**Improving the Resilience of Infrastructure to Create Sustainable Futures**

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**Abstract**

Climate change cause extreme weather patterns that have adverse effects on the infrastructure in UK, resulting in disruption to all stakeholders. These include extreme temperature highs; storms, windstorms, hurricanes; high levels of precipitation and associated flooding and lack of precipitation and associated drought. In recent years flooding has had severe impact on infrastructure and related physical assets in UK. The transport systems struggle to cope even though advancements are made in research and mitigation strategies. This paper examined areas of infrastructure related to land transport that fail or seem to fail and cause extreme disturbance to its users. It sought to identify the elements that are more vulnerable and need reinforcing in order to strengthen the resilience and the capability to cope in extreme weather. A broad-ranging literature review including government and stakeholder reports, case studies and action plans provided the foundation for the study. The paper attempted to capture the key lessons that can inform future adaptation and mitigating strategies and identifies areas that need further improvements in strengthening the resilience of the key infrastructure facilities. The information illustrated that it is not only the responsibility of one organisation but also a collective effort from government, local authorities, health, police and other infrastructure providers. Roads, railways, ports and other infrastructure assets must be constructed, refurbished or retrofitted to withstand extreme weather conditions. The design standards and thresholds must be re-visited and reviewed to encompass new weather scenarios and effects.

**Key Words**- Infrastructure, Resilience, Resilient Infrastructure, Transport, Flooding

**1.0 Climate Change and the infrastructure**

Climate change is one of the major global challenges faced in the 21st century and has a significant impact on the built environment. The ‘extreme weather events’ caused by climate change include: extreme temperature highs; storms, windstorms, hurricanes; high levels of precipitation and associated flooding; and lack of precipitation and associated drought (Anderson et al, 2006). New research suggests that many areas in England are projected to see an increase in severe weather over the next 30 years (Oven et al 2012, BIOPICCC, 2011). These extreme events are associated with major disruptions to essential services such as transportation and communication networks, energy and water supplies and can have severe repercussions to people’s health, well-being, social and economic activity and employment. Safe guarding infrastructure to extreme weather works on three levels: maximising the physical resilience, ensuring processes and procedures are restored quickly and ensuring clear and effective communication to all stakeholders so that impact is minimised (CCC, 2017a). The transport functions that are most likely to be affected by climate change include, provision of public passenger transport including tube, rail, bus and river services and functions of Highway Authorities and Traffic Authorities for roads. In London, UK, Transport for London (2015) have forecasted the risks from climate change related extreme weather conditions for 2050 as -

• Higher summer temperatures- with the average summer days being 2.7°C warmer and very hot days 6.5°C warmer than the baseline average.

• Warmer Winters - with the average winter day being 2.2°C warmer and a very warm winter day 3.5°C above the baseline. Increase in seasonal rainfall – drier summers, with the average summer 19% drier and the driest summer 39% drier than the baseline average.

• Wetter Winters - with the average winter 15% wetter and the wettest winter 33% wetter than the baseline average.

• Sea level rise - projected to rise by up to 96cms by the end of the century.

Flooding is the most significant climate change risk to UK infrastructure and assets and according to UK Climate Change Risk Assessment (2017); the number of assets exposed could double under expected changes in climate by the 2080s. The most common sources of flooding include: river flooding, coastal flooding, surface water flooding (including sewer flooding caused by rainfall overwhelming sewer capacity), and groundwater flooding (CCC, 2017b). Storm surges and rising sea levels pose a major threat to coastal infrastructure as well as cause sea erosion. Rain runoffs quickly undermine structures such as dams, railroad beds, bridges, and buildings. In the future, tunnels may become more vulnerable, both because the risk of their entrances and vents flooding will be greater, and because the hydraulic pressure on the tunnel walls increases as water tables rise (Titus, 2002).

This paper examines various extreme weather phenomenon that have significant impact on infrastructure that result in major disruptions to its users. It focuses on land transport systems emphasizing the impact on road and rail networks and related assets. A broad-ranging literature review including government and other stakeholder reports, case studies and action plans provided the foundation and an understanding of the wider context and the debate. Methodology is based on both secondary and primary data sources captured from different case studies carried out in the region and synthesizing the information and findings to draw out lessons that can be learnt. The aim is to identify the key areas that need strengthening and have an insight to how the mitigation strategies adopted by individual stakeholders can contribute to the sector as a whole. An objective is to examine how the infrastructure providers can improve collaborative working to increase the future resilience and capability of land transport systems. This in turn can have a major influence on economic and community resilience that contribute to sustainable futures.

**2.0 Extreme weather and transport systems**

UK transport network is the most intensively used in Europe and this will increase steadily in the future as both passenger and freight demand grows (EWENT, 2014). Dependable transport systems are appreciated for safety, cost, travel time, and regularity of service (Koetse et al, 2009). Maintaining the volume of traffic flow on the network, whether public transport or private travel, is fundamental for production, logistics, and business (Jenelius et al., 2006). Heathrow is the most intensively used two-runway airport in the world in terms of takeoffs and landings per runway and Gatwick is the most intensively used single runway airport (Chapman, 2014). The Strategic Road Network managed by the Highways Agency is also intensively used, operating at capacity on a number of sections at busy times and with traffic volumes forecast to increase by more than 45% by 2040 (High Ways Agency, 2009). Many local roads are also similarly at or close to capacity at busy times. In recent years, the impact of extreme weather on transport systems has been significant and many road and rail users experienced major and prolonged disruptions. Flooding impacts this in a number of ways through both direct impacts (physical damage) and indirect impacts (disruption to traffic flow, business interruption, increased emissions) (Brown et al, 2016). Numerous local roads were closed due to flooding and falling trees brought down power lines, which resulted in road closures and blocked carriageways. The reduction in performance of transport systems due to flooding is the most detrimental factor for the society and economy and it has been estimated at around £100k per hour for each main road affected (Arkell et al, 2006). Meanwhile, studies have shown that roads are among the first cause of deaths in cities during flooding, due to vehicles being driven through flooded roadways (Jonkman et al, 2005). The airports were affected and Gatwick suffered severe disruption with partial closure of its terminals due to basement flooding disrupting power, communication and IT systems.

**2.1 Extreme weather impacts on road infrastructure**

The road transport network is known to be a key enabler of the UK economy (Eddington, 1996) and has been emphasized as the UK's most expensive asset (DfT, 2005). It is also understood to be running near capacity (CCC, 2017a) and weather is a key factor in causing frequent major disruptions and accidents. The most damaging weather conditions for roads are, flooding, heavy rain, low temperatures and heavy snowfalls and high gusts of wind (EWENT, 2014). A combination of these can cause major damages to the physical infrastructure and disruption to its users. Heavy rain may result in landslides, mudflows and floods that destroy and erode roads, break and wash away bridges, pavements, drains and culverts resulting in major disruption, injury to users and some times fatalities. Floodwater can also enter underground transport systems. Melting snow, heavy wind in costal areas can lift water and sea levels to abnormal high levels. Heavy snow and freezing rain result in poor visibility, slippery roads, slow traffic and accidents. Heavy snow and wind gusts result in fallen trees on roads, which again disrupt transport links.

According to the Department of Transport (2014), flash floods that start speedily due to heavy rain are the main cause of weather related disruption to the transport sector. This can be severe on the road network in urban areas owing to the high proportion of impermeable surfaces that prevent the infiltration of water into the soil (Chapman, 2014). Heavy rain causes over flows that can result in drains exceeding their capacity and increasing the likelihood they become blocked by debris, before flood warnings can be widely disseminated.

**2.2 Extreme weather impacts on rail infrastructure**

The most harmful weather conditions for rail are listed as snow, low temperatures, flooding, wind and a combination of these. Snow can block tracks, yards, and damage overhead cables. Low temperatures can freeze switches and locks and cause tensional failures (EWENT, 2014). Snow and freezing may cause loss of electricity and signaling failures. Freeze thaw processes are also known to put excess strain on material and equipment (Chapman, 2014).

In recent years flooding has had severe impact on rail transportation and the related physical assets in UK. Rails tracks are washed away; embankments, slopes, bridges and other supporting structures are damaged and flooded underground tunnels un-useable by passengers due to safety concerns. Strong winds, tornados and tidal waves in coastal areas have similar effects. Fallen trees and debris on tracks, dangers of lightning hitting traffic controlling apparatus are other disruptions that can be faced.

**3.0 Improving Infrastructure resilience-**

The literature highlighted substantial amounts of research into the impact of a wide range of natural hazards, including snow, ice, rain, fog, wind and heat, on transport disruption. These studies span events of different spatial scale and magnitude and include results from a number of different countries. The increased frequency of flooding is the most significant climate change risk to UK infrastructure including transport, energy, communications and services resulting in lengthy and expensive repairs averaging an estimated £1 billion per year in the UK (DEFRA, 2012). ‘A large number of assets (17% of railway tracks and 16% of railway stations, 9% of A-roads and motorways are in locations which are prone to river or coastal, ground or surface flooding and it is projected that this risk will increase. Future Climate Change predications involving 4°C of global warming by the 2080s imply large increases in possible flood damage in UK. This scenario would lead the 2,400km of the UK rail network vulnerable to flooding rising by 120% by the 2080s’ (CCC, 2017a).

Rainfall intensity has repeatedly been shown to be a factor in transport disruption, reducing driver visibility, and reduced speeds. More intense rainfall will also increase sewer-flooding events. Rising sea levels of 0.5–1m by the end of the century will increase the proportion of assets vulnerable to coastal flooding. The need to realign coastal defenses in some areas in response to rising sea levels will have implications for infrastructure assets in the coastal zone, increasing their annual cost of maintenance. In order to address these major issues the government has created a long-term statutory framework for assessing and managing the risks to the UK from the changing climate. The Act requires the Government to assess the risks and opportunities relevant to the UK every five years and present a report to Parliament. As a result of these assessments priorities for further action and research have been identified (CCC, 2017b):

• Residual risks: while investments have bee increased in flood prone areas, the residual risk of flooding remain high across the UK. Improved flood defenses will not be possible or affordable in every area, and with climate change a greater disparity in risk between protected and non-protected areas may emerge. Some individual coastal communities are vulnerable to coastal erosion and sea level rises.

• Urban water management: heavy rainfalls stretch the capacity of sewers in many urban areas already at or over capacity. Redesigning urban landscapes and sustainable drainage systems are needed to protect individual properties to be able to cope with more intense patterns of rainfall.

• People and communities: as well as residential homes and other buildings, a significant number of hospitals and other care facilities are located in exposed areas. The evidence suggests that the long-term health and wellbeing impacts of flood events are considerable and more research is needed to assess and understand how best to manage these.

• Infrastructure: electricity sub-stations, road and rail networks, water treatments works, ports and airports, and fixed line and mobile communications assets, are all exposed to increasing flood risks. Further work is needed to assess and address vulnerabilities, including interdependencies between networks and includes the risk of sewer failure and consequential flooding.

• Agricultural production: strategic choices need to be made about the value of protecting agricultural production in flood risk areas when this could further increase run-off rates, silt deposition in rivers and downstream flood risk.

Building the capacity for resilience to flooding needs both formal and informal structures and processes and importantly requires clear linkages and accountability between those structures, so that resources can be freely transferred and exchanged. Community resilience cannot be built in a vacuum (Defra, 2014). There is a range of academic literature that specifically addresses the issue of measurement of community resilience and social vulnerability to natural hazards such as flooding. The information shows that the extreme weather effects have an influence over infrastructure users and related staff as well as service provider personnel, physical assets, economic and commercial activities and social well being of communities. Case studies illustrate that it is not only the responsibility of one organization, but also a collective effort from government, local authorities, health, police and other infrastructure providers. Government support and funding are key factors in this process. Roads, railways, ports and other infrastructure assets must be constructed, refurbished or retrofitted to withstand extreme weather conditions. The design standards and thresholds must be re-visited and reviewed to encompass new weather scenarios and forces.

**3.1 Rail networks**

In relation to rail networks, the risks have not changed significantly since the risk assessments were carried out in 2011 (CCC, 2011) but the level of detailed internal analysis and the investments and implications on long-term resilience have changed. Table 1 illustrates weather related hazards, the risks that are associated with related assets and consequences.

Table 1- Key climate change risks to rail infrastructure (Network Rail, 2015)

|  |  |  |
| --- | --- | --- |
| Weather-related hazard | Asset associated with risk | Consequence |
| Temperature (high, low and rate of change) | Track  | Buckles and breaks and derailment risk, Reduced opportunities for track maintenance |
| Switches and crossings | Frozen or snow blocked points, Failure of point operating equipment |
| High temperatures | Overhead line equipment | Sag of overhead line and risk of de-wirement |
| Line side equipment | Failure of temperature controls and overheating of electronic equipment |
| Low temperatures | Third rail and overhead line, equipment | Loss of power to rolling stock due to ice and snow build up and contact failure |
| Overhead line equipment  | Icicle build up causes damage to pantograph |
| Buildings (depots, stations and offices) | Slips, trips and falls risk to staff and station users |
| Level crossings | Ice on roads and vehicle incursion onto track system |
| Increase in flooding  | All | Closure of line due to track flooding, Failure of line side equipment due to inundation of water, Access issues to depots, stations and offices, Scour of embankment material |
| Change in river flows | Bridges | Risk of asset failure from: Scour of river bed material at bridge, foundations due to hydraulic action, Accumulation of debris under structure |
| Increased rainfall | Earthworks | Landslip and earthwork failure and risk to rolling stock and staff |
| Decreased rainfall | Earthworks | Desiccation of embankments resulting in track geometry faults and failures in supported line side equipment |
| High winds | Overhead line equipment and track | Risk to rolling stock, staff and asset failure from falling trees and debris (plastic bags, sheds and trampolines) |
| Sea level rise and storm surge | Coastal assets | Closure of track due to flooding, Structure or earthwork failure and risk to rolling stock and staff, Increased overtopping and sea water ingress into rolling stock and line side equipment |
| Extreme weather | Staff | Poor working conditions for staff in extreme weather conditions |
| Seasonal changes | Vegetation | Changes in growth rates and impacts on maintenance budgets and leaf fall management, Changes in invasive species and impacts on maintenance budgets and risk based assessment |
| Lightning | Line side equipment | Asset failure as a result of lightning strikes and electrical surges |

Consequences of extreme weather events on rail infrastructure illustrate that frequent testing, monitoring, review and updating is essential to keep the infrastructure and assets from failing. While the main responsibility lies with the rail authorities, it also demonstrates that collaborative thinking and working is essential from several stakeholders as disruptions to one service can have a ripple effect and put pressure on to other services. Frequent and routine maintenance, new and innovative asset management techniques that identify potential failures well in advance are needed to identify risk and carry out mitigation and adaptation. Improved asset data shared by different infrastructure service providers in differing systems supported by a range of data maintenance and assurance procedures can be used to better understand the vulnerability of each asset type to climate impacts. Advanced methods and tools are also needed to capture, maintain and access high-quality asset data. The ability to join and view asset data in collaborative environments and share decision support tools to better manage the assets will help in improving future resilience.

**3.2 Road networks**

Flooding, snow and ice represent the biggest risks of disruption to the road networks. The majority of flooding events are localised and of short duration, typically resulting only in lane closures rather than complete closures of roads. However they can, cause more significant disruption. High winds are also a significant source of disruption because of the risk of high-sided vehicles being blown over, and the increased risk for other vulnerable vehicles such as motorbikes, caravans and other towed trailers. Extended hot periods can increase the risk of damage to certain types of road construction, due to thermal expansion, resulting in an uneven road surface that needs repair. Extreme heat can also accelerate the rate of deterioration of older types of road surfaces, such as those formed of hot rolled asphalt, through softening and rutting of the surface (Chapman, 2014). Hot conditions also pose a heightened welfare risk to road workers, road users and livestock in transit, particularly when vehicles are delayed. The impacts of high wind speeds on the strategic road networks are largely operational, because of the vulnerability of certain types of vehicle and the risk of accidents or vehicle blow-overs. The infrastructure itself, particularly its structures, is resilient to very high winds (CCC, 2017a). The main responsibility in these scenarios is therefore to manage user behaviour and access to minimise the risk of accidents and avoid the resulting disruption to traffic (CCC, 2017b).

**4.0 Embedding infrastructure resilience in sustainable development**

As a result of The UK Climate Change Risk Assessment 2017, ‘Flooding and coastal change risks to communities, businesses and infrastructure’ has been identifies as an urgent, high risk, priority area where immediate action is needed. It is also identified as a priority research area. Climate change risk assessment identifies and sets out the main threats and opportunities arising from climate change over a defined period and evaluate the risks for adaptation priorities. Adaptation is the adjustment or preparation of natural or human systems to a new or changing environment that moderates harm or exploits beneficial opportunities. Climate resilience is the capacity to anticipate, prepare for, respond to, and recover from significant climate threats (GLA, 2011). Physical and economic resilience can be improved through adaptation measures, which minimise the impacts from climate threats on businesses, workers, supply chain and the environment.

Table 2- Selected case study review- London, UK extreme Weather Incidents since 2011-2014 (TFL, 2015)

|  |  |  |
| --- | --- | --- |
| Year | Event | Actions/ Lessons Learnt |
| 2012 | Lightning Strike at DLR Cross harbour equipment room | Changed design standards to ensure that earthing and bonding is more rigorous and introduced measures to break the charge. |
| 2013 | Fore Street tunnel drain gullies temporarily blocked with ice by a hail storm | Needed help from the police to unblock the gullies, as contractors couldn’t access the site through the traffic jam. |
| February 2014  | Storms and subsequent groundwater flooding | Pumping processes in place. Local authority and emergency services assisted communities in Croydon to be evacuated due to groundwater flooding.  |
| July 2014 | Excessive Heat  | Control with passive and mechanical air conditioning |
| August 2014 | Localised rainfall in major roads | Major review of locations where topology and drainage could make them susceptible to a similar impact |
| 2014 | Cloudburst flooding affecting Island Gardens DLR station | Addressed through improved preventative maintenance (improved proactive gully sucking) |

The information from case studies (Table 2) illustrate that out dated design codes and standards need to be reviewed and changed to withstand extreme climate forces. If viable resilience targets are to be achieved, financial resources need to be allocated year on year and continuously developed. Infrastructure systems are inter-linked and a failure of one system can put pressure on the others. For example if rail networks are not performing to their capabilities the road networks will be stretched to their capacities with the extra passengers who will chose alternative transport methods. Rail and road networks have identified the main barriers for climate change adaptation of infrastructure as (Network Rail, 2015)-

• Funding, balancing short-term delivery of benefits with investment in long-term resilience.

• Uncertainties of long-term climate change impacts.

• Limited redundancy in the system.

• Competing priorities, e.g. biodiversity and environmental targets versus vegetation removal and safety impacts.

• Short-term reactive nature of media to individual extreme events.

• Regulations and legislation.

• Lack of information on some impacts such as rates of change and extreme events.

In addressing these barriers some roads and rail routes have applied for and received additional funding for specific resilience measures.

There is a need for green Infrastructure and sustainable drainage systems to be implemented at individual level as well as local, regional and national level. Transport for London has initiated installing, operating and maintaining vegetated tracksides and road verges as well as green infrastructure such as green walls and roofs and sustainable drainage systems (TfL, 2015). The need for more research in these subjects has been identified to reduce uncertainties. The need to embed resilience measures in organisational policy and regular reviews have been acknowledged and actioned with a legislative frame work so that new information can be absorbed in to new developments, not just ad hoc one-off actions. Improved relationships, sharing of activities and research with other infrastructure owners, providers and key stakeholders such as Environment Agency, Natural Resources Agency, Environment Protection Agency, National Grid, Highways England, water companies, HS2 and Transport for London is crucial in achieving robust, resilient infrastructure and asset base.

According to the Greater London Authority (2011) current and future flood risk in London can be reduced and managed by;

• improving the understanding of flood risk to identify areas at greatest current and future risk

• supporting collaborative working to enable a coherent cost-effective approach

• reducing flood risk to the most critical assets and vulnerable communities

• raising public awareness of flooding and individual and community capacity to cope and recover from a flood, to improve resilience to flood events.

**5.0 Conclusions**

The impacts of flooding and coastal change in the UK are already significant and expected to increase as a result of climate change. Improving protection for some communities will be possible whilst others will face the prospect of significantly increased risks. This will affect property values, risk and insurances, business revenues and in extreme cases the viability of communities. Risks to communities and local economies are closely linked to the resilience of local infrastructure, in particular transportation, energy and communications systems.

Although investments are made towards improving climate change resilience to extreme weather, there is still a long way to go. Joint up thinking, polies and strategies, pooling of resources, investing in stable and robust infrastructure via new design standards and codes, collaborative working seem to be the way forward. More actions are also needed to support communities facing increasing risks, especially in areas where formal flood defenses are unlikely and long-term viability is at risk. There are also gaps in research in areas such as the economics of climate change adaptation, metrics, system modeling and simulations, spatial decision tools and funding sources to drive this agenda forward.

The major challenge is maintaining a whole system approach, which balances the needs of the transport industry and integrate the different requirements of the systems so that joined up actions can be implemented. A coordinated approach and identification of independencies will support the industry to adapt to climate change more efficiently and to prioritise resources. A widely used resilience rating system applicable to both individual, public and business assets could support more informed decision-making around resilience setting requirements for new building developments and in designing new facilities. Individual and collective urban drainage and green infra structure systems must be incorporated to development standards and regulations in order to achieve resilient urban futures.

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