Vulnerability of the Scottish Road Network to Flooding

Image (Transport Scotland)

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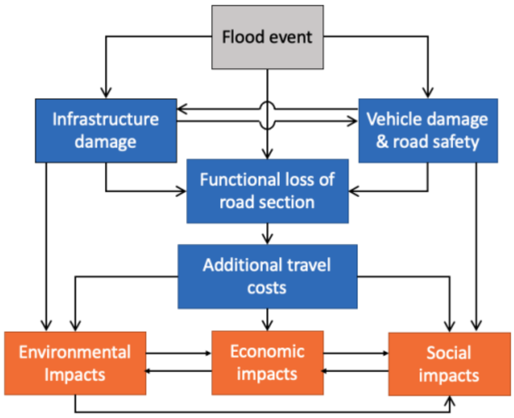
Executive Summary

Between 2014 and 2021 there were over 600 recorded flooding incidents per year on trunk roads managed by the four Operating Companies. Whilst many of these incidents were relatively minor in nature, around 9% of incidents resulted in a reduction in road width or at least one lane closure, and just over 1% led to a road or carriageway closure. Around half of all recorded flooding incidents had a duration of more than one hour, and 3.4% were longer than 6 hours. On average, there was at least one flooding incident on the trunk road network every two days. The maximum number of recorded incidents in a single day was 51, which occurred on 31st December 2015 during Storm Frank, and there were more than 15 flooding incidents in a single day on 40 occasions in the period 2014-2021.

Flooding on A76 (near Sanquhar); October 2023 (Transport Scotland)

Climate change is expected to increase the intensity of rainfall events throughout the year and to increase the total rainfall in Winter, Spring and Autumn. The mean sea level for Edinburgh is expected to rise by between 12 and 18cm in the 50 years to 2050. According to the 3rd Climate Change Risk Assessment (CCRA3), the length of the major road network in Scotland which is at significant risk of flooding is set to increase by 45-52% for fluvial flooding, 64-66% for pluvial flooding and 23-25% for coastal flooding by 2080 under a +4oC emission scenario, depending on the level of adaptation carried out.

Flooding has the potential to damage road infrastructure and vehicle assets, to cause the injury or death of road users, and to increase the length and duration, or result in the re-scheduling or cancellation, of journeys.



Potential Impacts of Flooding

The susceptibility of a road to flood damage depends on the characteristics of the road; and the extent of any damage is conditional on the severity of flooding. This predisposition to damage reflects the vulnerability of the road asset or section to flooding. The vulnerabilities of vehicles, their occupants and the travel being undertaken can be similarly defined.

In addition to these direct impacts, flooding-related disruption can negatively affect communities and businesses which are dependent on the transport system to enable the inward and outward flow of goods, services and people to parts of the country. These indirect social and economic impacts are not always easy to identify and, as a result, are liable to under-estimation. Islands and remote mainland areas are particularly vulnerable to disruption because alternative routes typically involve long detours or do not exist.

Vulnerability assessment is a process used to identify critical locations in the network i.e., those locations which would have the greatest impact if flooded, and also to estimate the expected impact on the road network for a given flooding scenario. Vulnerability also forms part of the assessment of risk which combines vulnerability with hazard (probability and severity of flood event) and exposure (value of asset, vehicles etc.) to give an estimate of the expected annual losses from flooding. Hence, the assessment of vulnerability can feed into adaptation planning exercises to identify those actions which represent best value for money.

The aim of this project was to develop a framework for defining the vulnerability of roads to adverse weather-related flooding events. This framework could then be applied to evaluate the vulnerability of the Scottish road network and to assess its risk to critical flood events, allowing the identification of the most vulnerable components and support risk mitigation strategies and management actions.

Literature Review

Road Infrastructure Damage

The two principal mechanisms by which flood damage occurs are (1) saturation of unbound materials in the pavement or its foundations resulting in loss of bearing capacity, and (2) erosion/scour of pavement surfacing and earthworks. Roads which have combined drainage and are at risk of water ponding (e.g. roads located in cuttings) for a day or more may experience sub-base saturation. The existence of pavement cracking will reduce the time needed to reach saturation. Roads with relatively thin asphalt layers are susceptible to damage as a result of bearing capacity loss. At the extreme end of the damage spectrum, a road may be partially or fully destroyed by flood water ("washout") which occurs when torrential surface water flows intersect with road infrastructure, often at culverts

Vehicle Damage and Road User Injury

Vehicles and their occupants are placed at risk, particularly if flood water rises rapidly. Vehicles caught in a flood will be damaged when the level of flooding is above the door sill, air intake or exhaust pipe. Vehicle instability occurs at flood depths above 0.30 metres in stationary water, and above 0.1 metres when the flow velocity is greater than 1 m/s. Vehicles swept away by floodwater increase the risk of vehicles colliding with, and damaging, infrastructure, blocking drainage channels or injuring people.

Full aquaplaning represents a risk to vehicles travelling at speeds in excess of 70 – 80 km/h when the depth of surface water is above 2.5 mm. Isolated flooding incidents may constitute a greater risk, particularly at night-time, or at locations where tyre-surface friction is important, e.g. on horizontal curves or the approach to junctions. Locations which are susceptible to blocked side drainage and partial flooding of the carriageway may also increase the risk of aquaplaning incidents.

Reduction in Level of Service

Flooding reduces the speed and capacity of affected road sections resulting in increased journey times. Roads become impassable to vehicles at flood depths of above 0.30 metres. Severe flooding will result in the closure of the carriageway, and the diversion, re-scheduling or cancellation of trips.

Vulnerability Assessment

"Depth-damage" vulnerability functions estimate the expected economic loss resulting from damage caused by flooding of a given depth. Functions developed by van Ginkel et al. (2021) distinguish between different types of road. According to these functions, maximum loss occurs in flood depths ranging from 0.25 to 0.60 metres. The effect of higher flow velocities is significantly more marked for lower classes of road and for roads without expensive electrical and electronic systems compared to the most sophisticated motorways.

Alternatively, indicator-based methods, e.g. ROADAPT guidelines, use a weighted function of indicators which reflect exposure and susceptibility to flooding to identify the most vulnerable locations. The main limitation of this approach is that the vulnerability of a location is not conditional on flood magnitude, hence expected losses cannot be estimated.

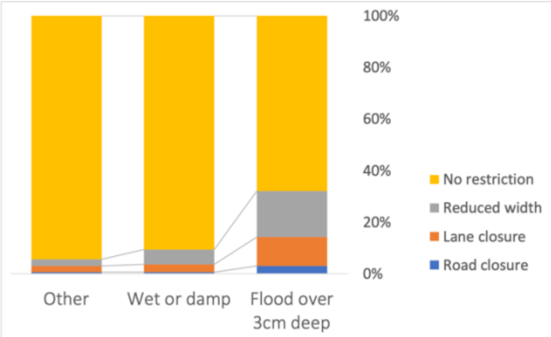
There exists a wide variety of approaches to estimate operational losses caused by a reduction in the level of service of a road section. For sparse networks in remote areas with relatively light flows and straightforward disruption scenarios, simple traffic models or accessibility-based indicators are suitable for most purposes. Dense, congested networks with more complex disruption scenarios (e.g. significant infrastructure damage, concurrent events) require more advanced transport models to give appropriate outputs to assess network performance, accessibility loss and resilience.

Findings

Impact of Flood Depth

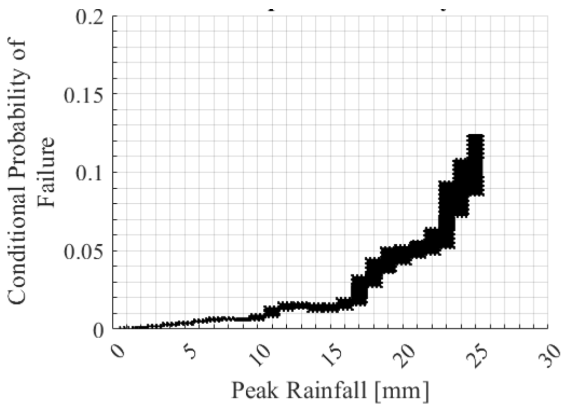
It was not possible to identify a source of data which contained a record of damage to the road pavement or associated infrastructure in the aftermath of a flooding incident. Longer-term damage linked to previous flood events may be revealed in pavement maintenance records but this data is time-consuming to extract and therefore proved beyond the scope of this study.

Around 4.3% of incidents where the flood depth was greater than 3cm in depth resulted in a road closure, and a further 12.1% of incidents brought about the closure of at least one lane. Similarly, 3.4% of flooding incidents with flood depth greater than 3cm were classified with an impact level in the range A-C according to Transport Scotland's Disruption Risk Assessment Tool (DRAT).



Proportion of Flooding Incidents Categorised by Flood Depth

Using rainfall and flood incident records, fragility curves were estimated for peak hour and 24-hour cumulative events which give the probability of a road section being disrupted for a given level of rainfall. There is scope to produce more accurate estimates with a longer time series of data and the inclusion of additional factors which influence the probability of flooding of a road section reflecting e.g. the local catchment and road geometry.



Variation in the Probability of Flooding Disruption with Peak Rainfall

Accident Risk

A total of 44 road traffic collisions on the trunk road network between 2016 and 2020 were associated with a flood of more than 3cm in depth. It can be tentatively estimated that there were 0.079 casualties per flooding incident where flood depth was greater than 3cm, which is equivalent to around 10.31 casualties per annum on the trunk network managed by the four operating companies.

Recommendations

Data Quality

The collection of higher resolution and more comprehensive data on flooding incidents and the resulting impacts would provide empirical support for future vulnerability assessments. Whilst recognising the challenges of recording data at the same time as dealing with live incidents, consideration should be given to enhancing the incident data collection process. In particular, it is recommended that the maximum depth and extent of flooding should be recorded, including any flooding which occurs outside the road carriageway. The cause of each flooding incident should be recorded as well as actions taken to alleviate the flood including the use of any plant.

A record of post-flood clean-up operations, any defects and repairs and traffic management should also be maintained. Road traffic accidents are categorised separately from flooding incidents. Care should be taken to record surface conditions accurately for road traffic accidents as this would enable non-injury crash data to be combined with Stats 19 injury accident data in future analysis.

Data Integration

Enhance asset management systems to make it easier to relate flood incident records to asset data and pre- and post-incident maintenance records in order to identify suitable vulnerability indicators and/or estimate vulnerability functions for the Scottish road network.

Network Losses

Develop appropriate models to enable the performance of the road network and the impacts on road users caused by reductions in the Level of Service from flooding (and other) incidents to be assessed.

Flooding Scenarios

Develop a series of plausible future flooding scenarios with which to test the performance of the road network.

Research & Innovation

Road embankments are susceptible to subsidence and instability as a result of flooding. Further research is recommended into the extent to which road “washout” is caused by internal/external erosion of the soil forming the road foundation and its interplay with the initially partially saturated conditions of the soil.

Use data collected at flooding incidents (see Data Quality above) to create new or to calibrate existing vulnerability functions which relate flood depth to loss or damage in order to identify vulnerable locations and assess future flood risk to the network. Explore the potential value of incorporating site-specific factors into these vulnerability functions to address known limitations.

As a complement to the above, estimate the return periods of the rainfall associated with flooding incidents in order to create fragility/vulnerability functions which relate rainfall intensity to loss or damage in order to identify vulnerable locations and assess future flood risk.

Consider the impact of flooding on non-trunk roads, and also the impacts of flooding on public transport, walking and cycling.

Review methods to assess the indirect social and economic impacts from flooding-related disruption and their applicability in Scotland.

Acknowledgements

Thanks are due to Drew Hill for providing assistance throughout the research project and to Mark Scott for supplying flood incident data. Comments and feedback from board members of the Scottish Road Research Board and the members of Transport Scotland's Vulnerable Locations Group are also gratefully acknowledged.

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Abbreviations

ACCAR	Approach to Climate Change Adaptation and Resilience
CCRA	Climate Change Risk Assessment
CEDR	Conference of European Directors of Road
DBFO	Design Build Finance Operate
DRAT	Disruption and Risk Assessment Tool
HAZUS-MH	Hazards US Multi-Hazard
IPPC	Inter-Governmental Panel on Climate Change
IRIS	Integrated Road Information System
NFRA	National Flood Risk Assessment
NTS2	National Transport Strategy 2
OC	Operating Company
ROADAPT	Roads for Today Adapted for Tomorrow
RTC	Road Traffic Collision
SCCAP	Scottish Climate Change Adaptation Programme
STPR2	Strategic Transport Projects Review 2
TRISS	Trunk Road Incident Support Service
VAST	Vulnerability Assessment Tool
VLG	Vulnerable Locations Group
VLOG	Vulnerable Locations Operations Group

1 Introduction

The trunk road network provides strategic transport links between cities and towns, as well as ports, airports and other key destinations across Scotland. The network is over 3,500 km in length and consists of a diverse range of motorways, dual-carriageways and single carriageway sections. Whilst it represents only 6% of the total Scottish road network, it carries over 35% of all traffic and 60% of heavy good vehicles (Transport Scotland, n.d.). A map of the trunk road network is shown in Figure 1. Transport Scotland has maintenance contracts with four Operating Companies covering the North West, North East, South West and South East Units, and Design Build Finance Operate (DBFO) Contractors on some of the more recently constructed road sections.

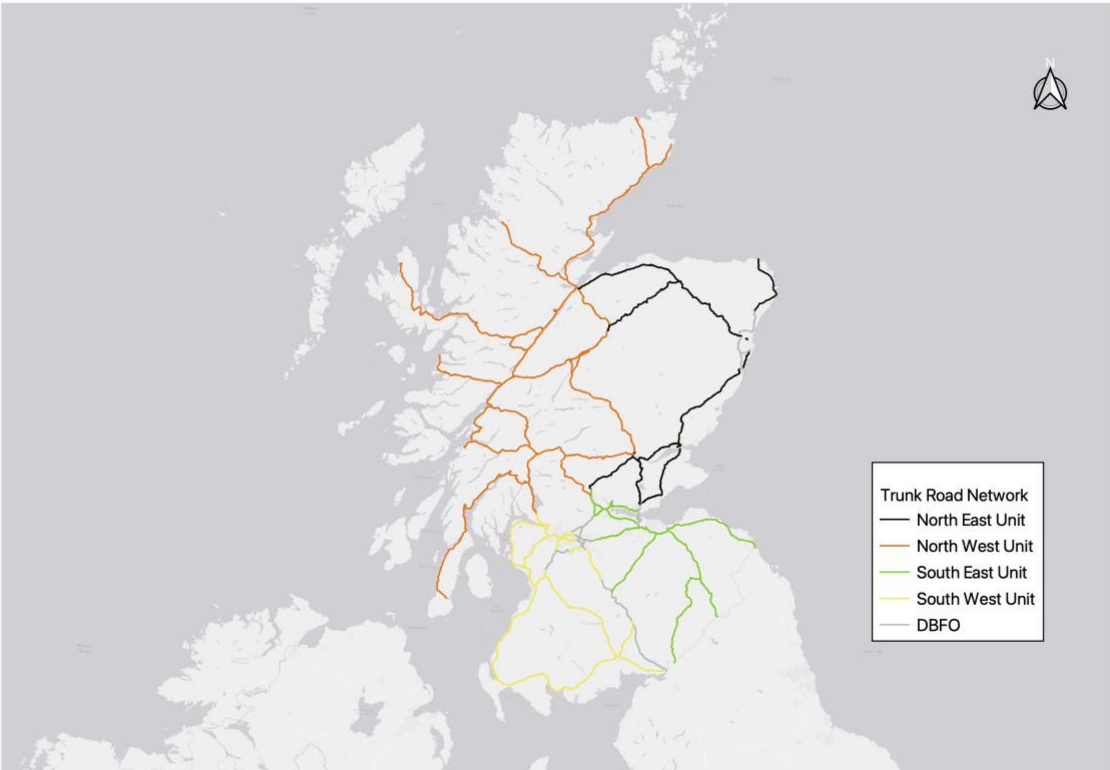

Figure 1 - Scottish Trunk Road Network

This project was carried out on behalf of the Scottish Road Research Board, with the collaboration of Transport Scotland.

The aim of this project was to develop a framework for assessing the vulnerability of roads to adverse weather-related flooding events. The framework could be applied to evaluate the vulnerability of the Scottish road infrastructure and to assess its risk and resilience to critical events, allowing the identification of the most vulnerable components and support risk mitigation strategies and management actions.

The project was organised into four separate work-packages (WP's):

WP1. Critical vulnerability indicators
Conduct a review of damage and loss mechanisms and identify critical factors that affect the vulnerability of roads to flooding.

WP2. Vulnerability assessment methods
Evaluate existing methods which have been used to assess the vulnerability of roads to flooding.

WP3. Data analysis
Classify incidents by severity using historic flood incident data from IRIS and Stats 19 datasets, and estimated rainfall intensity from SEPA's rain gauge network.

WP4. Vulnerability estimation
Based on the outputs of WP's 1-3, estimate the probability of road section failure by flooding or rainfall intensity.

This report is structured as follows:

Chapter 2 provides a background to road flooding and vulnerability assessment. Chapter 3 then reviews the international literature with the aim of identifying key vulnerability indicators and models for vulnerability assessment which are evaluated in Chapter 4. The results of statistical analysis of flooding incidents recorded in Transport Scotland's Integrated Road Information System (IRIS) are given in Chapter 5. The IRIS data is then used to estimate the expected impact of flood events on trunk roads in Chapter 6. Chapter 7 contains the results of fragility analysis of the trunk road network to flood-related disruption based on rainfall intensity which was estimated using a combination of observed rainfall at nearby weather stations, radar rainfall data and the topographic characteristics of the road section. Conclusions and recommendations are given in Chapter 8.

PART I Background and Literature Review

2 Background

2.1 Flooding

Flooding is a meteorological/hydrological risk which occurs when water accumulates on or flows across land surfaces which are normally dry (e.g. Lu, 2019). Road flooding can be considered as an accumulation or flow of water on or across a road which may include the paved carriageway, hard strip/shoulders, central reserve, adjacent verges, side slopes and berms.

Road drainage systems and, where necessary, flood defences (e.g. walls, embankments), are designed to resist flooding[1]. The configuration of drainage systems will vary across the network, reflecting the age, type, history and location of the road. A road will flood when an event with a magnitude in excess of the design capacity of its drainage system or level of its flood defences occurs. The condition of a road's drainage and flood defence assets may reduce its capacity to resist flooding to a level below that for which it was designed, resulting in more frequent and more severe flooding incidents.

The most common sources of flooding are:

- **Surface water flooding** – occurs when heavy rainfall overwhelms the road's surface drainage system and water then flows along the impermeable road surface or adjacent areas and either pools at low, flat sections of the road, or flows on to adjacent land. Flooding is exacerbated when the drainage system is partially or fully blocked in advance of or as a result of debris or damage during the rainfall event. Intense rainfall can cause the rapid onset of flash flood events which can catch drivers off guard. In urban areas, the severity of road surface flooding may be increased by water flowing from adjacent land or upwards from inundated combined sewer systems carried below the road.

- **Fluvial flooding** – occurs when the water level in a river rises and flows on to adjacent road infrastructure. The characteristics of fluvial flooding are influenced by catchment topography. In flatter catchments there is a time lag between severe or prolonged precipitation and a rise in major river levels. This rise may be exacerbated on tidal stretches of a river during high flood tides, particularly during storm events (Berguijs *et al*, 2019). Flooding occurs relatively slowly and may remain for days, even after river levels have fallen (Wuebbles, 2017). In contrast, flash flooding of smaller rivers in hilly or mountainous catchments occurs shortly after intense rainfall upstream and results in potentially destructive flows of fast-moving water, and possibly also debris, which subside quickly.

- A combination of fluvial and surface water flooding may be at play when water run-off from a hillside during heavy or prolonged rainfall results in road flooding.

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[1] Road drainage systems comprise land drainage (where the road intersects with natural drainage paths), sub-surface drainage (to prevent excess moisture in unbound layers of the pavement) and surface drainage (to remove water from the road surface and reduce the risks of skidding, aquaplaning and spray (Todd, 2015).

- **Coastal flooding** – occurs when the road infrastructure is inundated by sea water as a result of a high tide and/or a storm surge driven by high wind.

Although the main driver of surface water and fluvial flooding in Scotland is severe or prolonged rainfall, snow melt on the road surface or from surrounding areas may also lead to flooding during winter periods.

The characteristics of a flood give an indication of its likely impacts and include (Scottish Government, 2019):

- Spatial extent
- Depth
- Duration
- Flow velocity
- Flood water quality
- Sediment content

2.2 Vulnerability

In general terms, vulnerability is a weakness in part of a system (asset, person, organisation etc) which makes it susceptible to damage or loss from a hazard or threat (IPPC, 2022). Vulnerability is a property of the system, reflecting its inherent qualities and deficiencies that affect its ability to withstand adverse events.

The concept of vulnerability encompasses three distinct but inter-related categories (Atzl and Keller, 2012):

- Physical/built environment
- Social environment
- Natural environment

Within the literature, two broad definitions of vulnerability have emerged. In engineering, the concept of vulnerability has developed largely within a risk framework (see Section 2.3) and can be considered to be the ***expected loss*** to a system as a result of exposure to a hazard of a given magnitude. Within the social sciences, vulnerability reflects the ***potential for loss*** within a system prior to encountering a hazard (Cutter et al., 2003; Aven, 2007; Agarwal, 2015)).

Some conceptualisations of vulnerability also explicitly include exposure and/or adaptive capacity of a system – the latter implicitly linking the concepts of vulnerability and resilience (see Section 2.4 below). For example, the Inter-Governmental Panel on Climate Change (IPCC) defines, vulnerability as:

> "the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC, 2022).

Taking an engineering perspective, the physical vulnerability of a road asset to flooding depends on the asset characteristics, and damage is conditional on the severity/magnitude of flooding. The vulnerabilities of vehicles, their occupants and the travel being undertaken can be similarly defined.

Vulnerability models (or functions) relate expected (physical) damage to hazard magnitude. Damage is typically measured on a (0, 1) scale, in which 0 indicates that an asset is not damaged, and 1 means that it is completely destroyed or lost. Multiplying damage by the value of an asset (e.g. the asset replacement cost) provides an estimate of direct loss.

Another related concept is that of fragility. Fragility models quantify the probability that a defined damage level will be exceeded in the event of a hazard of a given magnitude occurring.[2] With suitable cost data for different levels of damage, a vulnerability model can be estimated from a fragility model (see Appendix A).

Vulnerability can also be expressed using indicators within a framework such as the hazard-of-place model (Cutter et al, 2003)), where indicators reflect separate dimensions of vulnerability. Principally applied to assess social vulnerability, indicator-based methods have more recently been used to assess the vulnerability of physical assets: on their own (e.g. Papathoma and Dominey-Howes, 2003; Benedetto and Chiavari, 2010), or in combination with vulnerability functions ((Godfrey et al., 2015). Indicator-based vulnerability approaches can relate to a specific hazard (e.g. flooding) or be hazard-free, and assume that vulnerability is independent of hazard magnitude (therefore adopting a social sciences interpretation of vulnerability as discussed earlier in this Section).

2.3 Risk and vulnerability

Road flooding has the potential to cause loss of life or injury, damage to infrastructure and vehicles, social and economic disruption, or environmental degradation.

The severity of flood risk can be assessed with reference to the likelihood of a flood event occurring with a specified magnitude and the expected impacts of the event. This assessment may be carried out using qualitative, semi-qualitative or quantitative methods. The resulting assessment can then be used to identify critical elements in the road network and to design improvements to reduce risk.

In a quantitative flood risk assessment, **Risk** (R) is a function of the **Hazard** (H), i.e. the likelihood of a flood event of a specified magnitude occurring in a given time period, **Exposure** (E) – the location, attributes and value of the system assets exposed to the hazard – and the **Vulnerability** (V) of the exposed assets to damage or disruption. Hazard, Exposure and Vulnerability are regarded as the three determinants of risk (see Figure 2).

[2] Fragility models are defined using expert judgement, structural analysis or derived using empirical damage data. The vulnerability of an asset to a hazard of a given magnitude is the damage level (full, partial etc.) weighted by the probability of a defined damage level (DS_i) being exceeded, i.e. $V|H = p_1DS1 + p_2DS2 + \cdots$.

Figure 2 – Three determinants of Risk: Hazard, Exposure and Vulnerability

2.4 Resilience and vulnerability

The Royal Academy of Engineering defines resilience as "the ability [of a system] to anticipate, assess, prevent, mitigate, respond to, and recover from hazards" (RAE, 2020). Resilience relates to the performance of a system over time when subjected to a disruptive event (Agarwal, 2015), and resilience management focusses on the steps taken before, during and after disruption (see, e.g. Linkov and Trump, 2019, p10) to minimise system performance loss, and potentially improve future performance. Note also that resilience is not related to any particular hazard type, in contrast to some definitions of vulnerability.

Quantitative approaches to resilience assessment are often undertaken with reference to a plot of system performance over the time period of disruption – see, for example, Figure 3 (adapted from Bruneau et al., 2003). The shaded area in this figure illustrates "Resilience Loss" (RL). Larger values of RL indicate less resilience, and vice versa. Actions taken before, during and after the event to reduce the magnitude of initial loss and/or the time to recovery will strengthen system resilience.

Resilience can be characterised using the following four properties (Bruneau et al., 2003).

- Robustness – the ability to withstand shocks without or with limited degradation of service
- Redundancy – the extent to which there are alternative units that can functions as substitutes and hence absorb the consequences of degradation
- Resourcefulness – the capacity to identify problems, prioritise actions and mobilise necessary material and human resources to adapt and recover the system
- Rapidity – the capacity to recover in a timely and efficient manner.

The resilience property which is most closely related to that of vulnerability is robustness. In this sense, robustness is the opposite of vulnerability. Robust systems can withstand shocks without significant damage – vulnerable systems are damaged and suffer performance loss from adverse events. This conceptualisation of vulnerability is most relevant in the context of the physical damage of assets.

Other conceptualisations of vulnerability where the time taken to recover from a disruptive event is relevant in the calculation of loss (e.g. user delay, accessibility loss) incorporate other resilience properties (redundancy, rapidity, resourcefulness). In this case vulnerability is synonymous with resilience loss. Particular care must be taken when using the term vulnerability within the context of resilience.

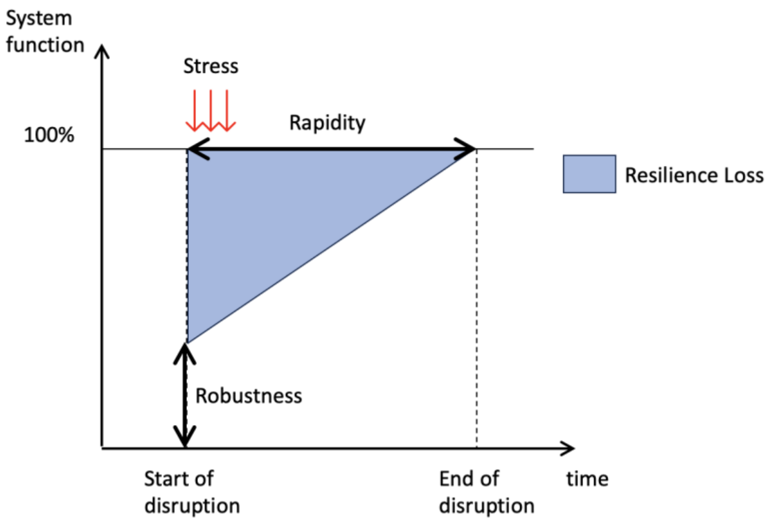

Figure 3 – Loss and recovery of system functionality after a disruptive event. Resilience can be characterised with reference to robustness and rapidity of recovery. Shaded area illustrates resilience loss (adapted from Bruneau et al. (2003) and Jenelius and Mattsson (2021)

2.5 Classification of potential flooding impacts and their interdependencies

Potential transport-related negative impacts from flooding can be split into direct and indirect impacts (Jongman *et al*, (2012), Meyer *et al* (2013)), with a further sub-classification into tangible and intangible impacts.

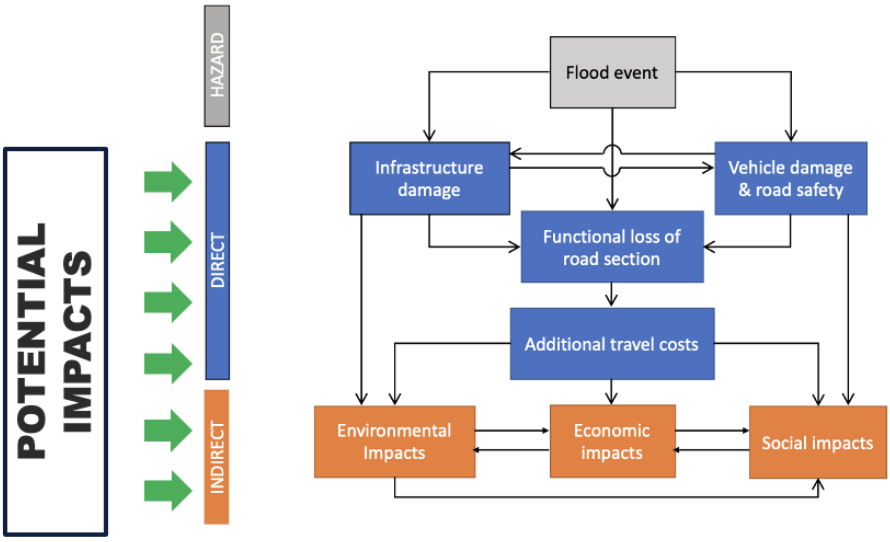

Figure 4 – Interdependencies between principal categories of potential impact resulting from flooding

Direct impacts are those which occur as a result of "contact" with the hazard event, e.g. road damage, delay to road users, potential injury or loss of life (Hochrainer-Stigler *et al*, 2022).

Direct impacts may also expose other vulnerable ("at-risk") elements to damage or loss (see Figure 4). These are known as indirect impacts which stem from direct impacts and arise as a result of interdependencies within the road system. For example, flood damage to the road network may disrupt industry supply chains, or prevent healthcare professionals treating patients. In some cases, the physical impact of a flooding event may generate a sequence or cascade of indirect impacts across the system which are separated in time and space from the original event (Sitzenfrei *et al*. (2011), Gill *et al*, (2022)).

Tangible impacts (direct and indirect) are those that can be expressed on a monetary scale which offers the advantage of being able to compare diverse impacts on an objective basis within a Cost-Benefit Analysis Framework. The conversion of a quantifiable impact to a monetary scale requires the impact to be assigned a market value, e.g. damage repair costs or a traveller's willingness-to-pay to avoid travel time delay. For example, Winter and Bromhead (2012) proposed an economic assessment framework which encompassed "indirect consequential economic impacts" reflecting the costs borne by transport-dependent activities, in addition to direct economic impacts (e.g. clean-up and repair of damaged infrastructure, search and rescue), and direct consequential economic impacts (e.g. accidents, user delays).

By definition intangible impacts are not straightforward to convert to a monetary scale often because of a lack of good quality data (Meyer *et al*, 2013)[3] and it may not be appropriate to attempt to do so. Examples of indirect impacts include health, environmental and cultural heritage impacts. Within the social vulnerability literature, it is

[3] Meyer et al. (2014) reviewed a number of methods for estimating the monetary value of intangible impacts.

common to focus on the socio-economic factors that determine a household's capacity to adapt and respond to hazard impacts. These factors are typically combined into a vulnerability index which is then used to evaluate the socio-spatial variation in susceptibility to hazard impacts (Cutter et al., 2003; Singh et al., 2017).

It is worth noting that repeated exposure to flood events may also damage infrastructure assets over time. Likewise, those who use or rely on the transport system may modify behaviour or suffer economic or other impacts in the longer-term as a result of repeat events.

2.6 Interdependencies with other infrastructure systems

Disruption to the transport systems as a result of flooding may have knock-on impacts with other infrastructure systems and services (Figure 5).

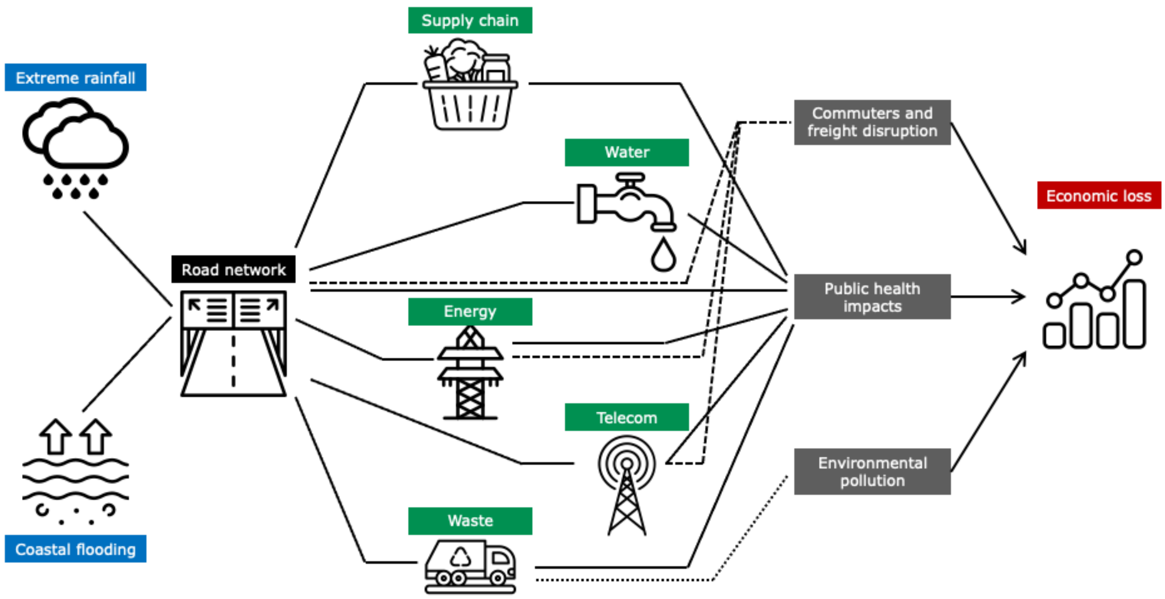

Figure 5 – Dependency of infrastructure systems and services on the transport system (based on AECOM, 2017)

2.7 Climate Change

2.7.1 Observed and projected climate change in Scotland

The intensity, frequency and spatial extent of rainfall events are key drivers of pluvial and fluvial flooding. Likewise, the sea level and the magnitude of storm surges affect the risk of coastal flooding. The extent to which these drivers have changed and are expected to change as a result of climate change has been synthesised by Slingo (2021) based on the most up-to-date scientific evidence for the UK.

In summary:

- In the last 30 years, annual rainfall has increased in Scotland by around 10% on average compared to the long-term average up to 1970. Average winter rainfall has increased by a higher percentage.
- In the future, winter rainfall is projected to increase as a result of increases in both the frequency of wet days and the rainfall intensity on these days (Figure 6).
- Summers are expected to become drier. Whilst the number of wet days is projected to decrease, the intensity of rainfall on wet days is expected to increase across most of the country.
- The frequency of more intense hourly rainfall events is also expected to increase in all seasons. It is currently uncertain if climate change will have any influence on the spatial extent of rainfall events, and if so in what direction.
- The mean sea level around the UK has risen by around 1.4mm per annum since 1901. Sea levels are expected to continue to rise as a result of global warming; for example, the mean sea level for Edinburgh is projected to increase by between 12 and 18cm in 2050 compared to 1981-2000 depending on future greenhouse gas emissions. At present, it is unclear what future change, if any, there will be in the size of storm surges.

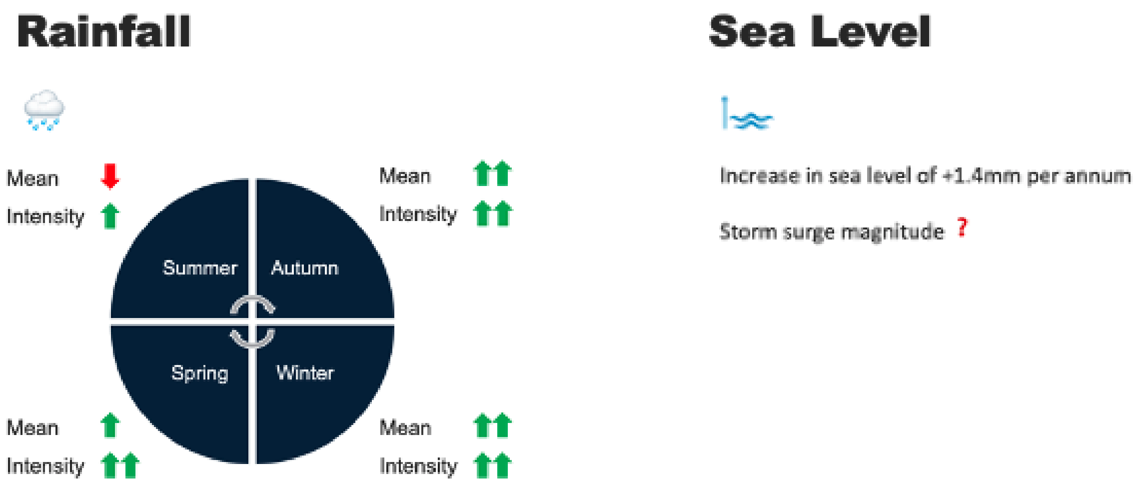

Figure 6 - Projected impacts of climate change in Scotland on rainfall and sea level

2.7.2 Statutory Climate Change Adaptation Framework

The UK Climate Change Act 2008 requires an assessment of the risks from current and predicted impacts of climate change to be undertaken every five years. The third and most recent Climate Change Risk Assessment (CCRA3)[4] was published in 2022.

The Climate Change (Scotland) Act 2009 requires an adaptation programme which addresses the risks identified for Scotland by the CCRA and sets out objectives in relation to adaptation and proposals and policies for meeting those objectives. The legislation also requires Scottish Ministers to publish progress reports to be published annually. The first adaptation programme, known as the Scottish Climate Change Adaptation Programme

[4] https://www.ukclimaterisk.org/

(SCCAP), was published in 2014. The current programme (SCCAP2) was published in 2019[5] and the third and most recent annual progress report on SCCAP2 was published in 2022.

The Climate Change (Scotland) Act 2009 also requires two phases of independent assessment of progress towards implementation of SCCAP within each five year planning cycle. The first such, conducted by the Climate Change Committee, was published in 2022.[6]

A third adaptation programme – the Scottish National Adaptation (SNAP3) – is scheduled for publication in 2024 in response to the risks identified in CCRA3.

2.7.3 Assessment of Climate Change Risk

CCRA3 identified five specific risks to infrastructure which directly relate to flooding. Table 1 provides a description of each risk and the assigned level of urgency to address the risk based.

Risk Number	Risk Description	Urgency Score[7]
In1	Risks to infrastructure networks (water, energy, transport, ICT) from cascading failures	More action needed
In2	Risks to infrastructure services from river and surface water flooding	More action needed
In3	Risks to infrastructure services from coastal flooding and erosion	Further investigation
In4	Risks to bridges and pipelines from flooding and erosion	Further investigation
In5	Risks to transport networks from slope and embankment failure	More action needed

Table 1 – Infrastructure risks and associated urgency score identified in CCRA3

Table 2 summarises CCRA3 analysis which indicates that there is expected to be a substantial increase in the length of the major road network at significant risk of all types of flooding by 2080 on a +4°C emission scenario at the current level of adaptation and also with enhanced whole system adaptation (Sayers et al. (2020)).

[5] Climate Ready Scotland: Second Scottish Climate Change Adaptation Programme 2019-2024 (otherwise known as SCCAP2)
[6] Is Scotland Ready? 2022 Report to the Scottish Parliament.
[7] **More action needed** – "New, stronger, or different Government action, whether policies, implementation activities or enabling environment for adaptation – over and above those already planned – are beneficial in the next five years to reduce climate risks or take advantage of opportunities." **Further investigation** – "On the basis of available information, it is not known if more action is needed or not. More evidence is urgently needed to fill significant gaps or reduce the uncertainty in the current level of understanding in order to assess the need for additional action."

		Current Level of Adaptation		Enhanced Whole System Adaptation	
	Present Day	2080's			
Fluvial	984,908	1,496,446	+52%	1,429,300	+45%
Surface Water	1,425,478	2,359,965	+66%	2,337,410	+64%
Coastal	290,232	362,553	+25%	356,515	+23%

Table 2 - The length of the Scottish major road network (m) at significant risk of flooding at present and by the 2080's on +4°C emission scenario by flood type for (a) the current level of adaptation (CLA), and (b) enhanced whole system (EWS) adaptation (Source: Sayers et al. (2020))

2.7.4 Adaptation of the Road Network to Climate Change

SCCAP2 sets out a range of policies which are relevant to the resilience and adaptation[8] of the road network in response to risks identified in CCRA2. Cross-cutting policies include the establishment of the Infrastructure Investment Plan, the publication of the National Transport Strategy 2 (NTS2) and the National Flood Risk Assessment (NFRA) 2018, and the second phase of Dynamic Coast. Sector-specific policies include the publication of the Strategic Transport Projects Review 2 (STPR2) and the use of the Integrated Roads Information System (IRIS) and the Disruption Risk Assessment Tool (DRAT) to record flood incidents, identify vulnerable locations and prioritise locations for engineering intervention or ongoing monitoring.

The independent assessment of SCCAP2 recommended that Transport Scotland's adaptation strategy should include specific adaptation objectives, and that risks from infrastructure interdependencies should be planned for and managed. Lessons from regional adaptation programmes such as Climate Ready Clyde should be applied at national level.

SCCAP3 in response to CCRA3 is due to be published in 2024.

Transport Scotland's Approach to Climate Change Adaptation and Resilience (ACCAR) (Transport Scotland, 2023) sets out a framework to address the risks identified in CCRA3 up to 2030 (including the flooding-related risks set out in Table 2). This framework pulls together current actions, plans and guidance relating to climate change adaptation and resilience within an overall vision underpinned by four strategic outcomes and associated sub-outcomes.

Relevant parts of this framework which relate to flooding are as follows:

- The development of flood risk maps produced in conjunction with SEPA

[8] In the context of SCCAP2, "adaptation" is the preparation for the impacts of climate change which will take place, and "resilience" is the ability to respond to the weather-related impacts of climate change and maintain normal operation of a system and its associates services.

- Major capital projects designed in accordance with the Design Manual for Roads and Bridges (DMRB) and based on latest climate change predictions
- Asset management delivered in accordance with Transport Scotland's Scottish Trunk Road Asset Management Strategy and its Road Asset Management Plan.
- Transport Scotland's Manual of the Risk of Unplanned Network Disruption updated covering flooding management plans and the adoption of a proactive approach to managing weather-related impacts. The potential impact of extreme weather on the structural integrity of trunk roads is also noted.
- Scotland's Road Safety Framework to 2030 aims to mitigate the negative impacts of climate change on road safety and recognises the need for road users to gain the knowledge, skills and experience to deal with extreme weather conditions.
- The establishment of a Vulnerable Locations Group (VLG) and a Vulnerable Locations Operations Group (VLOG) for trunk roads within Transport Scotland which are responsible for strategic oversight and operational delivery of adaptation schemes respectively.

2.8 Previous studies on Trunk Road Flooding

As part of a piece of work on surface water forecasting, SNC Lavalin/Atkins (2020) used historic flood incident data for the period 2016-18 to identify pluvial flooding hotspots on the trunk road network.

Zanganehasadabadi (2021) undertook an SRRB-sponsored project which sought to characterise the restoration of road infrastructure following extreme flood events. A workshop attended by transport professionals considered the risk of road infrastructure damage and restoration time for several hypothetical flooding scenarios. Flood characteristics (i.e. flow velocity and duration) and the condition of road and drainage assets were identified as key risk factors. In terms of restoration time, it was established that resources normally exist to accelerate the time required to restore a road if necessary, e.g. in situations where a road closure leaves a community with limited or no access. In situations where multiple sections of the road network are affected concurrently, additional resources could be brought into an affected area under the principal of "mutual aid" which exists between operating companies, although restoration time may be longer than usual. Other factors that may affect restoration time include the availability of specialist plant and equipment, the presence of utilities in damaged sections of road and the ability to communicate between the on-site engineering team and off-site decision-makers. Moreover, access to affected locations may be restricted by closures on other parts of the network as a result of damage or on a precautionary basis e.g. bridges at risk of scour damage.

3 Direct Impacts of Flooding

3.1 Introduction

Flooding may damage road infrastructure and vehicles, reduce the functionality of flooded road sections and puts the lives of road users at risk. This chapter reviews direct impact mechanisms and identifies factors that influence the extent of any damage or loss. The cited literature includes articles published in peer-reviewed journals and technical reports written on behalf of government bodies.

3.2 Road Damage

A road and its associated earthworks are vulnerable to flooding. In this case, the term 'road' is interpreted broadly to include the bound and unbound layers of the road pavement and its foundations, as well as adjacent verges, kerbs, footpaths and so on. Drainage infrastructure, lighting, signage and other such assets are also included. In addition, the vulnerability of utility infrastructure carried by a road should also be considered if the full extent of any damage and resultant costs are to be estimated accurately.

The main causes of road damage from flooding stem from the ingress of water to the road pavement and its foundations, debris deposition on the road surface, embankment/verge scour and, in extreme cases, road washout (Lu, 2019).

3.2.1 Water Ingress

During flooding, water ingress to a flexible road pavement may occur through surface cracking, from the side of the road[9], or from below for roads in a cutting or with a high water table (Walsh, 2011) and affect pavement performance as follows:

- Moisture in bound layers reduces the strength of the adhesive bond between bitumen and aggregate, increasing the likelihood of stripping.
- High levels of trapped moisture may weaken the bond between layers.
- Saturation of the sub-base and/or subgrade reduces its load-bearing strength to a level below its maximum strength at optimum moisture content.
- Movement within or loss of fines from unbound layers may reduce load-bearing strength.
- Freezing and thawing will exacerbate the effects of water ingress.

For ingress through the road surface, the rate at which water is able to enter the pavement depends on the permeability of the asphalt which in turn is a function of the percentage of air voids[10], aggregate gradation and aggregate shape, and also the extent of any surface discontinuities such as cracking and joints.[11]

[9] Roads with 'over-the-edge' combined surface water and filter drains with highly porous granular material to the surface of the verge are susceptible (Walsh, 2011)

[10] The intrusion of water is greatly reduced when air voids are 7% or less in the asphalt mixture (Chen, Lin and Young, 2004).

[11] In cracks wider than 2 mm, permeability may increase significantly along with a corresponding reduction in tensile strength which may lead to the rapid failure of the pavement (Chen, Lin and Young, 2004).

Loss of Load-Bearing Strength
Any reduction in load-bearing strength may persist for anything from a few hours to several weeks or even longer, depending on sub-surface drainage. There is consequently a risk of traffic damage to the road during or in the aftermath of a flood event. In extreme cases, the extent of strength loss may result in rapid failure, particularly if the road is used by heavy vehicles for repair and clean-up activities (Mallick et al., 2017a). In less extreme cases, flooding may accelerate the deterioration of the road in the longer term resulting in a reduction in its service life (Lu, Tighe and Xie, 2020).

Evidence of road pavement damage from loss of load-bearing strength as a result of flooding is summarised below, followed by a review of the various analytical models which have been developed. Caution should be employed when making a comparison of evidence from different countries as a result of varying environmental conditions, and the use of different pavement design standards and construction materials.

Available Empirical Evidence
United States
In the aftermath of Hurricane Katrina, selected flood-affected asphalt concrete road sections in Louisiana were weaker and had a lower subgrade resilient modulus in comparison with unflooded sections (Gaspard et al., 2007; Zhang et al., 2008). Whilst pavements with a thickness of less than 178 mm were more susceptible to weakening than thicker pavements, there was no observed difference between the strength loss in road sections which had been inundated for one week compared to those which had been inundated for two or more weeks.

Shortly after flooding of the Missouri in 2011, the surface and subgrade elastic moduli of a single road section which had been partially submerged for a period of two months[12] were 25%-30% lower than a comparable section of unflooded road (Vennapusa, 2013). Furthermore, this difference in elastic moduli persisted for a period of at least 9 months.

Australia
Parts of Australia experienced heavy rainfall and flooding in the period December 2010 to January 2011. Increases in structural deterioration and surface distress were observed in a small sample of flooded-affected roads compared to pre-flood observations (Sultana et al., 2015; Sultana et al., 2016). Subsequent work developed mechanistic-empirical models to estimate the deterioration of flood-affected pavements in the weeks following inundation. These models showed that the structural strength of lightly-trafficked asphalt concrete pavements with a thickness of 45-60 mm declined more rapidly than anticipated in the six week period following inundation. Models to predict the increase in rutting and roughness of local roads for up to 172 days after flooding were also developed (Sultana et al., 2018). In a similar vein, Khan et al. (2014) developed probabilistic rutting and roughness-based road deterioration models for different road groups based on traffic loading, pavement type and strength.[13] Stronger and more highly-trafficked flexible pavements were less affected by flooding than weaker roads carrying less traffic. These models covered the whole road

[12] Hot mix asphalt with a depth of 360 mm supported by an unbound base of 300 mm
[13] Pavement strength reflected the age and thickness of the road, whilst the level of traffic was considered as an indicator of design and maintenance standards.

network in Queensland, Australia and were subsequently used to identify flood resilient pavements (Khan, et al., 2017a) and to assess the risk of the road network to flooding (Khan et al, 2017b).

UK
Walsh et al. (2011) found no evidence of pavement damage in terms of wheel track rutting and ride quality following flooding of depth in excess of 1.4 metres on the M50 motorway.

Analytical Models
Multi-layer elastic analysis was used to study the effect of a fully saturated granular base layer on the vertical compressive strain at the top of the subgrade (associated with rutting) and horizontal tensile strain at the bottom of the asphalt layer (associated with cracking) (Elshaer and Daniel, 2018). Vertical and horizontal strains were shown to be higher at saturation than at optimal moisture content for various combinations of pavement depth, and base layer and subgrade material types.

Mallick et al., (2017a) modelled the time it would take for flooding to saturate a granular sub-base layer. Water was assumed to infiltrate downwards through the asphalt upper layers of the pavement at a rate dependent upon the mix design and the extent and width of surface cracking. The time to full saturation took less than 7 hours in all cases[14], and was significantly affected by asphalt layer thickness and permeability. Only a single depth of flooding was considered (1 metre) and drainage conditions were not included in the model.[15] Further work by Mallick et al., (2017b) combined hydraulic and structural models to estimate the time for a flexible pavement to recover its strength following the saturation of the unbound base layer as a result of flooding. Pavements with an asphalt surface layer of 200 mm in depth were estimated to recover full strength in around 2 days. However, weaker pavements remained susceptible to damage under heavy traffic loading three weeks after saturation. Using finite element analysis to model the loss of pavement strength, Nivedya et al. (2020) explored the variation in saturation at different levels within a granular base layer for various levels of hydraulic conductivity following a flooding event. Whilst pavements with a thin surfacing (depth of 75 mm) and a granular base layer with a low level of hydraulic conductivity exhibited strength loss for many weeks after a flood event, pavements with an asphalt surface layer of 150 mm were largely unaffected by flooding both in terms of strength loss and the length of recovery period.

Road management in the aftermath of flooding
Qiao et al. (2017) proposed a Bayesian decision tree approach to support the re-opening of flood-affected roads which sought to balance the risk of structural damage in the event of re-opening a weakened road with the user costs resulting from delay and diversion if the road remained closed.

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[14] The maximum surface layer thickness tested was 200 mm
[15] By way of comparison, Walsh et al. (2011) estimated that it would take approximately 83 hours of continuous rain or flooding to saturate a 250mm thick sub-base layer with no drainage. Water was assumed to enter the sub-base via the central reserve.

Repeated flooding incidents
Repeated exposure to high levels of moisture through recurring rainfall and flood events may result in a reduction in the service life of a road (Caro et al., 2008; Dawson, 2008; Lu et al., 2020; Mallick 2021)[16, 17] with any reduction being accelerated if the road is in poor condition. Where the time interval between successive flood events is short, or perhaps where a flood event is preceded and/or succeeded by lengthy periods of rainfall then a granular layer is more likely to reach full saturation.[18]

Discussion
Post-flood observations and analytical modelling suggest that roads with relatively thin asphalt layers and granular sub-base layers are susceptible to the loss of bearing capacity, which increases the expected rate of pavement deterioration. A recent risk assessment framework developed for the Iowa Department of Transportation in the United States proposed that thin-surfaced pavements with an asphalt concrete thickness of less than 64 mm or with a surface treatment-seal coat combination should be classified as vulnerable to flood damage, and that pavements with 64 to 140 mm of asphalt concrete surfacing should be classified as potentially vulnerable (Alipour et al., 2021).

A flood-affected road is susceptible to damage if the duration of the flood lasts at least as long as the time required for the granular base to reach saturation. This time depends on a number of factors including the initial saturation level, the thickness of the pavement and its constituent layers, the permeability of asphalt, the permeability of any flow paths connecting side verges (and central reserve) with the granular base, and the extent to which the sub-surface drainage system operates during the flood event. With regard to the latter, sag curves in cuttings are considered to be particularly vulnerable (Walsh et al., 2011)[19]. The existence of pavement cracking increases the permeability of the pavement and hence reduce the time to saturation.

Where the depth of flooding is not negligible (flood depth greater than around one-tenth of pavement depth),[20] the resulting hydraulic head of ponded water increases the infiltration rate. There is little available evidence on the time needed to reach saturation in different contexts; the literature suggests that time to saturation could lie in the range 10-100 hours.[21] For roads in UK, Walsh et al. (2011) concluded that:

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[16] Lu *et al* (2020) used AASHTO's mechanistic-empirical pavement design guide (AASHTO, 2015) to simulate the effect of different combinations of flood depth[16], duration (1-61 days) and frequency (1-3 cycles) on the long-term pavement performance of thin (120-160 mm) asphalt pavements. Results highlighted the projected loss of road surface quality as measured by the International Roughness Index for increases in each of the three variables tested.

[17] Mallick (2021) employed a system dynamics model to capture the inter-dependency between fatigue cracking and granular base saturation for low and medium-volume roads (corresponding to a thin (75-150 mm) AC layer over a granular base). Results illustrate how pavement damage is accelerated by water ingress and consequent base layer weakening over the life of the road without appropriate maintenance interventions to reduce permeability.

[18] Assuming that input to granular layer is greater than drainage capacity throughout – i.e. the road is unable to drain fully between events.

[19] Sag curves in cuttings are particularly susceptible as surface water drainage is required to remove flood water (Walsh et al., 2011)

[20] Based on Green-Ampt equation used by Mallick et al (2017a) to estimate time to saturation.

[21] *cf.* Mallick (2017a) – 7 hours and Jacobs (2011) - 83 hours

> "where a flood has persisted for a long period, e.g. > 3 days on a road with positive drainage and a sealed verge/central reservation, or > 1 day with combined drainage, it may be prudent to close the road to traffic not just whilst it is under water but also until the sub-base is no longer saturated. It may not be all that easy to tell when it is safe to reopen it."

3.2.2 Erosion/scour of pavement and surrounding earthworks

Water flowing at high velocity over the pavement surface may scour the asphalt (Walsh et al., 2011), a process exacerbated by defects such as cracking and potholes.

Road verges, foundations, downslopes, drainage channels and inlets and outlets of culverts are vulnerable to scour erosion of unbound material if exposed to a rapidly moving flow of water (Vennapusa *et al*., 2013). The critical velocity that may damage the pavement structure or its foundations depends on the gradation of materials present, and typically ranges from 0.7 to 1.3 m/s (Mallick *et al.,* 2017a).

3.2.3 Washout

At the extreme end of the damage spectrum, a road may be partially or fully destroyed by flood water ("washout") which occurs when torrential surface water flows intersect with road infrastructure, often at culverts. If waterlogging occurs, water can infiltrate into the unsaturated subgrade/infill generating a loss of shear strength and, hence, foundation subsidence/instability (Chen and Liang, 2017). If water flows over the road, surface erosion of the soil adjacent to the road can propagate retrogressively undermining the roadbed. If floodwater flows around a culvert because the hydraulic capacity of the culvert is exceeded, internal erosion can trigger roadbed subsidence/instability. The damage in such cases may extend beyond the road pavement and include the subsequent loss of stability of a road embankment or slope.[22]

The extent to which washout is caused by internal/external erosion of the soil forming the roadbed and its interplay with the initially partially saturated conditions of the soil are poorly understood and are worthy of further investigation.

3.2.4 Debris and contaminated material

Debris is associated with moving flood water and is both a cause and a consequence of flooding. Debris frequently compounds the impact of flooding by reducing the capacity of the drainage system during a flood event or even damaging infrastructure in some instances.[23] The deposition of debris on the road surface poses a risk to moving vehicles and may reduce the skidding resistance of the road. In addition to the direct cost of removing debris from the road and drainage systems, road user delay will increase the longer it takes to clear debris.

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[22] Note the ongoing project sponsored by the North Carolina Department of Transportation (NCDOT) which aims to predict road washouts based on forecast rainfall (https://connect.ncdot.gov/projects/research/Pages/ProjDetails.aspx?ProjectID=2021-03)

[23] Martínez-Gomariz *et al*., (2017) highlight the case in Bocastle, UK where vehicles which had been swept away by floodwater blocked a bridge which resulted in its subsequent failure.

3.3 Vehicle Damage and Road User Safety

3.3.1 Water damage

Vehicles are vulnerable to damage (and their occupants to injury and death) as a result of flooding. Water will enter the vehicle cabin when the depth of water is above the door sill height. In such cases the vehicle is likely to be written-off by insurance companies (Penning-Rowsell et al., 2013). Water entering the air intake or the exhaust pipe is also likely to lead to extensive vehicle damage.[24]

3.3.2 Vehicle instability

Vehicles in floods (with or without occupants) are subject to hydrodynamic forces which may result in floating, sliding or toppling mechanisms. For example, the overtopping of roads by floodwater represents a risk to vehicles and their occupants in certain circumstances.

Floating occurs in relatively deep floodwater when the lifting forces are greater than the vehicle weight. In contrast, sliding occurs when the drag force exerted by fast-moving water flow exceeds the friction between the tyres and the road surface (Shand *et al.*, 2011). The magnitude of sliding and floating forces vary depending on the depth and velocity of floodwater (Martínez-Gomariz, Gómez and Russo, 2017). As a result of the uneven distribution of vehicle weight, floating starts at the rear of most vehicles. Once a vehicle is partially afloat there is a reduction in tyre-surface friction which creates more favourable conditions for sliding to occur (Bocanegra, 2021). In extreme cases, a vehicle that is already floating or sliding as a result of flooding may experience toppling on impact with irregular ground (Shand *et al.*, 2011; Bocanegra, 2021).

Vehicle stability models relate flood hazard parameters, such as flow velocity and water depth, and vehicle characteristics to loss of stability. Shand *et al.* (2011) proposed stationary water flood depth thresholds of 0.30 metres for small passenger vehicles, 0.40 metres for large passenger vehicles and 0.50 metres for large 4 wheel-drive (4WD) vehicles. These thresholds are reduced for flow velocities above 1 m/s such that at a flow velocity of 3 m/s the depth thresholds for small passenger and large 4WD are 0.1 m and 0.2 m respectively. These thresholds are contained in the Australian Rainfall and Runoff guidelines and have been widely used in the literature for flood impact assessment of the road network (Martínez-Gomariz *et al.*, 2016; Pyatkova *et al.*, 2019).

Unstable vehicles which are swept away increase the risk of vehicles colliding with, and damaging, infrastructure, blocking drainage channels or injuring people.

3.3.3 Vehicle entering floodwater

Vehicles and their occupants may be swept away by floodwater when drivers attempt to cross a flooded road section (Diakakis and Deligiannakis, 2013). Human factors and the

[24] A flood depth of above 35cm is likely to lead to an average car being written off (Penning-Rowsell, *et al.* (2006))

characteristics of the flooded road section contribute to the risk of entering floodwaters (Gissing *et al.*, 2019).

Although there is a substantial body of literature exploring drivers' characteristics that affect their willingness to enter floodwaters (e.g. (Drobot *et al.*, 2007; Yale *et al.*, 2010; Pearson and Hamilton, 2014; Hamilton *et al.*, 2018; Enríquez-de-Salamanca, 2020)), much less research has been carried out on the road characteristics that affect safety in these situations. Using an inventory of flood-related fatalities in Greece, Diakakis and Deligiannakis (2013) found that most incidents occurred at night and in rural areas, and in all but one case, no advance warning signs of the flood were provided. This suggests that in these conditions, drivers are less likely to detect flooding, and also their ability to assess flood depth and flow velocity is impaired.

Gissing *et al.* (2019) explored the environmental factors and road attributes that contribute to vehicle fatalities in Australia, using historical accident records. Road and environmental characteristics were categorised into three groups of risk factors, namely those that influence the driver's decision to enter flood waters, those that affect the likelihood of a vehicle getting washed away and those that influence the occupants' survivability. This study revealed that the absence of roadside barriers or lighting, lack of kerbs and gutters and the inability of drivers to turn around due to the geometric configuration of the road were factors present in more than 50% of incidents.

3.3.4 Aquaplaning

Water on the road surface reduces tyre-road friction and spray from other vehicles affects forward visibility. Drivers may lose control of the ability to steer and brake their vehicles when they encounter surface water because of the loss of contact between the vehicles' tyres and the road surface (Woodward, 2015). This phenomenon is known as aquaplaning[25] and occurs when a thin layer of water exists between a vehicle's tyres and the road surface. Full aquaplaning occurs when the axle weight is fully supported by a layer of water resulting in a complete loss of tyre grip and a substantial reduction in the speed of tyre rotation ((Huebner, Reed and Henry, 1986) (Bullas, 2004), (Micaelo et al., 2015)).[26] For aquaplaning to occur, a vehicle needs to be travelling above a threshold speed, commonly referred to as the aquaplaning speed, which varies by water depth, tyre tread depth, tyre pressure and road surface characteristics. Partial aquaplaning may occur in wet conditions at speeds below this threshold speed, with the loss of tyre grip increasing with vehicle speed until full aquaplaning speed is reached (Spitzhuttl *et al*, 2020).

Many researchers have focused on developing aquaplaning models which estimate the vehicle speed and water depth required for the phenomenon to occur. Numerical models on the development of aquaplaning simulate the tyre deformation and movement as well as fluid flow with the aid of hydrodynamic theories. Recent examples include the work of Ong *et al.* (2007), Kim and Jeong (2010), Nazari *et al.* (2020), and Yan, Zhang and Hui, (2021). A comparison of several models concluded that the aquaplaning speed reduces with increasing water depth up to a depth of around 2.4 mm, above which aquaplaning speed is

[25] Alternatively know as hydroplaning
[26] Bullas (2004) - to around one-tenth of the vehicle's speed

constant and lies in the range 63 km/h to 87 km/h (Micaelo and Ferreira, 2015). For practical purposes, a threshold water depth value of 2.5 mm is suggested by Todd (2015).

Previous studies have also considered the minimum length of flooding required for aquaplaning to occur. Balmer and Gallaway (1983) (cited by Mounce and Bartoskewitz, 1993) suggested that full aquaplaning is possible when the length of flooded carriageway is greater than 10 metres which is also the value recommended by Nygårdhs (2003) following a review of aquaplaning risk factors.

Loss of surface texture and the presence of rutting increase the risk of aquaplaning in wet conditions; the latter potentially leading to the ponding of water along the wheel paths of vehicles. The risk of aquaplaning on roads with a standard cross fall of 2.5% requires a rut of above 12.5 mm in depth (Lister and Addis, 1977). However, where the cross fall is below 2.5% (e.g. on a transition from standard cross fall to superelevation), a rut depth of more than 7 mm is sufficient to increase the potential of aquaplaning (Hicks, Seeds and Peshkin, 2000).

There is also the risk of a vehicle losing control when it encounters a partially flooded road in which the left and right wheels are affected by different water depths causing the vehicle to slip sideways in the direction of the flood water. Although no specific studies into this phenomenon were identified, research into the effect of water ponding in ruts of different depths gives potential insight into the extent of the safety hazard involved. For a vehicle travelling at 100 km/h, the time taken for the lateral slip to exceed 0.5 metres was 5.2 seconds when the difference in water depths was 6 mm reducing to 4.8 seconds for a depth difference of 7 mm (Yan *et al*, 2021).

Nonetheless, full aquaplaning accidents are considered to be relatively rare events in comparison with the number of accidents occurring at lower speeds in wet conditions (see, for example, Blythe and Day (2002)). Although there is little in the way of published evidence, recent analysis of the German In-Depth Accident Study data estimated that full aquaplaning accidents represent only 0.6% of all accidents which occur in wet or damp conditions (Spitzhüttl *et al*, 2020).

Discussion

Full aquaplaning represents a risk to vehicles travelling at speeds in excess of around 70 – 80 km/h, depending on water depth, tyre tread depth and surface texture. At lower speeds there is also a risk of partial aquaplaning. During periods of high intensity rainfall or prolonged periods of rainfall resulting in widespread surface water flooding, drivers have been observed to lower their speeds which may explain why the accident risk is low (Mounce and Bartoskewitz, 1993; Spitzhüttl *et al*, 2020). Isolated flooding incidents may constitute a greater risk, particularly at night-time, or at locations where tyre-surface friction is important, e.g. on horizontal curves or the approach to junctions.

Locations which are susceptible to blocked side drainage and partial flooding of the carriageway may also increase the risk of aquaplaning.

3.3.5 Other road users

As far as could be ascertained there are no reported research studies which have investigated the impact of flooding on the safety of cyclists or pedestrians.

3.4 Functionality Loss

The impact of flooding on the functionality of a road section depends on the characteristics of a flood. The depth-disruption function shown in Figure 7 relates vehicle speed to flood depth based on a synthesis of previous studies (Pregnolato *et al.*, 2017a). A reduction in vehicle speed will increase user delay and travel times. The flood depth at which a road becomes impassable for vehicles is estimated to be 30 cm.

Partial or full carriageway flooding will reduce the capacity of the road section, which is relevant in congested networks.

Road users will also be subject to travel time delay and diversion in the period after a flood event where clean-up operations or damage repair is required.

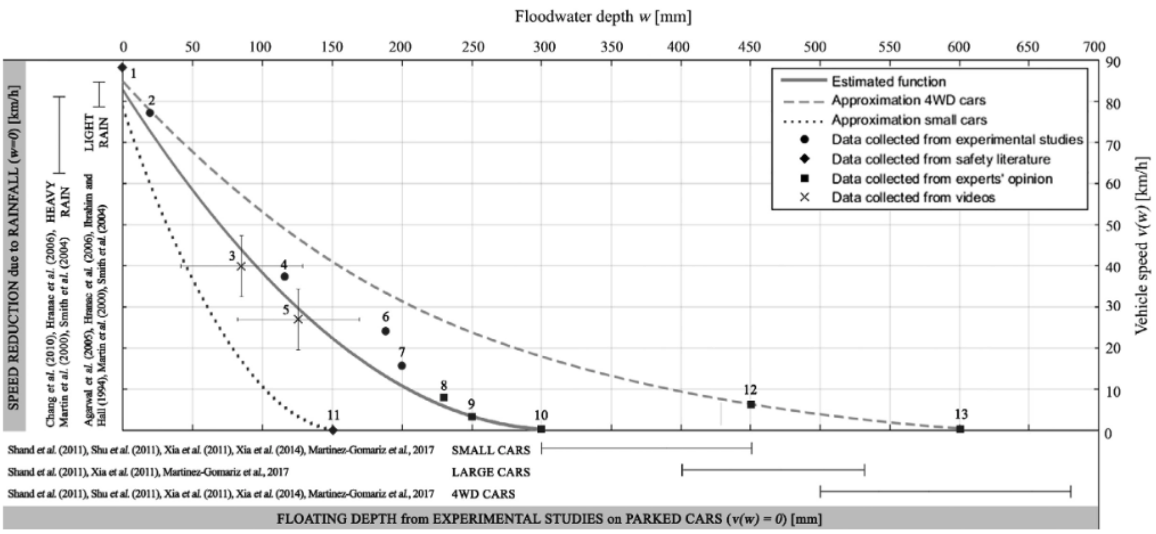

Figure 7 – Depth-disruption function relating flood depth on a road with vehicle speed (Pregnolato et al, 2017a) ((Creative Commons Attribution 4.0 Licence)

3.5 Conclusions

This chapter has reviewed direct impact mechanisms arising from flooding and identified key factors that influence the extent of any damage or loss.

Road Infrastructure Damage

1. Roads with relatively thin asphalt layers and granular sub-base layers are susceptible to the loss of bearing capacity during flooding caused by the saturation of the sub-base layer. The time taken to reach saturation depends on the initial saturation level, the thickness of the pavement and its constituent layers, the permeability of asphalt, the permeability of any flow paths connecting side verges (and central reserve) with the granular base, and the extent to which the sub-surface drainage system operates during the flood event.

2. The existence of pavement cracking increases the permeability of the pavement and hence reduces the time to saturation.

3. There is little available evidence on the time needed to reach saturation in different contexts, nor the time required for the degree of saturation to return to normal levels following flooding.

4. In extreme cases, a road may be partially or fully destroyed ("washout") by flood water intersecting with road infrastructure. The damage in such cases may extend beyond the road pavement and include the subsequent loss of stability of a road embankment or slope. The extent to which washout is caused by the scouring of materials or the saturation of subgrade/infill materials is not fully understood and is worthy of further investigation.

Damage to Vehicles and Road User Injury

5. Vehicles caught in a flood will suffer water damage when the level of flooding is above the door sill, air intake or exhaust pipe.

6. Vehicles and occupants are placed at risk as a result of vehicle instability at flood depths above 0.30 metres in stationary water, and above 0.1 metres when the flow velocity is above 1 m/s.

7. Unstable vehicles which are swept away increase the risk of vehicles colliding with, and damaging, infrastructure, blocking drainage channels or injuring people.

8. Full aquaplaning represents a risk to vehicles travelling at speeds in excess of 70 – 80 km/h when the depth of surface water is above 2.5 mm. Isolated flooding incidents may constitute a greater risk, particularly at night-time, or at locations where tyre-surface friction is important, e.g. on horizontal curves or the approach to junctions.

9. Locations which are susceptible to blocked side drainage and partial flooding of the carriageway may also increase the risk of aquaplaning incidents.

Functionality Loss

10. The free flow speed of vehicles decreases with increasing water depth up to a value of 0.30 m at which the lane/carriageway becomes impassable for most vehicles.

11. Partial or full carriageway flooding reduces the capacity of a road section which affects the operation of congested parts of the road network.

Interaction Between Physical Damage and Functionality Loss

12. The extent of clean-up operations and damage repair following a flood event extends the duration of functionality loss.

4 Vulnerability Assessment

4.1 Introduction

In the context of this report, the assessment of vulnerability involves the identification and understanding of the factors and processes that increase the susceptibility of “at-risk” elements or sets of elements to loss or harm from flooding (Fuchs et al., 2012).

4.2 Vulnerability Assessment – Methods

Vulnerability functions and indicator-based methods are two of the most commonly used methods to assess flooding vulnerability. The vulnerability function approach originates from a technical perspective which regards vulnerability as the expected loss resulting from a flood hazard of a given magnitude. On the other hand, indicator-based methods were first developed in the social sciences to identify population sub-groups with a propensity to be harmed but have subsequently found application in infrastructure engineering (Fuchs et al., 2012; Singh et al., 2018).

4.2.1 Vulnerability functions

A vulnerability function describes the relationship (and associated uncertainties) between the expected degree of loss and hazard intensity (Porter, 2021). In relation to the physical damage of infrastructure, it is common to measure loss as the ratio of expected repair costs to the cost of replacing the asset (known as the replacement cost new, or RCN). Safety loss can be expressed as the proportion of users who are killed or injured, whilst functional loss can be measured as the reduction in speed of a road section (see e.g. the depth-disruption model developed by Pregnolato et al., (2017a) which is discussed in Section 3.4 above).

As discussed in Section 2.2, a vulnerability function can be estimated from a fragility function if the loss arising from each relevant damage state is known. See Appendix A for an illustration of the link between fragility and vulnerability functions.

4.2.2 Indicator-based methods

The objective of indicator-based methods is to reveal how factors which characterise a system element combine to render that element more or less vulnerable to a hazard. Indicator-based methods do not explicitly take into account the intensity of a hazard. Statistical methods (e.g. Principal Components Analysis) can be used to calculate an indicator based on the sum of the scores (weighted or unweighted) of factors, each of which reflects some aspect of the vulnerability.

Indicator-based approaches have been used to assess the vulnerability of infrastructure assets as an alternative to the use of vulnerability functions (e.g. Papathoma and Dominey-Howes, 2003; Benedetto and Chiavari, 2010) or to augment a vulnerability function (Godfrey et al., 2015). One of the advantages of this latter approach is that it takes into account a wide range of factors whilst being able to quantify expected losses from a hazard of given intensity.

4.3 Vulnerability Assessment – Applications

4.3.1 Damage (loss) functions

In the past few decades, vulnerability functions have been developed to estimate the monetary losses resulting from physical damage caused by a flood hazard of a given intensity. These models typically use flood depth as the sole measure of flood intensity (Jongman *et al.*, 2012).

Although the literature on flood damage curves is rich and well-developed for various types of assets, limited attention has been given to transportation infrastructure (Habermann and Hedel, 2018). In Europe, one of the most widely used vulnerability models for roads is that of Huizinga et al. (2007). Referred to as the JRC model (after the European Commission's Joint Research Centre), it relates flood loss in both relative and absolute terms to water depth, for generic flooding events. The JRC model includes country-specific curves as well as an average European curve. Huizinga et al. (2017) used a similar approach to develop global flood damage curves for each continent. The global and European models have been used to estimate economic losses induced by historic flood events (e.g. Frongia et al. (2015), Jongman et al. (2012), Tanoue et al. (2020), Van Ginkel et al. (2021)), conduct present or future flood risk assessments (e.g. Alfieri (2018), Feyen et al. (2012), Koks et al. (2019), Țîncu et al. (2020), Van Ginkel et al. (2021), Wang et al. (2014)) and appraise adaptation measures for risk mitigation (e.g. Dottori et al. (2021), Rojas et al. (2013)). Despite its extensive use, the European model has been tested and validated for only a few past events, namely in Germany (Jongman *et al.*, 2012; Van Ginkel *et al.*, 2021), UK (Jongman *et al.*, 2012) and Italy (Frongia, Liberatore and Sechi, 2015), while no such validation has been performed for the global model.

Other vulnerability functions that are widely used are the Rhine Atlas model (ICPR, 2001) and Flemish model (Vanneuville *et al.*, 2003) both of which were developed for fluvial flood events. The former was developed using a combination of empirical loss data, and expert judgement. The Flemish model was developed based on existing literature, however the methodology for its creation is unclear. Extensive work has also been conducted in the Netherlands, where the Standard Method was established with the aim of developing vulnerability functions for various types of asset (Kok, Huizinga and Barendregt, 2005; de Bruijn et al., 2015). After a series of revisions and adjustments, the most recent functions are those of de Bruijn et al. (2015). The functions for transport infrastructure were formed based on expert judgment for fluvial and coastal flood events characterised by low flow velocities. Furthermore the functions provide relative loss estimates, but are accompanied by proposed maximum damage values per road classification (regional roads, highways, not highways) that facilitate cost estimations for different types of roads.

Most of the aforementioned models employ a single function for all transportation infrastructure, which in some cases refers to both railway and road assets (e.g. Vanneuville et al. (2003)). Consequently, important attributes of transportation assets (e.g. road type) that influence the magnitude of loss are not taken into consideration. In all cases, the determining factor used to estimate loss is flood depth, and some models apply only to slow-moving fluvial flood events. More recently, Koks et al. (2019) developed a set of vulnerability functions for roads which apply to all flood types and also distinguish between paved and unpaved roads.

A more thorough approach than previous models was proposed by Van Ginkel *et al*. (2021), who estimated vulnerability functions which were dependent on road classification and the presence of road accessories such as lighting (see Figure 8 and Figure 9 below). Vulnerability functions were also developed for the upper and lower values of the speed of flow occuring in relatively slow-moving flood water which is typical of floods in larger catchments (>500km^2). These functions show that the degree of loss increases with flood depth, and with maximum loss occurring in flood depths in the range 250 to 600 mm. Upper flow speeds during slow-moving floods cause embankment/pavement erosion and stability issues. The effect of upper flow speeds is significantly more marked for lower classes of road and for roads without expensive electrical and electronic systems compared to the most sophisticated motorways. A limitation of these functions is that they do not extend to fast-moving flood water (> 2 m/s) which is more likely to occur in mountainous areas, with smaller catchments and is associated with the structural damage of roads (Kreibich *et al.*, 2009).

Figure 8 – Vulnerability functions (relative loss and absolute cost) for motorways and trunk roads under low and high-flow conditions (van Ginkel et al, 2021). (Creative Commons Attribution 4.0 Licence)

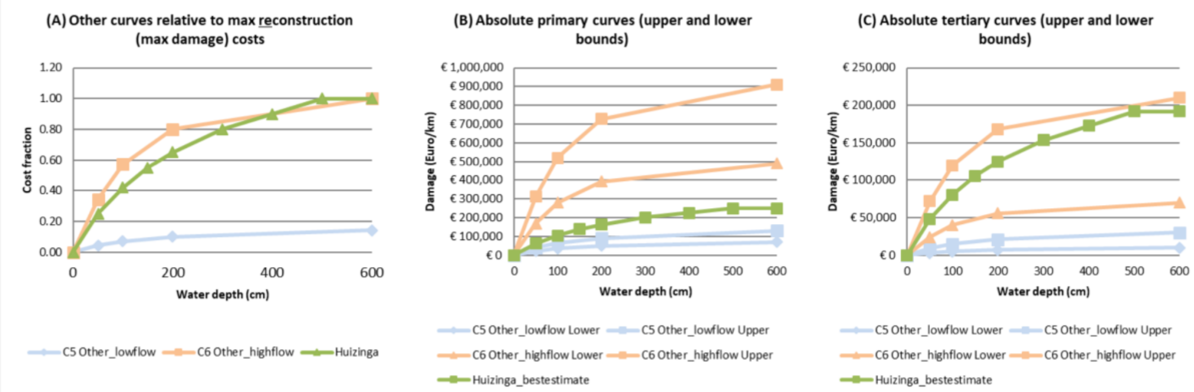

Figure 9 – Vulnerability functions (relative loss and absolute cost) non-trunk roads under low and high-flow conditions (van Ginkel et al, 2021). (Creative Commons Attribution 4.0 Licence)

4.3.2 Appraisal Method for Flood Risk Management Strategies – Scotland (SEPA)

As part of a methodology for the appraisal of flood risk management strategies, physical damage to road infrastructure (excluding bridges) was estimated using a step function in which road damage occurred when flood depth and flow speed were above defined thresholds (0.15 m and 0.31 m/s respectively).

4.3.3 Vehicle instability

Depth-damage curves have been developed for a range of vehicle types exposed to flooding for HAZUS-MH (FEMA, 2015), CRUE (Francés et al, 2008) and the US Army Corps of Engineers (USACE, 2009).

Bocanegra and Francés (2021) estimated stability thresholds for floating and sliding based on flood depth and velocity of flow for different vehicle types as shown in Figure 10.

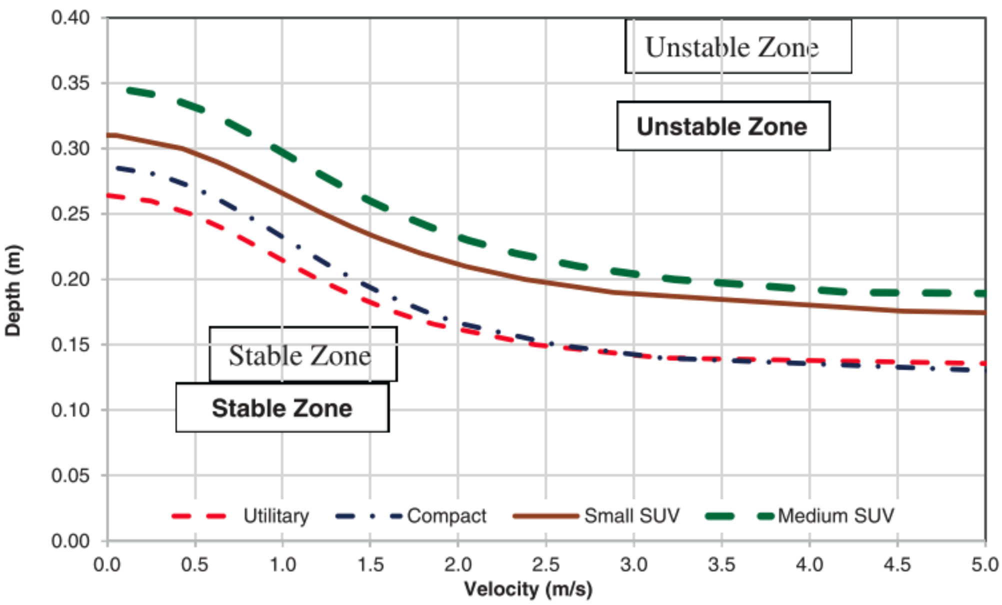

Figure 10 – Stability thresholds by vehicle type (Bocanegra and Francés, 2021). (Creative Commons Attribution Licence)

4.4 Indicator-Based Methods

4.4.1 Road asset/infrastructure damage

Benedetto and Chiavari (2010) created separate vulnerability models for grade level road sections, and sections in cuttings and on embankments based on data from Northern Italy. Model parameters reflected the geometric and hydrodynamic characteristics of road sections. Whilst no further applications of this approach to road infrastructure were found in the literature, Godfrey et al. (2015) proposed a method to assess the vulnerability of buildings to flooding which combined a generic vulnerability function for all buildings with an index derived from multi-criteria analysis to estimate a revised vulnerability function reflecting specific building characteristics.

4.4.2 ROADAPT VA

Vulnerability assessment for roads forms part of the Conference of European Directors of Road (CEDR) ROADAPT guidelines. Part C of these guidelines describe a GIS-based approach to calculate a vulnerability index to extreme weather threats for roads (Falemo et al., 2015).

It is important to note that in these guidelines vulnerability is defined as a function of exposure, sensitivity and adaptive capacity.

The process involves identifying relevant vulnerability factors for a specific threat, where exposure is represented by contextual site factors (such as topography, vegetation), sensitivity is captured by infrastructure-intrinsic factors (such as road surface level, hydraulic capacity of culverts) and adaptive capacity is dependent on the characteristics of the infrastructure owner. For each raster cell along a road corridor, factors are scored on a three-point ordinal scale, where 0 indicates that the factor does not increase vulnerability, +1 indicates that the factor increases vulnerability and +2 indicates that the factor considerably increases vulnerability. Unweighted or weighted scores are then summed and converted into a normalised vulnerability index for raster cells on a scale from 0 to 100.

4.4.3 Vulnerability Assessment Tool (VAST) – Federal Highways Agency

As for *ROADAPT VA*, vulnerability is defined as a function of exposure, sensitivity and adaptive capacity. This approach uses an Excel spreadsheet template to undertake a vulnerability analysis of road assets. The spreadsheet contains libraries of potential indicators for exposure, and sensitivity and adaptive capacity for consideration by the analyst. Indicators are assessed on a 5-point ordinal scale (0 to 4) and combined (weighted or unweighted) to produce an overall score for each asset.

4.5 Network Vulnerability Assessment

4.5.1 Introduction

As discussed in Section 3.4, carriageway flooding reduces vehicle speeds, and also reduces the capacity of the road leading to congestion when traffic flows are significant. In these circumstances, drivers may try to reduce delay by diverting to other routes. Where flooding results in the closure of a road, it is standard practice to implement a signed diversion route if a suitable route exists. Substantial increases in travel time or distance, or in the case of a road closure, the lack of an alternative route, may result in drivers delaying the start of their journey, choosing another mode of transport, substituting their planned destination with another, or cancelling their journey.

The principal aims of network vulnerability assessment are to evaluate the consequences of the failure of one or more network components (typically a road section/link or junction) and to identify the most critical network components – i.e. those components which represent the highest risk to network performance (Taylor and Susilawati (2012)).

Reviews of previous research on network vulnerability have been undertaken by Faturechi and Miller-Hooks (2014) and Mattsson and Jenelius (2015). There is considerable variation in the approach taken in reviewed studies which depends *inter alia* on the hazard under investigation[27], the scenario(s) being explored, the availability of data and transport modelling tools and the scope of the analysis. In the following sub-sections, the various approaches which have been used to evaluate network vulnerability are considered first of all. Next there is a brief overview of the flooding scenarios used in these studies. Thirdly,

[27] Although this review concerns the vulnerability of roads to flooding, approaches adopted to research network vulnerability to other natural hazards or no specific hazard are also relevant.

the methods taken to model the impact of a hazardous event on the functionality of the network are reviewed. Finally, the modelling approaches which have been used to study the response/behaviour of transport system users to disruption are examined.

4.5.2 Review of network vulnerability approaches

Network vulnerability can be analysed using one of the following approaches:

- Disruption rank/index
- Network topology
- Network functionality
- Accessibility loss
- Resilience

Disruption rank/index

These methods represent a model-free approach to estimate network disruption. For example, in Scotland, the Disruption Risk Assessment Tool (DRAT) classifies the disruption impact level of historic events based on the position of a road section within the asset management hierarchy (which reflects economic, social and integrated transport factors), and the extent and duration of road closure (Transport Scotland, 2011).

Similarly, a Flood Severity Index was created for the English Strategic Road Network based on road type, traffic volume, the extent of blocked carriageway and the duration of carriageway blockage. This index was combined with the frequency of historical flood events (over a 5 year period) to identify flooding hotspots (Hankin et al., 2016)

Network topology

The mathematical properties of a network can be used to identify important/critical links (e.g. Demšar et al., 2008; Duan and Lu, 2014) and to evaluate the performance of a network under given flood scenarios. For example, the centrality of a node or link (defined in terms of the number of shortest paths between all other nodes which pass through or along the node/link) can be taken as a measure of its importance to the network. Similarly, aggregate measures of the centrality of links which remain open during a flood event provide a measure of the impact of the event on the network (e.g., Papilloud and Keiler (2021)). One of the main strengths of this approach is that the data and computational requirements are relatively low. A significant limitation is that it is difficult to capture realistically the full range of network dynamics and user behavioural responses which occur when a network is disrupted.

Network performance

Transport models can be used to estimate the functional performance of a disrupted network. Predicted increases in travel time and distance can be converted to monetary units using standard transport appraisal techniques (e.g., Jenelius, Peterson and Mattsson (2006); Erath *et al*., (2009)). Expected changes in other performance metrics such as accidents and pollution are also relatively straightforward to calculate from standard output. The number of cancelled trips (i.e., trips that are either not possible to complete or would take so long as to be impractical) can also be estimated.

Accessibility loss
The loss in accessibility resulting from network disruption (e.g., Taylor and Susilawati, 2012) can be considered as a measure of vulnerability. Loosely speaking, accessibility is the ease by which valued opportunities can be reached, and is commonly computed as the sum of these opportunities (e.g., jobs, people) weighted by a function of travel time or distance. Accessibility reflects the performance of the transport network as well as the spatial distribution of the population and available opportunities within the land-use system.

The theoretical basis of accessibility and the analytical framework which has been developed provides a great deal of flexibility in its use within vulnerability studies. For example, previous work has explored the change in accessibility to the population of the study area before and after a flood event (Borowska-Stefanska et al., 2019; Sohn, 2006), to jobs (Chen et al., 2015; Papilloud and Keiler, 2021; Noland et al., 2019), to schools (Papilloud and Keiler, 2021; Siqueira-Gay et al., 2017), to health facilities (Siqueira-Gay et al., 2017), to emergency services (Gori et al., 2020) and for a multi-modal network (Chen et al, 2015). Sohn (2006) developed a composite accessibility metric which combined a standard distance decay formulation with an adjustment term to take into account the level of traffic carried by disrupted road links.

Resilience-based approaches
On the distinction between vulnerability and resilience, see Section 2.4.

Most of the resilience assessment literature has focussed on how well the transport system recovers following an extreme event, such as an earthquake, in which the network is seriously degraded at multiple locations and/or there is a lengthy recovery period (e.g. Stevanovic and Nadimpalli, 2010; Henry and Ramirez- Marquez, 2012; Nogal et al., 2016; Twumasi-Boakye and Sobanjo, 2018; Kilanitis and Sextos, 2019; Vishnu, Kameshwar and Padgett, 2019; Twumasi-Boakye and Sobanjo, 2019).

In terms of transport resilience to flooding, Gori et al., (2020) used a combination of fluvial flood simulation and road network analysis to model the temporal progression of flooding impacts and resulting accessibility loss over several days in Houston, Texas during Hurricane Harvey in 2017.

Various studies have evaluated the efficiency of established repair strategies (Chang, 2003; Zhang, Alipour and Coronel, 2018; Zhou, Banerjee and Shinozuka, 2010; Decò, Frangopol and Bocchini, 2013; Nifuku, 2015; Aydin et al., 2018). For example, Sohn (2006) developed a method to compare criteria to prioritise retrofitting of roads damaged by flooding. A major strand of research sought to optimise the scheduling, sequencing or allocation of resources to repairs, (e.g., Pellicer Pous and Ferguson, 2021), or the selection of specific routes for repair. Another consideration in resilience assessment is that post-disruption travel demand may differ significantly during, and potentially after, the recovery phase compared with pre-disruption travel demand depending on the severity, extent and duration of the disruption and the characteristics of the restored network (Khademi et al., 2015).

4.5.3 Flooding scenarios

The approaches discussed above (Section 4.5.2) require the selection of a flooding scenario with which to "disrupt" the studied network. To do so, many studies have adopted a systematic, "hazard-free" approach whereby a single link is selected for closure, the consequences of that closure are modelled, and then the process is repeated for all links in a network. This approach is known as a *full network scan* and is often used to identify those link closures which would have the greatest impact on network performance.

The computational effort required for a full network scan can be high, depending on the complexity of the transport model used. To reduce this effort, various techniques have been proposed which use the physical and operational attributes of links to screen the network and identify potentially critical links for further investigation (e.g. Tampère, 2007; Knoop et al., 2012; El-Rashidy and Grant-Muller, 2014; Martín et al., 2021). Another proposed technique is to rank each link based on the expected impact of its closure on the local area network, and then to compute the impact on the whole network of the closure of the most highly-ranked links (Chen et al., 2012; Esfeh et al., 2022).

Location-specific flood models may be used to generate flooding scenarios which are then overlain on a map of the road network to identify disrupted road network sections. One of the main advantages of this approach is that the combined effect of multiple link disruptions can be investigated. Table 3 provides a summary of notable studies. The flood modelling approach depends on the flood type under investigation and the spatial context of the study, e.g., urban or regional. Chang et al., (2010), Suarez et al., (2005), and Pregnolato et al., (2017b) included climate projections as inputs in to the flood modelling process, and the latter study also explored the effect of adaptation interventions on network vulnerability. The recent study of Papilloud and Keiler (2021) selected 5 flood scenarios from 150 different scenarios generated in a previous study (Zischg et al., 2018). The selection process used indicators to assess the potential flood impacts on the road network based on the surface area of the road network affected by flooding and the centrality of affected links.

4.5.4 Partial link functionality loss

The reduction in speed and/or capacity of road links subjected to flooding under scenarios generated by location-specific flood models is discussed in Section 3.4.

Whilst many studies have treated all flooded roads as being closed no matter the depth of flooding (e.g., Suarez et al., (2005), Borowska-Stefánska et al., (2019)), other studies have applied a single flood depth criterion to determine whether a road is closed or not (e.g. road closure if flood depth > 20 cm (Papilloud and Keiler, 2021)). Pyatkova et al., (2019) combined a flood depth threshold of 30 cm for road closures with a speed reduction of 20km/h for vehicles on roads where flooding was below this value. Zhu et al., (2018) applied speed reductions to vehicles based on depth of flooding and the sex and age of drivers.

Pregnolato et al. (2017b) used a previously developed depth-disruption function relating flood depth to vehicle speed (Pregnolato et al, 2017a) (see Figure 7 above) to assess the impact of network-wide flooding caused by simulated short-duration, high intensity rainfall events on the operation of the urban road network in Newcastle upon Tyne.

Authors	Study Area	Flood Type	Flood Scenarios	Climate Change
Papilloud and Keiler (2021)	Aare river basin, Canton of Bern, Switzerland	Pluvial based on 3-day probable maximum precipitation	5 scenarios selected from initial set of 150 based on impacts on road network	
Pregnolato *et al.*, (2017b)	Newcastle upon Tyne, UK	Pluvial flash flood	1/10 and 1/50 year events; with/without adaptation strategies	Present epoch and 2080s epoch
Zhu *et al.*, (2018)	Lishui, Zhejiang Province, China	Pluvial flash flood based on 2 hour rainfall period	6 scenarios: peak/off-peak x 1/10, 1/20 and 1/50 year events	
Borowska-Stefánska *et al.*, (2019)	Warta Water Region, Poland	River flooding	1/100 year flood risk map	
Suarez *et al.*, (2005)	Boston Metro Area, USA	River and coastal flooding individually and combined	24 hour - 1/100 and 1/500 year events	Projected increase in probability of extreme events used to estimate aggregate effects of climate change in period 2000 – 2100.
Chang *et al.*, (2010)	Portland, Oregon, USA	Fluvial	1/100 year events	2 x climate projections for period 2020 – 2049
Chen *et al.*, (2015)	Hillborough County, Florida, USA	Coastal		Projected sea level rise of 0.6m
Pyatkova *et al.*, (2019)	Central Marbella, Spain	Pluvial flash flood	Flash flooding 1/100 year	
Yin *et al.*, (2016); Li *et al.*, (2017)	Shanghai, China	Pluvial flash flood	1/5, 1/10, 1/20, 1/50 and 1/100 year events	

Table 3 – Summary of flooding scenarios used in previous vulnerability studies

4.5.5 Transport models

Various transport network modelling approached have been used to assess network vulnerability. These models can be divided into three main groups (1) assignment-based models, (2) simulation models and (3) transport demand/activity models.

Assignment-based models estimate link flows in a network for a given level of travel demand. A key limitation of assignment-based models is that the output is based on user equilibrium traffic flows. This is not a realistic assumption in congested networks during periods of disruption when users do not have full knowledge of the existing state of the network. To address this limitation, a dynamic equilibrium-restricted assignment method has been proposed which is designed to better reflect user knowledge and behaviour during disruptive incidents (Nogal, et al., 2016). For capacity-reducing incidents spanning multiple days, dynamic day-to-day assignment methods have been proposed in which vehicle routing is influenced by travel experience on previous days (e.g. He and Liu, 2012; Gauthier et al., 2018).

Simulation models represent vehicles individually or as "packets" which are routed through the network based on drivers' perceived travel times (e.g., Gauthier et al., 2018). Past experience and current travel times may inform these perceptions. These models are well-suited to studying the dynamic nature of non-recurring incidents. For example, Pellicer Pous and Ferguson (2021) developed a simulation model to assess the vulnerability of a network to capacity-reducing incidents in which drivers based routing decisions on previous experience and travel information provided roadside and in-vehicle systems.

One the main limitations of assignment-based and simulation models is that travel demand is treated as being inelastic. A fixed trip matrix is used as an input to these models. Origin-destination routing and, in some models, departure time vary in response to network disruption, and trips which are either impossible or infeasible can be removed. However, there is no scope to capture other behavioural responses which may occur particularly if disruption is sever or long-lasting such as switching to another transport mode or destination, or adapting planned daily schedules. The third approach couples a model of transport demand/activity with either an assignment-based or a simulation model.

Knapen et al., (2014), Dobler et al., (2012) and Li and Ferguson (2020) extended agent-based models to enable the re-scheduling of travel and activities as a result of unexpected disruption. Saadi et al., (2018) more realistically estimated the impacts of fluvial flood events in the Liege area of Belgium using an activity-based microscopic model.

4.5.6 Other road users

The vulnerability of the public transport network to disruption has also received considerable attention in the literature – see Mattsson and Jenelius (2015) for a review of notable studies. Much of this research has addressed fixed track public transport systems which are typically more sensitive to disruption than road transport because of the limited number of available diversion routes and the knock-on effects of delay to subsequent services. Some of these limitations are shared by the bus system in the sense that not all diversion routes that are suitable for cars are also suitable for buses, and that delays to crew and vehicles can cause further perturbations through the system.

BusMezzo is a dynamic simulation tool for public transport networks which has been used to study public transport network vulnerability under various disruption scenarios (e.g., Cats and Jenelius, 2015).

4.6 Conclusions and Discussion

This chapter has summarised the main methods for carrying out the assessment of vulnerability, which was followed by a review of specific applications of these methods to the road transport system. The assessment of the direct impacts of disruption on road users has generated a rich literature which offers a variety of potential approaches encompassing resilience and repair strategies in addition to vulnerability.

1. Multiple "depth-damage" vulnerability functions exist for various types of physical assets. Many of these functions employ a single function for all transportation infrastructure and thus make no distinction between road and railway infrastructure, nor take into account potentially significant attributes such as road type. In nearly all cases the determining factor used to estimate potential loss is flood depth.

2. A set of functions recently proposed by van Ginkel et al. (2021) take into account road type and a range of flow velocities. These functions show that the degree of loss increases with flood depth, and with maximum loss occurring in flood depths in the range 250 to 600 mm. Upper flow velocities during slow-moving flood (< 2m/s) cause embankment/pavement erosion and stability issues. The effect of higher flow velocities is significantly more marked for lower classes of road and for roads without expensive electrical and electronic systems compared to the most sophisticated motorways.

3. There are two limitations with van Ginkel's functions. Firstly, the extent to which flood duration influences the degree of loss is not clear. For example, a minimum flood duration threshold is not stated. Secondly, these functions do not extend to fast-moving floods (> 2m/s) which are more likely to occur in hilly or mountainous areas and are associated with the structural damage of roads, potentially in short periods of time.

4. The degree to which established flood-damage vulnerability functions are applicable to the Scottish road network is not clear.

5. Applied indicator-based methods such as ROADAPT VA enable a broader range of factors to be taken into account compared to the vulnerability function approach. Road segments can be ranked by vulnerability and the most vulnerable segments identified. The main limitations of this approach are that vulnerability is not conditional on hazard intensity and that there is no link with expected loss in monetary terms. The method Godfrey et al. (2015) is promising because it combines a generic vulnerability function with an index derived from site-specific factors.

6. The review of road network vulnerability assessment reveals the breadth of methodologies available to estimate and assess network losses caused by flooding. For sparse networks in remote areas with relatively light flows and straightforward disruption scenarios, topological-based indicators, network performance or accessibility-based indicators which use a simple traffic model are suitable for most purposes. Dense, congested networks with more complex disruption scenarios (e.g. significant infrastructure damage, concurrent events) would require more advanced transport models to give appropriate outputs for indicators of network performance, accessibility or resilience. Moreover, as discussed above, a sequential approach could be adopted with topological-based indicators being used to select the most disruptive flood scenarios prior to conducting more in-depth analysis using a more sophisticated technique (Papilloud and Keiler, 2021).

7. A key limitation of the vast majority of these studies is that their primary focus is limited to the direct impacts of functionality loss[28] - principally increases in travel costs and cancelled trips. Indirect social and economic impacts arising from network disruption are not considered. Meyer et al. (2013) reviewed methods to assess the indirect costs of natural hazards including Input-Output models and Computable General Equilibrium (CGE) Models, both of which operate at a regional level. Recently, Wei et al. (2022) developed an integrated transport network and CGE model and applied this to an earthquake scenario which disrupted seaports and the highway network. The applicability of these methods to sub-regional levels is dependent on the availability of relevant data on input costs, production levels and demand for goods and services at a suitably fine scale.

8. Accessibility indicators offer flexibility and a range of valuable insights into the consequences of disruption which have not been fully explored to date. For example, the impact of disruption depends on the types of opportunities which cannot be reached and for how long. Accessibility loss reflects *inter alia* the relative importance of these opportunities, their typical frequency of use, and whether or not the same or a similar activity can be undertaken in some other way. Being unable to reach the accident and emergency unit of a hospital is of critical importance because this need can arise at any time and at short notice, whereas other valued activities may have in-built flexibility such that they can easily be postponed for a day or two without any significant loss. Planned travel may also be substituted by other means (e.g. a face-to-face meeting may be replaced by a virtual meeting) with only limited loss in value. Moreover, the impact of network disruption in terms of potentially reduced demand for goods and services, such as hotel rooms and restaurant bookings – can also be explored using accessibility indicators. Finally, incremental changes in accessibility over time for given disruption scenarios can be used within an assessment of resilience to plan how best to allocate available resources to restore a network.

[28] That is, the direct consequential economic costs arising from network disruption as defined by Winter and Bromhead (2012).

PART II – Analysis of Historic Flooding Incidents on the Scottish Trunk Road Network

5 Historic Flooding Incidents

5.1 Flood Incident Data

Trunk road incidents were recorded in Transport Scotland's Integrated Road Information System (IRIS) by the Operating Companies contracted to maintain the network (see Section 1). The location (i.e. road section and coordinates) and date of each incident were recorded, and incidents were classified by incident type (e.g. flooding), the road condition at the time of the incident, duration and the extent of disruption caused.

An extract of all incidents recorded in IRIS in the period January 2014 to December 2021 was provided by Transport Scotland. A total of 4,961 incidents met the condition Incident Type = "Flooding" or Road Condition = "Flood over 3cm in depth". Inspection of text-based comments revealed a small number of incidents which had been incorrectly classified as flooding based on the above condition. These incidents were removed leaving a total of 4,898 flooding incidents in the final dataset.

The duration of each incident was classified into one of five intervals: < 1 hour, 1 – 2 hours, 2 – 6 hours, 6 – 24 hours, and > 24 hours.

A short free text description[29] of recorded flooding incidents was provided in the Comments field of the IRIS dataset. Where possible the proximate cause(s) of each incident was identified from inspection of this text e.g. water flowing on to the road from adjacent land, blocked drainage asset, insufficient drainage capacity. For some incidents, a description of mitigating actions was also given.

It should be noted that all recorded incidents were restricted to trunk roads managed by North East, North West, South East and South West Operating Companies (OC's). The IRIS dataset did not contain records of incidents on more recently constructed roads operated and maintained under DBFO contracts.[30]

The analysis of flooding incidents was based principally on the fields listed in Table 4.

Field	Road Condition	Disruption Type	Duration of Incident	Maintenance Hierarchy
Value	Dry	Full road closure (Both directions of dual)	Days, Hours, Mins	Motorway
	Flood over 3cm deep	Carriageway closed		Dual All Purpose
	Frost or ice other	Lane or lanes closed		Single All Purpose
	Snow	Reduced lane width		
	Wet or damp	Other		

Table 4 - Principal IRIS fields used in analysis of flooding incidents

[29] It is assumed that these comments were recorded by an operative attending the incident.
[30] M6DBFO, M8 DBFO, M77DBFO, M80DBFO, FBOC, and A737 Dalry Bypass.

Table 5 contains a note on the quality of flood incident data stored in IRIS and recommendations to improve the quality of this data.

IRIS Data Quality
The proportion of actual flooding incidents recorded in the IRIS dataset is unknown. It seems reasonable to assume that all of the most severe incidents are recorded. However, the potential for systematic geographical and temporal bias in less severe incidents is unknown. Data collection could be biased by various factors including road type, traffic, time of day and day of the week, incident duration[31], proximity of a flooding location to a depot or patrol station or route, and the flooding frequency of a location. The number of incidents occurring during periods of intense or prolonged wet weather when resources are stretched may be under-recorded. Likewise, the time taken to respond to or manage flooding will depend on the availability of resources at the time. In terms of data entry, where the actual co-ordinates of a flooding incident were not recorded in IRIS then the coordinates of the start of the road section were given by default which introduced a spatial error into some of the above analysis. The depth of flooding was extracted from the *Road Condition* field in the IRIS dataset. Excluding the values "SNOW" and "FROST OR ICE", three levels of flood depth were recorded – "DRY", "WET OR DAMP" and "FLOOD OVER 3CM DEEP" which matches the *Road Surface Condition* field in Stats 19 road casualty data.[32] The literature review identified flood depth as an indicator of road and vehicle damage, functionality loss and road user injury risk. For example, the flood depth at which a road becomes impassable for cars is estimated to be 300 mm (Pregnolato *et al.*, 2017).[33] Likewise, the vulnerability functions for physical damage to a roads produced by van Ginkel *et al*. (2021) have an upper limit of flood depth of 6,000 mm, and at depths of 50 mm, the cost of damage as a percentage of the construction cost ranges from 0.2 to 12% depending on road type and flood conditions. To estimate vulnerability functions that are suitable for the Scottish trunk road network or to carry out a vulnerability assessment with existing or newly-estimated functions would require more finely-grained flood depth data than currently exists in IRIS. The length and width of road affected by flooding were not collected/included in the IRIS dataset. The area of road affected by flooding is relevant to the possible damage to the road pavement. Where flooding occurs in dips in the road or at the bottom of sag curves, the depth of flooding will vary. Knowledge of the start and end points of flooding along with the longitudinal profile of the road would enable the variation in flood depth to be estimated. The IRIS dataset provides the duration of each incident. It is not clear how the end time of a flooding incident was defined and how this time may have differed from e.g. the time

[31] For example, short duration events associated with flash flooding may be missed

[32] Stats 19 Road Surface Condition – 1-Dry, 2-Wet or damp, 3-Snow, 4-Frost or ice, 5-Flood of 3cm. deep, 6-oil or diesel, 7-Mud

[33] Small cars = 150 mm and 4WD = 600 mm

at which the road was cleared of flood water, any damage to the road was repaired or debris cleared, or traffic management restrictions were removed. It would be useful to have more detailed information on the chronology of incident management in order to undertake a more accurate assessment of vulnerability.

The speed of water flow is a contributory factor of physical damage to the road pavement and earthworks (Kreibich *et al*., 2009; van Ginkel *et al*., 2021), and also presents a risk to vehicles and their occupants at high speeds. No data was explicitly recorded on the speed of water flow although the descriptive comments were used in this analyses to identify flood incidents where water entered the road from adjacent land or water.

In the absence of a clear and consistent record of the cause or causes of flooding incidents, and the actions taken to remove flood water, manage traffic and repair the road or drainage system, the descriptive comments were used in this analyses to extract whatever information had been recorded for each incident. A more rigorous and reliable approach would require the explicit recording of relevant data.

Table 5 - Note on Data Quality of Recorded Flooding Incidents

5.2 Road User Injuries and Fatalities

Road user personal injury data for the period 2016 to 2020 derived from Stats 19 was obtained from the Department for Transport (DfT, 2022). Incidents which took place on the trunk road network where the depth of flooding was greater than 3 cm were extracted.

5.3 Descriptive Analysis of Historic Flooding Incidents

Table 6 summarises flooding incidents by Road Condition and Disruption Type. Around one fifth of recorded flooding incidents had a flood depth of more than 3 cm. Disruption Type was not specified on most occasions (4,127 (84.3%)). Whilst it may be assumed that vehicles were able to use the full width of the carriageway during these events, it is also possible that there was some (unrecorded) level of traffic disruption (e.g. reduced vehicle speeds) in cases where flood depth was over 3cm in depth (644 events (13.1%)).

There was a full road closure on dual carriageway roads or the closure of a carriageway (single or dual) on 68 occasions (1.4%), a lane closure on 217 occasions (4.4%) and reduced lane width on 196 occasions (4.0%).

Road Condition	Disruption Type						
	Full road closure (both directions of dual)	Carriageway closed	Lane(s) closed	Reduced lane width	Other	Not specified	Grand Total
Dry	1	0	6	1	13	355	376
Wet or damp	12	8	81	97	183	2702	3083
Flood over 3cm deep	24	19	120	98	84	644	989
Frost or ice	0	0	2	0	0	11	13
Other	0	0	1	0	2	43	46
Snow	0	0	3	0	2	26	31
Not specified	2	2	4	0	6	346	360
Grand Total	**39**	**29**	**217**	**196**	**290**	**4127**	**4898**

Table 6 - Flooding incidents (2014-2021) disaggregated by Road Condition and Disruption Type

Table 7 gives a cross-tabulation of Duration and Disruption Type of flooding incidents.

The vast majority of incidents had a duration of less than 2 hours, with 944 incidents (19.3%) having a duration of more than 2 hours, 167 incidents (3.4%) having a duration of more than 6 hours, and only 22 incidents (0.4%) having a duration of more than 24 hours.[34]

In terms of capacity reduction due to lane width reduction or closure of a lane, carriageway or road, 191 (3.90%) flood incidents lasted longer than 2 hours, 55 (1.12%) lasted longer than 6 hours and only 5 incidents (0.10%) lasted longer than 24 hours.

The location of incidents all flooding incidents were plotted using GIS software and were found to be widely scattered across the trunk road network. Kernel density estimation was used to create a heatmap of flooding incidents on the trunk road network (Figure 11).[35] The parts of the network which flooded most frequently are highlighted with red shading. Hotspots were identified on the road network which runs through Glasgow and alongside the River Clyde and upper stretches of the Firth of Clyde (A78, A8/M8 and A82), Dundee (A90), Tarbet (A82/A83), Fort William (A82), Inverness (A9), Keith (A96) and along the M9, A84 and A85.

The locations of incidents with flood depth > 3cm and duration > 2 hours which resulted in a lane or carriageway closure, or a reduction in lane width are also shown in Figure 11. The map inset shows a cluster of incidents in this category on the A82 between Glasgow and Balloch, and on the M8, A8 and A78 between Largs and Glasgow (via Greenock).

The annual flood incident rate (incidents per km) was determined for each road type (Table 8). The incident rate was disaggregated by season and by operational unit (area) to control for possible differences in factors such as rainfall patterns, topography, and road and drainage design standards. The overall incident rate for all road types and operational units was 1.216 incidents per km per year.

For comparison, the overall incident rate for floods with depth greater than 3 cm was 0.257 incidents per km per year.

The highest incident rate was observed in the Winter followed by the Autumn, with the exception of the North East where the incident rate was higher in the Autumn than in the Winter. The lowest incident rate was observed in the Spring in all areas.

The incident rate was highest on Motorways followed by Single All Purpose roads and then Dual All Purpose Roads.

The highest incident rate was in the South West operational unit (1.703 incidents per km per year), and the lowest incident rate was in the South East operational unit (0.870 incidents per km per year).

[34] See Appendix B for a map of recorded flooding incidents by incident duration

[35] Whilst the heatmap identified parts of the trunk road network with higher flood incident rates, it would not be safe to assume that incidents at these locations shared the same underlying cause(s).

For each road section in the trunk road network, the relative difference between the observed incident rate and the expected incident rate was calculated as follows:

$$D_i = \frac{I_i - R_{a,t}}{R_{a,t}} \qquad \textit{Equation 1}$$

where

D_i is the relative difference between the observed and expected incident rates per km for a road in operational unit (area) a of type t.
I_i is the observed incident rate per km per year
$R_{a,t}$ is the expected incident rate per km per year for a road in operational unit (area) a of type t.

The map shown in Figure 12 highlights sections of the trunk road network which have relatively high incident rates compared to roads of the same type in the same operational unit of Scotland.

Appendix C contains a table of the top 50 road sections ranked by D_i.

Duration	Disruption Type					
	Full road closure (both directions of dual)	Carriageway closed	Lane or lanes closed	Reduced lane width	Other	Not specified	Total
< 1 hour	12	5	65	66	231	2205	2584
1 – 2 hours	5	0	60	77	40	1171	1353
2 – 6 hours	8	9	70	49	13	628	777
6 – 24 hours	13	14	19	4	3	92	145
> 24 hours	1	1	3	0	2	15	22
missing	0	0	0	0	1	16	17
Total	**39**	**29**	**217**	**196**	**290**	**4127**	**4898**

Table 7 – Flooding incidents (2014-2021) disaggregated by Duration and Disruption Type

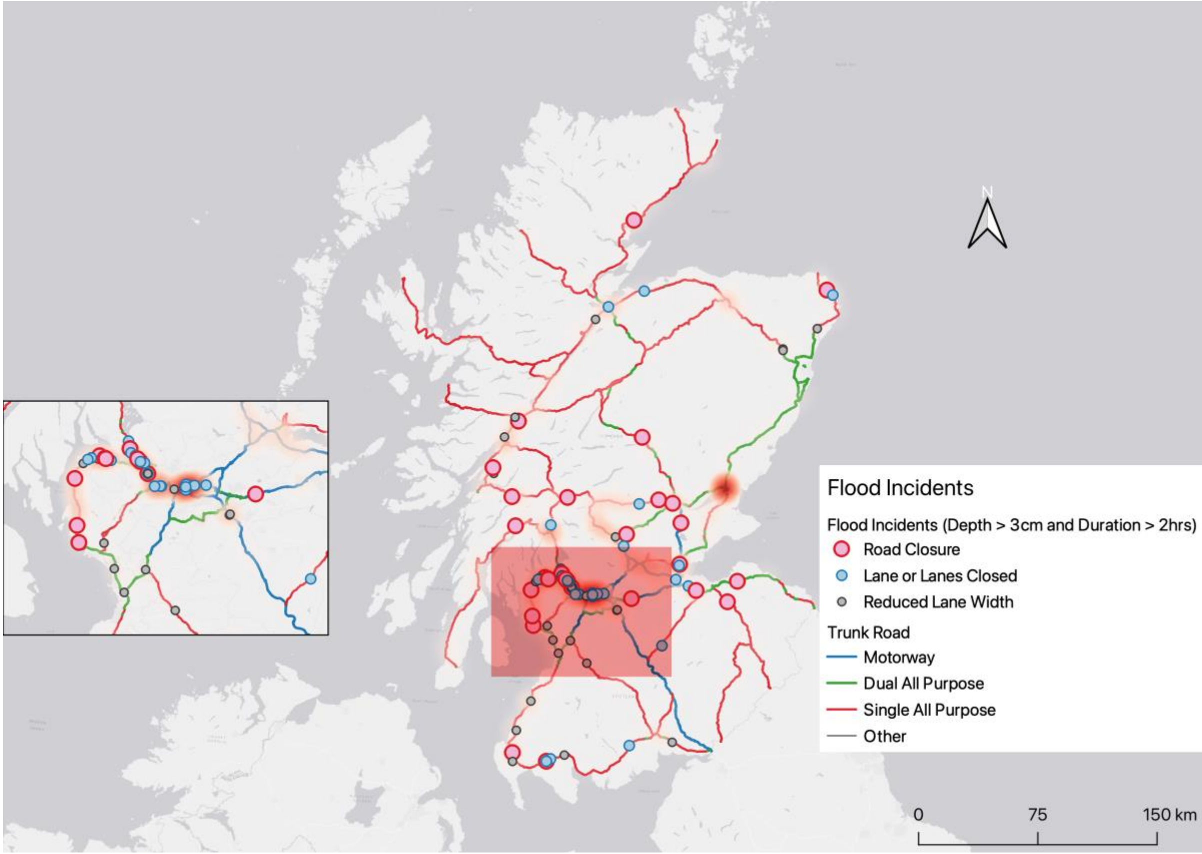

Figure 11 - Flood incident heatmap and major incident locations

	Road Type			
Season	Motorway	Dual All Purpose	Single All Purpose	All Incidents
South East				
Autumn	1.112	0.421	0.938	0.882
Spring	0.556	0.187	0.308	0.373
Summer	1.112	0.468	0.448	0.701
Winter	2.078	0.632	1.526	1.523
Annual	1.214	0.427	0.805	0.870
South West				
Autumn	2.826	1.483	1.945	2.039
Spring	0.926	0.404	0.521	0.592
Summer	2.485	0.910	0.837	1.283
Winter	3.849	2.157	2.847	2.898
Annual	2.521	1.238	1.538	1.703
North East				
Autumn	*0.228*	1.352	1.894	1.407
Spring	*0.076*	0.634	0.889	0.661
Summer	*0.266*	1.185	1.301	1.117
Winter	*0.304*	0.960	2.023	1.251
Annual	*0.219*	1.033	1.527	1.109
North West				
Autumn		*0.333*	1.667	1.527
Spring		*0.333*	0.504	0.484
Summer		*0.360*	0.557	0.534
Winter		*0.721*	2.059	1.916
Annual		*0.437*	1.197	1.115
Incidents per km per annum	1.610	0.910	1.257	1.216

Table 8 - Annual flood incidents per km by operating unit and road type. (Note: Blanks are in operating unit areas where there are no roads of the specified road type. Italicised figures are in operating units where there is only a short length of roads of the specified road type.)

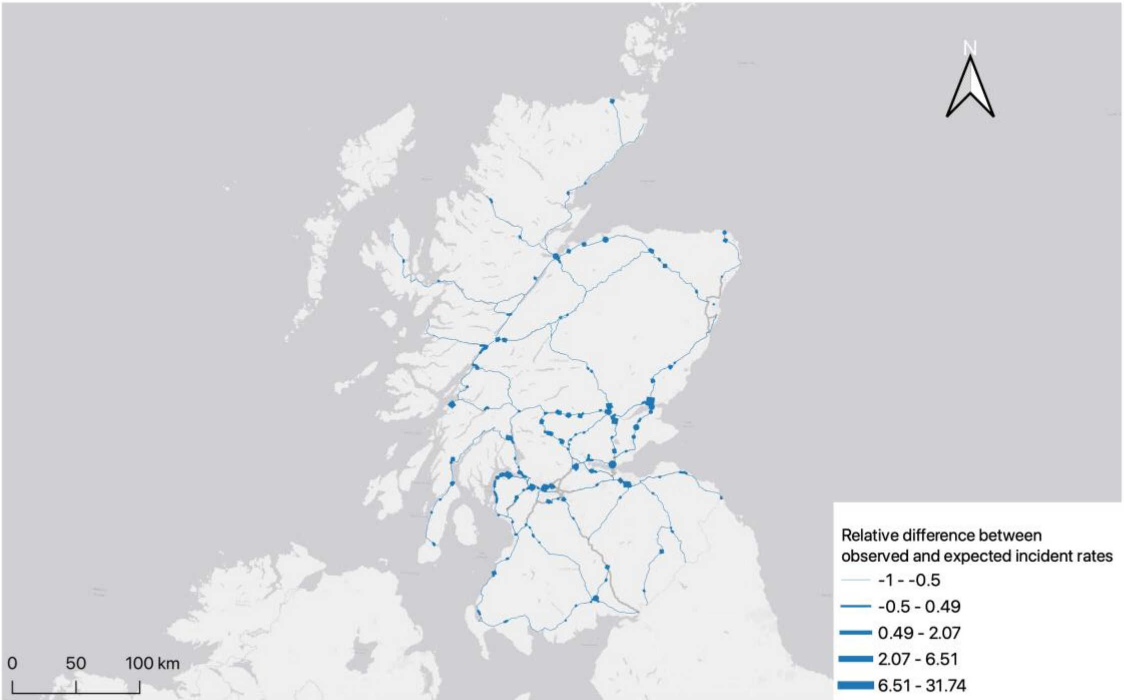

Figure 12 - Relative difference (D_i) between observed and expected incident rate for road section in area a and of road type t. Mean = -0.614. (Note: DBFO sections shaded grey were excluded from analysis because no flood incident data was available for these sections).

5.4 Temporal analysis of flooding incidents

Figure 13 shows a time series of recorded flooding events on the trunk road network between January 2014 and December 2021. Superimposed on the time series are the dates of severe weather events which affected the Scotland.

There was at least one flooding incident on 1,319 days (45%) within the eight year period. The maximum number of recorded events in a single day occurred on 31st December 2015 (51) which coincided with Storm Frank. Furthermore, within the time period considered, there were more than 15 flooding incidents on 40 days.

Maps of the days with the highest number of flooding incidents within the time series disaggregated by severity are given in Figure 14.

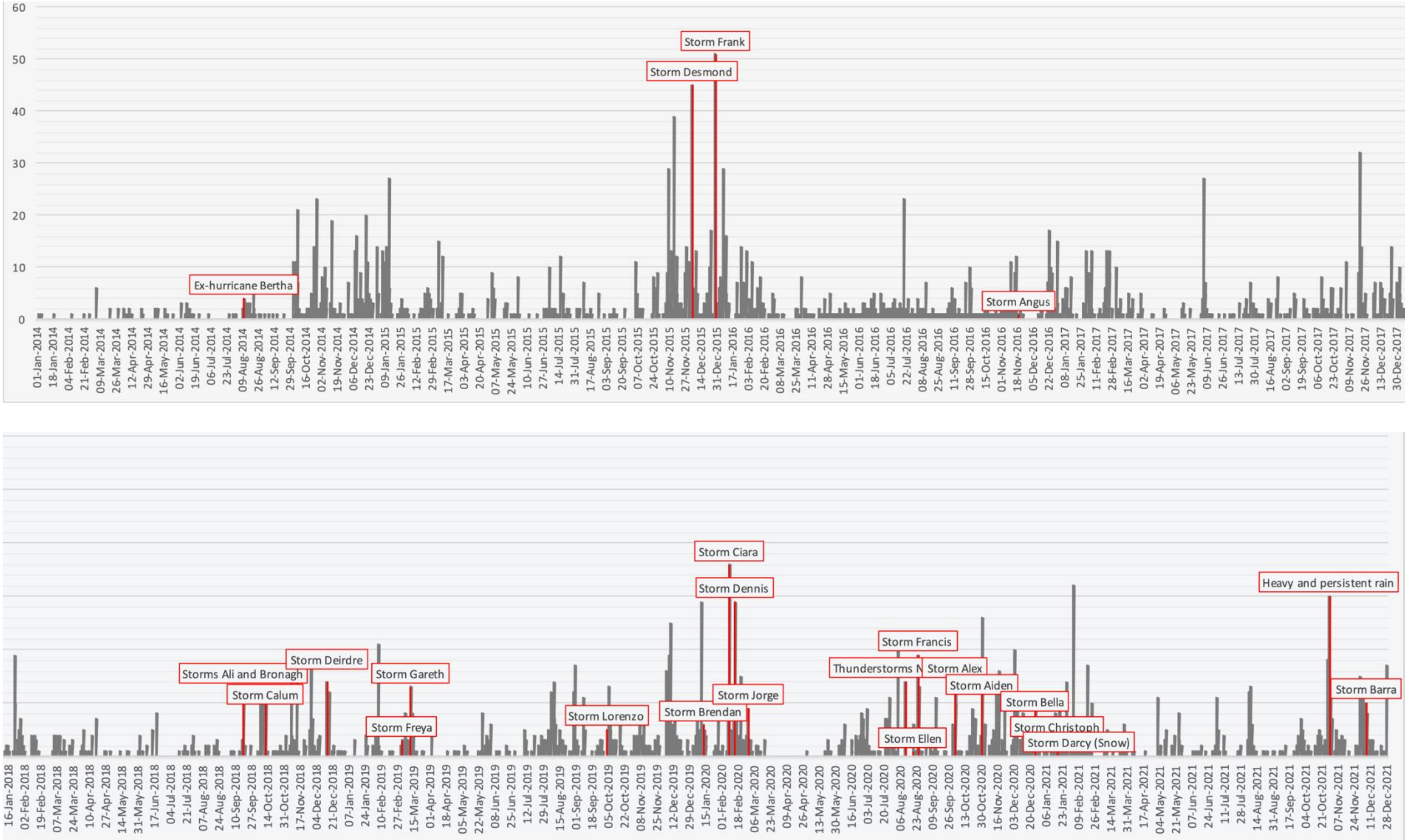

Figure 13 - Time series of trunk road flooding incidents by day (2014-2021) in grey. Dates of severe weather events indicated in red.

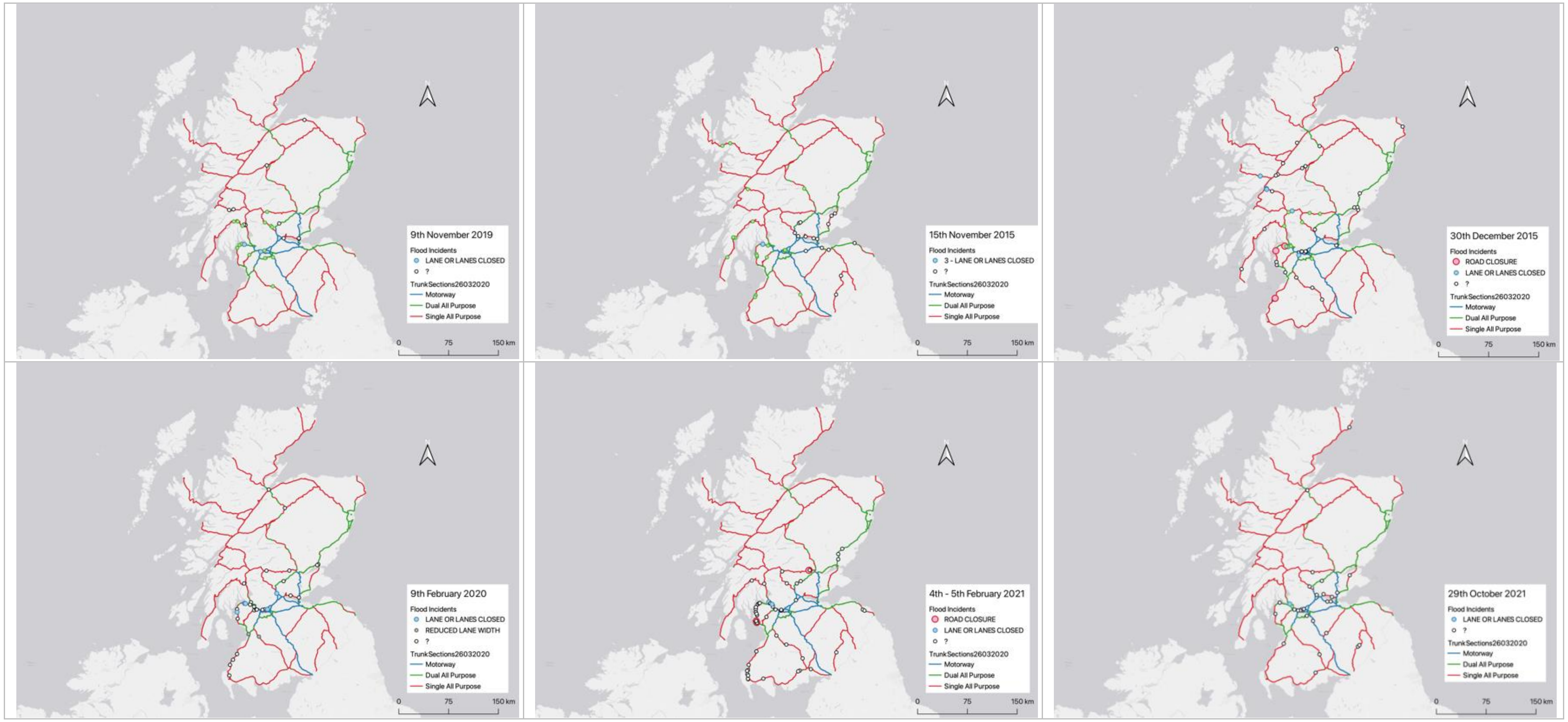

Figure 14 - Days with the highest number of flooding incident by severity. Left to right, from top left – 9th November 2015, 15th November 2015, 30th December 2015, 9th February 2020, 4-5th February 2021 and 28th October 2021.

5.5 Contributory factors and restoration actions

Incidents were not classified by flooding type (i.e. pluvial, fluvial or coastal) and there was no clear record of the principal cause(s) of each incident. Where possible, inferences about flooding mechanisms were drawn from analysis of free text comments. The following analysis should be treated with caution. As a result of inconsistencies and omissions in the free text comments, incidents may have been misclassified, and knowledge of contributory factors or restoration actions may be partial.

Free text comments were used to identify incidents in which a blocked or damaged drainage asset[36] appeared to be a contributory factor, although it is important to note that a blockage could be a cause or a consequence of flooding, and that actions taken to clear drainage assets may have been pre-cautionary. 1,928 flooding incidents out of 4,898 incidents (39.4%) belonged to this category. Further analysis revealed that a blocked culvert was a contributory factor on 133 occasions.

The literature review identified flowing water, particularly water flowing at a high speed, as a risk to road infrastructure and users. Using the above approach, three incident categories were defined in which the descriptive comments indicated that water had flowed on to the road from adjacent land or water[37] as follows:

- Sea or loch
- River or burn
- Land

A total of 153 incidents were identified as belonging to one of these categories. A heatmap (Figure 15) shows those areas of the network most frequently affected by this type of flooding. Roads highlighted by this analysis are sections of the A78, M9, A84 and the A702

Finally, incidents which require the deployment of plant such as pumps, sweepers, and drainage clearance equipment impose an additional cost on the restoration of the road. A total of 546 incidents (11.1% of all flooding incidents) were found in this category.

5.6 Road Traffic Collisions

According to DfT (2022) (Stats 19), a total of 44 Road Traffic Collisions (RTC's) occurred on the trunk road network in the five year period from 2016 to 2020 in which a flood over 3 cm in depth was recorded. A total of 60 casualties (killed, seriously injured or slightly injured) occurred in these RTC's.

The locations of these RTC's are shown in Figure 16. The RTC rate was highest for motorway sections (Table 9).

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36 Examples of free text comments are "blocked gully", "gullies cleared" and "offlets dug".

37 Examples include water flowing from a field, track or side road, hills, banking, verge or railway; burn or river flood; coastal/tide or loch water level.

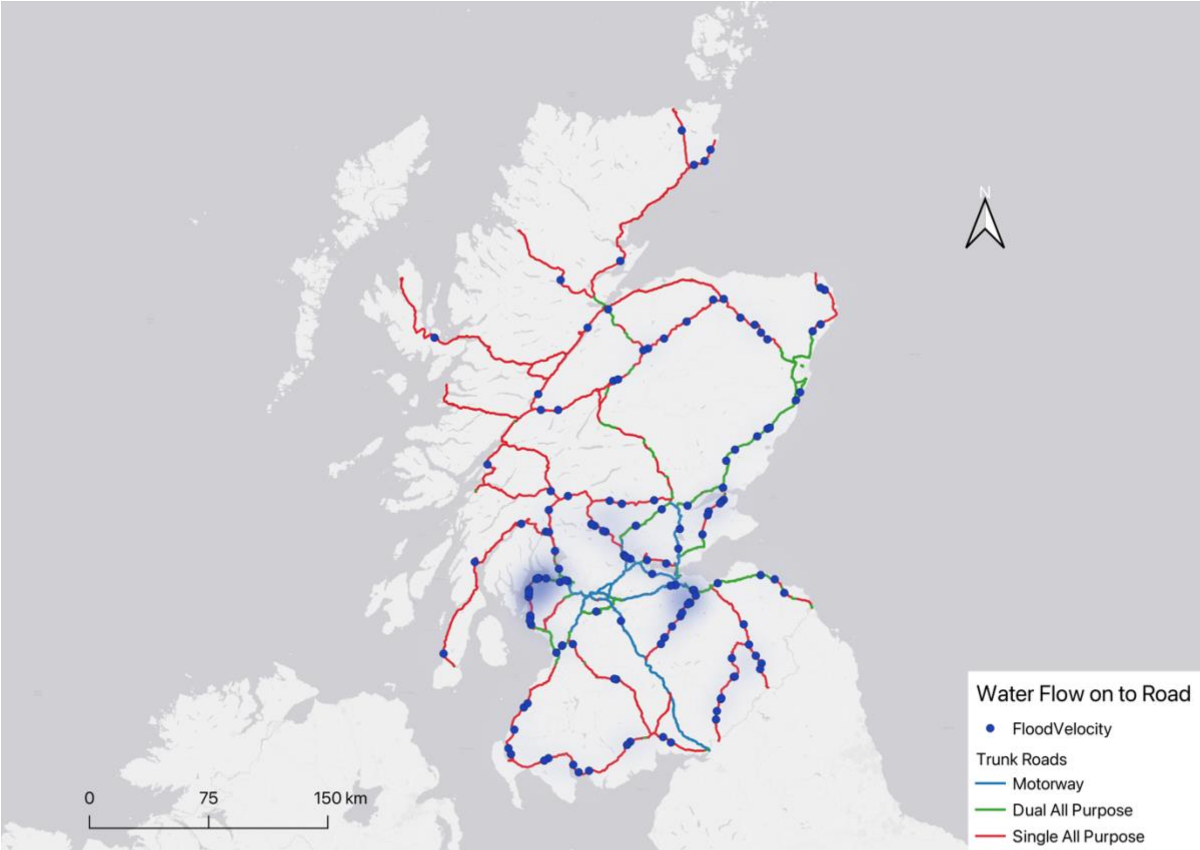

Figure 15 - Location and heatmap of flooding incidents caused by water flowing on to the road

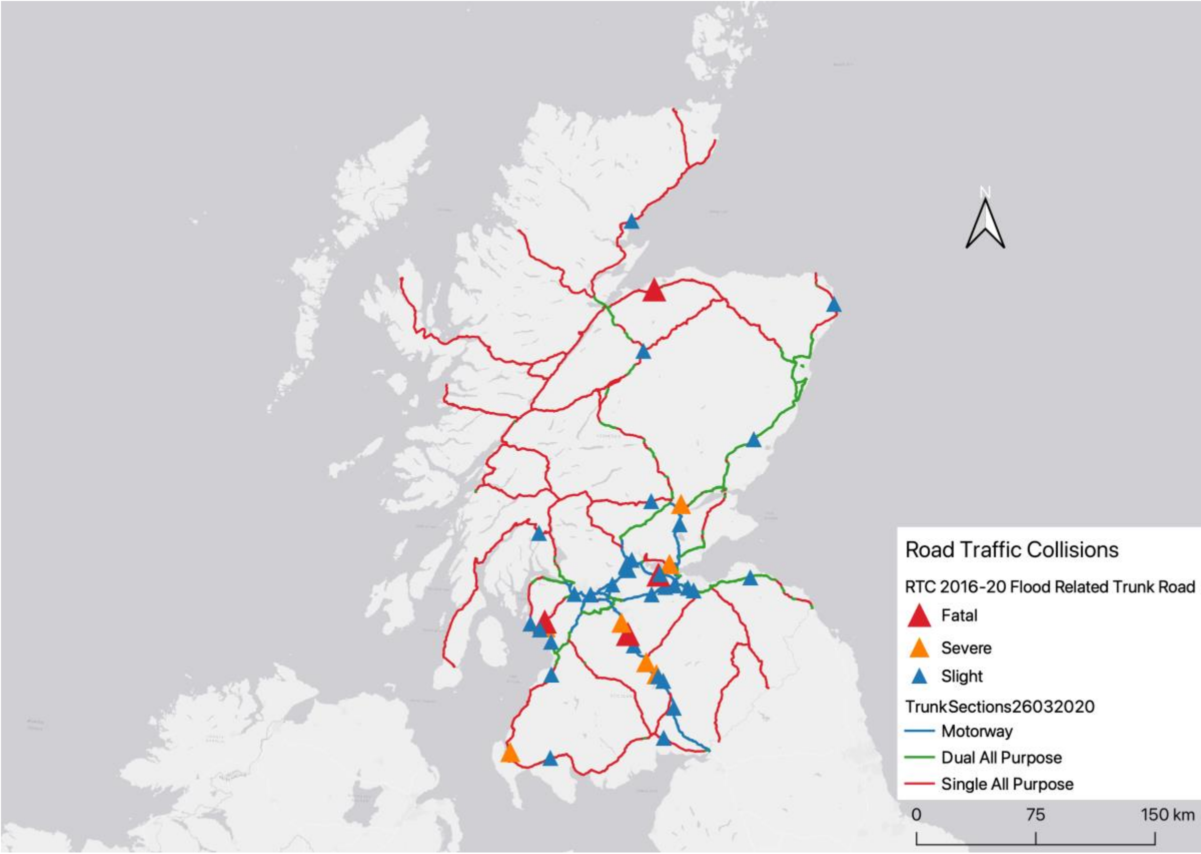

Figure 16 – Road Traffic Collisions associated with road surface flooding of at least 3 cm. (Source: DfT (2022)).

	All RTC's	Fatal	Severe	Slight	Network Length (km)◊	RTC Rate (per km per year)
Motorway	22	2	3	17	1,081	4.069×10^{-3}
DAP	7	0	1	6	1,284	1.091×10^{-3}
SAP	15	2	3	10	2,395	1.252×10^{-3}
Total	**44**	**4**	**7**	**33**	**4,761**	$\mathbf{1.849 \times 10^{-3}}$

Table 9 – Road Traffic Collisions (total and by severity) associated with a flood of more than 3cm in depth disaggregated by road type between 2016 and 2020. Annual RTC rate was calculated by dividing the number of RTC's by road length. (◊ Network length based on carriageway length)

5.7 Conclusions

1. There were 4,961 flooding incidents recorded in the IRIS dataset in the period January 2014 to December 2021. Just under 10% of these incidents disrupted the carriageway to some degree, ranging from reduced lane width to a full road closure. The flood depth was greater than 3 cm in approximately 20% of incidents.

2. Most recorded flooding incidents (52.8%) had a duration of less than one hour. 333 incidents (6.8%) lasted for at least one hour and caused carriageway disruption to some degree, whilst 55 disruptive incidents (1.1%) lasted for at least 6 hours. Very few incidents had a duration of more than 24 hours.

3. The overall flood incident rate was 1.216 incidents per km per year. Road sections with higher than average incident rates were identified. The highest incident rate was on motorway links. Not surprisingly, most flooding incidents were observed in the Winter and Autumn. The lowest incident rate was observed in the Spring.

4. On average there was a flooding incident on the trunk road network every 2.21 days. The maximum number of incidents on a single day was 51 which occurred on 31st December 2015 during Storm Frank.

5. Analysis of free text comments indicates that blocked or damaged drainage assets was a contributory factor in 39.4% of incidents.

6. The Road Traffic Collision rate associated with surface water over 3 cm in depth was 1.849×10^{-3} per km per annum for the period between 2016 and 2020. The injury rate on the motorway network was 3.25 times higher than the average rate for single carriageway roads in the trunk road network.

7. Gaining a clear understanding of the factors associated with higher levels of flood damage, and obtaining empirical evidence to estimate vulnerability functions requires the collection of accurate and comprehensive data from flood incidents. Specifically, the maximum depth and extent of flooding both longitudinally and transversely should be recorded, which should include flooding which occurs outside the road carriageway. The cause of each flooding incident should be recorded as well as actions taken to alleviate the flood including the use of any plant. A record of post-flood clean-up operations, any defects and repairs and traffic management should be maintained.

9. The collection of higher resolution and more comprehensive data on flooding incidents and the resulting impacts would provide empirical support for future vulnerability assessments. Whilst recognising the challenges of recording data at the same time as dealing with live incidents, consideration should be given to enhancing the incident data collection process. In particular, it is recommended that the maximum depth and extent of flooding should be recorded, including any flooding which occurs outside the road carriageway. The cause of each flooding incident should be recorded as well as actions taken to alleviate the flood including the use of any plant.

A record of post-flood clean-up operations, any defects and repairs and traffic management should also be maintained.

10. Road traffic accidents are categorised separately from flooding incidents. Care should be taken by Operating Companies to record surface conditions for road traffic accidents attended by Trunk Road Incident Support Service (TRISS) vehicles as this would enable non-injury crash data to be combined with Stats 19 injury accident data in future analysis.

6 Direct effects of flooding

This chapter builds on the descriptive analysis carried out in Chapter 5 above in order to explore how direct impacts vary with the recorded characteristics of flooding incidents. As discussed in Section 5.1, there are limitations on what is known about each flooding incident, both in terms of the characteristics of the flood itself but also on its direct impact. For example, the classification of incidents by flood depth does not permit any distinction to be made between flooding incidents with a depth greater than 3 cm. Likewise, the effects of flooding are limited to the specific impact on the road section itself (e.g. road closure) or were extracted from descriptive comments.

6.1 Direct effects – road damage

It was not possible to identify a source of data which contained a record of damage to the road pavement or associated infrastructure in the aftermath of a flooding incident. Longer-term damage linked to previous flood events may be revealed in pavement maintenance records but this data is time-consuming to extract and therefore proved beyond the scope of this study.

6.2 Direct effects – mitigation and clean-up

Based on free text comments in each IRIS record, around 12% of incidents where the flood depth was greater than 3cm required operatives to clear the flood (see blue portion of right hand column in Figure 17); just under 19% of these incidents involved the use of plant either to clear flooding or clean-up the road afterwards or both which constitutes around 190 incidents in an 8 year time period.[38]

The expected direct losses of managing flooding incidents could be estimated if the average cost of deploying plant were known. In a similar vein, the total resources required to alleviate flooding and clear up after extreme weather events (historic or hypothetical) could be estimated (see e.g., Section 5.4 on the spatio-temporal footprints of recent concurrent flooding incidents).

A more systematic approach to recording the actions and resources used to manage flooding incidents would improve the accuracy of estimates (see Section 5.1).

[38] 1,002 of 4,961 incidents had a flood depth greater than 3 cm.

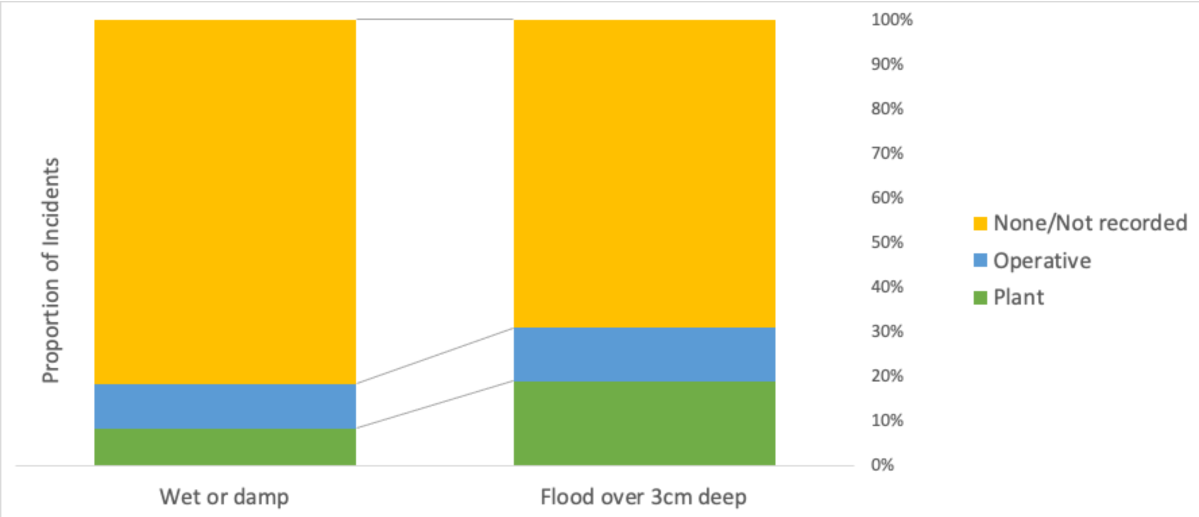

Figure 17 – Proportion of flooding incidents (2014-2021) which required the deployment of plant or operatives to alleviate/clean-up after a flood event of a given depth

6.3 Road Traffic Collision casualties

Based on Stats 19 data, the estimated casualty rate[39] was 2.521×10^{-3} casualties per km per annum on the trunk road network when road surface flooding over 3 cm in depth was recorded.

According to the IRIS dataset, the estimated annual flooding incident rate on the trunk road network where depth > 3cm was 0.302 per km per annum. Assuming both datasets represent complete and accurate records of injury and flooding incidents[40] and that flood casualty risk is the same on OC and DBFO-managed roads, tentative estimates of the annual number of casualties per flooding incident by severity and road type can be made (Table 10). Overall, there were 0.079 casualties per flooding event (depth > 3cm)[41], which is equivalent to around 10.31 casualties per annum on the trunk road network managed by the four operating companies. The number of casualties per flooding incident is higher for motorways than for dual and single carriageways.

[39] Each RTC has one or more casualties classified as killed, seriously injured or slightly injured.

[40] Stats 19 data collected for entire trunk road network whereas IRIS has no flooding incident records for DBFO sections. Assume IRIS is a complete record of flooding incidents and that incidents in Stats 19 are accurately recorded. Assume also that road surface condition (Stats 19) is a causal factor in the accident. No data for incidents where only vehicle was damaged.

[41] (2.521×10^{-3} / 0.302)

	Fatalities	Severe injuries	Slight injuries	All
Motorway	0.0083	0.0166	0.0748	0.0997
DAP	0.0000	0.0171	0.0569	0.0740
SAP	0.0107	0.0133	0.0375	0.0616
All	**0.0079**	**0.0157**	**0.0551**	**0.0787**

Table 10 – Estimated RTC Casualties per flooding incident (depth > 3cm) per annum by road type on the trunk road network

6.4 Functionality loss

Figure 18 provides an insight into the impact of flooding on the functionality of affected road sections. Around 4.3% of incidents (n = 50) where the flood depth was greater than 3 cm in depth resulted in a road closure[42], and a further 12.1% of incidents (n = 127) in this category brought about the closure of at least one lane.

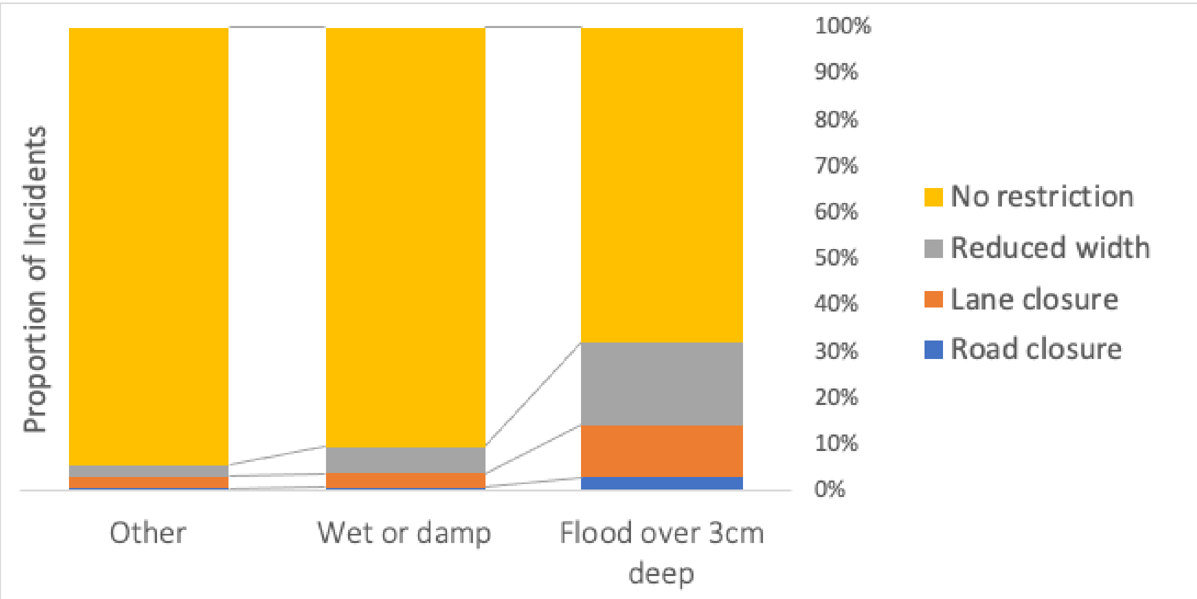

Figure 18 – Proportion of incidents (2014-2021) which resulted in different levels of functionality loss for a given flood depth

Just under 60% of incidents where the flood depth was more than 3 cm and which had a duration of between 6 and 24 hours were linked with a road closure (see Figure 19). The probability of a road being closed for more than 24 hours is less than the probability of a closure lasting between 6 and 24 hours. The direction of causality between incident duration and functionality loss is not known: (a) incidents which take longer to manage because of the depth of flooding or some other characteristic could increase the likelihood of a road closure or (b) incidents in which a decision has been taken to close a road could take longer to manage, or (c) both causal directions.

[42] Road closure combines the categories "Full road closure (both directions of dual)" and "Carriageway closed".

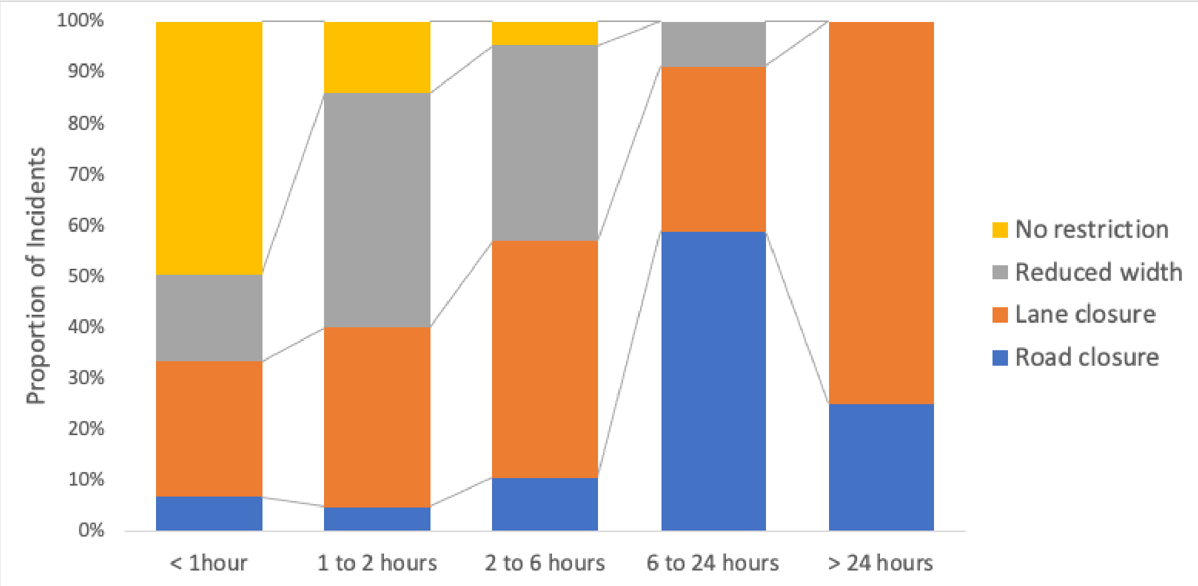

Figure 19 – Proportion of incidents (2014-2021) which resulted in different levels of functionality loss for a given duration of flood incident

6.5 Disruption

Assessment of disruption caused by flooding incidents was carried out in accordance with Transport Scotland's Disruption Risk Assessment Tool (DRAT). The impact level of each incident was based on the position of the route on which the incident took place within the Asset Management Hierarchy, the nature of disruption (i.e., full road closure, carriageway closure, lane(s) on dual-carriageway or motorway short of carriageway closure) and the duration of the incident. Impact levels range from A (highest) to F (lowest).

The results of this assessment are shown in Table 11. The vast majority of incidents created no disruption impact at all, and just over 1% of incidents were ranked with an impact level in the range A-C.

DRAT Impact Level	Incidents (%)
A	7 (0.14)
B	14 (0.29)
C	30 (0.61)
D	68 (1.39)
E	119 (2.43)
F	47 (0.96)
No impact	4613 (94.18)

Table 11 - Number (percentage) of flooding incidents (2014-2021) classified according to DRAT impact levels (A-F)

The percentage of incidents classified by impact level for floods over 3cm in depth is shown in Figure 20. 3.4% of incidents with flood depth > 3cm were ranked with an impact level in the range A-C.

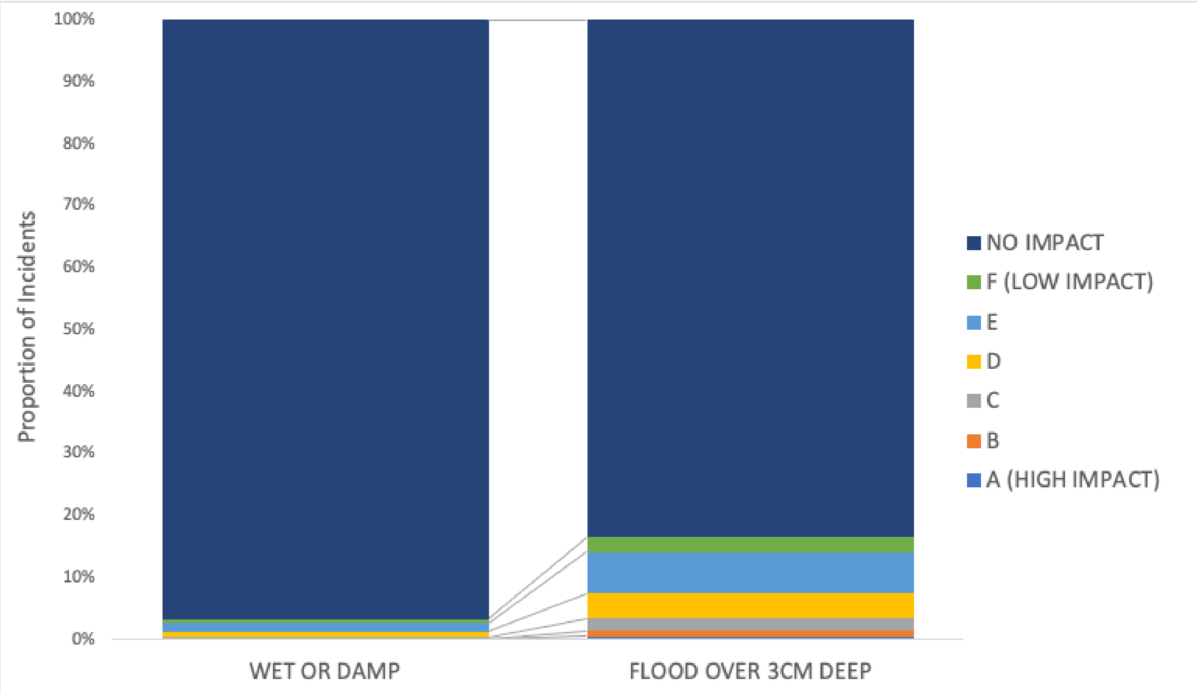

Figure 20 - Proportion of flood incidents (2014-2021) classified by DRAT impact level (A-F) for a given flood depth.

6.6 Conclusions and discussion

This chapter sought to estimate the direct impacts of the flooding incidents recorded in the IRIS dataset.

1. It was not possible to estimate short or longer-term damage and associated costs to the road pavement and associated infrastructure as a result of flooding. To address this limitation, a system should be set up which would enable post-flood defects and remediation actions to be cross-referenced with flood incident reports.

2. Based on free text comments, approximately 19% of flooding incidents where the depth of flooding was greater than 3 cm required the use of plant either to clear flood water or clean debris from the road surface.

3. Tentative analysis of RTC casualties and flooding incident data indicates a casualty rate of approximately 0.079 casualties per flooding event (depth > 3cm) per annum which is equivalent to around 10.31 casualties per annum on the trunk road network managed by the four operating companies.

4. In terms of the direct impacts on road users as a result of functionality loss, the probabilities of full and partial road closures both increased with an increase in flood depth.

Likewise, the probability of the requirement for a road closure increased with an increase in incident duration.

5. A full impact assessment of a road closure would require network-level analysis and depend on the characteristics of alternative routes (including established diversions), the level of affected traffic and the duration of the closure. These impacts include increases in travel time, operating costs and accident risk, but in extreme cases may lead to a trip cancellation. Moreover, in congested networks, the impact of diverted traffic on the operation of the wider network may also be significant.

6. The partial closure of a road will affect the speed-flow relationship of the flooded section. The impact on users will depend on the reduction in carriageway width relative to the original width, the level of traffic and the duration of the lane closure. The specific lanes affected may also affect the impact. Some traffic may divert to alternative routes if the lane closure(s) results in congestion.

7. The closure of one lane of a section of motorway or dual carriageway where there are no nearby junctions will reduce the capacity of the road in the region of 2,000 vehicles per hour. The impact of a lane closure near to a junction would depend on the configuration of the road and the movement of traffic between entry and exit points, and would require traffic modelling to predict accurately.

8. For a single carriageway road, the closure of a lane of traffic would reduce the capacity of the road from around 2,000 vehicles per hour in each direction to something in the order of 500 vehicles per hour in each direction. The impact would be higher for longer lengths of lane closure and for locations in the vicinity of junctions.

7 Impact of rainfall intensity on road functionality

As discussed in Section 5.1, the flood characteristics recorded in IRIS for each incident were limited to whether or not flood depth was greater than 3 cm. As a result, the assessment of functionality loss presented in Section 6.4 is fairly rudimentary. This chapter takes an alternative approach to estimate the relationship between functionality loss and hazard intensity by replacing flood depth with rainfall intensity which is the main driver of surface water and fluvial flooding. This approach requires accurate estimates of rainfall on flood-affected trunk road sections. To achieve this, spatial interpolation was carried out using a combination of observed rainfall at nearby weather stations, radar rainfall data and the topographic characteristics of the road section. Fragility analysis of the trunk road network to flood-related disruption was then carried out by estimating the likelihood of disruption for given rainfall intensities.

7.1 Data and methods

Flood incidents (n = 506) taking place on the trunk road network between 2015 and 2021 which disrupted a road section by reducing lane width, closing one or more lanes, or closing the road or carriageway were selected from the IRIS dataset provided. The altitude of each affected road section was extracted from Google Elevation API and added to this data.

Hourly rainfall data for the same time period was obtained from SEPA's rain station network (https://www2.sepa.org.uk/rainfall).

Radar-based rainfall data on a 1km Cartesian grid from the Nimrod system was downloaded from CEDA (Met Office, 2003) and aggregated to hourly intervals (mm/h). Figure 21 shows an example rainfall map from Nimrod for 01/01/2015 averaged across the period 00:00 to 01:00.

The accuracy of the radar data was assessed by comparing radar measurements with recorded rain station observations. Figure 22 shows that the correlation between these two data sets decreases as the distance from the nearest radar station increases. Thus, the accuracy of the radar data is dependent on radar station proximity.

The rainfall at incident locations was estimated using regression kriging which is a spatial interpolation technique combining the autocorrelation of observations taken at known locations and spatial information from one or more covariates which are believed to be related to the target variable. Here, the autocorrelation of rainfall at weather stations as combined with radar rainfall data and the altitude of disrupted road sections to produce a rainfall time series for each disrupted road section for time period 2015 - 2021.

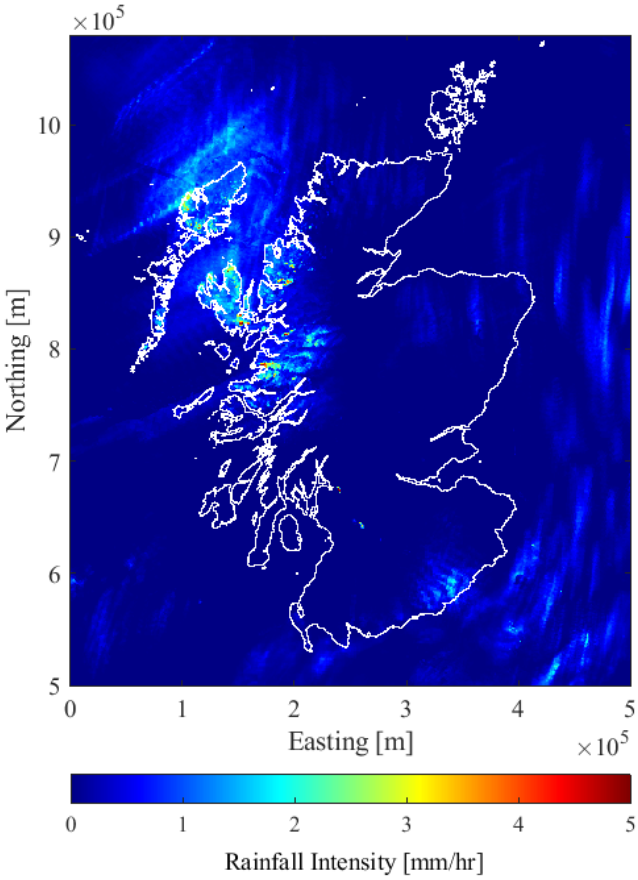

Figure 21 - Example rainfall map from Nimrod for 01/01/2015 averaged across the period 00:00 to 01:00.

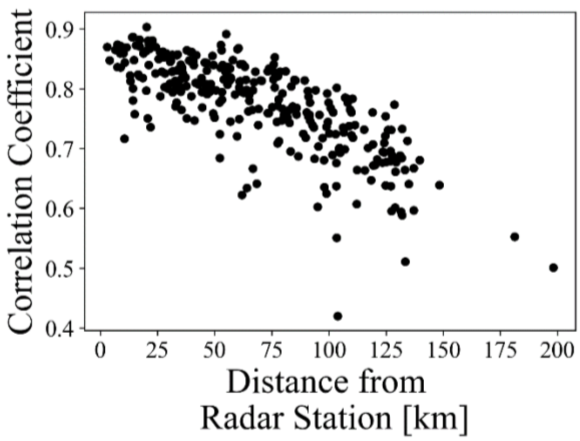

Figure 22 - Correlation between hourly rainfall station observations and radar hourly rainfall estimates for the same location, against distance from the nearest radar station.

At each incident location, the peak hour rainfall and the peak 24-hour cumulative rainfall were calculated for the 48-hour period centred on midnight prior to the date of each incident. The resulting data was divided into class intervals of length 2mm. Next, at each incident location, the number of observations of rainfall within each class interval was calculated. The conditional probability of flood-related disruption (D) occurring as a result of rainfall of intensity I on a road section where at least one incident was recorded was then calculated according to:

$$P(D \mid I = x) = \frac{number\ of\ failures\ when\ I{=}x}{number\ of\ observations\ when\ I{=}x} \qquad \textit{Equation 2}$$

Monte Carlo simulation was used to estimate a 95% confidence interval for probability estimates based on a normally distributed error of mean zero and variance from kriging process.

The conditional probabilities (along with upper and lower confidence limits) were plotted for peak hour rainfall and 24-hour cumulative rainfall. The highest observed UK values of rainfall were added to each plot with a disruption probability equal to 1. The UK maxima for one hour and 24-hour periods are 92mm and 238mm respectively.

7.2 Results

The results for peak hour and 24-hour cumulative rainfall are presented in Figure 23 and Figure 24 - Histogram of mean and lower and upper 95% confidence bounds for 24 hour cumulative predictions associated with the 506 disruption events (left). Empirical Disruption/Conditional Probability Curve for 24 hour cumulative rainfall (right).respectively.

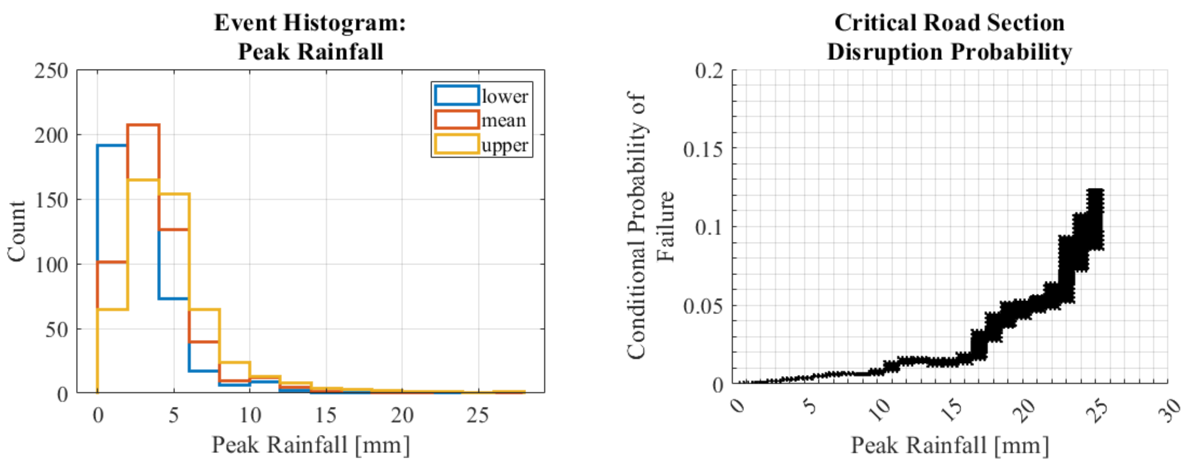

Figure 23 - Histogram of mean and lower and upper 95% confidence bounds for 24 hour cumulative predictions associated with the 506 disruption events (left). Empirical Disruption/Conditional Probability Curve for peak hour rainfall (right).

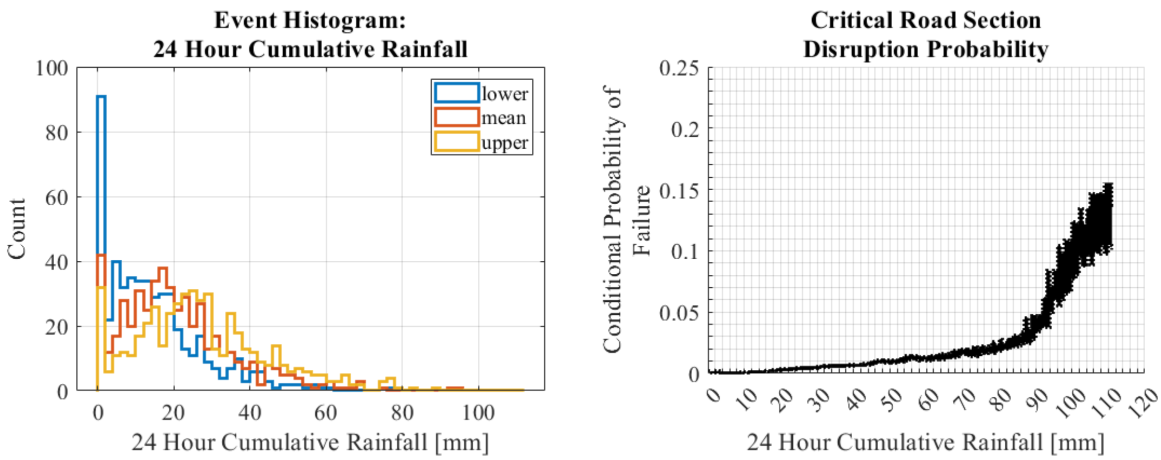

Figure 24 - Histogram of mean and lower and upper 95% confidence bounds for 24 hour cumulative predictions associated with the 506 disruption events (left). Empirical Disruption/Conditional Probability Curve for 24 hour cumulative rainfall (right).

7.3 Conclusions and Discussion

This chapter presents empirical fragility curves for peak one hour and 24-hour cumulative rainfall which relate the conditional probability of flood disruption to the intensity of a rainfall event. The probability estimates are presented along with 95% confidence intervals to reflect uncertainty in the estimation process.

While these results fill a gap in the analytical framework of road disruption risk to rainfall, there are several limitations to the present analysis.

Firstly, the analysis was carried out using data collected over a 7 year timespan which is a relatively short period with which to produce accurate probability estimates, particularly for low probability events. The longer the time period over which data is collected, the more likely the conditional probability of failure estimates will converge to its true values. Additionally, the range of observed rainfall will increase and include higher rainfall totals which will improve the fragility curve estimates. It should be noted that extrapolating beyond the observed range of data is not advisable, and the true structure of fragility curves in the most extreme regions of rainfall is unknown.

Secondly, and related to the first point, different levels of functional loss (e.g. lane(s) closure)) were aggregated into a single damage category of ”flood disruption” within the fragility analysis. More observations would enable specific levels of functional loss to be modelled separately.

Thirdly, the analysis is based on the assumption that all trunk road flooding incidents are included in the IRIS database. However, as discussed in Section 5.1 the proportion of actual flooding incidents recorded in the IRIS dataset is unknown and there is potential for systematic geographical and temporal bias in the data. In particular, during periods of intense or prolonged wet weather when resources are stretched may be under-recorded the number of incidents may be under-recorded. Hence the true value of the probability of failure is likely higher than the values that are presented within this report.

Finally, an area of improvement regards the assumption that rainfall (and altitude) are the only factors which influence the probability of flooding. This assumption does not take into consideration the relative position of the road to the surrounding landscape or the geometry of the road itself. It is likely that a number of flood events are caused by runoff from the surrounding landscape and so it may be beneficial to improve the analysis by using a block or catchment approach where each location is assigned a catchment and the total rainfall for the catchment, perhaps normalised by the area of the catchment, is considered instead of simply the rainfall at each incident location.

8 Conclusions and Recommendations

The aim of this project was to develop a framework for defining the vulnerability of roads to adverse weather-related flooding events.

Vulnerability is a weakness in part of a system which makes it susceptible to damage or loss from a hazard (IPCC, 2022). Potential losses (i.e. negative impacts) can be divided into direct and indirect losses, with a further division into tangible and intangible losses. A comprehensive assessment of the vulnerability of the trunk road network to flooding requires the consideration of all impacts, including those that cannot easily be quantified/monetised. Careful consideration should be paid to the spatial and temporal scales of potential indirect impacts, as well as the socio-economic and geographical contexts. The potential cumulative impacts of repeated exposure to floods and other disruptive events should also be taken into account.

PART I

The two principal mechanisms by which road infrastructure may be damaged are (1) saturation of unbound materials in the pavement or its foundations, and (2) erosion/scour of pavement surfacing and earthworks. Roads in cuttings or those which are susceptible to ponding water may experience sub-base saturation under certain flood duration and drainage conditions. Road embankments may be susceptible to subsidence/instability. The extent to which road “washout” is caused by internal/external erosion of the soil forming the road foundation and its interplay with the initially partially saturated conditions of the soil are poorly understood and are worthy of further investigation.

Vehicles and their occupants are placed at risk from flooding, particularly if flood water rises rapidly or if flooding occurs at locations where forward visibility is restricted. Full aquaplaning represents a risk to vehicles travelling at speeds in excess of 70 – 80 km/h when the depth of surface water is above 2.5 mm. Isolated flooding incidents may constitute a greater risk, particularly at night-time, or at locations where tyre-surface friction is important, e.g. on horizontal curves or the approach to junctions.

Flooding may reduce the speed and capacity of the affected road section resulting in increased journey times. Severe flooding will result in the closure of the carriageway, and diversion/postponement/cancellation of trips.

Two methods to conduct vulnerability assessments were examined – vulnerability functions and indicator-based methods. Vulnerability functions relate the degree of loss, which is normally expressed as the percentage of rebuild or renewal costs, to hazard intensity – which in the case of flood hazards is normally represented by flood depth. Indicator-based methods involve the identification and statistical summary of parameters/factors which make some part of a system (i.e. person, community, asset) more or less susceptible to harm or damage. Vulnerability functions can be combined with information on hazard and exposure to undertake a quantitative risk assessment. On the other hand, vulnerability indicators are independent of hazard intensity.

The set of vulnerability functions proposed by van Ginkel et al. (2021) are promising because these are designed to be used with vector-based maps of transport infrastructure and also differentiate between road types. However, the suitability of these vulnerability functions for roads in Scotland would require careful assessment before their use. This assessment should include consideration of assumptions relating to flood duration. The road repair/reconstruction cost database used with these functions would also require to be updated using Scottish data.

Applied indicator-based methods, such as ROADAPT VA, enable a broader range of contextual factors to be taken into account than vulnerability functions. These methods require relevant data to be retrieved from a transport authority's asset management system for each road segment. It is recommended that the availability and ease of extraction of relevant data for the Scottish trunk road network should be explored.

The potential of combining a generic vulnerability function with an index derived from site-specific factors as proposed by Godfrey et al. (2015) should also be examined. Doing so would overcome some of the existing limitations of vulnerability functions whilst enabling the assessment of risk in future climate scenarios and mitigation/adaptation actions.

Multiple approaches have been developed to assess the direct costs of the loss of road network functionality. These methods can be distinguished in various ways including assumptions relating to user behaviour and the degree to which network dynamics are captured over time. For less severe and short duration incidents, models which treat transport demand as inelastic (i.e. insensitive to disruption) should normally be suitable, particularly those models which are not strictly equilibrium-based. For major or long-lasting incidents, models which capture behavioural responses such as switching to other transport modes or destinations, or adapting planned daily schedules should be considered. With regard to the latter, the ability to work and carry out activities at home as a substitute for travel increases the adaptive capacity of some road users to cope with disruptive events.

Methods also exist to assess economic and social vulnerability (i.e. indirect impacts). Economic models may provide insight into the potential economic costs of disruption, including repeated events. Likewise, indicator-based methods could be used to assess community vulnerability. In both cases, the assumptions underpinning these models and data requirements should be explored further, including the availability of relevant data at a suitably fine scale.

PART II

Findings

Flooding Incidents

Between 2014 and 2021 there were over 600 recorded flooding incidents per year on trunk roads managed by the four Operating Companies. Whilst many of these incidents were relatively minor in nature, around 9% of incidents resulted in a reduction in road width or at least one lane closure, and just over 1% led to a road or carriageway closure. Around half of all recorded flooding incidents had a duration of more than one hour, and 3.4% were longer than 6 hours. On average, there was at least one flooding incident on the trunk road network every two days. The maximum number of recorded incidents in a single day was

51, which occurred on 31st December 2015 during Storm Frank, and there were more than 15 flooding incidents in a single day on 40 occasions in the period 2014-2021.

Impact of Flooding
It was not possible to identify a source of data which contained a record of damage to the road pavement or associated infrastructure in the aftermath of a flooding incident. Longer-term damage linked to previous flood events may be revealed in pavement maintenance records but this data is time-consuming to extract and therefore proved beyond the scope of this study.

Around 4.3% of incidents where the flood depth was greater than 3cm in depth resulted in a road closure, and a further 12.1% of incidents brought about the closure of at least one lane. Similarly, 3.4% of flooding incidents with flood depth greater than 3cm were classified with an impact level in the range A-C according to Transport Scotland's Disruption Risk Assessment Tool (DRAT).

Impact of Rainfall
Using rainfall and flood incident records, fragility curves were estimated for peak hour and 24-hour cumulative events which give the probability of a road section being disrupted for a given level of rainfall. There is scope to produce more accurate estimates with a longer time series of data and the inclusion of additional factors which influence the probability of flooding of a road section reflecting e.g. the local catchment and road geometry.

Accident Risk
A total of 44 road traffic collisions on the trunk road network between 2016 and 2020 were associated with a flood of more than 3cm in depth. It can be tentatively estimated that there were 0.079 casualties per flooding incident where flood depth was greater than 3cm, which is equivalent to around 10.31 casualties per annum on the trunk network managed by the four operating companies.

Recommendations
Data Quality
The collection of higher resolution and more comprehensive data on flooding incidents and the resulting impacts would provide empirical support for future vulnerability assessments. Whilst recognising the challenges of recording data at the same time as dealing with live incidents, consideration should be given to enhancing the incident data collection process. In particular, it is recommended that the maximum depth and extent of flooding should be recorded, including any flooding which occurs outside the road carriageway. A dataset of post-flood clean-up operations, any defects and repairs and traffic management for each incident should also be maintained.

Road traffic accidents are categorised separately from flooding incidents. Care should be taken to record surface conditions accurately for road traffic accidents as this would enable non-injury crash data to be combined with Stats 19 injury accident data in future analysis.

Data Integration
Enhance asset management systems to make it easier to relate flood incident records to asset data and pre- and post-incident maintenance records in order to identify suitable vulnerability indicators and/or estimate vulnerability functions for the Scottish road network.

Network Losses
Develop appropriate models to enable the performance of the road network and the impacts on road users caused by reductions in the Level of Service from flooding (and other) incidents to be assessed.

Flooding Scenarios
Develop a series of plausible future flooding scenarios with which to test the performance of the road network.

Research & Innovation
Road embankments are susceptible to subsidence and instability as a result of flooding. Further research is recommended into the extent to which road “washout” is caused by internal/external erosion of the soil forming the road foundation and its interplay with the initially partially saturated conditions of the soil.

Use data collected at flooding incidents to create new or to calibrate existing vulnerability functions which relate flood depth to loss or damage in order to identify vulnerable locations and assess future flood risk to the network. Explore the potential value of incorporating site-specific factors into these vulnerability functions to address known limitations.

As a complement to the above, estimate the return periods of the rainfall associated with flooding incidents in order to create fragility/vulnerability functions which relate rainfall intensity to loss or damage in order to identify vulnerable locations and assess future flood risk.

Consider the impact of flooding on non-trunk roads, and also the impacts of flooding on public transport, walking and cycling.

Review methods to assess the indirect social and economic impacts from flooding-related disruption and their applicability in Scotland.

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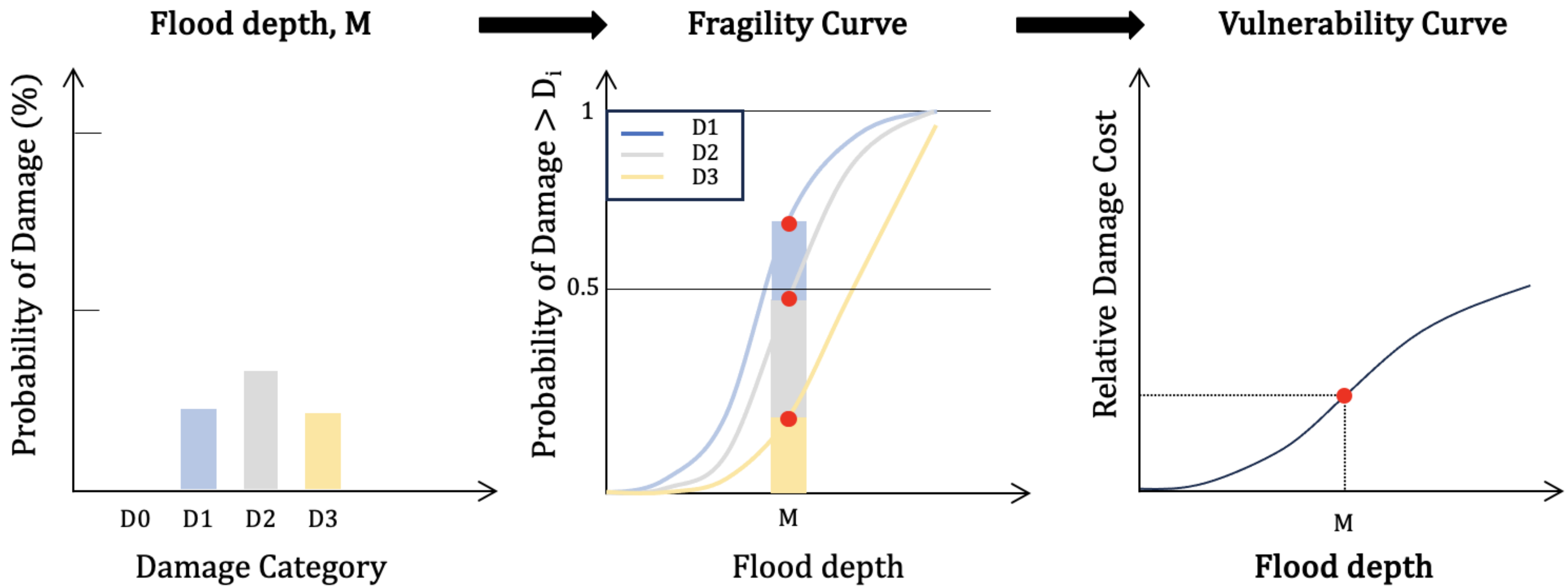
Appendix A – Link between Damage Level, Fragility and Vulnerability



Appendix B – Flooding Incidents by Duration

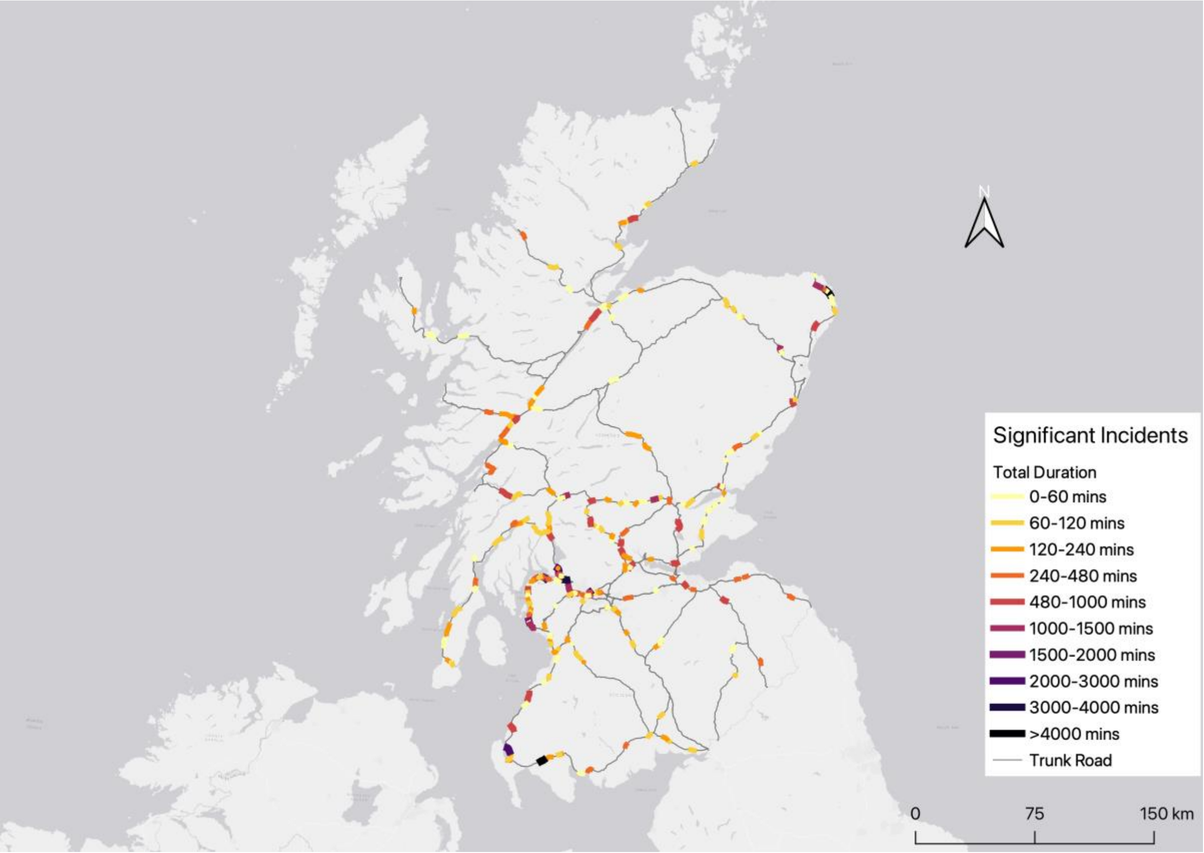


Figure 25 - Recorded flooding incidents by duration

Appendix C - Top 50 road sections ranked by the difference between observed and expected incident rates

SECTION_UI	SECTION_CO	SECTION_NA	ROAD	AREA	DIVISION	Road Type	Total Incidents (2014-21)	$R_{a,t}$	I_i	D_i
5628	12215/07	With: Start of Forfar Rd to Claverhouse Rd Jn	A90	North East Unit	Tay - Premium	Dual All Purpose	184	1.033	33.824	31.743
1872	14635/00	QUEENSFERRY ROAD R/B AT NORTH POINT	A985	South East Unit	Tay - Premium	Single All Purpose	6	0.806	10.000	11.407
5627	12215/12	Against: Claverhouse Jn to Change of lane no.	A90	North East Unit	Tay - Premium	Dual All Purpose	52	1.033	11.265	9.905
5433	13111/23	TINWALD DOWNS ROUNDABOUT	A701	South West Unit	South West - APU	Single All Purpose	6	1.537	11.538	6.507
2631	13714/22	WITH: SLIP FROM R.RD RBT TO START VIADUCT WB	M8	South West Unit	Clyde - Premium	Motorway	39	2.520	18.750	6.440
1870	14630/00	KINGS ROAD R/B AT NORTH POINT	A985	South East Unit	Tay - Premium	Single All Purpose	3	0.806	5.282	5.553
2767	15535/12	WITH: A912 JCT AT BRIDGE OF EARN TO M90 ENTRY SLIP	M90	North East Unit	Tay - Premium	Motorway	1	0.219	1.250	4.708
3544	13865/49	WITH:BOGSTON LANE TO SINCLAIR ST	A8	South West Unit	Clyde - Premium	Dual All Purpose	43	1.238	6.272	4.066
2221	11940/51	AGAINST: JCT VICTORIA CRESCENT TO DUNOLLIE ROAD	A85	North West Unit	Control Site 2	Dual All Purpose	1	0.436	2.193	4.030
360	10454/00	LONGMAN ROUNDABOUT	A9	North West Unit	Control Site 1	Single All Purpose	9	1.197	5.625	3.699
5999	10432/04	2 Way Slip Road From/to A9 NB	A9	North West Unit	North West1 - APU	Dual All Purpose	1	0.436	1.923	3.411
1329	14875/90	MELVILLE LODGES ROUNDABOUT AT NORTH POINT A914	A92	North East Unit	Tay - Premium	Single All Purpose	10	1.527	6.579	3.308
3242	14895/95	TAY BRIDGE ROUNDABOUT	A92	North East Unit	Tay - Premium	Single All Purpose	12	1.527	6.383	3.180

5701	14401/87	WITH: SLIP ROAD EXIT TO START OF 2-WAY SLIP	M876	South East Unit	Forth - Premium	Motorway	6	1.214	4.839	2.986
5092	12625/88	FORRES ENTERPRISE PARK ROUNDABOUT	A96	North East Unit	North East - APU	Single All Purpose	5	1.527	6.010	2.936
3121	14255/95	AGAINST: JCT 20 SLIP RD ON TO M8 EB	M8	South West Unit	Clyde - Premium	Motorway	25	2.520	9.470	2.758
3402	11240/10	WITH:EAST OF DREGHORN JCT TO WEST OF DREGHORN JCT	A720	South East Unit	Forth - Premium	Dual All Purpose	8	0.427	1.504	2.522
2864	13905/05	A85 RBT EAST OF A9	A85	North West Unit	Control Site 4	Single All Purpose	2	1.197	4.167	2.481
1793	10530/10	SIR JOHNS SQUARE TO JUNCTION TRAILL ST/OLRIG ST	A9	North West Unit	Control Site 1	Single All Purpose	5	1.197	3.676	2.071
6020	10867/70	Copach Roundabout	A82	North West Unit	Control Site 2	Single All Purpose	3	1.197	3.676	2.071
1383	12435/90	FRASERBURGH RBT (S)-FRASERBURGH RBT (S)	A90	North East Unit	North East - APU	Single All Purpose	3	1.527	4.688	2.070
3741	12220/15	EMMOCK ROAD ROUNDABOUT	A90	North East Unit	Tay - Premium	Single All Purpose	5	1.527	4.596	2.010
2776	15535/89	AGAINST: SB M90 INT BRIDGE TO ENTRY SLIP TO M90	M90	North East Unit	Tay - Premium	Motorway	1	0.219	0.658	2.004
5354	14000/90	BANKFOOT RBT	A78	South West Unit	South West - APU	Dual All Purpose	4	1.238	3.650	1.948
1541	17670/46	JUNCTION B9014 DUFFTOWN TO JUNCTION REGENT COURT	A96	North East Unit	North East - APU	Single All Purpose	15	1.527	4.464	1.924
5532	12680/50	CROY ROUNDABOUT	A96	North East Unit	North East - APU	Single All Purpose	6	1.527	4.412	1.889
5431	14330/90	Roadhead Roundabout	A737	South West Unit	South West - APU	Single All Purpose	5	1.537	4.281	1.785
3108	14250/11	AGAINST: M8 EB JCT 19 ON SLIP	M8	South West Unit	Clyde - Premium	Motorway	11	2.520	6.807	1.701

3399	11240/06	WITH:WESTBOUND SLIP FROM DREGHORN LINK ROAD	A720	South East Unit	Forth - Premium	Dual All Purpose	3	0.427	1.074	1.516
3264	16575/05	A8015 TARBERT PIER ROAD TO UC36 DRILL HALL JC	A83	North West Unit	Control Site 5	Single All Purpose	8	1.197	2.933	1.450
3099	14245/30	WITH: JCT 18 TO JCT 19	M8	South West Unit	Clyde - Premium	Motorway	38	2.520	6.098	1.420
3573	15110/49	BRANCHTON ROAD TO CUMBERLAND ROAD	A78	South West Unit	South West - APU	Single All Purpose	8	1.537	3.663	1.383
2751	15517/09	WITH: JUNCTION A909/B914 TO SLIP RD ENTRY M90 N/B	M90	North East Unit	Tay - Premium	Motorway	2	0.219	0.517	1.359
219	13713/93	WITH: RENFREW RD SLIP TO A741 RENFREW RD OBR	M8	South West Unit	Clyde - Premium	Motorway	17	2.520	5.870	1.329
6013	12430/90	With: Start 1 way (WB) to JN T A952 Cortes	A90	North East Unit	North East - APU	Dual All Purpose	1	1.033	2.273	1.200
3429	11250/80	AGAINST: GOGAR TO SIGHTHILL LINK ROAD	A720	South East Unit	Forth - Premium	Dual All Purpose	6	0.427	0.938	1.196
2978	14890/05	FIVE ROADS ROUNDABOUT	A92	North East Unit	Tay - Premium	Single All Purpose	5	1.527	3.289	1.154
2895	13925/05	B827 TO BRACO TO U199 GLENEDNOCK ROAD	A85	North West Unit	Control Site 4	Single All Purpose	7	1.197	2.574	1.150
3403	11240/12	AGAINST:W OF DREGHORN JCT TO E OF DREGHORN JCT	A720	South East Unit	Forth - Premium	Dual All Purpose	5	0.427	0.915	1.143
1874	14636/00	ADMIRALTY R/B AT NORTH POINT	A985	South East Unit	Tay - Premium	Single All Purpose	5	0.806	1.727	1.142
2867	13910/06	A85 RBT WEST OF A9 TO U45 RUTHVENFIELD	A85	North West Unit	Control Site 4	Single All Purpose	5	1.197	2.551	1.131
359	10453/05	WITH: RAIGMORE INTERCHANGE TO LONGMAN RBT	A9	North West Unit	Control Site 1	Dual All Purpose	13	0.436	0.918	1.106

1145	16215/38	30MPH CALLANDER SOUTH TO START OF MAIN STREET	A84	North West Unit	Control Site 4	Single All Purpose	3	1.197	2.500	1.089
5055	11039/07	DOVEMOUNT PL RBT TO JCT WILTON HILL TERR	A7	South East Unit	South East - APU	Single All Purpose	2	0.806	1.678	1.082
2723	10786/08	AGAINST: S/B SLP EAST/WST SPLIT TO A723 E/B MWELL	M74	South West Unit	Clyde - Premium	Motorway	9	2.520	5.208	1.067
2654	10309/87	WITH: WESTBOUND SLIP TO A801 (LATHALLAN)	M9	South East Unit	Forth - Premium	Motorway	6	1.214	2.508	1.066
2868	13910/07	U45 RUTHVENFIELD TO C410 HUNTINGTOWER	A85	North West Unit	Control Site 4	Single All Purpose	18	1.197	2.467	1.061
3310	13920/85	30 SIGNS EAST OF COMRIE TO B827 TO BRACO	A85	North West Unit	Control Site 4	Single All Purpose	11	1.197	2.464	1.059
1523	17649/53	RIVER BOGIE BRIDGE (E) TO RIVER BOGIE BRIDGE (W)	A96	North East Unit	North East - APU	Single All Purpose	1	1.527	3.125	1.046