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An Ghníomhaireacht um Chaomhnú Comhshaoil

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Implementation of Climate Adaptation Indicators: Lessons Learned from the Transport Sector

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EXECUTIVE SUMMARY

As the climate changes rapidly, the impact of severe weather events on natural and artificial systems is becoming more detrimental. Sectors with responsibility for managing these systems must identify how their assets and operations will be impacted and what adaptive measures they can take to ensure the integrity of their assets and the smooth running of their operations. To understand progress in climate adaptation it is necessary to establish a monitoring, reporting and evaluation framework. A well-designed set of indicators can form part of this framework and provide a means to measure and quantify the status of climate adaptation, and the progress of adaptation actions in producing the desired outcomes. Such indicators help to define an existing situation and to track changes or trends over time. They can provide both qualitative information on, for instance, the degree of development or implementation of a policy process, or quantitative information, such as the total seasonal rainfall in a given area, or number of road bridges maintained to reduce impacts of severe weather events.

In previous work carried out for the EPA, Flood et al., (2021) identified a suite of 127 climate adaptation (resilience) indicators of potential use across all national sectors. These indicators were aggregated into four categories, namely climatological, impact, implementation and *outcome* indicators. The case study presented in this report addresses some elements of the national transport infrastructure and is a first attempt at selecting and assessing the potential application of a relevant subset of these indicators in a practical setting. The lessons learned in the process can inform the guidelines being developed to support the updated National Adaptation Framework and will also be of value to all sectors in understanding the process for identifying climate adaptation indicators of relevance to their own sectors.

Ireland´s key transport infrastructure includes road, heavy and light rail, aviation and maritime transport. Transport Infrastructure Ireland´s (TII) responsibilities are focussed on national primary and secondary roads, light rail, rural cycleways and national and regional greenways, land, buildings, and people. Regarding national roads these are managed and operated by TII through different contractual arrangements, with private operators and local authorities. With respect to light rail, TII is responsible for the life cycle asset management of all Luas infrastructure and rolling stock (TII, 2023b), whereas operation of the network is sub-contracted to another entity.

TII has recognised the need to look towards identifying and implementing a set of climate adaptation indicators within their processes. Recent work has focused on improving understanding of potential risks to their various assets; this is a necessary precursor to work on identifying and selecting relevant indicators. The work presented here builds on a collaboration that already existed between MaREI and TII and was formalised in TII's Climate Adaptation Strategy in December 2022.

A scope of work document was developed by MaREI with input from TII and the EPA. This identified the expected outcomes of the work as:

- TII will have developed its understanding on how adaptation indicators can be used to support its adaptation actions,
- A set of indicators will be identified. TII can prioritise the development of these indicators as a means of furthering its understanding and working towards utilisation of indicators within its operations,

- The methodology for indicator selection will be detailed and a set of lessons learned can be extracted to inform the guidelines for adaptation plans in other sectors,
- Challenges associated with identifying and implementing relevant adaptation indicators for sectors will be highlighted.

TII carried out a Climate impact screening, concluded in late 2023, which supported understanding on what key asset-hazard vulnerabilities exist. Based on the outcomes of this analysis it was then possible to carry out an informed evaluation of the initial indicator list, provided by Climate Ireland to TII, and based on the Flood et al. (2021) report. The evaluation focussed on the climatological and impact indicators in the first instance, as implementation and ultimately outcome indicators are dependent, on the impact indicators selected.

Through the co-development process an initial set of potential climatological and impact indicators were identified. These address the national roads and the light rail network. Once agreement on these potential indicators was reached, work moved on to determining a set of potential implementation and outcome indicators. Further discussion in relation to the possible hazards that could impact rural cycleways and national and regional greenways, land and people are necessary to determine relevant indicators for those assets. Once a detailed climate risk assessment has been undertaken and completed in 2024 (as outlined in action 2 of TII's Climate Adaptation Strategy, 2022), TII will be better positioned to address potential indicators for these assets. In total, 43 adaptation indicators were identified for national roads and light rail; this comprised 19 climatological, six impact, 11 implementation and 8 outcome indicators.

It should be noted that although a set of potential indicators has been identified, TII will not be able to implement them with immediate effect. Further consultation and identification of the resources needed to move to implementation will be required.

The co-development work carried out for this case study has resulted in the identification of a total of fourteen lessons which can be of value to other sectors as they start the process of adaptation indicator selection and implementation. These are listed here:

1. Comprehensive climate impact screening and prioritisation are required to improve understanding of specific climate hazards affecting a sector before indicators can be considered.
2. Ensuring comprehensive engagement with key actors with expertise in different areas of a sector will ensure that vital criteria are not overlooked in the indicator selection and implementation process.
3. The resilience indicators listed in Flood et al., (2021) form a good basis to begin consideration of adaptation indicators. Nonetheless, they require systematic consideration, discussion and revision to meet the purposes of specific sectors.
4. The number of indicators selected should be kept to the minimum necessary but must be sufficient to capture the key processes and issues within each sector.
5. The operational realities of a sector will influence its ability to access the information relevant to report on an indicator.
6. Separating impacts to sectoral assets and operations due to climate change, from other contributing issues is often not possible as these can be due to multiple processes and a compounding set of conditions.

7. Phased development of indicator sets is often more appropriate. It allows progress to be achieved and avoids blocking the whole process due to inability to agree on a full and comprehensive set of indicators.
8. The co-creation process is critical in order to engage different departments and bring actors and expertise together, both within sectors and across sectors, to facilitate a robust selection of useful indicators.
9. Relevant data need to exist and be accessible to determine the adaptation indicators. If organisations have not already done so they should identify and begin collecting baseline data to inform adaptation needs.
10. Sectors need to identify dependencies between different entities and organisations and explore solutions to ensure that the required data are available to inform effective indicator development and avoid maladaptation.
11. National level indicator reporting should not impose significant additional work on sectors. It should be easy to compile the indicators from work that is being carried out as a necessary part of the various sectors´ efforts to adapt to climate change.
12. Development of sectoral climate adaptation indicators should be informed by work being conducted in other countries.
13. Any additional costs of construction, remediation, or maintenance of transport infrastructure due to climate change impacts are currently not possible to identify as they are embedded in general costs of raw materials, construction, general maintenance, labour and inflationary effects.
14. Consider and address mitigation and adaptation in tandem and identify any co-benefits.

Based on the experience of this case study carried out in collaboration with TII, and taking into consideration the above lessons learned, the following recommendation were identified that can assist other sectors in addressing the development of a set of climate adaptation indicators for national reporting:

- **Start the process as soon as possible**. The development of relevant indicators for each sector is a long and complex process that takes significant time. It demands a deep understanding of an organisation´s assets, how climate change may affect them, operational procedures, data availability, and existing reporting procedures, among others. By starting the process early, issues and challenges will come to light and measures can be taken to start addressing them, as some may take years to resolve.
- **Do not develop indicators in a vacuum.** Sectors need to be aware of the most recent international best practice in this area and learn from the failures and successes in other organisations and jurisdictions.
- **Partnership working is essential.** A co-creation process ensures that all relevant actors and departments within a sector or organisation are represented in the decision making. The impact of climate change and adaptation measures across the sector and beyond and associated interdependencies need to be understood to ensure successful adaptation that is practical and relevant. By collaborating with others, including consultants, competent authorities and specialists, resources and information can be shared, and adaptation can be more efficient and effective, addressing key challenges within and across sectors. National

intersectoral communication (e.g., through the creation/or adaptation of a steering group that meet on a regular basis) to ensure coherence and the exchange of learning and ideas on the development and implementation of indicators would be invaluable.

- **Ambition for the future is necessary.** Sectors must not restrict indicator identification and selection based only on current data availability. Consider what information will be essential to the sector in the future and begin the process of measuring this now, even if the initial starting point is to begin collecting data that has not been collected up to now.
- **Climate adaptation and mitigation need to be considered in tandem.** Proposals for future developments within a sector should include an assessment of how both are being addressed as part of their business case analysis.
- **Climate adaptation and related reporting processes needs to be properly resourced at all levels.** The setting of ambitious sectoral goals will require additional support from national government to allow for adaptation action and associated monitoring, reporting and evaluation (MRE) that is successful and cost-effective in the long-term.

1. INTRODUCTION

1.1 Background and Context

In an Irish context the concept of resilience forms a key component of the 2018 National Adaptation Framework (NAF) (DCCAE, 2018). Climate resilience is defined within the NAF as:

"The capacity of a system, whether physical, social or ecological, to absorb and respond to climate change and by implementing effective adaptation planning and sustainable development (including governance and institutional design) to reduce the negative climate impacts while also taking advantage of any positive outcomes. This will allow the system to either return to its previous state or to adapt to a new state as quickly as possible" (DCCAE, 2018).

In order to track progress in implementing adaptation actions but more importantly to evaluate the outcomes of such action it is necessary to ensure that a monitoring, reporting and evaluation (MRE) system is in place. Climate adaptation indicators, when properly designed and implemented, are valuable measures to incorporate into a MRE and can provide information on the level of resilience of the system.

An indicator is a characteristic or variable which helps to describe an existing situation and to track changes or trends over a period of time. In terms of climate, resilience and adaptation are terms that are often used interchangeably (Leiter et al., 2019), however, they are distinct concepts. Resilience indicators specifically consider the ability or capacity of an organisation or community to cope with both immediate climate change impacts, while adaptation indicators address long-term abilities to respond to specific stressors (adaptive capacity) (Engle et al., 2013; Wong-Parodi et al., 2015). These indicators can provide either qualitative information on for instance, the degree of development and implementation of a policy process, or quantitative information, such as the total seasonal rainfall or number of climate adapted bridges (Flood et al., 2021).

A set of 127 national climate adaptation resilience indicators was proposed in EPA Report 379 (Flood et al., 2021). This set covered *climatological, impact, implementation* and *outcome* indicators and are associated with different sectors and local authority needs. One of the recommendations of that report was that an agreed subset of those indicators should be implemented in a pilot study. In 2022 the Department of Transport requested that the implementation be piloted in the transport sector, building on collaboration that already existed between MaREI and Transport Infrastructure Ireland (TII).

In the case of this report, and after discussions with TII, it was decided to consistently use the term adaptation indicators. Adaptation indicators were considered to be more relevant, and less broad, as a metric for TII than resilience indicators, as they delve more into direct action and have been found to be central to the learning process, as well as in guiding future adaptation efforts (Leiter et al., 2019). Resilience is a much broader concept and is often used to encompass shocks from a range of hazards, for example cyber attacks, health pandemics, civil unrest, and natural hazards.

The work was formalized by the EPA in the Climate Ireland workplan for 2023, based on action AD/23/1 in the Climate Action Plan 2023 (DECC, 2022). This action states "identify a methodology for the use of climate indicators in sectoral adaptation planning process." Moreover, TII formally included the activity in its workplan. This was achieved via the publication of the TII Climate

Adaptation Strategy in December 2022 (TII, 2022c). In that document action No. 5 states: "continue TII's working relationship with Climate Ireland and University College Cork (UCC) to support the definition of a final list of climate resilience indicators."

A scope of work document was developed by MaREI with input from TII and the EPA. This identified the expected outcomes of the work as:

- TII will have developed its understanding on how adaptation indicators can be used to support its adaptation actions,
- A set of indicators will be identified. TII can prioritise the development of these indicators as a means of furthering its understanding and work towards utilisation of indicators within its operations,
- The methodology for indicator selection will be detailed and a set of lessons learned can be extracted to inform the guidelines for adaptation plans in other sectors.

It should be noted that although a set of potential indicators have been identified, TII will not be able to implement them with immediate effect. Further consultation as well as identification of the resources needed to move to implementation will be required.

This report should be of interest to those charged with developing guidelines to support implementation of the new National Adaptation Framework to be published later in 2024. This study will inform other sectoral actors on how they can start the process of designing and deploying climate adaptation indicators within their own organisations. Moreover, it will be of interest to national government departments in order to enable them to understand how progress on practical activities being undertaken to adapt to severe weather events can be influenced by a number of factors that may not fully be within the control of an organisation, such as the responsibility for and ownership of assets, current service level agreements and data availability for monitoring.

1.2 Report Outline

- Chapter 1 presents the background and context to the case study carried out with TII.
- Chapter 2 provides an overview of the six sets of transport assets within TII's remit. It outlines the climate impact screening process carried out at TII and how a prioritisation exercise in relation to their assets´ vulnerability to different climate hazards was achieved. An overview of international experience, with examples, in implementing adaptation indicators for the transport sector is provided.
- Chapter 3 gives a summary of research work done to date in Ireland in relation to climate adaptation indicator identification. A list of potentially relevant indicators for the transport sector, extracted from recently published work is provided across the four categories of climatological, impact, implementation and outcome indicators.
- Chapter 4 provides insights into the co-development process carried out between MaREI and TII and highlights the methodology adopted for indicator selection. The final sets of selected indicators across the four categories are tabulated and discussed. A number of considerations in relation to national reporting on such indicators are provided.
- Chapter 5 lists and discusses a series of lessons learned from the process and the practical work carried out on indicator selection.
- Chapter 6 concludes the report with a set of high-level recommendations.

2. TRANSPORT ASSETS AND RELATED CLIMATE HAZARDS

2.1 Overview of Key Transport Assets

TII has defined six key asset groups including road, light rail, rural cycleways & national & regional greenways, land, buildings and people (Figure 2.1), and control over half a million assets under these different groups (Appendix 1). These assets are all integral to the operation of the transport network, however, the first two (national road and light rail) are the assets that are initially being focused on as part of the scope of this study. The asset groupings of cycleways & greenways, land and buildings will follow as its climate impact screening process for climate change adaptation progresses. The asset group people had a more detailed initial climate impact screening with the information obtained expected to be used to support discussions on how to develop adaptation plans. People is an asset that organisations often do not think about. However, during both normal and extreme operations, people are critical to the running of networks.

Figure 2.1: TII's six major asset groups

National Roads

Ireland's primary and secondary roads network consists of approximately 5,306 km and includes motorways, dual carriageways and single lane roads. While this only accounts for 5% of the overall road network, it carries 45% of the traffic, all managed and operated by TII through different mechanisms. These are subdivided into 3 categories: Motorway Maintenance and Renewal Contract (MMaRC) operators (~750 km), Public Private Partnerships (PPP) (~450 km) and roads (~4,100 km), managed directly by the local authorities in partnership with TII. TII is directly responsible and has complete access to data for only MMaRC roads, however, these represent the busiest routes on the national road network. The national roads network is essential for the functioning of society, much of the critical infrastructure needs the road network to operate, some of the national roads having been deemed 'lifeline' roads in more rural areas, where they provide the sole transport infrastructure and only available connection for surrounding communities (National Roads 2040, 2023).

Light Rail

The light rail network (Luas) consists of two tram lines which extend from Tallaght in the southwest of Dublin to the 3Arena in the Dublin Docklands, and from Brides Glen in the southeast of Dublin to Broombridge in the northwest of the city. Together these lines consist of 42.4 km of track and allow the operation of a fleet of 81 trams. Public transport is essential in urban areas and the Luas has recorded over 430 million passengers since the service begun in 2004, helping Ireland to reduce carbon emissions and meet EU carbon targets. TII is responsible for the life cycle asset management of all Luas infrastructure and rolling stock, but the light rail network is operated and maintained under a Service Level Agreement by Transdev.

Greenways and Cycleways

In September 2021, TII received written Direction from the Minister for Transport, passing responsibility to TII for the management and delivery of the relevant Greenway programme, including as "Approving Authority" under the Public Spending Code. Greenways and cycleways are essential as we move towards a more active lifestyle, supporting not only increased positive mental and physical health benefits for Irish citizens but also to support Ireland's net zero carbon emissions targets by 2050. Under the National Development Plan 2021 – 2030 (2021), 20% of the transport capital budget is committed to active travel in order to support this.

Land

TII manages large sections of soft landscaping adjacent to national roads and the light rail network (TII Adaptation Strategy, 2022), which includes turf, trees, grass, shrubs and flowers. TII oversees approximately 3,500 ha of transport corridor and roadside landscapes and has agreements in place with local authorities, who are the owners of the land, to maintain it appropriately. TII recognises the potential for operations to impact biodiversity and has developed a biodiversity plan and is committed to reducing and removing negative impacts (TII Biodiversity Plan, 2023).

Buildings

Building assets generally associated with the transport network, typically the road and light rail asset groups, are maintained by TII and a number of other entities. TII is directly responsible for its headquarters in Dublin and a number of depots throughout the country.

People

TII is responsible for all its workforce staff members, but also has a commitment to people working for and with TII, such as those within its supply chain, local authorities, and others responsible for developing, operating and maintaining the networks. In the case of severe weather events and disruption to the networks, people will be impacted in various ways, through transport delays, but also through increased work hours and the wellbeing of staff who may be out on site in adverse weather conditions in order to return service to normal operating functionality.

2.2 How Climate Hazards Impact on TII Assets

Using the process proposed in the Sectoral Adaptation Planning Guidelines (DECC, 2018) developed through the Climate Ireland programme, which was intended to support a consistent approach to sectoral adaptation planning in Ireland, TII has begun developing methods to better understand the risks to TII's networks from climate change, in order to be able to develop appropriate adaptation plans. (Figure 2.2).

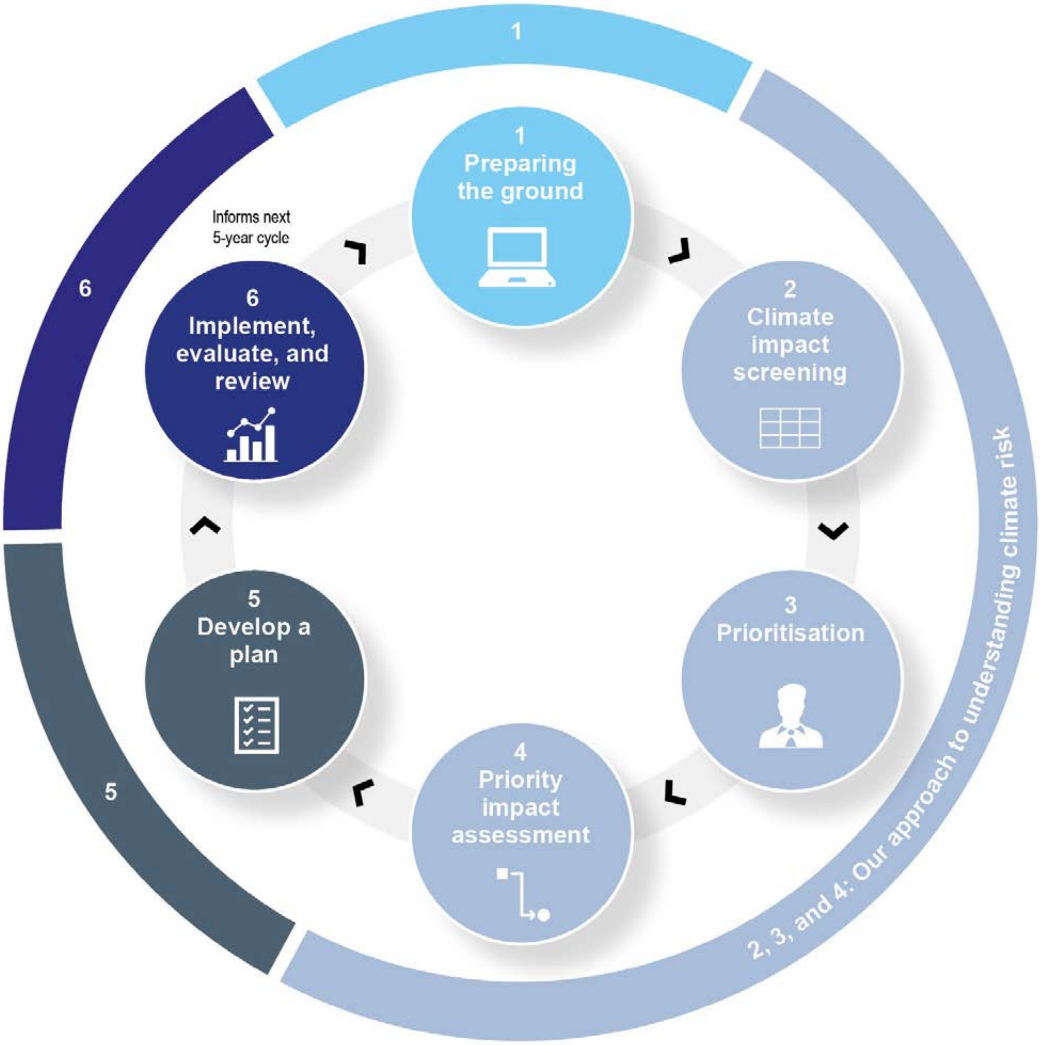

Figure 2.2: Diagram of TII's six stage approach to climate adaptation (TII Adaptation Strategy, 2022)

Assets can be impacted by climate hazards (described in Appendix 1) in a number of ways, including disruption of the use of the network (e.g., congestion and delays), physical damage to the network and impacts to the safety of those using or working on the network. The case study outlined in Box 2.1 highlights the effect that flooding can have on the network and the potential knock-on impact on the surrounding communities.

An initial qualitative climate impact screening has been carried out by TII on the vulnerability of the network to various climate hazards (TII, 2023a). This climate impact screening represents Stage 2 of TII's climate adaptation approach and aligns with the approach and processes set out in TII´s technical guidance in ´Climate Guidance for National Roads, Light Rail, and Rural Cycleways (Offline & Greenways) -Overarching Technical Document PE-ENV-01104´ (TII, 2022a) and ´Climate Assessment of Proposed National Roads – Standard PE-ENV-01105´ (TII, 2022b). These documents aim to ensure that climate adaptation (and mitigation) is considered in all new projects/schemes, which is a requirement for the national roads network (i.e., PE-ENV-01105). The climate impact screening outlines the vulnerability of the different asset categories by breaking down the process into 3 steps: (i) a sensitivity analysis (i.e. how sensitive a particular asset is to a climate hazard) and (ii) an exposure analysis (i.e. how likely the climate hazard is likely to occur) which when combined, provide (iii) a vulnerability assessment.

Sensitivity was calculated by reviewing how assets have historically performed when exposed to the climate hazards. TII guidance set out an initial list of assets and hazards to consider, but performance of assets under different weather hazards came from expert judgement and experience from other infrastructure owners and countries, alongside TII asset managers. The sensitivity of many of the different asset groups will vary, depending on asset age, characteristics and design standards (i.e., whether assets have been designed to modern standards and have factored in climate change). These issues will be considered further during the detailed risk assessment process. A limitation of this assessment is that if no previous relationship exists between a hazard and an asset (or if the relationship is based on limited information) then future inferences from some climate hazards cannot be drawn accurately. Exposure was calculated by assessing both the current and future exposure of assets to climate hazards. For current exposure this was calculated based on how often asset thresholds were exceeded. For future exposure, two climate scenarios were used: 2050's medium to low emissions and 2050's high emissions. Projections for these scenarios were applied to the network and once again based on how often climate limits (derived from qualitative data) were likely to be breached, exposure at a national level was calculated.

Case Study - Luas Substation Flooding

Description: Following severe weather in July 2013 a Luas substation was flooded by a nearby overspilling river. The water exceeded the capacity of the water pumps installed on the site and it took around a week for the site to be completely drained. Due to the existing redundancy, wherein each line was able to operate with one substation switched off, the Luas system was able to keep running with only minor disruption. However, it was 18 months before the substation was restored. During this time there was no redundancy for the Green Line substations and ordinary maintenance was more difficult to perform.

Flooding on Jones Road in Dublin. Pic: John Courell

The event highlighted three key issues:

- The substation flooded despite being raised above the normal flood elevation. This was reportedly because the flood event was more severe than previously experienced (a 100-year flood) and because the position of the substation in relation to the surrounding ground had not been considered, water was channelled along the tracks and into the vicinity of the substation.
- Substations are highly vulnerable to flooding if the water level exceeds the structure's elevation. This then has the potential to disrupt the entire line.
- During the initial response to the flooding, it was believed that the fire brigade had taken control of the area to pump water from the substation. This was not the case, and the response was therefore delayed.

In response, measures were put in place to prevent a similar event occurring again. These included:

- Changing standards for substations to ensure they are designed for a 100-year event and can survive a 300-year flood event.
- The installation of flood protection walls and improving pumping capabilities for all substations.
- Improved interfaces with the emergency services to improve the response to similar issues. Since this event occurred, no similar flooding of a Luas substation has taken place, despite flood events of a similar magnitude having occurred in Dublin.

While this method was used to derive the vulnerability of five of the asset groups, for the asset category 'People', a slightly different method of calculating vulnerability was used. This asset group required consideration of the roles and teams of relevance to TII, a list of climate hazards which may impede workers carrying out these roles and a list of the different working environments.

Following the calculation of the exposure and sensitivity of each of the asset categories from across the five asset groups: light rail, national road, rural cycleways & national & regional greenways, land and buildings, vulnerability was prioritised using a rating system of *low*, *medium* and *high*, with an associated score as outlined in Table 2.1. TII has prioritised a more detailed risk assessment on all those asset categories that scored 6 or above and were rated as highly vulnerable. Assets that scored 2 or less and were rated with low vulnerability have all been placed on a watching brief and will be reviewed at each 5-year cycle if there is a significant climatic event or if new information on a hazard should appear. However, assets that scored 3-4 and were rated medium vulnerability, were split into those that would be taken forward for a more detailed risk assessment due to the potential level of disruption, damage or safety impacts that could ensue if they were impacted (score 4) and those that would be placed under a watching brief (score 3). It was also deemed prudent for some of these assets and hazards to have separate/additional research commissioned to better understand how they might be impacted by specific hazards.

Table 2.1: Vulnerability Rating for TII assets

Vulnerability = Sensitivity X Exposure		Exposure		
		Low (1)	Medium (2)	High (3)
Sensitivity	Low (1)	1	2	3
	Medium (2)	2	4	6
	High (3)	3	6	9

Score	Rating
1	Low
2	Low
3	Medium
4	Medium
6	High
9	High

2.3 Influence of Transport Asset Management on Climate Indicator Selection

While all of TII's assets are important, the national road network in particular is critical infrastructure for Ireland, with it being the main mode of transport for a majority of the population. It is absolutely critical for social links in rural areas, particularly in the case of lifeline roads, as many people have no other options for transport. The roads network also carries 99% of land freight and is essential for the economy and growth (Moran and Campbell, Spending Review, 2021). Protection and renewal of the national roads network already represents a large annual expenditure for TII, representing approximately 70% of the annual roads budget. However, as the population continues to grow, increased travel demand will lead to further use and consequent degradation. This, alongside aging assets and the expected climate impacts to the road network will require a significant investment to ensure the roads network is maintained and improved to allow for safety and connectivity.

TII´s national roads assets have current winter thresholds, set out in the winter maintenance plan, by which weather events/hazards trigger specific operational responses that are intended to limit the impact of such events. These thresholds are derived from Met Éireann severe weather warning information. Severe weather reports follow a severe weather event and describe the location and impact of an event.

Typically, every region should have a severe weather plan in place, however, the level of monitoring varies across the country, as it is often carried out by different organisations (e.g., local authorities, PPS, MMaRC contracts, etc.) who operate or own the affected assets. While TII monitors specific assets, the information that is collected differs between and within asset groups. There is currently no standardised approach to data collection, with some information such as light rail maintenance expenditure, collected and collated by an operator and protected by service level agreements (SLA's). This makes it difficult to determine how specific asset groups have been and will continue to be impacted by different hazards.

2.4 Priority Climate Hazards and Related Transport Assets

An initial vulnerability assessment and prioritization was carried out for each asset category, under national roads, light rail, rural cycleways & national & regional greenways, land, buildings, and people. An example of the outcomes of this process for the asset category drainage, under the asset grouping roads, is shown in Table 2.2. This shows that drainage assets on roads is considered highly vulnerable – with a score of 6 or higher- across a number of climate hazards (i.e., flooding, drought, engineered slope failure, coastal erosion). Although a number of other hazards were evaluated, vulnerability to these is found to be currently low. Whie these findings are draft and subject to change by TII they provide baseline knowledge on the vulnerability of assets to severe weather events.

Table 2. 2: Initial draft findings of Climate impact screening on asset category drainage for the roads network

Asset Category – Road Drainage	
Climate Variable	**Vulnerability Score**
Flooding (coastal) - including sea level rise and storm surge	6
Flooding (fluvial / river)	9
Flooding (pluvial / surface water)	9
Flooding - groundwater (driven by low intensity, prolonged rainfall)	6
Extreme heat	6
Extreme cold (including freeze-thaw cycles)	6
Wildfire	2
Drought	6
Extreme wind	2
Lightning	2
Hail	2
Natural landslides	3
Engineered slope failure	6
Fog	2
Coastal erosion	6

Based on TII's climate impact screening and prioritization process (Table 2.3) the prioritization of each asset group across all asset categories (collectively) to the climate variables identified during the initial risk assessment has been determined. Flooding is by far the most significant hazard facing TII, with all asset categories rated highly vulnerable to pluvial and fluvial flooding. The asset categories national roads, light rail, rural cycleways & national & regional greenways and land were also found to be vulnerable to engineered slope failure, something that flooding can contribute to through structural damage, submersion and scour. Engineered slope failure is an extremely difficult hazard to predict and ARUP are working with University college Dublin on the *GEOTECS Project* to develop tools that are capable of monitoring the condition of infrastructure slopes, specifically for the transport network and how climate may affect this across the network.

Extreme heat is also a cause for concern across all asset groups, and while wildfire is only considered as a priority hazard for the asset groups land and people, it is expected to become more severe in Ireland in the future, as extreme heat periods increase in frequency. Lightning is a low priority across all asset groups, while, with the exception of the asset grouping people, fog and hail are also low priority climate hazards. Overall, based on the number of times high vulnerability for an asset category was identified within an asset group, there is a slightly higher level of vulnerability for the asset groupings of land and people, which are highly vulnerable to almost half of the climate variables identified.

Table 2. 3: Prioritization across asset groups following vulnerability scale outlined in Fig.2.3 (divided cells show where asset groupings are equally split between 2 prioritization ratings, while greyed out cells show no data)

Climate Variable	Asset Group					
	Road	Rail	Greenway	Land	Buildings	People
Flooding (coastal) - including sea level rise and storm surge						
Flooding (fluvial / river)						
Flooding (pluvial / surface water)						
Flooding - groundwater (driven by low intensity, prolonged rainfall)						
Extreme heat						
Extreme cold (including freeze-thaw cycles)						
Wildfire						
Drought						
Extreme wind						
Lightning						
Hail						
Natural landslides						
Engineered slope failure						
Fog						
Coastal erosion						
Increased annual average temperature						

TII supported by their consultants ARUP are currently in the process of carrying out a more detailed risk assessment. This will identify current thresholds and test them against future scenarios, allow for spatial analysis of the expected impact on the different asset groupings across the network and a more granular understanding of the exposure of assets to specific climate hazards. This will in turn allow for more detailed risk metrics to be collected and will inform the development of an adaptation plan for each of TII's asset groups.

2.5 The Need for Adaptation indicators in the Transport Sector

Much of the transport infrastructure requires a significant level of investment and planning as it is long-lived and influences how the country will develop. TII took part in this co-creation study with MaREI, the Environmental Protection Agency (EPA), Department of the Environment Climate and Communications (DECC), and the Department of Transport as one activity in its planning for these future climate impacts, which as previously outlined can potentially have devastating consequences on the transport network and simultaneously on Ireland′s other critical infrastructure, society, economy and the environment. The establishment of a suite of indicators that are most relevant for TII is necessary for long-term strategic planning to ensure a coordinated approach to climate adaptation for the sector.

Although the Department of Transport carried out a sectoral vulnerability assessment of impact chains in 2019, which highlighted a number of climate impacts to the transport network (Appendix 1), TII's climate impact screening has provided a more detailed assessment of asset categories and groupings, something that will be built upon in the detailed risk assessment that will ultimately inform the development of an adaptation plan and the measures necessary to adapt the network appropriately. Common impacts identified in both the TII climate impact screening and Department of Transport risk assessment include flooding, precipitation and storm surges, but there are also a number of differences. High temperatures in particular were identified by TII as a high priority in a majority of the asset categories across all asset groupings, however it is rated as only moderate risk in the Department of Transport assessment (Figure A1.2). This may be due to the fact that it is an emerging issue rather than a long-established one, but it does highlight the need for more in-depth impact analysis in the transport sector and also in other sectors.

2.6 International Experience of Relevance to Transport Sector

Across the world, countries are highlighting the need for an indicator suite to monitor, evaluate and report on climate adaptation for different sectors. Work has already begun in the UK, Finland, Austria, Spain, Slovakia, Germany, France, as well as many others, and in Ireland the work of Flood et al. (2021) has identified a suite of climate resilience indicators that are used here as a baseline for the development of the adaptation indicators for TII.

Some countries that have comparable climates to Ireland have already begun the process of selecting adaptation indicators for the transport sector and three case studies, from New Zealand, Scotland and Australia, are outlined in Appendix 2. Their experience can help inform the adoption and implementation of climate adaptation indicators for Ireland.

3. ADAPTATION INDICATORS

3.1 Overview of Adaption Indicators for Ireland

In 2018 Kopke et al. carried out one of the first desk-top studies in Ireland on climate adaptation indicators. It was based on an analysis of international best practice at the time. In the report a suite of 70 adaptation indicators were proposed for local authorities and the agriculture and marine and fisheries sectors. An additional 197 indicators were proposed for a number of other sectors. That report also recommended engagement with stakeholders at all levels of indicator development and implementation and furthermore testing and refinement of the adaptation indicator development process outlined in the report.

Flood et al., (2021) built on this work by reviewing international best practice and carrying out stakeholder engagement across Ireland. This process enabled identification of a typology of four climate change adaptation indicator types (Figure 3.1) that were comprehensive but not overcomplicated, and specific to Ireland. These four types are defined in the report as follows:

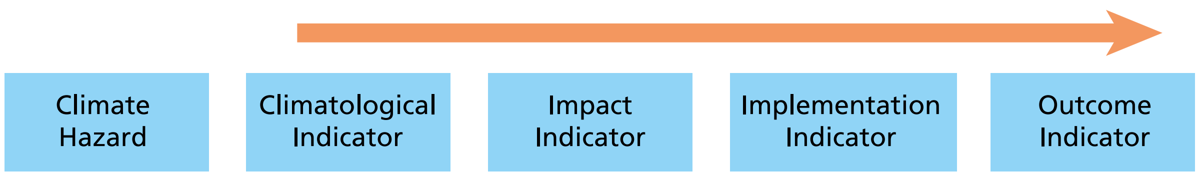

Figure 3.1: Climate change adaptation indicator typology (from Flood et al., 2021, Figure 2.2)

1. Climatological indicators capture information about observed climatic conditions – e.g., temperature, rainfall and extreme events;
2. Impact indicators capture information about the observed impacts of climate variability and change on socio-ecological systems – e.g., number of properties damaged due to floods;
3. Implementation indicators provide information to help track the implementation of adaptation actions or strategies, and
4. Outcome indicators provide information to help track the outcome or results of adaptation actions or strategies.

This typology was applied to the possible metrics that could form an adaptation indicator suite for Ireland grouped under three major sets of climate hazards: (1) pluvial and fluvial flooding; (2) extreme events (extreme heat, extreme wind, drought and frost); and (3) coastal flooding and erosion. These hazards were deemed to be priority following consultation with relevant stakeholders across different sectors and local authorities in Ireland. The outcome from the co-design process was the identification of a suite of 127 recommended indicators – 15: climatological, 23: impact, 32: implementation and 21: outcome.

Among the recommendations of that study was one that stated an agreed subset of the indicators should be implemented in a pilot study. This is the work that is the subject of this report.

3.2 Data Sources to Inform the Indicators.

Robust and reliable data are vital to ensure that indicators can be calculated. Such data may be a combination of spatial and non-spatial and be quantitative and qualitative in nature. The spatial scale of the data to be employed for indicator calculation should be appropriate – often the challenge is in securing good quality data at local scale. Issues of data availability, data sources, data ownership, data quality, etc. are highlighted in Flood et al., (2021) and underpin the ability to generate climate adaptation indicators. The tables presented in appendix 3 include a qualitative estimate on the level of availability of data for the proposed indicators and also identify a potential data source.

Resources are required to ensure data on the condition of assets and their climate risks are collected. There needs to be a consistent approach across networks and it needs to be carried out methodically with relevant KPIs and contractual obligations where necessary. It should be noted that in the case of TII that ownership and contractual requirements vary across and within its networks.

Regarding the climatological indicators presented in section 3.3, data availability is an issue that is currently being tackled through the Met Éireann funded TRANSLATE project (see Appendix 4) which has worked to provide projections of future climate hazards as well as to standardize current datasets for sectors to use. This work will continue through TRANSLATE 2 and will provide additional data that will be useful for sectors.

3.3 Potentially Relevant Adaptation Indicators for the Transport Sector

An initial screening, by MaREI, of the Flood et al., (2021) indicator suite identified 52 indicators of potential relevance to the transport sector, namely the road and rail (including light rail) infrastructure. These indicators were distributed across the four different categories as shown in table 3.1.

Table 3.1: Number of adaptation indicators of relevance to the transport sector identified under each of the categories described in the Flood et al., (2021) report.

Indicator Type	Number
Climatological	11
Impact	12
Implementation	15
Outcome	14

The specific indicators in each category are presented in appendix 3, with an indication of data availability and potential data sources. These tables, with additional detail, were shared with TII for initial review in order to identify indicators that could be adopted by them for implementation in relation to the road and light rail assets under their management. The process and subsequent steps are the subject of the next chapter.

4. CO-DEVELOPMENT AND SELECTION OF INDICATORS WITH TII

4.1 Co-development Process

There is no standard definition of co-development or co-creation, which is also known as co-design. Nonetheless there are certain characteristics which are common to a co-development process (Vincent et al., 2018).

- Oftentimes, it is a non-linear process of thinking and creation that is applied to address complex problems that requires the combined effort of multiple stakeholders.
- It involves the recognition of different knowledge, and it can lead to the production of new knowledge.
- It involves collaboration between different actors, is founded on trusted relationships and is a social learning process.

Three principles identified by Vincent et al. (2018) as fundamental to the co-development process are collaboration, inclusivity and flexibility.

Moser (2016) identified a range of benefits of co-design, based on an analysis of 16 research projects that implemented a co-design methodology. Some of these benefits included:

- research collaboration,
- enhanced understanding of the topic in question,
- improved communication,
- more relevant outputs, and
- greater trust between partners.

Nonetheless, co-development is not without its challenges. It is time-consuming and it involves many rounds of meetings and interactions. It is necessary to find a common language; it is necessary to maintain enthusiasm and engagement with the process and it needs to be well prepared and planned to be most effective. All parties need to be committed, allocate people, time, financial and other resources and there is a need for flexibility throughout the process, as exact results cannot be predicted. Another issue that may occur in a co-design process is that if the decisions ultimately made have implications for one or more parties involved in the process, there may be a reticence to be ambitious and to make choices that may require significant additional work, changes to work practices or the need to explore or develop new approaches to achieve the identified aims.

This co-development process emerged from previous engagements TII had with MaREI on climate adaptation work. TII recognised the need to look towards identifying and implementing a set of climate adaptation indicators within their processes. However, the focus of current work has been on improving understanding of potential climate risks, which is a necessary pre-cursor to work on identifying and selecting relevant indicators. Based on the work reported in Flood et al., (2021) MaREI and TII agreed to collaborate on an activity around indicators. The work started in the middle of 2022. An initial set of potentially relevant indicators were extracted from the Flood et al., (2021) report and shared with TII (and ARUP) for initial comment. Discussions ensued and, in the Autumn of 2022, it was agreed that TII needed to engage its networks operations division which ultimately would be responsible for the collection of data to inform the climate indicators and subsequent reporting. Therefore, no further collaborative work was done on the activity until the spring of 2023, following the publication of the Climate Action Plan 2023 (DECC, 2022), TII's Climate Adaptation Strategy in December 2022 and the agreement of Climate Ireland's workplan (2023) as outlined in Section 1.1.

The process has involved sharing of written information and reports both from MaREI to TII and vice-versa. It has also involved numerous virtual meetings. These have focused on building understanding of TII's needs, clarifications in relation to what climatological indicator data may be available (primarily from the Met Éireann funded TRANSLATE project), discussions on TII's climate impact screening, technical discussions on specific potential indicators, existence of and access to data and metrics to inform the indicators, issues of scale and granularity of indicators and updates on progress. There have also been meetings with other stakeholders including the EPA, DECC and the Department of Transport, which have been helpful in contextualizing the activity in relation to national developments and timelines such as the development of a new NAF and associated guidelines.

The benefits of the co-development process to date can be identified as:

- Better understanding of TII's remit, processes and needs in relation to indicators, as well as the variation in the ownership and management of its assets, e.g., national roads managed through a mix of PPPs, MMaRC, or local authorities with different associated contracts,
- Better understanding of issues related to indicators needed for design and maintenance of transport infrastructure compared to national scale indicators needs for high level reporting,
- Clarity on climatological indicator needs and how ongoing related projects (e.g., TRANSLATE, FLARES-PPLUS) may be able to provide some useful data,
- An understanding of operations and processes within TII and how these can impact on the data and information required to inform potential indicators,
- Clarity on the positioning of this work in relation to national needs,
- Building of trust between participants and development of good working relationships.

The process of co-development has been generally smooth over the course of the activity, nonetheless the main challenges identified are in relation to identifying clear expectations, outcomes, roles and responsibilities. Nonetheless, regular interactions between the parties have ensured that these issues have been overcome. In addition, there has been a need to ensure that networks operations divisions within TII are supportive of the indicators being proposed, therefore this has required additional input and feedback which extends the time required.

It is noted that the information and data available from TII alongside the various processes and assessments are being constantly updated. For example, a detailed climate risk assessment has yet to be undertaken, which may identify new risks that need to be considered in relation to indicator development. Also, there are continuous updates to asset data (e.g., asset management systems), asset operations contracts, TII standards and guidance and training which will allow relevant information to be collected to inform the indicators.

4.2 Indicator Selection Methodology

A pre-requisite to indicator identification and selection is the completion of the climate impact screening step of the adaptation planning process. In the case of TII, it has helped to understand what key asset-hazard vulnerabilities exist. This facilitates their prioritisation for more detailed assessments which will ultimately support the development of climate adaptation plans. It is important in this step that future and emerging hazards (e.g., extreme heat and wildfires) and vulnerabilities are also considered, as historical occurrences may not be sufficient to account for the increasingly frequent and severe future impacts related to the identified climate hazards.

Based on the outcomes of this analysis it was possible to carry out an informed evaluation of the initial indicator list, which was provided by MaREI to TII, based on the Flood et al. (2021) report (cf., section 3.3). The evaluation focussed on the climatological and impact indicators in the first instance, as implementation and ultimately outcome indicators are dependent, in particular, on the impact indicators selected. During this evaluation, the indicators were discussed, clarifications sought and ultimately it resulted in the indicators being assigned to one of four possible categories:

- **Relevant as is:** the proposed indicator was deemed to be relevant and useful as described,
- **Relevant with modifications:** the proposed indicator was deemed relevant but needed to be modified or fine-tuned in order to be fit for purpose,
- **Rejected in current form:** the proposed indicator was deemed to be not relevant, or useful or implementable or needed to be reformulated before additional consideration,
- **New Indicator proposed:** where certain hazards were not fully addressed in the initial indicator list or where a certain vulnerability did not appear to be properly addressed a new indicator was proposed.

Table 4.1 provides an example of an indicator from each of the above categories to illustrate the process.

Having identified a potential set of indicators, there were further discussions in relation to measurement units, data required and their availability to calculate or inform each indicator, the need to generalise or aggregate indicators to identify versions that would be appropriate for national reporting and ultimately a prioritisation of the indicators. TII will need detailed metrics to monitor progress of the adaptation of their assets and network resilience to climate change impacts. These metrics will feed into the high-level indicator reporting by being aggregated up to show the complete impact and subsequent measures of overall adaptation progress by TII across its national networks.

Another challenge is related to attribution of an impact to a climate related event. Some impacts may be acute (e.g., a flood following heavy rainfall leading to bridge scour or erosion of an embankment). Others may be chronic (e.g., cyclical freeze-thaw events, often over multiple-seasons, contributing to deterioration of a road pavement). In addition, there are compound impacts where multiple processes contribute to the outcome. For example, a deterioration in road pavement condition could be partly due to severe weather events (e.g., freeze-thaw cycles leading to road pavement cracking and rainwater infiltration), but also the amount and type of traffic, the materials used to build the road and its general state or level of maintenance may all be compounding factors.

Table 4.1: Examples in each of the four categories by which indicators were evaluated.

Category	Indicator	Remarks
Relevant as is	Number of very wet spell days (days with rainfall > 30mm)	Sub-daily rainfall extremes would also be useful to understand potential inundation of drainage which is designed to specific sub-daily extremes.
Relevant with Modifications	Traffic Disruption to road network as a result of climatic factors/events	Amalgamates a number of issues into one high level indicator.
Rejected in current form	Percentage of river embankments including height to protect against future flood risk	This might incentivise the construction of embankments across the network, with a higher carbon cost, compared to taking more nature-based and landscape/ catchment-based approaches to flood risk management.
New Indicator Proposed	Extreme cold	Frost days (< 0°C) may not be an issue but temperatures below -5°C or -10°C will have physical impacts on roads.

4.3 Indicators Shortlisted

Through the co-development work an initial set of potential climatological and impact indicators were identified. These address the national roads under TII's remit and the light rail network. Once agreement on these potential indicators was reached, work moved on to determining a set of potential implementation and outcome indicators. Further consideration of the possible hazards that could impact rural cycleways and national and regional greenways, land and people is necessary to determine relevant indicators for those assets. Once a detailed climate risk assessment has been undertaken, TII will be better positioned to address potential indicators for these assets, hence they are not addressed in this report.

The indicators are presented below as a set of summary tables of indicator names associated with each hazard identified. A brief description of each indicator is provided along with the relevant measurement units. Data sources to enable determination of each indicator are also provided (e.g., Met Éireann, MÉRA reanalysis, TRANSLATE data, etc.).

It should be noted that these are a set of potential indicators. In many cases, the data does not currently exist or is not accessible to TII to allow calculation of robust indicators. However, there is an intention to put in place processes that would ultimately allow their determination.

Climatological Indicators

A total of 19 climatological indicators were identified (Table 4.2). Six of these are based on precipitation; four are based on temperature; three are based on wind; three are based on flood extents and three are composites (storms, fire risk and extent). The indicators identified here would be calculated based on climatological data coming from sources external to TII. These indicators will help TII understand their current vulnerabilities, their operation and maintenance responses and could be used to support decision making in relation to asset design, maintenance and operations for any future climate hazards that TII might face.

Table 4.2: Climatological indicators identified including a description and potential data sources to inform the indicator. The key climate hazards that each indicator addresses are also shown.

Indicator	Description/Measurement units	Source
Number of very wet days ● Pluvial/Fluvial Flooding ● Engineered slope failure and natural landslides	A wet day is defined as one during which there is more than 30mm of rain in a 24-hour period. This could be aggregated per month/year	Output from the TRANSLATE project.
Maximum consecutive 5-day precipitation ● Pluvial/Fluvial Flooding ● Engineered slope failure and natural landslides	Daily precipitation is summed into 5-day cumulative bins	Output from the TRANSLATE project
Total Annual precipitation ● Pluvial/Fluvial Flooding	Total precipitation in a given year	Output from TRANSLATE project
CFRAM River Flood Extents (Medium) ● Pluvial/Fluvial Flooding	Modelled extent of land that might be flooded by rivers in a severe flood event with a 1-in-a-100 chance of occurring or being exceeded in any given year	OPW river flood extent modelling database for Ireland
Number of hot days Extreme Heat	Days with max. daily temperature above given thresholds for assets on the network	Output from the TRANSLATE project
Heatwave days (where heatwave is at least three consecutive days of daily max temperature above 90th percentile) ● Extreme Heat	Consecutive temperatures above given thresholds for assets on the network	Output from the TRANSLATE project
Meteorological Drought ● Extreme Heat	A dry spell is a period of 15 or more consecutive days with less than 1 mm of rainfall. An absolute drought is a period of 15 or more consecutive days with less than 0.2 mm on each. A partial drought is a period of at least 29 consecutive days with a rainfall total averaging less than 0.2 mm of rain per day.	Output from the TRANSLATE project
Extreme wind speed days ● Extreme Wind	Days with max. daily wind speeds above given thresholds for assets on the network	MÉRA reanalysis data combined with historical observational data available from Met Éireann

Indicator	Description/Measurement units	Source
Gale Gusts Days ● Extreme Wind	Days with daily wind gust speeds above given thresholds for assets on the network	MÉRA reanalysis data combined with historical observational data available from Met Éireann
Daily Mean wind speed ● Extreme Wind	Days with average daily wind speeds above given thresholds for assets on the network	MÉRA reanalysis data combined with historical observational data available from Met Éireann
Extreme cold ● Frost and extreme cold	Days with max daily low temperatures beyond given thresholds for assets on the network	Output from the TRANSLATE project
Freeze-thaw ● Frost and extreme cold	The frequency of diurnal cycles of temperature above and below 0 degrees Celsius.	It may be possible to calculate this for some weather station historical records and MÉRA reanalysis data. Output from TRANSLATE project may also be used.
CFRAM Coastal Flood Extents (Medium) ● Coastal flooding and erosion	Modelled extent of land that might be flooded by the sea in a severe flood event, with a 1-in-a-200 chance of occurring or being exceeded in any given year.	OPW coastal flood extent modelling database for Ireland
Coastal storm events ● Coastal flooding and erosion	Number and height of coastal storm events (linked with coastal surge) within set parameters	Met Éireann Major Weather Events and Marine Institute Weather Buoy Network
Soil moisture deficit ● Engineered slope failure and natural landslides ● Groundwater Flooding	An indication of ground saturation. Values of >75mm indicate drought conditions and possible cracking/ subsidence, while values of -10mm indicate waterlogged ground and therefore potential for ground flooding and slippage.	Met Éireann historical data should be available based on observations at their weather stations. Should also be possible to calculate based on TRANSLATE outputs
Groundwater Flood Maps ● Groundwater Flooding	Maps showing the probability of a flood event occurring in any year assuming current climate conditions	GWFlood Project - GSI groundwater flooding probability and historic flood maps
Number of heavy snowfall days Snow	Heavy snowfall above given thresholds for assets on the network in a 24-hour period. This could be aggregated per month/year	It may be possible to calculate from outputs from TRANSLATE project
Fine fuel moisture code ● Wildfire	Fine fuel moisture code from 0 to >80 (condition green 0<50, condition yellow 50<70, condition orange 70<80, condition red >80). Daily fire risk is calculated based on data for some weather stations.	Met Éireann outputs from historical data
Wildfire projection maps ● Wildfire	Spatio-temporal distribution of fire projection using satellite data	Such data are not yet available. They are an expected output in 2025 from the currently EPA funded FLARES-PPLUS project

Impact Indicators

The impact indicators listed in table 4.3 have been informed by the climate impact screening carried out by TII. A challenge with impact indicators is to develop an understanding of what is driving asset deterioration and conditions from a particular metric, as the loss of performance of an asset will likely not be solely as a result of climate, but rather a combination of climate, design, construction, material properties and usage factors. During discussions it was agreed that some of the potential indicators initially suggested (Table A3.2) could be rationalised and combined to provide a higher-level indicator. Rather than defining individual impact indicators for each hazard separately (e.g., flooding, heat, cold, etc.), composite indicators are defined that combine the effects of all potential climate hazards. These were deemed to be more feasible to implement and more useful for national level reporting. A total of five impact indicators were identified, three related to the national roads network and two related to the light rail network.

Table 4.3: Impact indicators identified including a description and potential data sources to inform the indicator.

Indicator	Measurement units/Description	Source
Roads		
Traffic Disruption to road network as a result of climatic factors/events	Hours of (full or partial) closure or traffic restrictions on critical road network sections, due to risk, occurrence and remediation due to climate events aggregated to national level (annually)	TII will review how such information can be collated for national road network sections managed under MMaRC contracts.
Risk to road users as a result of climatic factors/events	Number of collisions above and beyond the average, during a climatic event	TII is examining methodologies for the collection and analysis of data to quantify this metric
Maintenance cost of roads due to climatic factors/events	The cost in Euros (or % of overall annual TII budget) of repairs to roads impacted by climatic factors/events (as annual amounts).	This information is currently not available. TII will review whether such information could be accessed and quantified for the managed road network (MMaRC contracts).
Light Rail		
Disruption to rail as a result of climatic factors/events	Km's lost due to (full or partial) closure or restrictions to critical light rail network sections, due to risk, occurrence and remediation aggregated to network level (monthly/annually)	TII collect outages, not as hours but as km's lost (that is the KPI)
Maintenance cost of rail due to climatic factors/events	At the moment amount spent on existing light rail maintenance is difficult to measure quantitatively, as TII do not have sight of costs/hours/resources consumed in performing it	This information is currently not available. TII will review how such information can be collated for the light rail network. Modifications to SLAs would be required.

TII's position is that it is currently not possible to determine maintenance costs due to climatic factors/events with regards to light rail, as the operation and maintenance of the network is subcontracted to an external entity, Transdev, under a fixed-cost Service Level Agreement. To inform metrics for such an indicator, the conditions of future contracts would need to be analysed and potentially modified in order to determine what relevant information could be provided by the system operator to TII to inform the calculation of an indicator that can be used for national reporting.

Implementation Indicators

Having refined the climatological and impact indicators, MaREI identified a tentative list of implementation indicators. These were discussed with TII via multiple meetings and email exchanges and were subsequently refined and adapted further. Table 4.4 represents the list of indicators agreed as being potentially feasible. However, it is important to note that in many cases processes (e.g., data collection and access) at TII are not yet in place, or sufficient resources are lacking, to be able to report on these.

In relation to roads, TII's position is that it is currently not possible to identify infrastructure that is to be improved or maintained solely due to (potential) impacts of severe weather events. Road pavement improvement and maintenance priorities are currently decided on the condition, condition modelling and deterioration of the road pavement, irrespective of the cause of degradation. Also, information on severe weather management plans held by local authorities is not reported to TII. It is the Department of Transport which is responsible for leading the National Emergency Group, which TII supports, as necessary.

For the light rail sector, as its operations and maintenance are outsourced, TII does not have sight of the actual costs, hours, and resources consumed in carrying out tasks that may be related to climate change adaptation measures. It is recommended for the next contracting cycle that ways in which some, or all of these metrics could be identified via changes in tender conditions be explored, in order to make information related to such interventions available.

Regarding the cross-cutting actions, projected climate scenarios are currently not used by TII in modelling for development of strategic plans. Nonetheless, as robust climate change projections become available (e.g., TRANSLATE), TII will endeavour to embed these into its long-term planning. Capacity building initiatives already take place as it is important that everyone is aware of potential climate impacts and how best to respond to them. However, a measure of number of events or number of staff involved in such initiatives was deemed not to be a useful measure. What is critical is that those in strategic positions, with decision making powers, are appropriately informed about climate change adaptation and issues of relevance to the transport sector.

Table 4.4: Implementation indicators identified including a description and potential data sources to inform the indicator.

Implementation Indicator	Measurement units/Description	Source
Roads		
Proactive Road Maintenance to decrease impact of climatic factors/events	Number of bridges/kms of roads that have maintenance to reduce impacts of climate hazards/events	TII is reviewing how such data for this metric can be collated.
Severe weather management plans account for present and increasing climate risks and impacts	Severe weather management plans regularly updated to include adaptation parameters (update frequency)	Information can only currently be collated by TII for the MMaRC managed network, however, TII will review how this could be expanded to the wider national road network.
Investment in improving road network resilience to climate hazards	Level of capital investment in new road builds and amount spent on existing road maintenance. The consideration of climate standards in all new schemes	TII is building climate change related aspects in its modelling of pavement asset management.
Light Rail		
Proactive light rail maintenance to decrease impact of climatic factors/events	At the moment difficult to measure quantitatively, as TII do not have sight of costs/hours/resources consumed in performing maintenance	This information is currently not available. TII will examine how this information can be collated for the light rail network. Modifications to SLAs would be required.
Severe weather management plans account for present and increasing climate risks and impacts	Severe weather management plans updated as required based on reassessment of thresholds	TII internal reporting
Investment in improving rail network resilience	Level of capital investment in new light rail schemes; The consideration of climate standards in all new schemes; At the moment amount spent on existing light rail maintenance is difficult to measure quantitatively, as TII do not have sight of costs/hours/resources consumed in performing it	TII will review how to collect and analyse data to determine such a metric in the future.

Implementation Indicator	Measurement units/Description	Source
Cross-Cutting		
Risk assessments used to identify locations that could be impacted by climate hazards	Detailed climate impact screening metrics across all asset groups inform an adaptation strategy/action plan and reviewed and updated at regular intervals	TII will review how this data can be collated and managed to determine such a metric in the future.
Climate projections integrated into long-term strategic planning	A range of future climate scenarios modelled to understand future risks to the network and inform asset management	TII will embed climate change projections, as they are further developed, into its long-term planning.
Best practise methodologies for data collection and assessing costs in place to inform climate adaptation	Regular (annual) reviews of data collection processes and procedures to identify information gaps; methodologies for adaptation cost-benefit analysis developed.	TII internal reporting.
Capacity building initiatives related to understanding/managing weather/climate change impacts conducted across the TII network	Level of engagement across the network (internal and external people and asset group divisions and supply chain) to reach milestones and key objectives and build organisational resilience	TII internal reporting
Initiatives that include both mitigation and adaptation benefits developed	Percentage of new initiatives/projects that consider mitigation and adaptation equally/opportunities for co-benefits exploited	All new projects are required to examine mitigation and adaptation according to TII's standards and technical guidance documents. TII will implement, evaluate and review these adaptation measures and will use this knowledge for future projects.

Outcome Indicators

Having refined the climatological, impact and tentative implementation indicators, MaREI also identified a tentative list of outcome indicators. These were discussed with TII during multiple meetings and via email exchanges and were subsequently refined and adapted further. Table 4.5 represents the list of indicators agreed as being potentially feasible. However, it should be noted that as with the tentative implementation indicators, in many cases structures (e.g., data collection and access) at TII are not yet in place, or sufficient resources are lacking, to be able to report on these at present.

These indicators are tentative only and will be subject to change following detailed climate risk assessments which are currently being undertaken by TII. Outcome indicators will only have meaning in a number of years when adaptation measures have been identified and implemented, and trends can be confidently measured. The indicators identified in Table 4.5 will be subject to amendment in line with the results of the impact and implementation indicator reporting, and aligned with TII's Climate Adaptation Strategy (TII, 2022c) and goals for the future in enhancing resilience of the transport network to extreme weather events.

Table 4. 5: Outcome indicators identified including a description and potential data sources to inform the indicator.

Outcome Indicator	Measurement units/Description	Source
Roads		
Changes in road traffic disruption following implementation of climate adaptation measures	Number of bridges/kms of roads that have changed disruption levels from climate hazards/events	Information can only currently be collated by TII for the MMaRC managed network.
Changes in risk to road users as a result of climate adaptation measures	Change in number of collisions during a climatic event, following the introduction of climate adaptation measures	Information can only currently be collated by TII for the MMaRC managed network. TII is examining methodologies for the collection and analysis of data to quantify this metric
Changes in cost of road maintenance due to climate adaptation measures	Changes in capital investment in new road builds and amount spent on existing road maintenance.	Additional costs due to climate change impacts are currently not possible to identify as they are embedded in general costs. TII will explore potential for identifying such costs for the MMaRC managed network.
Light Rail		
Changes in rail disruption due to climate adaptation measures	At the moment difficult to measure quantitatively, as TII do not have sight of costs/hours/resources consumed in performing maintenance	This information is currently not available. TII will examine how this information can be collated for the light rail network. Modifications to future SLAs would be required.
Changes in cost of rail maintenance due to climate adaptation measures	Changes in capital investment in new light rail schemes; At the moment amount spent on existing light rail maintenance is difficult to measure quantitatively, as TII do not have sight of costs/hours/resources consumed in performing it	TII will review how to collect and analyse data to determine such a metric in the future. Modifications to future SLAs would be required.

Outcome Indicator	Measurement units/Description	Source
Cross-Cutting		
Current and best practise data availability for all indicator metrics across asset groups	Regular (annual) reviews of data collection processes and procedures to identify information gaps	TII internal reporting
Relevant staff have appropriate knowledge of the impacts of climate change and are empowered to drive necessary changes across different asset groups to increase resilience	Level of engagement across the network (internal and external people and asset group divisions and supply chain) to reach milestones and key objectives and build organisational resilience	TII internal reporting
Mitigation and Adaptation are always considered in tandem	Processes in place to ensure that all new initiatives/projects consider mitigation and adaptation equally (i.e., TII´s climate guidance and standards enforce this)	TII's standards and technical guidance documents ensure best practice mitigation and adaptation measures

It is expected that the development of TII Climate Adaptation Plans will commence in 2025 which will provide an opportunity to consider the identified indicators in greater detail. The vast majority of impacts to TII's network and asset groups are a combination of factors, including impacts from climate change. These impacts are chronic, and compound and it is TII's position that it is currently not possible to draw out the nuances of damage/costs to the TII network from severe weather and climatic events compared with the general maintenance costs and standard deterioration over time, which is why the implementation and outcome indicators remain tentative. It is only through the process of testing that these indicators will begin to yield valuable results and inform best practice measures for adaptation, therefore a level of flexibility is necessary throughout this process.

4.4 Reporting Process

Objective and Audience

Key questions in relation to reporting concern its objective, the audience for the reports and what outcomes and actions are expected. Answers to these questions will help determine the content and format of the reports on climate adaptation indicators.

The main objective of reporting via a set of climate adaptation indicators tailored for each major economic, social and environmental sector across Ireland is to be able to track progress from a national perspective in relation to implementing adaptation actions but also to allow evaluation of the outcomes of such actions and to avoid maladaptation (Flood et al., 2021). Moreover, such a set of indicators can be used in international reporting and will facilitate comparison with other countries´ actions and progress in relation to adaptation.

The primary audience for national level climate adaptation indicator reports is national government departments. Such information helps them to track progress on activities being undertaken to adapt to climate change and allows for reporting on progress in relation to relevant legislation, such as the Climate Action and Low Carbon Development (Amendment) Bill (2021). Such reports will help to highlight successes, but also challenges and issues in different sectors, and will help with identifying priorities for further government action. This could be in relation to targeted investments, design of new programmes or ultimately the development of new legislation.

Indicator reports allow sectors themselves to evaluate progress in meeting their objectives, identify gaps in implementation and help in prioritisation and allocation of resources. Reports can also help other sectors to measure progress, mutually learn from each other, identify areas where there is a need for collaboration or where there are dependencies. Reports are also of interest to other stakeholders including the public so that they are aware of progress towards climate adaptation goals, and it allows them to engage with decision-makers to support progress or to push for change or additional resources in areas where progress may be slower.

Reporting Considerations

Sectoral departments and agencies already have significant reporting burdens in relation to their activities. One overriding concern highlighted throughout this case-study is that irrespective of how the indicators are reported, the reporting should not generate significant additional work for sectors. The reports should flow from work that is being carried out anyway within the relevant organisations and where possible should utilise information that is already being collected. Ideally it should flow from existing reporting frameworks. Nonetheless, it may need to be packaged and delivered in a certain format to maximise its relevance and usage by the intended audience. The content and formats of reports should be harmonised across sectors , in order to ensure comparability.

The frequency with which reporting of indicators is carried out remains to be decided. Typically, internationally reporting periods are of the order 1 to 2 years, in line with standard time periods for reporting processes at the national level. This periodicity allows time for collation and analysis of data, for any emerging trends to be noted, and should not over burden sectors with excessively frequent reporting.

Reporting adaptation at a national level has the potential to inform national policy processes and development plans, as well as to help Ireland meet reporting requirements under international responsibilities such as the Paris Agreement. While this case study did not extend to a detailed consideration of the reporting of adaptation indicators, international research and case studies from other countries provide guidance on how this process could be carried out.

In comparing the status of different climate adaptation metrics at the national level it is important to consider the sectoral context and alignment of adaptation with specific stakeholder needs (Leiter et al., 2019). Aggregating indicators for reporting at a national level in different sectors cannot be a copy/paste exercise without losing the context-specificity of individual sectoral needs and priorities (Berrang-Ford et al., 2017). Having said that there is a fine balance that must be achieved, between a reporting system that allows for sectoral context and national comparisons and benchmarking. A report evaluating Scotland’s MRE framework for adaptation metrics (Moss, 2017) supports this balance, highlighting that a “one-size-fits-all” approach should not be utilised, but that some key aspects of reporting frameworks need to be consistent to enable effective, efficient and equitable adaptation. To ensure that reporting is comparable across broad themes, adaptation indicators should aim to promote learning and understanding of adaptation, partnership working, include both quantitative and qualitive data and build on existing knowledge, and utilise multiple data sources (Leiter et al., 2019).

5. LESSONS LEARNED

5.1 Prerequisites for Indicator Selection

Lesson 1: Comprehensive climate impact screening and prioritization are required to improve understanding of specific climate hazards affecting a sector before indicators can be considered.

One of the learnings from this project between MaREI, TII, the EPA and DECC was related to prerequisites for adaptation indicator selection. The Flood et al. (2021) report outlines 127 indicators that could be relevant for Ireland, however, in order to begin considering appropriate adaptation indicators within their own remit, TII needed to carry out a climate impact screening to understand better the specific climate hazards they may potentially face, how these are impacting assets now and could impact them in the future.

The initial priority climate impact screening and prioritisation process carried out by TII and ARUP and highlighted in Chapter 2, allowed TII to identify the climate hazards that may impact its assets and networks (Table 2.3). These included variables that had not been previously considered as a serious threat, such as extreme heat and wildfire. The subsequent prioritisation process highlighted potential vulnerabilities of TII assets to various climate hazards and based on the vulnerability score of the asset they have been either placed on a watching brief or will be taken forward for more detailed risk analysis. This prioritisation process is essential to address the vulnerabilities identified in a timely and efficient manner and mitigate potentially the most negative consequences for the sector. While a complete risk assessment is not essential to begin the indicator selection process, a baseline level of information, as derived from the climate impact screening and prioritisation process, is something that will be necessary across all sectors to select the most useful adaptation indicators for the sector and allow for progress in climate adaptation. Screening will need to be reviewed on an ongoing basis, every number of years or if a specific climate impact occurs that was not previously foreseen.

Lesson 2: Ensuring comprehensive engagement with key actors with expertise in different areas of a sector will ensure that vital criteria are not overlooked in the indicator selection and implementation process.

To carry out an effective climate impact screening, TII considered the historical and current impacts of various climatic conditions across its asset groupings. This required information of not only when particular climate events occurred but also knowledge of the various design parameters and thresholds associated with assets maintained by the organisation, and an understanding of where this information is available across all of the organisation. TII carried out comprehensive engagement with those working in all asset groups to develop their initial climate impact screening. TII is currently engaged in developing its approach to asset management, which varies across different assets, (e.g. the Eirspan management system is in place for bridges, and the pavement management system is being developed for national roads, but there is currently no equivalent for geotechnical assets) and are working to standardise data across the network.

5.2 Choosing appropriate adaptation indicators

> **Lesson 3:** The resilience indicators listed in Flood et al., (2021) form a good basis to begin consideration of adaptation indicators. Nonetheless, they require systematic consideration,discussion and revision to meet the purposes of specific sectors.

The categorisation into *climatological, impact, implementation* and *outcome* indicators was appropriate for the needs of TII and these four categories should work well for other sectors in Ireland, with similar elements employed by a number of other countries, as outlined in Appendix 2.

> **Lesson 4:** The number of indicators selected should be kept to the minimum necessary but must be sufficient to capture the key processes and issues within each sector.

To ensure that the number of indicators selected did not become unwieldly, MaREI worked with TII to select 54 of the original 127 indicators that that had been identified as the most relevant for the transport sector. Based on initial discussions the 12 impact indicators presented in table 3.1 were supplemented with five more, bringing the number of potential impact indicators to 17. However, with additional discussion, iteration and consolidation these 17 were reduced to five. Similarly, both the implementation and outcome indicators were considerably reduced in number. This reduction in number and reframing came about due to a number of reasons: (i) multiple detailed discussions took place on the exact definition of each indicator and the most appropriate metrics for its definition; (ii) information and related data are not available within TII for the granular level at which many of the original set of indicators were conceived; (iii) for national reporting dozens of similar indicators, mainly nuanced by the type of hazard involved is not appropriate; (iv) if such a scheme were to be proposed across sectors, it would results in hundreds if not some thousands of indicators, which would be unwieldy and ineffective for decision making.; (v) discussions with other jurisdictions (e.g., Scotland) indicated that reducing the number of indicators whilst trying to maximise the information from those chosen is the preferred approach. However, to ensure the information provided was meaningful and useful, indicators for each asset group were not aggregated, as this would result in disparate assets being measured together.

> **Lesson 5:** The operational realities of a sector will influence its ability to access the information relevant to report on an indicator.

Operational realities of a sector will dictate how data and information is collected and collated. For example, within the light rail division of TII, operations and maintenance of the system is contracted to Transdev through a Service Level Agreement (SLA). Any cost associated with disruption to light rail traffic or damage to infrastructure as a result of severe weather events are absorbed by the contracting company and are therefore not identifiable and available to TII. This therefore meant we were unable to select "Cost of disruption to the light rail network due to climate events/hazards" as a meaningful indicator. Any change to this would require a change in the terms of the contract between the parties which may take significant time and resources to implement, especially if current contracts still have a long time to run.

Lesson 6:	Separating impacts to sectoral assets and operations due to climate change from other contributing issues is often not possible as these can be due to multiple processes and a compounding set of conditions.

In relation to implementation indicators for the roads asset group of TII, "investment in improving road network resilience to climate change" was a proposed indicator. Although TII carry out annual road damage surveys and identify sections of roads to be repaired or maintained, the specific root causes of road surface deterioration cannot be determined. It may be due to a combination of traffic volumes, excessive HGV usage, climate hazards or any other factor. Therefore, specific investments to adapt to a changing climate cannot be identified. Similar situations will arise in other sectors.

Lesson 7:	Phased development of indicator sets is often more appropriate. It allows progress to be achieved and avoids blocking the whole process due to inability to agree on a full and comprehensive set of indicators.

Another key point from the indicator selection process in this study and from discussions with those working on indicator development in other countries, is that phased development of indicators may be more appropriate. Climatological and impact indicators can be identified after a detailed climate impacts analysis; implementation and outcome indicators are harder to identify and develop. This also allows for learning and experience to be gained and avoids that the process is blocked due to inability to agree on all indicators at the same time. On the other hand, in Scotland the process was reversed, with outcomes identified in line with national priorities and then indicators developed in relation to each outcome. Both of these processes have merit and sectors should consider which will work best for their own needs.

Lesson 8:	The co-creation process is critical in order to engage different departments and bring actors and expertise together, both within sectors and across sectors, to facilitate a robust selection of useful indicators.

Various departments within TII worked closely with MaREI throughout the process and this additional knowledge and perspective has been fundamental to the adaptation indicator development. Sectors should seek the support of an organisation familiar with climate adaptation indicator development for the compilation process.

It is not only within sectors that co-creation will be necessary. Adaptation indicator selection can help in identifying dependencies between sectors. Through this study with TII it has been highlighted that the national roads network is integral to the operation of many other critical infrastructure in Ireland. There needs to be communication across sectors on how specific assets that have knock-on impacts on other areas not necessarily within the sector´s remit, are prioritised in relation to this and how adaptation indicators are selected to reflect this.

5.3 Identifying Relevant Data Sources

There are a number of climatic data sources that are useful for all sectors, foremost among these is the repository of Met Éireann, where historic weather data are stored. Useful data to support the calculation of projected (period from now to 2100) climatological indicators will also be available through the Met Éireann funded TRANSLATE project, completed in June 2023, and its successor TRANSLATE2. To ensure the TRANSLATE team is aware of the needs of the sectors and the relevance of the outputs of TRANSLATE 2, sectors need to be more involved in the development of services. For example, sub-daily amounts of projected precipitation were identified as a measure that would be very useful to TII for its asset development and management, however this is not currently available through TRANSLATE. Nonetheless, many TRANSLATE datasets have already been included as relevant data sources in the co-development of the climatological indicators as outlined in Chapter 4 (Table 4.2).

Lesson 9: Relevant data need to exist and be accessible to determine the adaptation indicators. If organisations have not already done so they should identify and begin collecting baseline data to inform adaptation needs.

This includes both the underlying climate data from other national bodies and data from within the sector itself. This applies to data on impacts and specific asset-hazard interactions, including which thresholds may be an issue and the effect of chronic hazards (e.g. freeze-thaw cycles) causing deterioration and performance failures, especially for emerging hazards that have not previously been a factor, or where there are multiple factors leading to asset deterioration and failure (e.g. earthworks subject to wet and dry conditions which can lead to gradual deterioration). To overcome these issues, proxies are often used, and while not ideal, a lack of data should not be a sufficient reason to completely rule out a potentially useful indicator. Qualitative data through staff knowledge or expertise of climatic hazards and their impacts can also be used alongside quantitative data to support the development of adaptation indicators. Experience from other countries in similar situations and the challenges they have faced can also provide a source of information for how sectors can develop robust adaptation indicators.

Lesson 10: Sectors need to identify dependencies between different entities and organisations and explore solutions to ensure that the required data are available to inform effective indicator development and avoid maladaptation.

Data collection and access are also challenges when sectors or agencies subcontract operations to other entities or do not have responsibility for all assets covering a particular sector. In the case of TII, operations of the light rail network are contracted to Transdev under an SLA. Any climate related impacts and maintenance are handled by Transdev, however the details of those impacts and the costs related to disruption and remediation are not made available to TII under existing contractual conditions. This hinders the development of relevant climate adaptation implementation indicators and makes it difficult to track how investments to manage climate impacts change over time. Regarding the roads network TII has responsibility for the motorways under the MMaRC contracts, covering a total length of approximately 750 km. However, the approximately 4,100 km of the national primary routes are the responsibility of the various local authorities across Ireland. TII therefore only has access to information on its own managed network. Nonetheless, it does have access to traffic counter data across the full network, which makes the development of a traffic disruption indicator feasible. However, only a partial picture would be available to TII on causes of disruption and any work that may be carried out to reduce climate related impacts. Despite these challenges, potentially useful indicators can be highlighted now, and approaches and procedures explored and developed over the coming years to allow collection of and access to relevant data. For example, by identifying the contractual mechanisms necessary to gather the relevant data from subcontractors, organisations and sectors can put in place a process to allow for this data collection at the earliest opportunity.

5.4 Adaptation Indicators Aggregation

Lesson 11: National level indicator reporting should not impose significant additional work on sectors. It should be easy to compile the indicators from work that is being carried out as a necessary part of the various sectors´ efforts to adapt to climate change.

The need for metrics and indicators to support the design, implementation and monitoring of measures within sectors should not be confused with the indicators needed for national level reporting. Aggregation of impacts from the more granular levels can allow the identification of an indicator that can be used at the national level (Table 5.1).

Table 5.1: An example of national and sectoral level reporting metrics for TII with regards to flooding

Hazard: Pluvial and Fluvial Flooding	
National Level Indicator	**Sectoral Level Indicator**
Disruption to road network	Extent of damage to the road network (km^2)
	Level of damage to the road bridges and culverts
	Number of Flood events recorded
	Number of roads closed
	Recovery time following flood events
	Level of traffic disruption following flood events (critical road closure)

As can be seen from Table 5.1, the more granular metrics should automatically feed into the development of the national level indicator reporting.

5.5 International Experience

Sectors should also ensure awareness of international experience in indicator development so as to learn from best-practice and avoid making the same mistakes. In the future more severe weather events are likely to occur and so having an awareness of the work being done on adaptation indicators in countries not only with a similar climate profile but of those with a climate profile that Ireland may face under worst-case scenario changes is necessary. For example, TII is engaged with the Conference of European Directors of Roads (CEDR) ICARUS project[1] on the topic of climate resilience for highways, which is informing approaches.

> **Lesson 12:** Development of sectoral climate adaptation indicators should be informed by work being conducted in other countries.

5.6 Climate versus Wear and Tear

TII's entire physical network is subject to constant levels of wear and tear from a range of complex factors and the assets deteriorate over time; this is exacerbated by increased traffic levels and severe weather events compounded by climate change. However, differentiating between these factors with any accuracy is exceptionally difficult. Baseline wear and tear differs for a multitude of reasons and attributing any deviation from a baseline to impacts of climate change can be an unreliable assumption. The causes of network deterioration are not currently recorded and therefore there is no data available to separate this from other factors that may also cause damage.

Allied to this is the fact that in TII's opinion, it is currently not possible to separate out costs of construction, and interventions and maintenance as a result of climate change exacerbated severe weather events from the general costs of construction and maintenance as well as inflationary costs.

> **Lesson 13:** Any additional costs of construction, remediation or maintenance of transport infrastructure due to climate change impacts are currently not possible to identify as they are embedded in general costs of raw materials, construction, general maintenance, labour and inflationary effects.

5.7 Identify Co-benefits of adaptation and mitigation

When identifying adaptation measures TII considers how this affects carbon emissions for all assets, in particular in any new builds for the national roads network. The publication of the Climate Assessment of Proposed National Roads – Standard PE-ENV-01105 (2022), means that both mitigation and adaptation must be considered in all new projects. This is an opportunity to consider how one action can have multiple co-benefits and therefore improve efficiency and cost-effectiveness in any future developments.

> **Lesson 14:** Consider and address mitigation and adaptation in tandem and identify any co-benefits

1 *https://icarus.project.cedr.eu/* (last accessed 06 March 2024)

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Climate adaptation is not taking place at the rate it needs to in order to build the adaptive capacity necessary to face the increasingly frequent and severe impacts of climate change. The adaptation process is not adequately measured across Ireland, and this needs to improve in order to ensure positive outcomes from adaptation, and overall resilience of sectors to climate change impacts. Climate adaptation indicators play a critical role in the monitoring and evaluation of the impacts of climate change and the effectiveness of adaptation solutions. They provide a useful metric by which to measure progress and to understand where there are still shortcomings to be addressed.

TII has seven strategic objectives for climate adaptation with which we have attempted to align the adaptation indicators. These include: 1) Observe fewer network disruptions during climate-related events; 2) Rapidly recover from any climate-related events; 3) Have a robust, flexible, and equitable organisation that responds effectively during climate events; 4) Enhance the climate resilience of lifeline roads in order to maintain community accessibility; 5) Engage with the wider adaptation efforts across Ireland through partnerships and wider research; 6) Embed climate adaptation within TII's operations, policies, and procedures in order to ensure a safe and resilient network; and 7) Adopt a low-carbon approach in TII's designs, standards, and processes when considering climate adaptation, while also considering wider social and environmental benefits (TII Climate Adaptation Strategy, 2022). By looking at the adaptation indicators in the wider context of the sector's strategic goals for the future, we hope to generate more robust support for their uptake and usage and to reduce the burden on the sector when planning for and implementing adaptation actions.

The collaboration process between MaREI and TII to determine appropriate adaptation indicators in a real-world setting has been extensive. In total 43 adaptation indicators were identified for national roads and light rail; this included 19 climatological, five impact, 11 implementation and eight outcome indicators. The co-creation process has provided knowledge exchange on both sides and brought to light challenges that could not be anticipated in a theoretical study, and will not be unique to the transport sector, but will apply within all sectors.

The co-creation process can slow down the initial progress in identifying climate adaptation indicators, as it takes time to build mutual understanding and trust. Moreover, additional stakeholders may need to be consulted; numerous iterations may be required, and all parties need to be committed to the process in terms of time and resources. However, the overall outcome will benefit significantly from the use of co-creation, as there is a much deeper understanding achieved and all relevant parties have had their knowledge incorporated. Therefore, the final adaptation indicators developed will have the support of all parties involved and should be realistic and achievable.

6.2 Recommendations

Based on the experience of this case study carried out with TII and taking into consideration the lessons learned, we provide the following recommendation that can assist other sectors in addressing the identification and development of a set of climate adaptation indicators for national reporting.

- **Start the process as soon as possible.** The development of relevant indicators for each sector is a long and complex process that takes significant time. It demands a deep understanding of an organisation´s assets, how climate change may affect them, operational procedures, data availability, and existing reporting procedures, among others. By starting the process early, issues and challenges will come to light and measures can be taken to start addressing them, as some may take years to resolve.
- **Do not develop indicators in a vacuum.** Sectors need to be aware of the most recent international best practice in this area and learn from the failures and successes in other organisations and jurisdictions.
- **Partnership working is essential.** A co-creation process ensures that all relevant actors and departments within a sector or organisation are represented in the decision making. The impact of climate change and adaptation measures across the sector and beyond needs to be understood to ensure successful adaptation that is practical and relevant. By collaborating with others, including consultants, competent authorities and specialists, resources and information can be shared, interdependencies addressed and adaptation can be more efficient and effective, addressing key challenges within and across sectors. National intersectoral communication (e.g., through the creation/or adaptation of a steering group that meet on a regular basis) to ensure coherence and the exchange of learning and ideas on the development and implementation of indicators would be invaluable.
- **Ambition for the future is necessary.** Sectors must not restrict indicator identification and selection based only on current data availability. Consider what information will be essential to the sector in the future and begin the process of measuring this now, even if the initial starting point is to begin collecting data that has not been collected up to now.
- **Climate adaptation and mitigation need to be considered in tandem.** Proposals for future developments within a sector should include an assessment of how both are being addressed as part of their business case analysis.
- **Climate adaptation and related reporting processes needs to be properly resourced at all levels.** The setting of ambitious sectoral goals will require additional support from national government to allow for adaptation action and associated MRE that is successful and cost-effective in the long-term.

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Abbreviations

CARO	Climate Action Regional Office
CEDR	Conference of European Directors of Roads
CFRAM	Catchment Flood Risk Management System
CI	Climate Ireland
DAFM	Department of Agriculture, Food and the Marine
DCCAE	Department of Communications, Climate Action and Environment
DECC	Department of the Environment, Climate and Communications
D-TRANS	Department of Transport
EPA	Environmental Protection Agency
EU	European Union
FLARES	Fire, Land and Atmospheric Remote Sensing
FLARES-PPLUS	FLARES-Projections, Policy and Land Use and cover Synthesis
GSI	Geological Survey Ireland
GWL	Global Warming Level
HGV	Heavy Goods Vehicles
KPI	Key performance indicator
LA	Local Authority
MaREI	SFI Research Centre for Energy, Climate and Marine
MÉRA	Met Éireann ReAnalysis
MRE	Monitoring, Reporting and Evaluation
NAF	National Adaptation Framework
NRA	National Roads Authority
OPW	Office of Public Works
SFI	Science Foundation Ireland
SLA	Service Level Agreement
TII	Transport Infrastructure Ireland
UK	United Kingdom

APPENDIX 1 LITERATURE ON THE NEED FOR INDICATORS IN IRELAND

1.1 Climate Adaptation Drivers

Observed changes in Ireland's climate over the last century are in line with global and regional trends associated with human induced climate change (Cámaro & Dwyer, 2021). In a calculation of climate averages for the period 1991 to 2020, Met Éireann (Curley et al., 2023) shows that the average air temperature has increased by +0.7°C and the annual average rainfall has increased by 7% with respect to the period 1961 to 1990. An analysis of monthly rainfall records for the period 1711 to 2016 (Murphy et al., 2018) shows that decadal variability may be much larger than was believed the case when only digital records were taken into account. However, the decade 2006 to 2015 was the wettest on record and there is evidence in the dataset that there is an increasing trend in winter rainfall and a decrease in summer rainfall. In terms of drought, analyses have been carried out on observations from the precipitation network across Ireland for a 165-year period (1850 – 2015) which highlighted the occurrence of seven periods which were marked by major droughts, which showed variability in terms of location, onset and duration (Noone et al., 2017). Changes in climate are also noted in the ocean, freshwater and biosphere environments (Cámaro & Dwyer, 2021). Changes in climate, especially those accompanied by changes in extreme events increase the vulnerability of people, infrastructure and the natural environment not needed. As stated in the National Adaptation Framework (2018), key and coherent adaptation and mitigation approaches are thus needed to make Ireland more resilient to climate change and to reduce climate change impacts in the future.

A good summary of Irish climate policy is provided in Flood et al., (2021). Figure A1.1 has been reproduced from that report and highlights some of the key developments in the period 2012-2021. Some of the first steps were taken with the drafting of the non-statutory National Climate Adaptation Framework in 2012 (DECLG, 2012). Key moments in the following decade are reflected by the publication of a statutory National Adaptation Framework in 2018, the adoption of a Climate Action Plan in 2019, the publishing of sectoral adaptation plans and local authority adaptation strategies and the passing into law of the Climate Action and Low Carbon Development (Amendment) Bill in 2021. By the end of 2023, a new National Adaptation Framework is to be published and updated sectoral planning guidelines for climate change adaptation will also be subsequently published.

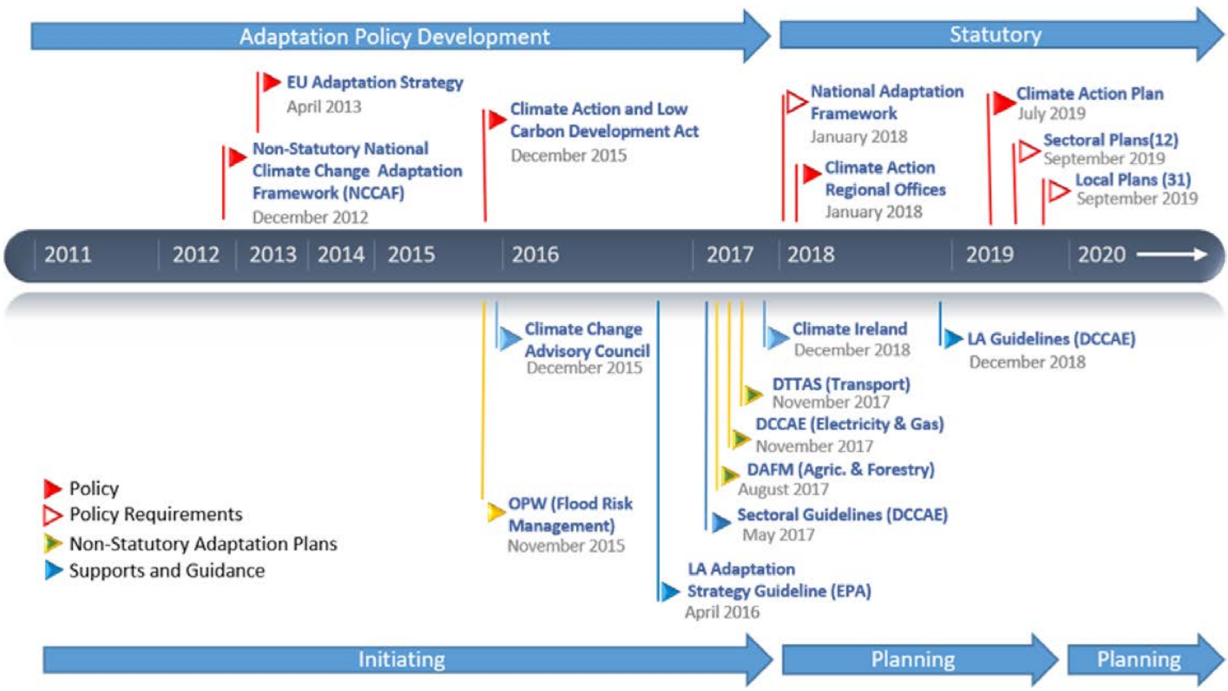

Figure A1.1: Evolution of Irish climate policy. DAFM, Department of Agriculture, Food and the Marine; DCCAE, Department of Communications, Climate Action and Environment; DTTAS, Department of Transport, Tourism and Sport; LA, local authority; OPW, Office of Public

TII published its first strategy for adapting to climate change on Ireland's light rail and national road network in 2017 (TII, 2017). In 2021 the Climate Action Plan (CAP21) (DECC, 2021) required that Transport Infrastructure Ireland publish an updated strategy on how it is to adapt its transport assets including the light rail and national road networks to climate change. TII published this strategy in 2022 (TII, 2022c) identifying seven climate adaptation strategic objectives. This work on climate adaptation indicators supports TII in their work to achieve these objectives.

1.2 Climate Hazards in the Transport Sector

Ireland's key transport infrastructure includes road, heavy and light rail, aviation and maritime transport. TII's responsibilities are focussed on national primary and secondary roads, light rail, rural cycleways and national and regional greenways, land, buildings, and people. Roads are subdivided into 3 categories: motorway maintenance and renewal contract (MMaRC) operators (~750 km), public private partnerships (PPP) (~450 km) and national roads (~4,100 km), owned by the local authorities and managed in partnership with TII. TII is directly responsible and has complete access to data for only MMaRC roads. With respect to light rail TII is responsible for the life cycle asset management of all Luas infrastructure and rolling stock (TII, 2023b).

As part of the climate change sectoral adaptation plan for transport (Dept. of Transport, 2019) a qualitative climate impact screening and vulnerability assessment was carried out. The identification and prioritization of sectoral risks was undertaken to identify future adaptation priorities. Figure A1.2 shows the outcome of this analysis for the whole transport sector.

The highest climate risks were associated with projected increase in precipitation extremes, flooding, high winds, increased storm intensity and projected sea level rise. Moderate risks were associated with extreme high or low temperatures and coastal erosion.

Precipitation extremes and flooding can cause degeneration of transport infrastructure, including disintegration of road, pavement and cycle lane surfaces; there can be an increase in bridge (road and rail) scour, which may cause structural instability and increased risk of landslides leading to blocked roads and rail. Maritime and aviation infrastructure and operations are also impacted by such weather events. All of these factors can render infrastructure inaccessible or unsafe for usage, leading to negative economic, social and environmental impacts.

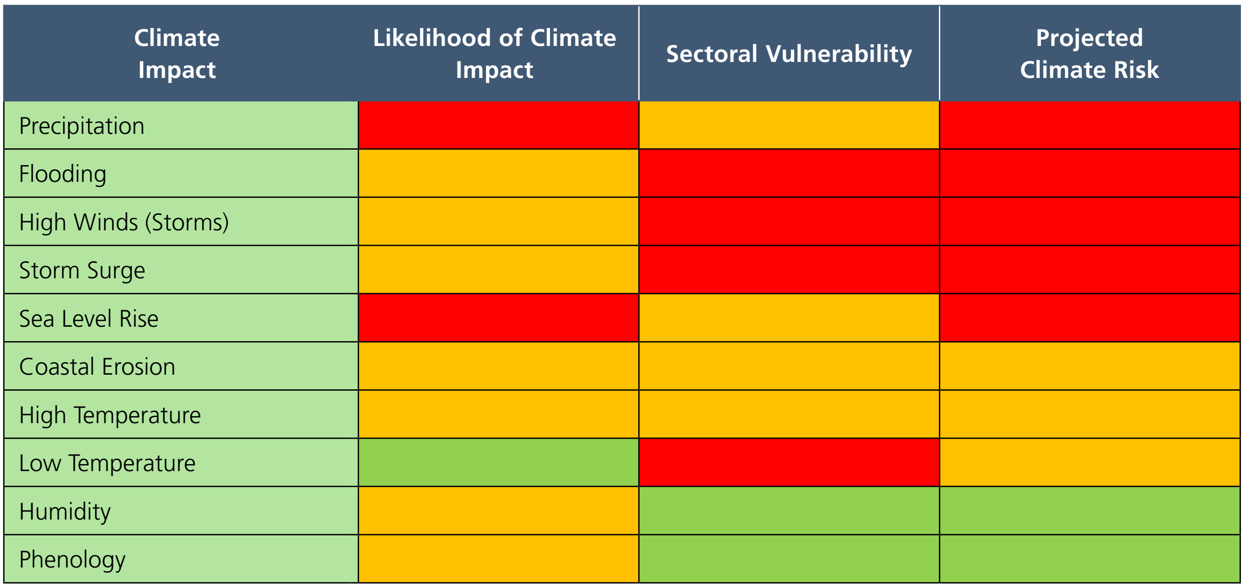

Figure A1.2: Priority Impact Chains for the Transport Sector. Green: low levels of projected climate risk; orange moderate levels; red; high levels of projected climate risk (based on Table 3.2, Dept. of Transport, 2019)

High winds, storms and storm surges have the potential to be highly impactful especially in coastal locations. Coastal transport infrastructure is particularly vulnerable to flooding and erosion leading to both disruption to transport users but also damage to the underlying infrastructure. High winds in any part of the country can result in trees and power cables falling, high sided vehicles being vulnerable to being blown over and makes it very hazardous for vulnerable road users such as cyclists, motorcyclists and pedestrians. High winds, storms and storm surges can lead to damage to transport infrastructure, road and rail closures and consequent disruption and ultimately compromise the health and safety of transport users and the public.

A more detailed climate impact screening assessment has been carried out by TII on its assets by consideration of their sensitivity, exposure and vulnerability to baseline and extreme weather events. This is in accordance with the transport sector's adaptation approach and TII's own climate adaptation strategy. An overview of this screening exercise is presented in chapter 2.

1.3 The Role of Climate Adaptation Indicators

To understand progress in climate adaptation it is necessary to establish a monitoring, reporting and evaluation framework. A survey of international progress on the MRE framework shows that most countries employ some sort of indicators, although there are some examples of countries which have steered away from them and prefer to assess progress based on all available information or on consultation and reflection among stakeholders (Leiter et al., 2019). Nonetheless, a well-designed set of indicators can help to identify whether the aim of achieving a climate resilient Ireland is being achieved in reality. They can do so by providing a means to measure and quantify status and progress from climate impacts to adaptation actions, to adaptation outcomes. In addition, there is the potential to understand the potential magnitude of costs associated with climate impacts within sectors. However, this is subject to appropriate data being available and accessible.

Flood et al., (2021) reported that several European countries and others were working on adaptation indicators at time of writing. They argued that uptake of adaptation or resilience indicators is challenging given the lack of long-term relevant datasets therefore compromising the ability to make future predictions and the need to define new and changing data needs that often disrupts the business-as-usual practices of organisations. Appendix 2 provides examples of adaption indicator development for three countries.

1.4 Informing Implementation across Sectors

Following on publication of the NAF in 2018, a number of sectoral adaptation plans were developed and published, namely:

- Agriculture, Forestry and Seafood
- Biodiversity
- Built and Archaeological Heritage
- Transport infrastructure
- Electricity and Gas Networks
- Communications Networks
- Flood Risk Management
- Water Quality and Water Services Infrastructure
- Health

These plans were developed following the six-step adaptation planning process described in the sectoral guidelines for climate change adaptation (DECC, 2018). The new NAF to be published in 2023 will be supported by an updated set of guidelines, (to be published subsequently) to aid sectors in developing new adaptation plans.

In the Flood et al., (2021) report, a suite of climate adaptation (resilience) indicators was identified and proposed for potential use across all the above sectors. This case study, which addresses some elements of the transport infrastructure, is a first attempt at assessing the potential application of a relevant subset of these indicators in a practical setting. The lessons learned in the process will inform the new guidelines and will support all sectors in adopting and using climate adaptation indicators.

APPENDIX 2 APPENDIX 2 – INTERNATIONAL EXAMPLES OF TRANSPORT INDICATORS

New Zealand

The approach in New Zealand is to combine climate hazards with other hazards that the network might face, including man-made hazards. The hazards are grouped under five transport outcome themes (Healthy and Safe People; Economic Prosperity; Inclusive Access; Resilience and Security; Environmental Stability) and consist of 37 indicators. These are shown in Figure A2.1. They cover all of the key transport modes within New Zealand, including walking, cycling, road, rail, maritime and aviation.

Table A2.1: Adaptation indicators for Transport Network Infrastructure in New Zealand (New Zealand Transport Authority)

Indicator		Associated Outcome	Walking	Cycling	Road	Rail	Maritime	Aviation
1	Transport-related deaths	Healthy and safe people 1.1	✔	✔	✔	✔	✔	✔
2	Transport-related serious injuries	Healthy and safe people 1.2	✔	✔	✔	✔	✔	
3	Transport-related work injuries	Healthy and safe people 1.3	-	-	✔	✔	✔	✔
4	Time spent travelling by active modes	Healthy and safe people 1.4	✔	✔	-	-	-	-
5	Harmful emissions from fuel combustion	Healthy and safe people 1.5	-	-	✔	✔	✔	✔
6	Exposure to elevated levels of noise from the transport system	Healthy and safe people 1.6	-	-	✔	Not avail	Not avail	Not avail
7	Contribution of transport and freight movements to New Zealand GDP	Economic prosperity 2.1	-	-	✔	✔	✔	✔
8	Passengers arriving and departing NZ	Economic prosperity 2.2	-	-	-	-	✔	✔
9	Travel time reliability within metropolitan and high growth areas	Economic prosperity 2.3	-	-	✔	Not avail	-	-
10	Travel time reliability on priority tourist areas	Economic prosperity 2.4	-	-	✔	✔	✔	Not avail
11	Freight imports and exports	Economic prosperity 2.5	-	-	-	-	✔	✔
12	Freight carried domestically (local and regional)	Economic prosperity 2.6	-	-	✔	✔	✔	✔
13	Travel time reliability for freight transportation	Economic prosperity 2.7	-	-	✔	✔	Not avail	Not avail
14	Load efficiency	Economic prosperity 2.8	-	-	Not avail	Not avail	✔	Not avail
15	Freight productivity / utilisations	Economic prosperity 2.9	-	-	Not avail	Not avail	✔	Not avail

Indicator		Associated Outcome	Walking	Cycling	Road	Rail	Maritime	Aviation
16	Farm expenditure on freight	Economic prosperity 2.10	-	-	✔	✔	✔	✔
17	Household spending on transport (% of income)	Inclusive access 3.1	-	✔	✔	✔	✔	✔
18	Population with access to frequent public transport services	Inclusive access 3.2	-	-	✔	✔	-	-
19	Access to jobs	Inclusive access 3.3	✔	✔	✔	✔	-	-
20	Access to natural environment	Inclusive access 3.4	✔	✔	✔	✔	-	-
21	Rural households without access to a motor vehicle	Inclusive access 3.5	-	-	✔	-	-	-
22	People unable to make a beneficial transport journey	Inclusive access 3.6	✔	✔	✔	✔	-	-
23	Unmet need for GP service due to a lack of transport	Inclusive access 3.7	✔	✔	✔	✔	-	-
24	Perception of public transport	Inclusive access 3.8	-	-	✔	✔	-	-
25	Perceived safety of walking and cycling	Inclusive access 3.9	✔	✔	-	-	-	-
26	Security incidents	Resilience and security 4.1	-	-	Not avail	Not avail	✔	✔
27	Perceived personal safety while using the transport system	Resilience and security 4.2	✔	✔	✔	✔	Not avail	✔
28	Operator risk profile	Resilience and security 4.3	-	-	Not avail	Not avail	✔	Not avail
29	Response capability	Resilience and security 4.4	-	-	✔	✔	✔	Not avail
30	Availability of viable alternative routes	Resilience and security 4.5	-	-	✔	-	-	--
31	Preparation for loss of traditional transport option	Resilience and security 4.6	✔	✔	✔	✔	-	--
32	Susceptibility to coastal inundation with sea level rise	Resilience and security 4.7	-	-	✔	✔	Not avail	Not avail
33	Marine oil spills in NZ waters	Environmental sustainability 5.1	-	-	-	-	✔	-
34	Greenhouse gases emitted from the NZ transport system	Environmental sustainability 5.2	-	-	✔	✔	✔	✔
35	Vehicle fleet composition	Environmental sustainability 5.3	-	-	✔	Not avail	Not avail	Not avail
36	Mode share of short trips	Environmental sustainability 5.4	✔	✔	✔	✔	-	-
37	Fuel efficiency	Environmental sustainability 5.5	-	-	Not avail	✔	✔	Not avail

While this method does not separate climatic variables from other hazards, there is still a number of useful high-level indicators such as those outlined under resilience and security that could inform the development of the Irish transport indicators, particularly around the response capability of the network, operator risk profile and the preparation for the loss of traditional transport options, which Ireland has not yet considered. The acknowledgement of data gaps and inclusion of indicators were further work is needed is also an important process used by the New Zealand Transport Authority to build the knowledge base (*Te Manatū, 2022*) and could inform further development of TII's approach.

Scotland

Scotland has identified 11 high level indicators of relevance to the transport sector that fall under the key aspects of risk, impact and action. These indicators refer specifically to the road and rail networks and climate impacts that may affect them. In this case, the hazards are similar to Ireland in that flooding, bridge scour and landslides are identified as the major hazards. These indicators have 34 associated metrics each one outlining how the indicator is measured (Table A2.2). Many of the Scottish indicators have comparable adaptation indicators to those outlined by Flood et al. (2021) for Ireland, however, the Scottish suite of indicators is much more succinct and provides an excellent example of how indicators could be used at a national level, when appropriate data are available.

Table A2.2: Adaptation Indicators for Transport Network Infrastructure in Scotland

Indicators	Type	Metrics for measurement
BT2 Road network at risk of flooding	Risk	BT2a Proportion of road length directly at risk of (fluvial) flooding (all roads)
		BT2b Proportion of road length directly at risk of (fluvial) flooding (trunk)
		BT2c Proportion of network that would be affected by this (fluvial) flooding (all roads)
		BT2d Proportion of network that would be affected by this (fluvial) flooding (trunk roads)
		BT2e Proportion of road length directly at risk of (pluvial) flooding (all roads)
		BT2f Proportion of road length directly at risk of (pluvial) flooding (trunk roads)
		BT2g Proportion of network that would be affected by this (pluvial) flooding (all roads)
		BT2h Proportion of network that would be affected by this (pluvial) flooding (trunk roads)
		BT2i Proportion of road length directly at risk of (coastal) flooding (all roads)
		BT2j Proportion of road length directly at risk of (coastal) flooding (trunk)
BT4 Flood events affecting the trunk road network	Impact	BT4a: Total number of reported trunk road flooding incidents
		BT4b: Proportion of reported trunk road flooding incidents located within Potentially Vulnerable Area (PVAs)
		BT4c: Proportion of reported trunk road flooding incidents resulting in road closure
		BT4d: Proportion of reported trunk road flooding incidents where flooding is over 3cm depth
BT6 Trunk road network benefitting from fluvial flood protection	Action	Proportion of the entire trunk road network benefitting from fluvial flood protection measures
		Proportion of the trunk road network at risk of a 1 in 200 year flood event benefitting from fluvial flood protection measures
BT8 Railway network at risk of flooding	Risk	BT8a: Percentage of rail network at risk of fluvial flooding
		BT8b: Percentage of rail network at risk of pluvial flooding
		BT8c: Percentage of rail network at risk of coastal flooding

Indicators	Type	Metrics for measurement
BT9 Disruption risk to railway services as a result of flooding	Risk	length of rail at direct (fluvial) flood risk (for a 1:200 year flood), for each of high, medium and low rail traffic volumes
		length of rail at direct (pluvial) flood risk (for a 1:200 year flood), for each of high, medium and low rail traffic volumes
		length of rail at direct (coastal) flood risk (for a 1:200 year flood), for each of high, medium and low rail traffic volumes
		length of rail at direct (combined) flood risk (for a 1:200 year flood), for each of high, medium and low rail traffic volumes
BT12 Flood events affecting the railway network	Impact	Schedule 8 costs provide a proxy for weather related impacts (including flooding) to the rail network. Network Rail incur flooding related Schedule 8 costs due to delays caused by fluvial, pluvial, groundwater and tidal (coastal) source flooding of rail assets.
BT16 Rail network benefitting from fluvial flood protection	Action	The proportion (length) of the entire rail network benefitting from fluvial flood protection (regardless of whether it is at flood risk or not)
		The proportion (length) of the rail network which is at fluvial flood risk and that also benefits from fluvial flood protection
BT17 Risk of traffic disruption as a result of flooding	Risk	% of the (critical) trunk road network is at risk of high levels of traffic disruption as a result of fluvial flooding (defined using average daily traffic volume thresholds)
		% of the (critical) trunk road network is at risk of high levels of traffic disruption as a result of pluvial flooding (defined using average daily traffic volume thresholds)
		% of the (critical) trunk road network is at risk of high levels of traffic disruption as a result of coastal flooding (defined using average daily traffic volume thresholds)
BT22 Landslide events affecting the road network;	Impact	BT22: Total number of trunk road landslide incidents
BT23 Road closures due to landslides	Impact	Number of these incidents resulting in road closure
		Number of these incidents located within very remote rural areas
BT26 Road and rail bridges vulnerable to scour	Risk	% of trunk road bridges have been assessed as high priority (or highly susceptible to scour).
		% of underline rail bridge assets have been assessed as high priority (or highly susceptible to scour).

Reporting is via a set of "indicator cards" which provides a narrative on the indicator with context, a discussion of limitations, expected future projections and additional information links. A number of quantitative metrics are also associated with each indicator (e.g., flood incidents recorded on trunk roads in a given period, proportion of incidents resulting in road closure). If there is sufficient data available, trends are indicated simply as upward, downward, or no significant trend. For indicators related to flooding, much of the flood protection data available for Scotland was from the Scottish Environment Protection Agency national flood maps covering multiple return periods and scenarios and the Scottish Flood Defence Asset Database rather than by specific sectors. However, incomplete and inconsistent quality information in these datasets mean that the information for the action indicators do not provide a precise, explicit assessment of flooding at every location measured. The set of indicator cards developed to date in Scotland constitute a useful baseline on which progress in adaptation actions can be built, however, they have not been implemented by the sectors and therefore a review of their effectiveness or suitability at the sectoral level does not exist.

Australia

An indicator list has been generated for the coastal transport infrastructure in Australia (Fisk, 2017). This list covers the various infrastructure types, including road, rail, airports and ports. Indicators have been suggested for climate risks or parameters (4 indicators), impacts (112 indicators) and adaptation actions (56 indicators). This model is similar to Scotland's but provides more granular detail for the impact and adaptation indicators, rather than the high level indicators provided by Scotland. The Australian indicators for impact and action are based around trigger points, or unacceptable impact levels across three themes (Table A2.3), which could inform how TII utilizes selected implementation indicators.

Table A2.3: Example adaptation action Indicators/triggers for the Coastal Transport Network Infrastructure in Australia (Fisk, 2017)

Financial/built environment indicators	Physico-environmental indicators	Workforce health and safety indicators
• replacement costs for assets (set as annual budget) • damage costs to assets • increased maintenance frequency or costs for assets • acceptable days or hours of shutdown/closure • acceptable days or hours of suspended or reduced work practices • acceptable days or hours of use of a particular asset or group of assets • cost/availability of insurance for one or more assets • full or partial engineering failure of an asset • approaching the end of life of an asset	• when erosion scarp reaches within defined distance from of existing asset (e.g. 50m) • when estimated or modelled hazard line occurs within the defined distance of existing asset (e.g. 50m) • measured extent of sea-level rise (with different depths for different development types) as an indicator of increased storm tide risk • measures extent of storm tide and/or flooding impact • depth of inundation events (depth in m) across property • frequency of coastal or flood inundation events (times per year or season) • frequency of very hot days (over 35°C) • frequency of extreme hot days (over 40°C)	• deaths or injuries attributable to hazards • loss of work productivity or time due to hazards • frequency of stop workages due to hazards • number and extent of evacuations

APPENDIX 3 RESILIENCE INDICATORS RELEVANT TO THE TRANSPORT SECTOR

Note that these tables are extracted from Flood et al., (2021) and were not developed in partnership with TII. Hence, there are inaccuracies with the terminology used for some of the indicators outlined, and in the column relating to data availability.

Table A3.1: List of climatological indicators of potential relevance to the transport sector extracted from Flood et al., (2021)

Hazard	Climatological Indicator	Data Availability	Data Source
Pluvial and Fluvial Flooding	Number of very wet spell days (days with rainfall > 30 mm)	Good	Met Éireann
	Total seasonal precipitation	Good	Met Éireann
	Maximum consecutive 5-day precipitation	Good	Met Éireann
	River Flood Index (runoff)	Good	OPW/EPA
	Total annual precipitation	Good	Met Éireann
Extreme heat	Number of hot days (days with max daily temperature above threshold)	Good	Met Éireann
	Heatwave days (where heatwave is at least three consecutive days of daily max temperature above 90th percentile)	Good	Met Éireann
Extreme wind	Extreme wind speed days	Good	Met Éireann
	Number of days with gale gusts	Good	Met Éireann
Frost	Number of frost days	Good	Met Éireann
Coastal Flooding and Erosion	Coastal storm events (linked with coastal surge) number of/height	Good	Met Éireann/Marine Institute

Table A3.2: List of impact indicators of potential relevance to the transport sector extracted from Flood et al., (2021). Note that these were not developed in partnership with TII, and there are inaccuracies with the terminology on the impact indicators outlined, and with the content for data availability outlined.

Hazard	Impact Indicator	Data Availability	Source
Pluvial and Fluvial Flooding	Extent (km^2) and grade of damage to roads as a result of flooding	Fair	TII/D-Trans
	Extent (km^2) and grade of road and rail bridge damage due to flooding (damage to bridge floors and water intrusion into abutments)	Fair	TII/D-Trans/Irish Rail
Extreme heat	Rail network (Euro cost) damage due to extreme heat	Fair	Irish Rail/Transdev/D-Trans
	Road melting damage due to extreme heat (Euro Costs)	Fair	TII/ Local Authorities

Hazard	Impact Indicator	Data Availability	Source
Extreme wind	Transport (Luas and DART) overhead power lines impacted by high winds (Cost impact)	Fair	ESB Networks/Eirgrid
	Windthrow tree fall (m3/economic cost)	Fair	DAFM
Drought	Road settlement impact (Cracking of local smaller roads on peatland due to drought conditions) (economic cost)	Fair	Local Authorities
Coastal Flooding and Erosion	Coastal erosion rates	Fair	OPW/Local Authorities
	Extent (km^2) and grade (in Euros) of damage to roads as a result of coastal flooding	Fair	TII/D-Trans
	Damage (in Euros) costs incurred by rail as a result of coastal erosion	Fair	Irish Rail /Transdev
	Damage (in Euros) costs incurred by rail as a result of coastal flooding	Fair	Irish Rail/Transdev
	Extent (km^2) of damage to roads as a result of coastal erosion	Fair	TII/D-Trans

Table A3.3: List of implementation indicators of potential relevance to the transport sector extracted from Flood et al., (2021)

Hazard	Implementation Indicator	Data Availability	Source
Pluvial and Fluvial Flooding	Proactive road drainage maintenance programme (to lessen or prevent flooding impact)	Fair	OPW/ Local Authorities
	Proactive bridge maintenance (as captured under the Eirspan Asset Management System) (to lessen or prevent flooding impact)	Fair	TII/Irish Rail/NRA
	Number of Sustainable (Urban) Drainage Systems (SUDs) in place	Fair	Local Authorities
	Investment in area of flood resilience (Euros)	Fair	OPW
	Percentage of river embankments including height to protect against future flood risk	Fair	OPE/Local Authorities
Hazard	Implementation Indicator	Data Availability	Source
Extreme heat	Mainstream mitigation against extreme heat risk on rail network in rail network management plans	Fair	Irish Rail/Transdev
	Use of stiffer binder in roads exposed to high temperatures (km^2)	Fair	TII/Local Authorities
Extreme wind	Implementation of (existing) Luas Severe Weather Management Plan to account for present and increasing high wind impact on power lines	Fair	Transdev
Drought	Proactive road maintenance programme (to lessen or prevent settling impact)	Fair	TII/Local Authorities

Hazard	**Implementation Indicator**	**Data Availability**	**Source**
Cross-cutting	Build internal capacity by engaging in knowledge sharing and information exchange to increase awareness of climate and adaptation issues across Departments and agencies (number of capacity building initiatives, staff engaged)	Fair	TII/D-Trans
	Review of the effectiveness of current quantitative data collection procedures for the impacts of extreme weather events	Fair	D-Trans/CAROs/Local Authorities
	Develop guidance for sectoral stakeholders to inform identification of critical transport assets, taking account of cross-sectoral interdependencies (action from Critical Infrastructure Working Group)	Fair	D-Trans
Coastal Flooding and Erosion	Investment (Euro) in programmes to monitor and forecast coastal erosion	Fair	OPW/D -Housing, Local Govt. Heritage.
	Proactive road drainage maintenance programme (to lessen or prevent coastal flooding impact)	Fair	OPW/Local Authorities
	Investment (Euro) in coastal protection/management measures to mitigate impact of coastal erosion	Fair	OPW/D -Housing, Local Govt. Heritage.

Table A3.4: List of outcome indicators of potential relevance to the transport sector extracted from Flood et al., (2021)

Hazard	**Outcome Indicator**	**Data Availability**	**Source**
Pluvial and Fluvial Flooding	Percentage change in road flooding impacts	Fair	OPW/ Local Authorities
	Number of climate adapted bridges	Fair	TII/Irish Rail/NRA
	Change in number of Sustainable (Urban) Drainage Systems (SUDs) in place	Fair	Local Authorities
	Percentage change of embankments including height to protect against future flood risk	Fair	OPW
	Extent of roads maintained (to lessen or prevent settling impact)	Fair	OPW/Local Authorities
	Change in incidence of road settling impact as a result of proactive road maintenance programme	Fair	TII/D-Trans
Extreme heat	Change in rail network (Euro cost) damage due to extreme heat due to climate mainstreaming in rail network management plans	Fair	Irish Rail/ Transdev
	Change in road surface melting impact (Euros) due to use of stiffer binder in road surfacing.	Fair	TII/Local Authorities
Extreme wind	Change in impact on power lines as a result of implementation of Luas Severe Weather Management Plan	Fair	Transdev

Hazard	Outcome Indicator	Data Availability	Source
Drought	Change in road settling impact due to proactive road maintenance programme	Fair	TII/Local Authorities
Coastal Flooding and Erosion	Change in extent (km2) and grade of damage to roads as a result of coastal flooding due to proactive road drainage maintenance programme	Fair	TII/D-Trans
	Change in damage (Euro) costs incurred by rail due to coastal erosion as a result of coastal protection/ management measures	Fair	Irish Rail/Transdev
	Change in damage (Euro) costs incurred by rail due to coastal flooding as a result of Investment in coastal protection/management measures	Fair	Irish Rail/Transdev
	Change in extent (km2) of damage to roads as a result of coastal erosion due to coastal protection/management measures	Fair	TII/ Local Authorities

APPENDIX 4 POTENTIAL DATA SOURCES

The TRANSLATE project outputs[2]

The TRANSLATE project *(https://www.met.ie/science/TRANSLATE)* was established by Met Éireann, in 2021 to produce standardised climate projections and climate services for Ireland. Projecting future climate change is inherently uncertain. To address this, TRANSLATE has incorporated three different sources of uncertainty by decomposing future climate projections into a matrix of discrete climates along 3 different dimensions (i.e., forcing, response sensitivity, and time-period). This matrix or "Rubik's cube" structure is shown schematically in Fig. A4.1. It is worth emphasising that each of the 27 distinct "climates" that make up the "cube" consist of an ensemble of 30-years of daily values for each of 4 variables (daily minimum, mean, and maximum of surface air temperature and daily precipitation).

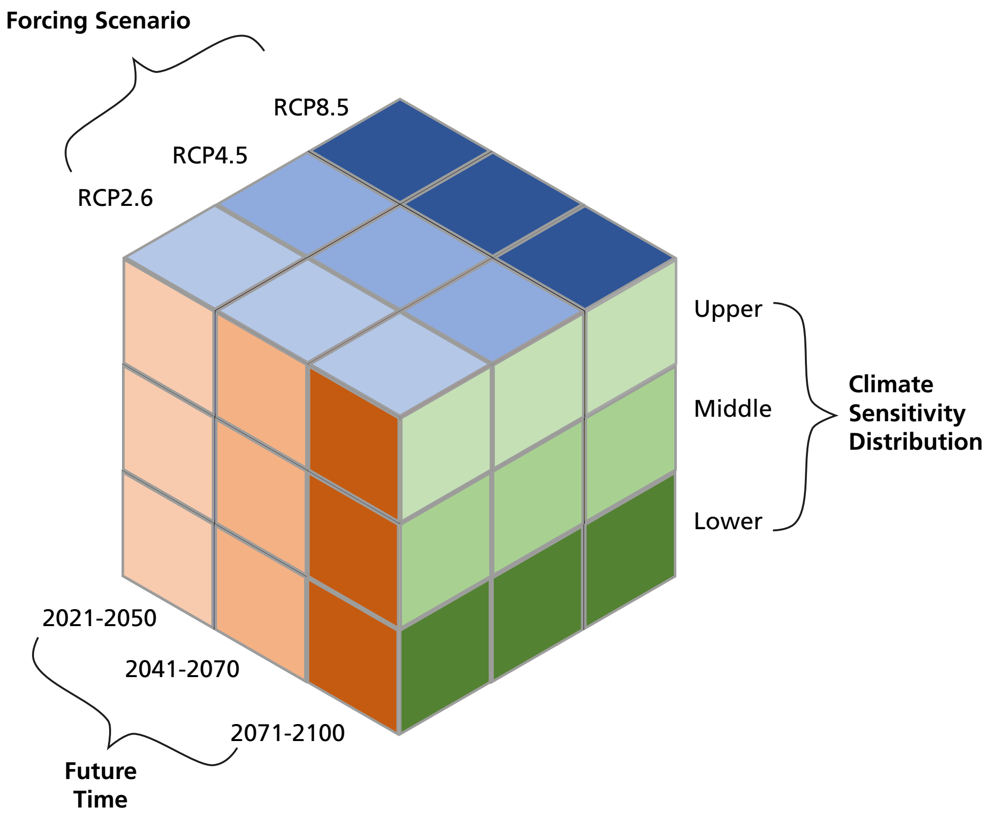

Figure A4.1: Schematic of how future climate uncertainties can be accommodated in a limited set of possible climates, adapted from Fig.10.9 of CH2018 (CH2018 report, 2018). Each sub-cube shown corresponds to an ensemble of long-term climate simulations. Different RCP emission scenarios represent forcing uncertainty, while the climate sensitivity axis represents response uncertainty (Taken from O'Brien, in press)

TRANSLATE supplemented the range of 27 "scenario"-based climates with a set of 5 temperature "threshold"-based climates, i.e., climates based on the 20-year time-periods centred on the year when each global climate model crossed specific "global warming level" (GWL) thresholds. The GWLs considered were 1.5, 2.0, 2.5, 3.0 and 4.0°C above pre-industrial levels. Therefore, the final

2 based on content in: O'Brien, E., Ryan, P., Holloway, P., Wang, J., Nowbakht, P., Phillips, C., Fitton, J., O´ Dwyer, B. and Nolan, P., (in press) *TRANSLATE Research Report*, Met Éireann

climate projections standardised product consists of over 30 separate projected "climates" of 4 main variables, namely daily minimum, mean and maximum temperature, and daily precipitation. The output includes a wide range of standard climate charts, a set of data files at daily resolution over a full annual cycle for different statistics of interest (means, standard deviations, percentiles, occurrence frequencies), and at the lowest level, 30-year time series of detrended and bias-corrected variables at daily resolution for each model ensemble member.

A step-by-step semi-quantitative risk analysis guide was also developed, which incorporates the TRANSLATE projections and includes computer code to support migration to a hexagon analytical grid format. While the semi-quantitative risk analysis approach is shown to be very useful for highlighting potential climate risk hot-spots nationally, it is limited when attempting to implement effective climate adaptation action. Consequently, as part of the TRANSLATE climate service offering a fully quantitative risk-based decision support guide was also developed. This approach is illustrated through a comprehensive case-study which was conducted in collaboration with Transport Infrastructure Ireland. It quantifies the impacts of projected climate change on national route road drainage systems. It also examines the effectiveness of a climate adaptation strategy for these systems. It was found that climate change impacts on probability of road flooding under intense rainfall are projected to increase beyond the current acceptable limits set by TII (0% probability for 5-year intense rainfall event). The analysis also indicated that a proactive climate adaptation strategy adopted by TII in 2015 may require adjustment, with a need to increase climate resilience of the pipe network, and the potential to make savings through adopting a less conservative adaptation approach for attenuation ponds. This showcases the strength of risk-based decision support in informing effective climate adaptation actions.

The derived data that have been produced by the project is indicated in Table A4.1. Other indicators may be derived from the underlying data described above.

Table A4.1: List of derived climatic variables produced by the TRANSLATE project

Climatic Variable	Hazard Indicator
Precipitation	Wet days
	Met Éireann Yellow Warning Days - Rain
	Met Éireann Orange Warning Days – Rain
	Met Éireann Red Warning Days - Rain
	Dry Periods
Temperature	Heat-stress Days (Max. Temp., days over 30°C)
	Met Éireann Yellow Warning Days- Low temperature/ice
	Met Éireann Orange Warning Days- Low temperature/ice
	Met Éireann Red Warning Days- Low temperature/ice
	Met Éireann Yellow Warning Days- High temperature
	Met Éireann Orange Warning Days- High temperature
	Met Éireann Red Warning Days- High temperature
	Heat Wave Index
	Growing degree days

MÉRA Reanalysis

Met Éireann has carried out a 38-year (1981 to 2019) very high resolution (2.5 km horizontal grid) regional climate reanalysis for Ireland which includes surface, near-surface and atmospheric parameters (Table A4.2) and is the first of its kind for Ireland. Three-hourly analysis data are available.

This Irish reanalysis dataset, called MÉRA (Met Éireann ReAnalysis) complements the observational network and extends the knowledge gained from observations as the model grid is much finer than observational coverage over Ireland. The advantage of performing this regional reanalysis rather than relying on existing global ones is that it can be run at high temporal and spatial resolution so that focus can be put on near surface parameters, extremes and frequency distributions. Moreover, its results are better than those from existing lower-resolution global models. In particular, Méra gives a vast improvement in precipitation forecasts.

More information on MÉRA here: https://www.met.ie/climate/available-data/mera

Table A4.2: Summary list of parameters available from MÉRA

Parameter
Mean sea level pressure
Surface pressure
2 m temperature
2 m relative humidity
Wind speed and direction at 10m
Total precipitation
Net shortwave irradiance
Net longwave irradiance
Direct shortwave irradiance
Longwave irradiance
Global irradiance
Direct normal irradiance
Upper air temperature
Upper air wind speed and direction
Soil temperature
Soil moisture content

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