infrastructure as 13 coastal shipping ports and many inland ports, and the air infrastructure as 37 commercial ports, many aerodromes, and many helipads. Many of these assets have long design lives but are also nearing the end of these lives. Typical design lives include 100 years for wharves and bridges, 50-100 years for "roll-on, roll-off" wharf equipment, 20-50 years for road pavements and culverts, and 20-30 years for container cranes (Gardiner, et al., 2009). Actual design lives can substantially exceed these expectations.

New Zealand's transport infrastructure is owned by a range of entities. The New Zealand Transport Agency (Transport Agency), a Crown entity, provides state highway roads. These highways are funded through the National Land Transport Fund (NTLF): a hypothecated fund receiving revenue from fuel excise duties, road user charges and vehicle registration fees. The Transport Agency also allocates NTLF funding to local road expenditure. Local councils own and manage local roads and paths, using local rates to supplement funding in an approximate 50/50 split with the Transport Agency. KiwiRail, a state-owned enterprise, owns and maintains rail tracks, along with other inter-regional rail stock and services. Auckland Transport and Greater Wellington own the local commuter rail stock in their regions, with service provision contracted to international company Transdev. Air and sea ports are mostly owned by local councils, either outright or in partnership with local corporates. The transport network generates much of its funding from within the system, either via the NTLF, local body rates, or operating revenue. Central government also provides occasional but significant funding. Some debt funding is supplied to local government and port companies. Most of the transport stock using the network is privately owned, and is funded by a mix of equity and debt.

The Ministry of Transport oversees the transport sector. However, regulators are spread across several bodies, including regional and local councils, the Transport Agency, and two other Crown Entities: Maritime New Zealand and the Civil Aviation Authority. The land transport system has a defined planning process that revolves around the Government Policy Statement (GPS) on land transport, provided every three years by central government, and the Regional Land Transport Plans, provided every three years by local councils through regional land transport committees. This planning process focusses on a ten-year horizon. The Transport Agency also overlays a multi-decade view when considering new infrastructure. Air and sea transport planning is tied to land transport planning to the extent that local councils have large ownership shares in ports. Otherwise, planning is mostly done independently for each port. Such planning includes anticipating demands from offshore air and sea transport operators.



The latest GPS, released in 2018, includes objectives directly related to climate change; namely reduced greenhouse gas emissions and improved network resilience.[3] The GPS explicitly states that "it is important that investment places sufficient focus on proactive risk management, particularly for natural hazard and climate change adaptation." The Transport Agency has a framework that further builds resilience into their operations and investment systems.[4]

CLIMATE CHANGE IMPACTS

Climate change refers to a change in the state of the climate that can be identified by changes in the mean or variability of its properties, and that persists for an extended period (IPCC, 2013). The climate change that we currently experience involves higher temperatures, changes in precipitation patterns, and sea-level rise. It also involves more frequent and intense extreme weather events. These events include floods, storms, tropical cyclones and droughts.

The Ministry for the Environment (2016) summarises anticipated climate change impacts in New Zealand. These include: higher sea levels and higher storm surges affecting all coastal areas; more extreme high temperatures and fewer extreme low temperatures; less rainfall on the east coast and more rainfall to the west; snow and glaciers retreating to higher altitudes; and more intense rain and wind events. However, the magnitude, timing and spatial allocation of these impacts are uncertain, and vary between models.

Supply-side impacts

Climate change impacts the transport network by damaging infrastructure and disrupting transport flows. For example, extreme winds and rainfall may slow traffic, delay ship and plane arrivals, and close roads and ports. Climate change impacts may also disrupt the network by damaging the fuel and electricity supply chains that enable vehicles to operate. These impacts limit transport supply, and have flow-on effects for the rest of the network and for the economy. For example, the Ministry of Transport (2013) report that the June 2013 storm in Wellington, which restricted traffic flows between the Wellington and Hutt cities for six days, cost $5.3 million in infrastructure repairs and remediation, $5.3 million in extra travel costs, and $2–32 million in lost output. These figures identify the types of costs associated with events analogous to those caused by climate change.

Gardiner et al. (2009) state that New Zealand's transport infrastructure is most exposed to coastal inundation from sea-level rise and storm surge, inland flooding, high rainfall and inland erosion, and prolonged high temperatures. Sea-level rise is widely anticipated while other climate impacts require further research. We discuss some of these impacts below.

Sea-level rise and storm surges

Average coastal sea levels in New Zealand rose by 17 centimetres over the past century (Hannah & Bell, 2012) and will likely rise by a further 60–110 centimetres by 2100 relative to 1986–2005 levels (Royal Society of New Zealand, 2016). Sea-level rise and larger storm surge tides increase the frequency of coastal inundation (Ministry for the Environment, 2016; 2017) and the rate of coastal erosion (Royal Society of New Zealand, 2016).

Bell et al. (2015) estimate that 2,121km of roads, and 46km of rail are exposed to a 1.5 metre sea-level rise, with less infrastructure exposed to smaller rises. NIWA (forthcoming) updates these figures and shows that the exposure can increase by 40% and 35%, respectively, in the event of a storm surge expected to occur once every century. Such exposure may change over time as land rises and falls (Houlié & Stern, 2017; Beavan & Litchfield, 2012).

Bell et al. (2015) also identify Waikato and Canterbury as the regions with the longest lengths of road below 1.5 metres above sea level. Otago has the longest length of rail below that height. The authors identify five coastal airports below a 1.5 metre elevation—Auckland, Tauranga, Gisborne, Napier and Nelson—along with Dunedin airport, 14 airstrips, and 1,547 jetties and wharves. Gardiner et al. (2009) report that sea-level rise will make seaports inoperable in low-lying areas such as Greymouth, Westport and Wanganui. On the other hand, they also report that sea-level rise will increase draft, and hence allow for larger ships, at seaports in Nelson, Timaru and Dunedin.

3. This note uses the word "resilience" to capture the general ability of the economy and community to resume normal activities following a climate change event, which could be achieved by increasing robustness, resilience or adaptability (Climate-Safe Infrastructure Working Group, 2018).
4. See https://www.nzta.govt.nz/roads-and-rail/highways-information-portal/technical-disciplines/resilience/resources-and-information/ (retrieved November 29, 2018).

We thank all dialogue participants, especially our presenters, for their discussions and feedback.

We also thank Arthur Grimes and David Greig for early conversations in preparation for this dialogue, and Russell Hawkes, Michelle Noordermeer and Stuart Woods for their feedback.

Heavy rainfall and landslides

Climate change also increases the frequency and intensity of heavy rainfall events. Carey-Smith et al. (2018) estimate a 14% increase in rainfall depth per degree of warming for a one hour-long rainfall event that occurs once every century and a 9% increase in rainfall depth per degree of warming for a 24-hour event that occurs once every century. Heavier rainfalls threaten more severe riverine floods, pluvial floods and landslides.[5] These events disrupt nearby transport infrastructure by, for example, blocking roads and rail bridges, and by causing temporary route closures during safety inspections (Gardiner, et al., 2009). However, there is limited available information on which transport assets are most exposed to floods.[6]

Heat extremes

The Ministry for the Environment (2016) forecast a New Zealand-wide increase in mean temperature of 0.2–1.7°C by 2040 and 0.1–4.6°C by 2090, both relative to 1995, as well as amplification in heat extremes. These extremes threaten road and rail buckling, and more frequent route closures while inspections and repairs take place. Similar closures may occur during and after fires. Extreme heat also disrupts air transport by reducing air density and lift (Anderson, 1999), and by necessitating weight restrictions as temperatures exceed safe operating levels (Coffel & Horton, 2015).

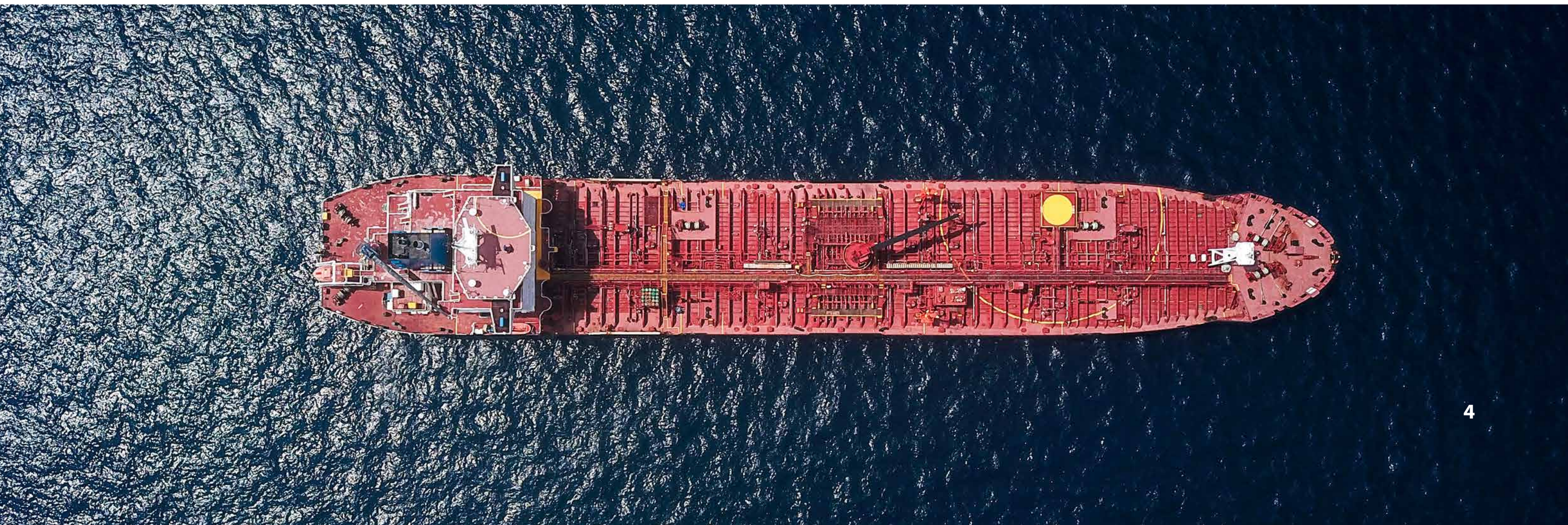
Criticality

The discussion above focused on the threat to, and exposure of, the transport network. The next issue to discuss is criticality. The International Infrastructure Management Manual (Institute of Public Works Engineering Australasia, 2011) defines critical infrastructure as having "a high consequence of failure, but not necessarily a high probability of failure." The Transport Agency assess criticality across the state highway network within their resilience program, using wider economic costs as a measure of criticality. The New Zealand Lifelines Council (2017) discusses nine infrastructure networks to which different criticality measures are applied. Zorn et al. (2017) consider the interaction between transport and other infrastructure networks, measuring criticality by the number of people affected. All studies provide interesting insights but none meet Gardiner et al.'s (2009) recommendation to list "inventories of critical transport links in light of climate change projections," which would consider the economic and social costs of climate change damage and disruption across infrastructure networks. An initial stage of such an assessment is determining how to measure criticality.[7]

Criticality itself depends upon many factors. One factor is the economic and social value placed on connectivity. Such value is determined by network users. However, these users have different wants and needs, and thus different perspectives on components' relative value. For example, it is difficult to compare the economic cost of milk becoming undeliverable to Fonterra's plant in Edendale with the social cost of a coastal community becoming isolated or being forced to retreat because the latter cost cannot be easily priced. Similarly, different stakeholders have different tolerances for network disruptions and hence different perspectives on criticality. Determining network components' relative criticality requires prioritising these differences in stakeholder preferences.

Criticality also depends upon the ease of substitution between network components. For example, tourist flows were recently diverted through Murchison when landslides closed the state highway segment between Christchurch and Kaikoura, but no alternative route was available when landslides closed the single road access to Milford Sound. Likewise, travellers can drive between centres if storms close airports. Such alternative travel options may arise due to the natural diversity of the transport network or may be actively provided by building redundancy into the network. In general, components with more substitutes are less critical.

5. Landslides are already a high risk in many parts of New Zealand due to heavy rainfall and earthquakes.
6. The Deep South recently announced funding for research into flood impacts on infrastructure and buildings. See https://www.deepsouth-challenge.co.nz/news-updates/funding-announced-climate-resilience-research (retrieved October 15, 2018).
7. Smith et al. (2002) provide an example of a multi-criteria criticality assessment. Faturechi and Miller-Hooks (2014) and Aecom (2016) provide reviews of methods to assess criticality.



Finally, climate change impacts on transport network components can affect other parts of the network. For example, inland floods may divert commuter flows away from low-lying areas and thereby place additional stress on alternative routes. Similarly, high winds may encourage transporting freight along road or rail rather than by air or sea. Route and mode substitutions are two ways that local impacts can "spill over" to other transport network components. The scale of these spill-overs depends on the criticality of the impacted component in the context of the wider network.

Demand-side impacts

Climate change also impacts other sectors that use the transport network. These impacts may cause both intra- and inter-regional shifts in the derived demand for transport. Impacted sectors include New Zealand's two largest export earners: primary production and tourism. These sectors are exposed to both domestic and international climate change impacts. Such impacts also affect migration and settlement patterns. These patterns determine the spatial allocation of economic and social activities, and hence determine derived demand for the transport network.

Primary production

Climate change has spatially heterogeneous impacts on land suitability for primary production (Timar, 2016). These impacts, coupled with shifts in international production and markets, are likely to trigger land-use changes (Rutledge, et al., 2011; Rutledge, et al., 2017). Such changes shift the spatial allocation of transport network use by, for example, increasing the demand for large-truck-bearing roads in areas converted to dairy production or forestry. However, it is unclear where and when these shifts in network use will occur. Moreover, as noted by the Ministry for the Environment (2017), the agricultural sector "has a long history of adapting to seasonal and annual variability in climate-related conditions, including coping with extreme events." The interacting uncertainties of climate change impacts and sector adaptation preclude identifying changes in agricultural practice that induce spatial changes in transport demand.

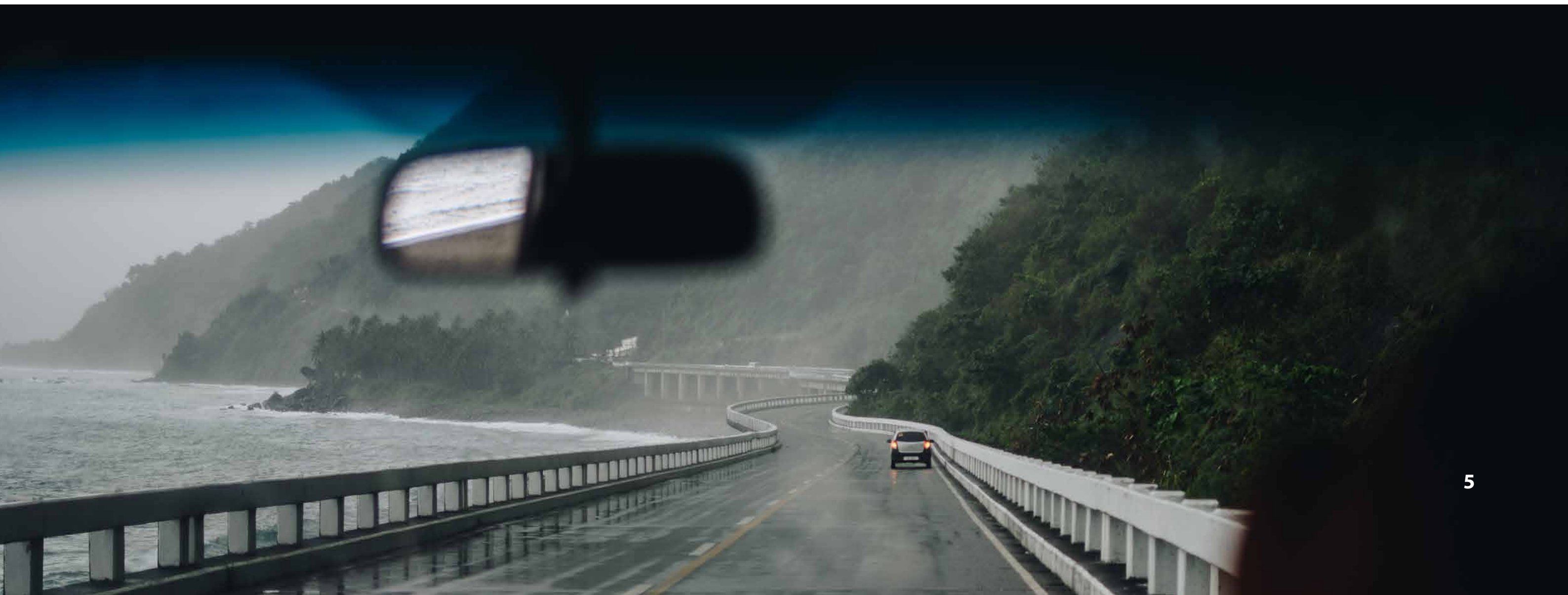
Tourism

Becken (2010) and Becken et al. (2010) discuss climate change impacts on tourism. Anderson (forthcoming) states that some reduction in glacier extent and volume is likely. Hughes Hutton (2017) argues that this may induce "last chance tourism." A consistent result of the tourism literature, as with agriculture, is that climate change adaptation within the sector is likely. Such adaptation may reinforce existing tourist destinations or establish new destinations in less exposed areas. Hence, it is uncertain how tourists' demand for the transport network will change in response to climate change.

Settlement patterns

Climate change also impacts settlement patterns. For example, sea-level rise leads to permanent displacements as coastal areas become uninhabitable (IPCC, 2014). These displacements shift settlements and transport demand inland. Other climate change impacts on location choice are less certain. For example, increased temperatures may cause people to settle more northward for an even warmer climate or more southward to retain current conditions. This ambiguity highlights the complex interaction between geographically heterogeneous climate change impacts and peoples' preferences.[8] Overall, it is unclear if or how this interaction will cause settlement shifts; Cameron (2018) models the inter-regional population effects of climate change and finds them to be minor.

8. Even in areas threatened by long-term climate change and sea-level rise, populations at risk do not always choose to migrate (IPCC, 2014). Residents may remain in vulnerable areas for reasons of culture and identity; see, for example, Mortreux and Barnett (2009).



Changes in settlement patterns within regions will depend on local and regional councils' response to climate change. We discuss these responses in the following section.

ADAPTATION OPPORTUNITIES AND CHALLENGES

There are many ways to adapt to climate change within the transport system. These include increasing network resilience (e.g., by raising rail levels), increasing network redundancy (e.g., by providing alternative routes), and altering land use in order to avoid impacts (e.g., by moving factories and settlements—and hence the access roads that serve them—away from exposed areas). The dialogue group discussed various examples of adaptation, many of which are already being applied, but the focus of our discussion quickly turned to the strategic nature of adaptation decisions.

Climate change adaptation involves strategic choices about what and where transport infrastructure is built, and about how that infrastructure is used and maintained. These choices must consider the fact that our transport system is a network, and must focus on the resilience of transport services as a whole rather than resilience only of specific modes or network components. Our ability to make balanced, well-informed decisions about changes to the transport network, and about how to fund those changes, relies on institutional structures that coordinate decisions and provide clear, time-consistent directions. Transport infrastructure decisions also have major implications for investments in other sectors. We discuss these issues below.

Decision making

Questions raised during the dialogue included which adaptation strategies to use, and where and when to apply them. Making these decisions requires trading off the cost of each strategy with its ability to mute climate change impacts. This trade-off is typically made explicit using cost-benefit analysis (CBA), which stipulates that the strategy with the largest net present value (NPV) should be chosen. However, the uncertainties and complexities of many adaptation decisions also require considering a wide range of scenarios rather than a single maximisation criterion. Better outcomes may be achieved by using a system-wide approach to decision-making.

Cost-benefit analysis

Consider, as an illustrative example, the choice of whether to raise the level of a road to reduce exposure to flood risk. CBA provides insight into whether society is made better off by raising the road, and identifies who bears the costs and receives the benefits. Conducting the CBA requires three sets of numbers: the immediate construction cost and the ongoing operational costs; the future benefit of avoiding damage and disruption; and the discount rate used to price these costs and benefits in present value terms.

The direct construction and operating costs of raising a road are relatively straightforward to estimate. However, this estimation faces the usual risk of optimism bias and includes the more difficult to measure disruption costs arising from route closures during construction.[9]

9. Likewise, it is easy to overlook disruption costs when evaluating adaptation projects in other sectors that use the transport network.

Estimating benefits is more challenging. For any given flood event, the benefit of raising the road level will mostly comprise avoided consequences: repair costs and network disruptions. The avoided repair costs may include the cost of repairing energy, telecommunications and other utility infrastructure that are co-located with the road. The avoided disruption costs depend on how easily road users can adjust their travel demand, either by using alternative routes or by engaging in alternative activities. In this way, the benefit estimation must consider the target road's criticality both as a transport network component and as a facilitator of economic activity. Criticality, in turn, depends on how other parties change their behaviour between now and the potential flood. Possible changes include peoples' use of transport routes and modes, and the location of homes, schools and workplaces. To further complicate matters, the benefit to be accrued is uncertain, both in value and in timing, due to the uncertain magnitude and timing of the avoided flood. Finally, this benefit may change over time as avoided floods accumulate; a particular problem when minor events that are not included in an assessment are repeated.

It is also challenging to determine the appropriate discount rate for evaluating whether the road should be raised because the chosen rate must capture the varied time-horizons and risk tolerances among network users. This is a contentious issue when CBA is used to compare costs incurred by current and future generations (Freeman, Groom, & Spackman, 2018). Such a comparison is necessary for many adaptation projects.

Adaptive scenarios

Given the uncertainties about climate change and its impacts, a more dynamic benefit assessment that considers a range of scenarios may be required. Real Options Analysis (ROA) is commonly recommended when decisions are costly to reverse or when there are opportunities to resolve uncertainties over time (HM Treasury, 2018).[10] Applying ROA to adaptation decisions acknowledges that planners hold a portfolio of flexibly deployable adaptation strategies. These strategies include delaying investment, expanding or contracting the scale of investments, and substituting between investments. However, undertaking ROA requires recognising the variation in flexibility across transport network components. Moreover, there may be time-varying constraints that influence the optimal sequence of adaptation decisions. These constraints include legal and political challenges, such as changes in governance that lead to adaptation decisions being reversed.

New information about climate change impacts, about the resulting changes in network demand and about adaptation strategies may become available over time. This possibility reinforces the need for an adaptable approach to transport decision-making. Delaying investment decisions, in addition to delaying investments themselves, until superior information is available may lead to better decisions.[11] However, passively waiting, actively learning or building optionality into design will usually come with costs. These costs include damage and disruption in the event that climate change materialises faster than anticipated, and heightened risk as developments on susceptible land continues in the meantime.

Ideally, decision-makers will implement adaptation strategies which are effective over a range of possible futures, are responsive to new information, are affordable, and are robust to legal challenges and political change. Adaptive Management (Chades, Tarnopolskaya, Dunstall, Rhodes, & Tulloch, 2015) has been suggested as a process that works towards this ideal, while Kodukula and Papudesu (2006) provide some guidance as to conditions suited to ROA. However, the challenges remains as to how to efficiently and effectively build ROA into adaptation decision-making.

10. See Dixit and Pindyck (1994) and Guthrie (2009) for overviews of ROA, and Byett et al. (2017) for discussion of its application to land transport in New Zealand.
11. An alternative strategy for navigating environmental and political uncertainty is though commitments by stakeholders and decision-makers. For example, community-level commitments to defend or retreat from areas with vulnerable transport infrastructure provides a coordination device for other parties making long-term investments to work around.

Decision criteria

The third element of any strategic decision about climate change adaptation is the decision criteria to apply. For example, CBA and ROA use expected, risk-adjusted net benefits as their primary decision criteria; that is, the perceived benefit that is experienced, on average, if potential events are repeated many times. This approach has five practical problems. First, the estimated benefit is unlikely to capture equity considerations. Second, the estimated benefit is also unlikely to fully capture benefits relating to intangible assets because these assets are difficult to value. Third, the risk aversion to particular outcomes may not be adequately or transparently captured within the CBA. Fourth, averaging may be inappropriate because climate change-induced events may not be repeated. Fifth, the probability of events considered in any analysis, including ROA, are not certain.

It is possible to take equity into account by applying distributional weights to benefits in a CBA.[12] However, equity is typically included as a single criterion, along with other benefits that are difficult to monetarise, within a multi-criteria analysis (MCA).[13] Similarly to CBA, MCA quantifies benefits and ranks project options, thereby lending itself to a maximisation decision rule. MCA is already being applied to New Zealand transport decisions. However, it is unknown to what extent the scoring within these analyses are introducing subjectivity biases.

One way to reduce sensitivity to specific criteria or assumptions is to implement Robust Decision-Making (Lempert & Collins, 2007). Using this method, decision-makers would choose between a range of adaptation strategies based on modelling those strategies' sensitivity to climate change impacts and to socio-economic outcomes. The method allows decision-makers to account for "avoid-at-all-cost" outcomes more easily than using CBA, ROA or MCA.

Systems approaches

Elements of CBA, ROA and MCA are being applied by multiple parties within New Zealand's transport sector. While some attention is being given to actions by other infrastructure and service providers, there is an opportunity to integrate these approaches more closely. At an analytical level, a network-wide simulation model, including multiple regions and multiple transport modes, would enable insights into the interconnectedness of transport network components and their relative criticality. Such models have been used internationally to assess vulnerability (Mattsson & Jenelius, 2015). Interdependencies can also be explored using probability modelling, decision trees and network models. At a decision-making level, a systems approach broadens the scope of infrastructure investment decisions to include, for example, changes in land use and optimisation across transport modes.

Financial and institutional challenges

Institutional arrangements must exist to efficiently and effectively implement adaptation decisions. The dialogue participants identified four fundamental challenges to deriving the optimal institutional arrangement for our transport system.[14]

First, the costs associated with climate change, including the costs of any adaptation, must be borne by some persons. These costs can be spread between people and across time, either before or after climate change impacts occur. This can be achieved through pricing, insurance, taxation, or using debt to shift costs to future generations.[15] Each mechanism allocates the cost to different groups and therefore requires judgment as to who should bear the burden. This judgment is non-trivial, and may take into account factors such as culpability (for causing the climate change itself or for making poor historical decisions that have imposed cost), benefit, affordability, capacity, default risk, and the variation in different parties' ability to pay.[16] The question of who should pay for adaptation featured prominently throughout the dialogue.[17]

12. See Chapter 18 of Boardman et al. (2014).
13. See Oldfield (2012).
14. Roggero et al. (2018) review the literature on institutional arrangements for climate change adaptation. Boston and Lawrence (2018) discuss the New Zealand situation.
15. The Civil Defence and Emergency Management Act imposes some restrictions on risk transfers.
16. Some of these factors are discussed under "climate justice" in Alger (2001).
17. Various funding arrangements have also been suggested, including use-based tax (Maddocks, 2010), vulnerability reduction credits (Shultz, 2018), resilience bonds (Vajjhala & Rhodes, 2017), revolving funds (Chou, Hammer, & Levine, 2014), and public private partnerships (Trusted Information Sharing Network, 2015).

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Second, New Zealand's transport network includes many long-lived assets that are owned and managed by multiple entities, with limited interaction between each entity. This decentralized ownership structure makes it difficult to coordinate decisions about how and where to allocate adaptation effort, and increases ambiguity surrounding who should pay for such effort. Moreover, different decision-makers have different timeframes on which they must make adaptation decisions due to the variation in climate change exposure and in network components' effective lifetime. It is unclear which institutional arrangements align these timeframe differences so as to facilitate coordinated adaptation decisions.

Third, communication will influence how people and businesses respond to climate change impacts. For example, real option values provide incentives for national and local governments to delay making adaptation decisions until more information is available. These delays may discourage private investment by increasing uncertainty around climate change effects. Such amplification of uncertainty may be reduced through decision rules that define, in a credible and time-consistent manner, which adaptation strategies the government and infrastructure providers will implement under different eventual climate change scenarios. However, again, it is unclear which institutional arrangements allow such signalling, and more generally good communication, to occur.

Finally, the response to climate change requires balancing the needs of many people. Climate change impacts will be felt at a national, community and individual level. While CBA, ROA and MCA can help choose appropriate strategic responses, a large degree of community engagement in the decision process is also necessary. It remains an open question whether the current institutional arrangements facilitate such engagement.

HIGH PRIORITY RESEARCH QUESTIONS

This note raises many issues concerning climate change adaptation within the transport network. The dialogue participants prioritised five questions. Some may be slightly out of scope for the Challenge but are nevertheless questions that were legitimately raised through the process:

1. What can mathematical and network models tell us about the relative criticality of transport network components, and how could this inform climate change adaptation?
2. How did previous climate change-analogous, transport-disrupting events impact individuals, households and firms?
3. What are the characteristics of transport projects and climate change uncertainty for which undertaking Real Options Analysis is likely to significantly change the adaptation guidance provided by traditional cost-benefit analyses?
4. What are the characteristics of institutional arrangements that credibly, efficiently and sustainably signal long-term policy changes such as those necessary for climate change adaptation within the transport sector?
5. What can transport regulators and planners learn from other networks (e.g., logistics, telecommunications, or electricity) that face, or have faced, increasing and disruptive uncertainty?

These questions reflect the uncertainty that exists in assessing criticality, in estimating consequences, in identifying suitable adaptation alternatives and assessing their financial implications, in establishing actionable and time-consistent policies on infrastructure management, and in creating a clear decision-making environment for planners and regulators.

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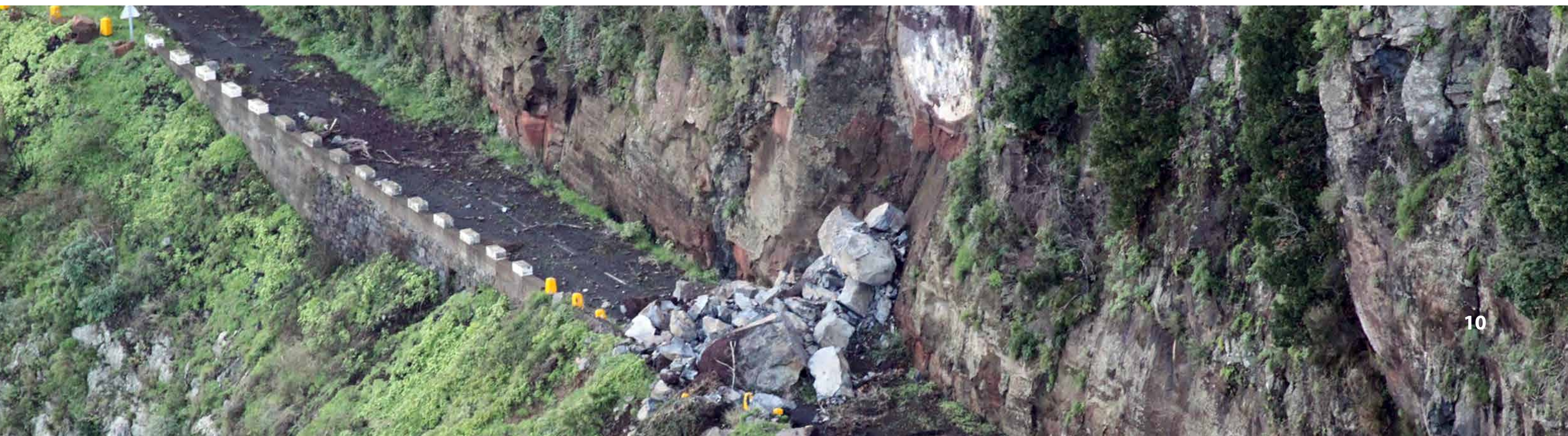

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