



# UNIVERSITY OF LEEDS

Individual Research Project – CIVE3750

Weather induced bridge closures in the UK and measuring  
the efficiency of the UK strategic road network.

Author: Hina Farooq

Student ID: 201441276

Supervisor: Nikolas Nikitas

Date: May 2023

## **Acknowledgements**

I would like to thank the following people for helping me throughout the process:

- Nikolas Nikitas – For supporting my research and supporting me through all the ups and downs
- Marco-Felipe King
- My friends and family – For always supporting me

## **Abstract**

With the increasing occurrence of false bridge closure decisions made in the UK ,it is now imperative to review systems in place across the UK that determine whether a bridge is safe for public use during severe wind conditions. This research aims to investigate the reliability and effectiveness of the systems employed by local authorities, such as Severe Weather Information Systems (SWIS) the Met Office, and local authorities in making accurate decisions regarding bridge closures. Severe wind conditions have become increasingly prevalent across the country depending on regional variations, making it necessary to carry out a comprehensive evaluation of the decision-making systems in place. This report focuses on examining the accuracy and effectiveness of the systems employed by local authorities to make these judgments in these situations as it is important to ensure that the information sources used by local authorities are as reliable as possible. However, instances of false closures resulting in public dissatisfaction and financial losses have raised concerns. This study aims to assess the extent to which systems such as Severe Weather Information Systems (SWIS) the Met Office, and local authorities' decision-making processes are accurate in safeguarding against harm caused by severe wind conditions. Furthermore, this study examines the consequences of issuing false information.

## Declaration

I, Hina Farooq declare that this dissertation and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a degree at this University.
2. This dissertation has not been previously submitted for the purposes of obtaining any other qualification at this University or any other institution.
3. Where any part of this dissertation has previously been submitted for any other qualification at this University or any other institution, this has been clearly stated.
4. Where I have consulted the published work of others, this is always clearly attributed.
5. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
6. I have acknowledged all the main sources of assistance with the preparation of this work.
7. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have done myself.
8. None of this work has been published before submission.
9. I authorise my dissertation to be shared with subsequent cohort of students for educational purposes.

Signature: Hina Farooq

## Contents

ABSTRACT	iii
DECLARATION	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	1
LIST OF TABLES	1
ABBREVIATIONS	1
1.0 INTRODUCTION	2
1.1 Overview of the SWIS Network	4
2.0 Aims and Objectives	7
2.1 Aims	7
2.2 Objectives	7
2.3 Methodology	8
3.0 Literature Review	9
3.1 Factors affecting bridge performance in Wind	9
3.2 Bridge safety protocol during Severe Wind Conditions	11
3.3 Challenges and Limitations of Current Systems	14
3.4 Research Gap and Rationale	16
3.5 Analysing High Wind Strategy and National Wind Management Guidelines of Transport Scotland and comparing it to the wind strategy adopted by Highways England	18
4.0 Analysis and Findings	21
4.1 Data collected from online resources regarding the selected bridges closures and incidents.	
4.2 Identification of errors and inaccuracies	24
4.3 Implications of False Closures and Absent Alerts	25
5.0 Discussion	26
5.1 Interpreting the Findings	26
5.2 Limitations of the study	26
5.3 Recommendations for System Improvement and Future Research Directions	27
6.0 Conclusion	29
6.1 Concluding Remarks	29
6.2 Reflections against objectives	29

7.0	Bibliography	31
8.0	Appendix	34
	8.1 Ethics Approval	34

## List of Figures

Figure 1 – Colour coded Map of SRN

Figure 2 – Tacoma Bridge

Figure 3 - Location of the weather station closest to Orwell bridge

## List of Tables

Table 1 – Impacts resulting from wind

Table 2 – Wind induced incidents on Bridges in the UK

Table 3 – Orwell Bridge Closures from 2013-2021

Table 4 – Total number of Severn Bridge Closures by year

Table 5 – Severn Bridge closures with wind speed and duration

## Abbreviations

SWIS	Severe Weather Information Service
UK	United Kingdom
SRN	Strategic Road Network
HE	Highways England
RTC	Road Traffic Collision

## 1.0 Introduction

Weather-induced bridge closures in the United Kingdom (UK) are a common occurrence due to the country's diverse climate. The UK gets subjected to a wide range of weather conditions throughout the year, such as powerful storms and heavy rainfall to freezing temperatures and occasional snowfall during the winter months. These severe weather events can significantly impact the structural integrity of bridges and can pose great risks to the safety of road users.

The UK hosts an extensive network of bridges such as the Tower Bridge in London which is a historical landmark to vital infrastructure connecting major cities and rural areas like the Severn Bridge - connecting England and Wales, or the Orwell Bridge in Suffolk. The closure of even a single bridge can result in a severe impact on the transportation network leading to increased costs due to transport delays and in extreme cases leaving entire communities isolated from the rest of the transportation system (Kim et al.,2018).

These bridges are subject to weather induced forces that they must withstand however, when adverse weather conditions arise, it becomes necessary to close a bridge to mitigate risks and protect public safety. These closures are crucial in order to prevent accidents, ensure structural stability, and maintain the functionality of the transportation network. Local authorities must act swiftly to weather related factors such as high winds when bridges are deemed unsafe. These protocols are generally established by organisations such as National highways, Local highway agencies, and bridge maintenance teams who closely monitor weather forecasts and conduct regular inspections to identify risks and prevent any accidents.

The key elements that generally encompass the weather-induced bridge closure protocols are:

- Proactive monitoring of weather conditions using trusted sources- this consists of collection of gathering meteorological data and utilizing weather stations located near bridges.
- Appropriate measures must be taken if the decision to close a bridge is made which includes informing the public and managing traffic flow by developing alternative routes. The public is usually informed in advance through use of local news networks, social media, and mobile applications.



Weather-induced bridge closures have a significant impact on the transportation network and the public, such closures can cause inconvenience and disruption to road users, particularly if alternative routes are congested or less efficient. Closures can also impact the mobility of communities, access to services, and emergency response capabilities in affected areas. However, the result of a bridge staying open during severe wind conditions can be detrimental and can lead to loss of life meaning that weather induced bridge closures can be inconvenient but are a necessary response to severe weather conditions in order to keep the public safe.

Bridge closure protocols in the UK determine whether the bridge should remain open or not on the basis of wind speeds in the region and the importance of wind monitoring on bridges cannot be stressed enough. Generally, bridges are exposed to strong wind currents hitting them perpendicularly and the load induced by the wind poses a risk to vehicles crossing the bridge and can cause them to overturn, an incidence like this happened on the Severn Bridge where a “spike in winds” Masters,A (2020) caused a Lorry to tip over injuring the driver and causing damage to the bridge barrier. This “spike of wind” wasn’t a surprise as earlier that morning the bridge was closed due to recorded wind speeds reaching 100MPH (Elgee, 2020). This is just one of the countless examples of accidents that could’ve been prevented if the correct measures were put in place at the correct time. This particular accident was due to a false reading or failure of sending an alert which could’ve potentially cost someone their life.

A huge question that comes to surface once we delve deep into the causation of these accidents is who is at fault, Is it the local authorities? Is it the information being used to determine the safety of the bridge? The answer to this would be that incorrect or inconsistent information is passed on to the local authorities which could be due to inaccuracies in wind monitoring , this information is passed on to them by National Highways. It is important to know how and where National Highways get their data from and if there are any discrepancies in this said data. There is a huge gap in research regarding this which demonstrates a gap in the existing knowledge, presenting an opportunity to critically analyse weather monitoring systems to decide whether errors exist in the system or no.

## 1.1 Overview of the SWIS network

National highways maintain much of the England's Strategic Road Network (SRN) which includes around 4,300 miles of motorways and 'A' trunk roads demonstrated in figure 1, this comprises of only 2% of the England's road network however, it carries 1/3 of all traffic and 2/3 of freight traffic, overall resilience of the SRN is key to UK economy trade (Pritchard et al., 2016). In order to keep a harmony, national highways need to manage the traffic in events of closures or accidents due to weather conditions as well as trying their best to avoid accidents in these conditions. In order to achieve this, national highways



*Figure 1 - The Strategic Road Network (red=motorway, blue=trunk road)*

need assistance from a series of comprehensive systems also known as SWIS. SWIS provides national highways with relevant and accurate timely information about severe weather conditions, this is done by collecting and analysing meteorological data from services like the MET office and are sent to individuals and organizations, by using SWIS national highways can provide valuable information and issue warnings about severe weather conditions to aid in decision making and ensure public safety. SWIS contributes to the overall safety and resilience of society in the face of severe weather challenges.

This study focuses specifically on the use of SWIS in relation to impact of wind on long span bridges which can make the bridge dangerous to use, this is due to the fact that bridges are flexible structures making them more likely to be affected by perpendicular wind loads which can cause excessive vibrations and in some extreme cases these vibrations can be seen. Although there have been numerous studies on how to control and decrease vibrations caused by wind loads, it is nearly impossible to completely get rid of them. Therefore, in order to ensure that a bridge is safe for use certain protocols need to be put in place, according to which once a certain wind limit has been reached the bridge should be closed for public use.

This method has been used by National highways for numerous years and although it keeps the situation in control, many times the bridge is closed due to local authorities' false results and at other times the bridge has remained open way past the wind speed limit. The consequences of falsely closing a bridge are just as dire as leaving the bridge open for use

despite the severe wind conditions as it can and has led to vehicles overturning injuring the public as well as damaging the bridge. Generally, the decision to close the bridge aren't made by National highways, this is due to the fact that National highways uses a comprehensive system called SWIS which uses EXTRAC navigation and reporting technology, the severe weather information service (SWIS) brings together critical information on weather forecasts, road treatment plans and winter fleet data into a single system. The data recorded is passed onto local authorities who then consider the alerts accordingly and follow the procedure that is set in place.

SWIS monitors weather conditions in real time using a combination of weather sensors and data collection systems allowing them to detect severe weather. The forecasts are created by analysis of real-time and historical data. It sends out alerts using communication channels, broadcast media, mobile apps, and emergency alert systems. SWIS provides with guidance to assist organizations and emergency management authorities during weather events, these can include, Evacuations, road closures, emergency response protocols and resource allocation. Extreme weather, particularly high winds and intense rainfall events causing poor visibility and reduced traffic speeds, can disrupt traffic flows and lead to incidents, which then cause further disruption. Highways England's focus is therefore rightly on measures to manage traffic flows during extreme weather and reduce the risk of incidents, and on processes to return operations to normal as rapidly as possible after any incident.

Meteorologists use SWIS to:

- Review the combined forecast and actual data
- Review which roads to treat
- Create action plans based on pre-defined routes held in the system

Although being well prepared for severe weather doesn't necessarily mean proactive improvement works should be undertaken for the performance of particular assets, the exceeded impacts of severe weather events should be understood in order to respond and recover appropriately. Severe weather is defined as "any meteorological phenomena with the potential to endanger safe passage or cause disruption on the SRN and includes snow, heavy rain, high winds, fog and high temperatures". SRN is relatively modern network with most assets having been built to a high engineering standard. These geotechnical assets have been

resilient during periods of severe weather to date, despite this there is a need to be able to anticipate the impact, reduce vulnerability and speed up recovery of geotechnical asset failures should they occur. Ensuring serviceability and speedy recovery of SRN during such events represents a key performance indicator for Highways England.

The identification of potential hazards and the assessment of the risks that severe weather might pose is key to ensuring a resilient network. Climate change is likely to have a significant impact on Highways England's operations in the future, by affecting the normal environmental conditions as well as the frequency and magnitude of severe weather events. Such increases will likely lead to accelerated geotechnical asset deterioration. (Pritchard et al., 2016).

SWIS can be used to assist national highways and local authorities to achieve all this through:

- Real-time tracking and comprehensive reporting,
- Managed round the clock monitoring and coverage by enhancing new features such as additional reporting and better vehicle management capability

Any changes or developments made are assessed by Civica to ensure that sufficient testing has been carried out before deploying anything (Civica, n.d)

According to a case study carried out by National highways SWIS provides the following outcomes:

- Effective data-driven decision-making for keeping England's trunk roads safe in winter
- Efficient management of nationwide fleet of 500+ specialist vehicles
- Scalable database supports daily data additions and long-term regulatory compliant storage
- Round-the-clock monitoring ensures critical system availability
- Ongoing collaboration ensures SWIS continues to meet needs of England's strategic road network winter maintenance community (Civica, n.d)

Despite, SWIS being an extremely useful asset to national highways that already allows them to provide customers with an efficient road network, they are developing an even more advanced platform for SWIS 2 with additional features while making the platform more functional for the future (National Highways, 2022).

## **2.0 Aims and Objectives + Methodology**

### **2.1 Aim**

To understand and validate the accuracy of the SWIS system used by national highways by evaluating past bridge closures across the UK and by comparing the bridge closure protocol that is used in the UK to that of other countries.

### **2.2 Objectives**

1. To evaluate the weather forecasting systems especially SWIS and identify any sources of errors that could lead to incorrect information being sent out:

- Write an overview of SWIS, how it works and mention any other weather forecasting networks used.
- Compare data retrieved from SWIS to actual bridge closures and determine its efficiency.
- Analyse past studies that have assessed the accuracy of weather forecasting systems system.
- Discover the link between the inaccuracy of the system and the bridge closure protocol.

2. Retrieve data for bridge closures and evaluate whether the system was correct or not:

- Develop an exclusion criterion to select individual bridges and assess these for accuracy as well as that identify any sources of error that lead to incorrect outcomes.
- Retrieve data of all bridge closures from last few years and analyse what happened.
- Analyse the results further by investigating the damage caused by these incorrect outcomes and evaluate how severe the repercussions are when the system is incorrect.
- Analyse how these inaccuracies impact road users.

3. Review the Bridge Closure Protocols of the selected bridges and suggest improvements that should be made in order to make the roads safer.

- Carry out a critical review and discover the common aspects that work/don't work and identify what and where the problems lie.
- Suggest any modifications that can be made to enhance the closure protocols.

4. Compare the bridge closure protocols used in the UK to other countries and evaluate their efficiencies:

- Compare with countries that are host to some of the large span bridges that are normally subjected to critical wind conditions and critical weather.
- Suggest any measures these countries use that can be used by network rail to improve road safety in the UK.

### **2.3 Methodology**

A methodology outlining the process of preparing, collecting, and interpreting secondary research has been detailed below.

- 1) Research weather related factors that impact the performance of a bridge and how these impact the safety of the bridge.
- 2) Research Bridge Safety Protocols that are in place.
- 3) Gather data on bridge closures from the past few years.
- 4) Decide on Case studies to research more in detail. This will be done by only taking long span bridges into account, to narrow the number of case studies further bridges that are susceptible to higher winds will only be considered.
- 5) Perform an overview of the performance of these.
- 6) Present and explain the results, suggest improvements.

### 3.0 Literature Review

#### 3.1 Factors affecting bridge performance under wind loads.

When studying bridges, it is important to remember that bridges are flexible structures which makes them susceptible to horizontal influence of wind. The wind affects the strength and the reliability of the structures, as a result of which reactions such as flutter phenomenon, galloping, vortex excitation, buffeting and parametric resonance occur, each of these possess a great risk to the public (Poddaeva et al., 2019).

Due to the unpredictable nature of wind, it is considered to be one of the most uncertain factors that influences bridge behaviour, the lack of knowledge regarding this has resulted in a series of catastrophic events in the past such as the Tacoma Bridge collapse in 1940, Zhang et al.(2012) where the bridge twisted and collapsed after being



*Figure 2 - Tacoma Bridge*

subjected to wind speeds of around 42mph for the first time. during investigations it was revealed that the collapse was due to an inadequate structural design for the site wind conditions. Modern bridges are constructed by taking wind profiles into account however, a bridge can still be considered dangerous even when its nowhere near collapse as it is normal for a bridge to experience a degree of structural deformation during harsh winds which is accounted for by engineers, but it still poses as a risk to drivers (WindCrane, n.d.). High sided vehicles are especially sensitive to harsh wind conditions as they are prone to overturning due to the wind facing area being larger than that off normal vehicles. A range of restrictions are put in place for high-sided vehicles under these conditions such as speed reductions or in some cases complete closure of bridge. E.g., Queensferry bridge in Scotland

- Speed restriction of 40mph when wind speeds exceed 50mph
- Double deck buses not allowed to travel when wind speeds exceed 60mph
- High-sided vehicles restricted from travelling when wind speeds exceed 70mph
- All traffic except cars restricted when wind speeds exceed 90mph
- Bridge closed when winds exceed 100mph

High winds induce instability and cause excessive vibrations in long-span bridges which can cause the bridge span to move excessively i.e. in the case of Tacoma Bridge where winds as low as 3-4 miles per hour would cause the centre of the span to rise and fall as much as four feet, road users would actively avoid the bridge however, engineers concluded the movements to be predictable (Berreby, 1992) which later on turned out to be false as the bridge collapsed just after 4 months of opening. In order to prevent this wind tunnel testing is commonly used for “wind sensitive” bridges to determine the susceptibility of the bridges to various aerodynamic phenomena (Chen and Duan, 1999). For this study the preventative design aspect of bridges against wind resistant will not be considered as it is solely focused on the effect extreme winds have on existing structures which were designed to sustain a reasonable amount of wind. In order to achieve these restrictions such as the ones mentioned above need to be considered. Abiding by the restrictions decreases the chances of accidents and overturning vehicles. Overturning is usually a risk in rural areas where there are no obstructions in place that could slow down the wind velocity, this leads the wind velocity being higher than usual. Restrictions are also sometimes needed in urban areas where ground level wind speeds around high-rise buildings can be sufficient to overturn a vehicle. However, for this report we will solely be focusing on impact of harsh wind conditions on bridges (Baker and Soper, 2022).

The Met Office has severe weather warning tables for different weather conditions, the impact table for strong winds is demonstrated below:

Very Low	Low	Medium	High
Loose debris blown around.	Some transport routes and travel services affected. Some journeys require longer travel times. Some disruption to road, rail, air and ferry transport.	Injuries and danger to life from flying debris.	Widespread danger to life from flying debris.
A few transport routes affected by difficult driving conditions.		Some structural damage, such as slates dislodged from roofs.	Widespread structural damage e.g., roofs blown off, mobile homes overturned, power lines brought down.
Instances of spray and large waves affecting coastal routes, sea fronts and coastal communities.	Difficult driving conditions for high-sided vehicles on	Transport routes and travel services affected. Longer journey times expected. Disruption	Transport routes and travel services affected for a



	<p>prone routes, such as cross winds on exposed or high-level roads.</p> <p>A few power interruptions.</p> <p>Coastal routes, sea fronts and coastal communities affected by spray and/or large waves.</p>	<p>to road, rail, air and/or ferry transport.</p> <p>Closure of some susceptible and key routes (e.g., some vulnerable bridges).</p> <p>Interruptions to power and/or other utilities and services.</p> <p>Casualties and danger to life from large waves/beach material being thrown onto coastal routes, sea fronts and coastal communities.</p>	<p>prolonged period. Long travel delays.</p> <p>Closure of main bridges, road and rail networks in many areas, and significant disruption to air and ferry transport.</p> <p>Widespread and prolonged disruption to power, and/or other utilities and services.</p> <p>Danger to life from large waves/beach material being thrown onto coastal route, sea fronts and coastal communities.</p>
--	--	--	--

Table 1 retrieved from (Met Office, 2022)

As mentioned in the table major bridges are generally closed due to severe wind conditions, this is being pointed out to demonstrate the amount of negative impact that an open bridge under strong wind conditions could have. Although many times bridge closures are due to false data national highways or local authorities cannot afford to doubt their decision as the results could be catastrophic. Therefore, in order to reduce the number of false closures research needs to be done to find errors and inaccuracies in weather forecasting networks so they provide more accurate alerts.

### 3.2 Bridge safety protocol under severe wind conditions

In order for public safety, it is crucial to establish bridge safety protocols that incorporate a set of restrictions in place, this can be in the form of speed limits or complete closures. These measures mitigate the risk of accidents that can occur when bridges remain open under unfavourable wind conditions, this can be done by installing wind screens or traffic control

actions, however these can have a negative impact on the aerodynamic stability of the structure (Kim et al., 2016). Numerous incidents have been documented where accidents occurred due to bridges being open when they should've been closed, some of these are listed in the table 2 below:

Date	Bridge	Location	Description	Reference
02/11/2022	Tay Bridge	Dundee	Truck overturned due to strong crosswinds causing temporary closure and traffic disruption. Gusts of 55-65mph.	(Love, 2022)
15/03/2013	Forth Road Bridge	Edinburgh	Lorry blown over in severe wind gusts leading to travel delays. bridge was closed to high-sided vehicles due to 50mph winds. No injuries.	(BBC News, 2017)
07/04/2016	Humber Bridge	Kingston upon Hull	Lorry blown over due to high winds.	(Storyful, 2016)
09/11/2018	Humber Bridge	Kingston upon Hull		
11/02/2020	Severn Bridge	Bristol	Unpredictable gusts of wind meant a lorry blew over, injuring the driver. Wind of over 50mph	(Owen, 2020)

The incidents in Table 2 serve as reminders of the potential risks associated with high wind speeds on bridges in the UK.

Most bridges in the UK that are subjected to severe wind loads have specific bridge closure protocols designed to address these conditions. In order to ensure a focused study, a selection of bridges has been chosen for assessment review. By examining the closure protocols for these selected bridges, a valuable insight is gained into the effectiveness and efficiency of the measures that are taken to keep the roads safe during strong winds.

The bridges that are going to be considered for this study are:

- Severn Bridge located in Bristol
- Orwell Bridge located in Ipswich

Severn Bridge is one of the UK's largest suspension bridges, Msaewe et al(2021), that carries the M48 motorway across the Severn Estuary and spans 1600m. The bridge generally closes during windy weather this is due to the fact that the Severn Estuary funnels strong gusts across the bridge which can be dangerous to the traffic, therefore access is restricted from time to time. The restrictions for this bridge are:

- When wind gusts of over 46mph are estimated, the Severn bridge is closed to all traffic until the wind speed has dropped down.
- However, when the gusts are over 80mph both bridges are closed to keep everyone safe.

Since there are numerous other ways through between England and Wales like M5, the traffic from the bridges can be diverted to these roads to avoid as much traffic and congestion. When the M4 bridge is not closed, the traffic is diverted to this bridge because of the wind barriers which reduce the impact of wind. The foot and cycle path are also closed depending on whether there has been a critical incident or not (National Highways, 2020). Advanced warning systems are used to inform drivers of any weather information and any updates on these systems.

The second bridge we would be considering for this study is Orwell Bridge, which is located in Ipswich, the bridge generally closes due to safety reasons and the local authorities put a conscious effort in ensuring that the bridge is closed for as little time as possible to keep a steady traffic flow. Prior to 2021 the bridge used to close for all traffic if wind gusts exceeded 50mph in a specific direction or it would close regardless of the wind direction when the wind speed hits 60mph. However, since 2021 changes have been made to the system that are listed below:

- if wind speeds exceed 45mph the driving speed is reduced to 40mph
- if the predicted wind speed is 60mph or higher than the bridge is closed as it poses a huge threat to motorcyclists.
- During low wind conditions the speed limit remains at 60mph (National Highways, 2020a).

The decision to close the bridge is dependent on the MET Office forecast rather than live wind speed data, the forecast allows people to be informed in advance, in order for the bridge to be reopened 3 consecutive readings of below 45mph have to be read. A new feature that installed is permanent signage which reduces the time required to implement or remove road closures. National highways decide whether the bridge will be closed or not, but they use information provided by the Met office's forecast as well as live data from the Orwell bridge station. Decisions to close the bridge should be made relatively quickly so appropriate warnings and safety measures can be implemented. The road closures must take place before the wind reached 50mph, in order to safely place cones and signs on the carriageway. When re opening the bridge after strong winds the bridge is considered safe to open based on advice from the Met Office and with 3 consecutive readings of below 45mph like mentioned above, if both conditions are met the closure is lifted however, national highways continue to monitor the wind speed data on bridge (National Highways, 2022).

Prior to the changes made in 2021, numerous studies were conducted to try to keep the bridge open for longer, a study undertaken by structural engineers at University College London concluded that "if the traffic speed limit was reduced from 60 mph down to 40 mph during high winds it could mean that the bridge may remain open during wind speeds of up to 70mph" (Ashwell, 2020). The conclusions from this study were however theoretical and real-life validation would be needed in order to introduce the new variable speed limit.

Keeping the bridge open for as long as possible is crucial as a debate about the closures of Orwell bridge during high winds took place in the House of Commons on 3<sup>rd</sup> December 2020 where Tom Hunt (the elected member of parliament for Ipswich) raised an issue about the number of times the bridge was closed due to high winds. During his claim he declared that every day the bridge is closed, it takes a huge toll on the local economy ( around £1 million to be precise) and pleaded for a new variable speed limit to be announced which as mentioned earlier was then lowered from 60mph to 40mph during high wind conditions allowing the bridge to remain open for longer periods of times (Hunt, 2020).

### **3.3 Challenges and limitations of current systems**

Forecasting the weather is essential however it does have its limitations and challenges, there are multiple reasons why forecasts cannot be accurate a major reason for that is data analysis

uncertainties, regardless of how precise it seems there are always uncertainties present. Computer models are used by meteorologists to predict the weather however, it is extremely difficult to predict the weather correctly ahead of time, this is due to 3 major factors:

- availability of data
- availability of time to analyse said data
- complexity of weather events
- nature and reliability of communication systems available (Smith et al., 1986)

Weather forecasting is dependent on large data collecting networks like the Met Office, the Met Office have over 200 weather stations located around the country that record a number of parameters such as air temperature, wind speed and temperature, rainfall and a few more. These weather stations collect data at a minute's interval using sensors, the data is then transmitted to a central collection system where the data goes through control checks (Met Office, 2016). The data is analysed by computer models however, despite these extensive models that use a variety of equations to predict the weather there are still errors present. This is due to the fact that computer models cannot fully simulate the continuous changes in the atmosphere, as well as this the data that is fed into them doesn't fully cover every corner of the entire atmosphere therefore the forecasts predicted cannot always be correct, although it is extremely close (Cho-Ming, 2021).

The Met Office official websites highlight the following key limitations that should be considered before using any results and data from them. Despite the advancement of technology over the years the climate models used by the Met Office are still not able to present certain features that are seen in present data (UKCP data caveats and limitations, 2020).

- Climate projections dependent on future greenhouse gases assumption
- Estimated ranges for Future climate are conditional: these are conditioned based on a set of modelling, statistical and dataset assumptions which means that there is a level of uncertainty regarding the accuracy of future possible outcomes.

- All future outcomes aren't captured due to the limited size of range; therefore, all possible future climates cannot be simulated.

Weather model forecasts generally have a number of errors which arise from the fact that we do not know the activity of every single molecule of air that is present in the atmosphere, while the models are great at predicting weather forecasts most of the times it is not possible for them to be 100% accurate. However, they do provide a rough estimate which most of the times will be very close to being 100% accurate but will never get there (Sillin, 2019). Forecast models are merely predictions which is why collecting real time data from sources such as SWIS is extremely important as there is always a possibility that the forecasts can be extremely wrong due to whatever unknown reason that might be.

Just because SWIS provides real-time data to the MET office doesn't mean it doesn't have its own limitations and challenges. A major limitation of weather forecasting is the variation and uncertainty which is due to the fact that a very small difference in temperature can lead to a drastic change in forecasts. Another major limitation that is faced in terms of collecting wind data from bridges comes in the form of the weather collecting station not being close enough to the bridge site. This location distance although small can have a big difference in temperatures which can lead to false closures in some cases and in some cases, this could lead to a bridge remaining open despite severe wind conditions.

According to the Kaufman (2020), the "absolute limit on weather prediction is around 2 – 3 weeks" and even with access to the latest technology it isn't possible to exceed this limit.

### **3.4 Research Gap and Rationale**

The existing research on weather forecasting systems and bridge closures has provided valuable insight into the subject. However, upon review, a significant research gap emerges, indicating a lack of comprehensive understanding and exploration in a particular area or perspective. Specifically, the gap lies in the limited examination of SWIS within the context of its accuracy and functionality. There is also very limited research exploring the causes of why certain bridges stay open regardless of the wind conditions being extremely dangerous and there being sufficient evidence present regarding this as there seem to be a pattern of the same few bridges that seem to have accidents due to the harsh wind conditions. This research

gap presents an opportunity for further investigation and contributes to the rationale for conducting this study.

There are several reasons that support the rationale for addressing the identified the research gaps. Firstly, exploring and filling this gap, the study aims to enhance the overall knowledge and understanding of how weather forecasting works and how it safeguards the public from severe weather events. The findings of this research can provide valuable insights and can potentially be used to further explore the areas highlighted throughout the study. Secondly, addressing the research gap can have implications for organisations such as SWIS, the Met Office, national highways as well as the emergency services. The outcome of this study offers a new perspective, suggests a few strategies and interventions that could be applied to improve the process of collecting, analysing, and communicating the weather forecasts. This can lead to tangible, benefits such as enhancing efficiency, effectiveness and accuracy of the weather forecasting system resulting in fewer accidents and fewer false closures leading to a more efficient road network.

Furthermore, closing the research gap contributes to the academic community by adding to the existing body of research which can serve as a foundation for future research, enabling experts in the field to expand upon the basic knowledge that is highlighted during this study.

Lastly, from a broader perspective, filling the research gap regarding evaluation of weather forecasting systems aligns with the overarching goal of creating a road network that is as efficient as it can be while keeping safety at its forefront. It reinforces the importance of staying up to date with problems that emerge from using newly developed networks.

Overall, identifying research gaps and the rationale behind the study serves as a basis for the importance and relevance of the research. By addressing this gap, the study aims to contribute to knowledge and provide insight into the shortcomings of the weather forecasting systems while drawing attention to the impact these shortcomings have on the road system and public safety.

### **3.5 Analysing High Wind Strategy and National Wind Management Guidelines of Transport Scotland and comparing it to the wind strategy adopted by Highways England**

Just like Highways England, transport Scotland also recognises the effect high winds have on any vulnerable sections of the road network. In order to not cause severe disruptions and provide a safe road network, Transport Scotland have developed robust and proportionate management procedure for various sections of the trunk road network however, since wind can occur anywhere along the road network certain structures have site specific procedures put in place to manage the impact of high winds. Similarly, to Highways England, Transport Scotland use a set of model results provided by the Met Office to identify mean wind speeds. The analysis is based on historical data from 1971- 2000. These results are available to all local authorities.

During the study carried out by Transport Scotland it was revealed that despite there being a number of existing wind monitoring and warning systems, there were no specific guidelines regarding this as a result of which site-specific procedures were adopted.

Transport Scotland follow a 10-step process for successful wind management which is highlighted below:

- 1) Risk identification – identify key locations and sites that are constantly exposed to high wind conditions.
- 2) Organisational Agreements – clarify responsibilities between the different stakeholders as well as that identify a decision-making path for distribution of information.
- 3) Diversion Route Planning – identify alternative routes for extended closures, create an efficient diversion management system and develop an effective communication system to inform travellers about the diversions in advance. Assess these routes for high wind impacts as well.
- 4) Monitoring – set up meteorological forecasters to obtain severe weather forecasts warning in advance providing the organisations in charge with a window of opportunity to prepare for the wind impact. Monitor real time wind speed and direction from weather forecast networks located on the road network within the proximity of the site.



- 5) Define Thresholds – wind speed thresholds as well as direction of wind need to be predetermined, this should include information regarding removal of restrictions as well. Each site should have site specific criteria due to difference in height, exposure, and road orientation.
- 6) Develop levels of restrictions – restrictions are dependent on wind speed, direction, geographical location, and local topography therefore, restriction of certain classes of vehicles such as HGVs must be put in place.
- 7) Enforcement – the police, local authorities, bridge boards, road maintenance organisations. Appropriate signage must be provided by the authority in charge.
- 8) Implementation of Traffic Management – this should include, pre-agreed alternative routes, if these aren't available sufficient parking for vehicles susceptible to wind must be provided.
- 9) Distribution of information – organisation responsible for procedures must send out regular updates to neighbouring road authorities, road maintenance services etc. as well as alerting the public through the use of media.
- 10) Lifting restrictions and information dissemination – relaxation of restrictions dependent on real time observed wind speed and direction. Any relaxation of restrictions must be communicated to the road users as soon as possible.

While putting closures into place its generally done in 2 stages; stage 1- closed to high sided vehicles, stage 2- closed to all traffic. This is due to the fact that high sided vehicles are susceptible to overturning due to high wind speeds (Phone, 2007).

An example of high wind procedure for Erskine bridge is briefly described below:

Wind forecasting and warning information as well as the live wind speeds is provided by the onsite wind data facility, the bridge is closed in 3 stages:

- 1) Warning Phase- wind gusts of 35 to 44 mph
- 2) Wind gusts of 45 – 60 mph, high-sided vehicles diverted (closed to high sided vehicles)
- 3) Full closure once wind gusts reach 70 mph regardless of direction of the wind
- 4) If wind gusts of over 80 mph are recorded, then a structural examination must take place.

After analysing the high wind strategy carried out by Transport Scotland it can be seen that the measures taken to ensure an efficient road network and pretty much the same for both organisations, Highways England, and Transport Scotland. There is a very high likelihood that this is due to the 2 organisations being in charge of neighbouring locations which experience very similar weather conditions and around the same time. However, something Highways England could implement in their wind management procedure is a threshold that if crossed requires a structural survey to take place in addition to the regular inspections as drastically high winds can impact the structural stability of the structure.

## 4.0 Analysis and Findings

### 4.1 Data collected from online resources regarding the selected bridges closures and incidents.

Orwell Bridge Closures demonstrated in Table 3:

Date	Duration (minutes)	Wind Speed max (mph)
27 october 2013	541	74
23 october 2013	388	66
26 December 2013	541	61
14 February 2014	681	65
27 March 2016	381	67
22/23 November 2016	N/A*	50
23 February 2017	628	70
22/23 November 2017	435	60
02/03 January/2018	988	66
18 January 2018	N/A*	72
23 January 2018	261	49
29 April 2018	470	52
29 November 2018	N/A*	50
13 March 2019	451	61
16 March 2019	371	52
02 November 2019	355	57
13 January 2020	341	46
14 January 2020	672	63
09 February 2020	1253	71
15/16 February 2020	1170	65
26/27 December 2020	660	56
20/21 January 2021	480	60
18/19 February 2022	1290	85

The table above shows a list of dates when Orwell Bridge had to shut due to severe weather conditions. The information was provided by National highways after a request was made, the request was dealt under the provisions of the Freedom of Information Act 2000.

Total number of Severn Bridge Closures by year shown in Table 4:

Year	Number of times restrictions or Closures were put in place	Reason for Closure
2013	12	12- Weather
2014	9	9- Weather (Strong Winds)
2015	16	1 x Vehicle Fire 2 x RTC 1 x Serious RTC within Wales
2016	15	2 x RTC 1 x Vehicle Fire 11 x Strong Winds
2017	13	1 x Police led incidents 1 x RTC 1 x RTC and vehicle fire 9 x Strong winds
2018	13	2 x RTC 11 x Strong Winds
2019	13	1 X RTC 12 X Strong Winds
2020	26	1 x RTC 25 x Strong winds
2021	13	1 x Police led incident 12 x strong winds

The table above (Table 4) details all the times the severn Bridge was closed from 2013-2021, some incidents are presented in detail in the table below.

Table 5 below details Severn Bridge closures with wind speed and duration:

Date of Closure	Start Time	End Time	Maximum Wind Speed (mph)
21/01/2015	03:00	20:00	67
08/02/2015	02:00	19:00	60
09/02/2015	06:00	17:00	70
10/02/2015	03:00	21:00	60
11/02/2015	00:00	11:00	61
12/02/2015	00:00	06:00	70
01/11/2015	10:00	03:00	50
02/11/2015	20:00	15:00	50
29/12/2015	09:00	16:00	60
30/12/2015	09:00	16:00	60
31/12/2015	09:00	16:00	60
08/01/2018	09:00	16:00	65
09/01/2018	09:00	16:00	65
17/01/2018	09:00	16:00	65
13/02/2020	08:00	22:00	56
19/02/2020	06:00	14:00	54
26/02/2020	10:00	23:00	55
28/02/2020	07:00	17:00	56
12/02/2021	04:00	15:00	60
13/02/2021	05:00	14:00	55
22/02/2021	04:00	15:00	61
01/03/2021	05:00	20:00	64

As seen above there is some data missing from the table 5 however, this can be accessed through the Highways England website and the link is available below in references.

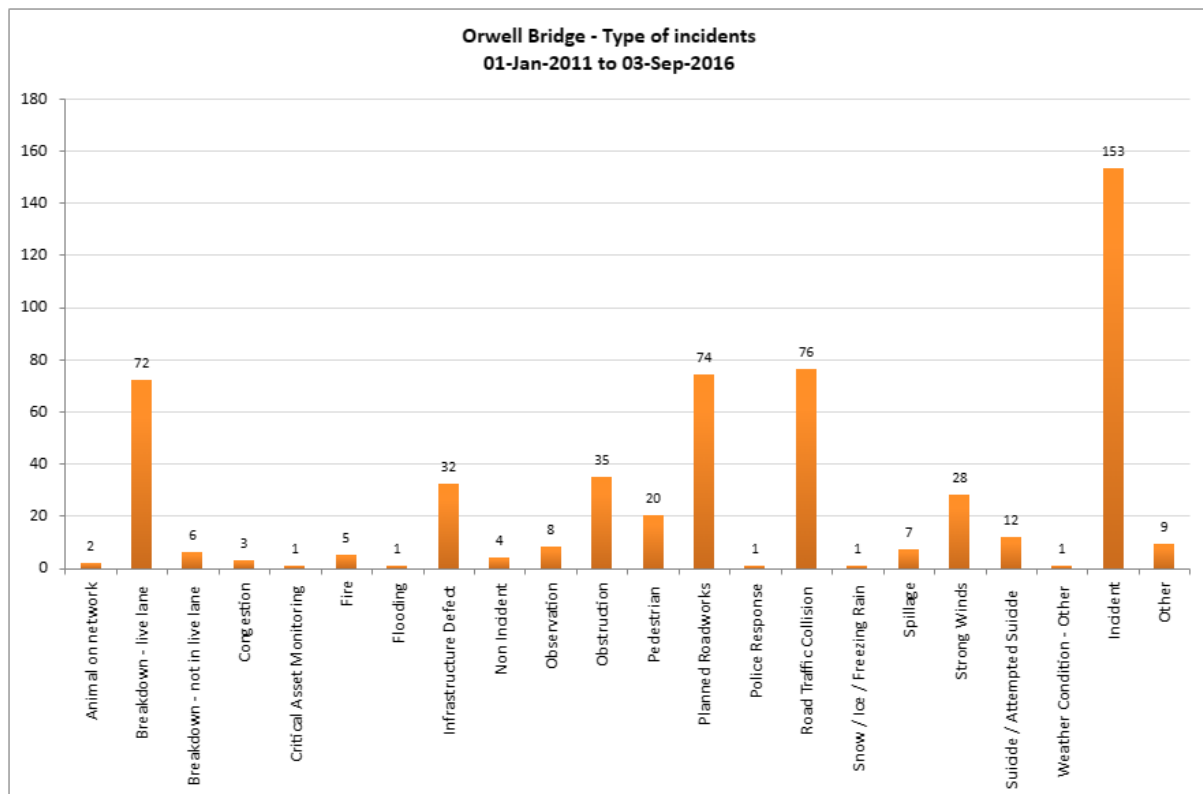
#### Case studies:

In order to take a closer look and inspect what went wrong we will focus on 2 incidents, one from each bridge and analyse them to find the error that might've lead to the incident:

#### Orwell bridge:

According to the information provided by Highways England the number of closures that took place due to high wind conditions is 23, the graph below shows the type of incidents that happened at the Orwell Bridge between 01/01/2011 and 03/09/2016:

According to the data in the graph a total of 28 incidents occurred due to strong winds during the time period mentioned above, most of these incidents were described as Network Monitoring.



Severn Bridge incidents:

The few recent incidents caused due to the excessive wind speeds on the Severn Bridge are listed below:

- 10 February 2020- Lorry overturned due to high wind conditions, Driver hospitalized
- 18 February 2022- HGV Lorry overturns due to overtaking in high wind conditions (Mcardle, 2022)
- 14 November 2022- Truck carrying propane overturns

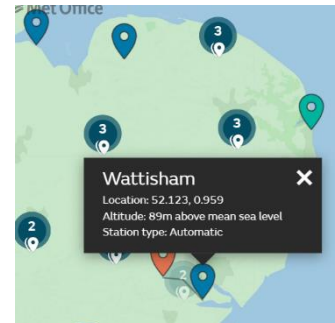
All data represented in tables retrieved from National highways Disclosure Log.

## 4.2 Identification of errors and inaccuracies

The Met Office measures wind using anemometers which record wind direction, speed and strength of gusts. Due to the fact that wind speed increases with height above earth's surface it's affected by obstructions (Met office, 2016), making it necessary for the anemometers to be placed at a location where there are no obstructions in its way. However this could pose further challenges as the height at which the bridge is located can experience different wind speeds to the ones recorded. There are other errors and inaccuracies present in the systems

used however, they were highlighted earlier so I won't be mentioning them again. It is crucial that any errors and inaccuracies are dealt with to provide the road users with an efficient and safe road network.

Another source of error are weather stations as the location of the weather station plays a huge role in whether the wind speed readings are accurate or not. Orwell Bridge is a prime example of this as the wind readings for the bridge are recorded at Wattisham which is almost 17.6 km away, there is quite a bit of distance between the point the data is recorded and the point where the wind is hitting the bridge. Due to this the wind speed readings could be highly inaccurate (Willyweather, 2023).



*Figure 3 - Location of the weather station closest to Orwell bridge*

#### **4.3 Implications of False Closures and Absent Alerts**

As it was mentioned earlier during the literature review, the local government of Ipswich claimed that a single day of closure costs the town as much as £1 million, this figure was calculated from an estimate of lost sales and productivity (BBC News, 2020). Although, there is no way to confirm whether or not this figure is accurate, it is important to recognise the affects of false closures as they cost money, resources and time. This is an important factor as there is only a limited amount of resources that Highways England has access to and using them on closures that are not necessary could mean that these resources are unavailable for when the wind conditions are actually really bad and they're actually needed.

Although false closures have a drastic impact on the economy and can lead to the public losing trust in the organisations in charge, the outcomes of absent alerts are far more serious than losing a bit of business. Absent closures can be due to incorrect readings, faulty equipment or due to irresponsibility of authorities in charge. Absent closures can lead to high sided vehicles overturning which could possibly cause collisions, it could cause damage to bridge structure and in worst case scenario could lead to loss of life. Weather alerts give authorities an advance warning to take any precautions that they might need to take to ensure safety of everyone involved.

False and absent closures should both be avoided at all times, both type of closures happen because of the same reasons. It is important to have real-time wind data from the bridge so that is what should be used whenever possible. Regular maintenance on equipment used should also be carried out as well as an extensive evaluation of the systems used as there is a possibility that the faults come from

the algorithms used by SWIS or Met Office while analysing so the faults could be in the way these systems operate.

## 5.0 Discussion

### 6.1 Interpreting the Findings

From the data collected from various sources it can be seen especially in the case of Severn bridge that despite the 130 closures that took place between the years 2013 and 2021, there were still several incidents where obstructions were created and public safety was endangered due to the bridge remaining open during high wind conditions. As mentioned in above the errors could stem from faulty equipment or the wind speed measurements being taken from a point that is too far out than it should be. It is very hard to come to a conclusion anything from the limited data provided as it is very basic and doesn't demonstrate much. The reasonings behind this are further discussed in the section below where the limitations of the study are discussed.

### 5.2 Limitations of the study

When conducting a study as broad as this one, it is essential to acknowledge the limitations of the study to ensure the research findings are interpreted within the appropriate context, the limitations of this study are listed below.

- 1) A major set back during this study was the lack of information present out there about SWIS with near to no research papers going in to detail about the network or evaluating the network. The information available was very brief and repetitive partly due to the fact that the network is fairly new.
- 2) The data used for the analysis is very brief and is a very small sample size of just 2 specimens, this was due to the limited time available.
- 3) The quality of data and reliability in the study cannot be promised to be of the best standards however, it is definitely satisfactory with room for improvement solely because it was recorded from Twitter, local news stations and Highways England site. This data was also collected by myself and there was no external validation for the data. This is an important factor to consider as my lack of experience there is a possibility



that the data collected could be less proficient. The data gathered analysed in the study is also very basic due to unprecedented circumstances and network errors.

- 4) Time and resources acted as a major constraint during this project as a result of which the depth and scope research are impacted. This is due to the fact that this study was being undertaken alongside studies and other commitments which left me with limited time for data collection and comprehensiveness.
- 5) Available regarding evaluation of weather systems, this impacts the study a lot as this was a desk based study where no primary research undertaken meaning this study was solely reliant on information found in journals, newspapers and online.
- 6) Due to the fact that a lot of the information was taken from the official websites of organizations such as; the Met Office, Highways England etc, the information provided could potentially be biased, which could result in this study being deficient in providing accurate information.

### **5.3 Recommendations for System Improvement and Future Research Directions**

There are quite a few recommendations that could be applied to further improve the system, these are listed below:

- 1) First and foremost the least likely factor that leads to false/ no closures in the location from which wind data is measured. Due to the fact that wind is very unpredictable and the slightest change in the atmosphere can cause it to fluctuate, it is very important to ensure that the data used to make decisions about bridge closures or safety protocols should be as close to the site as possible. This will give accurate readings almost every single time and even if the reading was to be correct, the degree of inaccuracy wouldn't be as large as it is if measured from a further weather station.
- 2) Another way weather forecast systems can be made more accurate is through innovation and technology, we are well aware of the fact that the current forecasting systems are nowhere near as accurate as they possibly could be. There are new technologies developing that allow a higher resolution atmospheric monitoring system resulting in an improved weather forecast (UKRI, 2022). Since most forecasting systems use some form of numerical models it is important to remember that these models regardless of how intricate they are cannot fully capture the complexities of the real world. DELFI is a machine learning system operated by StormGeo which

corrects forecast errors and improves their quality. The way the program works is through comparison, the program compares all available observational data using different methods and the method with the highest “score” is then used as the forecast for a coming week. This system largely differs from traditional weather forecasting systems as it reduces the need for manual intervention making it a lot more efficient as it has the ability to self detect errors within it self as well as the ability to reduce them (Kegouche, 2022).

3) Another improvement that can be implemented is already on the way since National Highways announced plans for SWIS 2 which will consist of the following:

- real-time spreading vehicle and floating car data
- real-time alerts and messaging for customers
- new management modules
- dynamic routing for traffic management
- network vulnerability mapping
- severe weather management decision support and smart dashboards (Browne, 2022).

Like briefly mentioned earlier there is a lot of scope for further research into this project as there are many aspects that are left unexplored and need further investigation as the time and resource limitations didn't allow the study to be as precise and detailed as I would've liked it to be. There is a lot of scope to research and analyse more data regarding bridge closures as there are countless more bridges that can be analysed, the study was limited to 2 bridges, which severely limited useful data analysis to be performed. To improve the study as well as to draw some more thoughtful conclusions further research into bridge closures is needed as comparing two sets of bridges doesn't provide enough information to draw logical conclusions as they could very much be coincidental. A topic that was barely touched upon during this study was comparison of bridge closure protocols used by national highways to those of other countries as there wasn't enough time and the objective to do so was largely over estimated. An attempt towards this was made by analysing the High wind strategy and wind management guidelines of Scotland. However there were quite a few overlaps making them very similar as they do share almost an identical geographical location.

## **6.0 Conclusion**

### **6.1 Concluding Remarks**

Conclusively, the weather induced bridge closures are very much necessary in order to maintain a safe road network, however it cannot be said that every bridge closure is necessary or that a bridge has never been operated under high wind loads without a warning. Whether or not the usage of bridge is safe it impacts local traffic and in cases like the Orwell Bridge it also greatly impacts local businesses. Therefore, SWIS needs to create action plans that are efficient and meet the present needs of a the road network while engineers should be developing ways to get on site data that is more likely to be precise than data that is taken a few miles out.

Considering how bridge safety protocol measures are included and followed by not just national governments but also local governments, it is important to ensure that the standards of the said protocols are as high and as accurate as possible. Doing this would lead the UK's SRN into an even more efficient network than it already is. In order to improve the efficiency of the UK road system, it is important to narrow down factors that need changing and target factors that might make the biggest difference for a consumer making the network easier and more efficient to use.

### **6.2 Reflections against objectives**

At the beginning of the study some aims and objectives were put in place to guide the very narrow down the research area into something more obtainable. There were 4 objectives set out at the beginning and throughout the study there was an effort made to try to ensure that each one of these were met. However, this isnt the case as the objectives set out at the beginning of projects are often very optimistic due to the fact that the limitations are unknown.

Objective 1 was partially met as there was extensive research carried out regarding weather forecasting systems including SWIS and Met Office. However, due to the limited resources available about SWIS the amount of evaluation that wanted to be done wasn't possible.

Objective 2- an effort was made to meet this objective as data was retrieved and briefly analysed however, due to some unprecedented circumstances the analysis is very much

incomplete and the data lacks depth. This opens up opportunities for future research and provides a basic set of data.

Objective 3 was achieved as bridge closure protocols were analysed and assessed. More research could be done for this but a good effort was made.

Objective 4- an effort was made to meet this objective as the bridge closure protocol of Scotland was compared to the one of the England but whilst doing this a realisation was made that both these were very similar due to obvious reasons such as they are neighbouring nations with similar road networks and climate.

Overall an attempt was made to achieve the objectives but there is so much more that is yet to be explored.

## 7.0 Bibliography

- Anon n.d. *Gov.uk*. [Online]. [Accessed 15 May 2023]. Available from: [https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/library-and-archive/library/publications/weather--climate-guides/weather\\_facts.pdf](https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/library-and-archive/library/publications/weather--climate-guides/weather_facts.pdf).
- (N.d.). Amazonaws.com. Retrieved May 17, 2023, from <https://s3.eu-west-2.amazonaws.com/assets.highwaysengland.co.uk/specialist-information/knowledge-compendium/2016-17/Geotechnical+resilience+enhancement+measures-+Final+report.pdf#page117>
- Baker, C.J. and Soper, D. 2022. Calculation of the overturning wind speed of large road vehicles at exposed sites. *Proceedings of the Institution of Civil Engineers, Transport*. **175**(2), pp.97–104.
- BBC News 2020. A14 Orwell Bridge closures cost Ipswich ‘£1m a day’. *BBC*. [Online]. [Accessed 15 May 2023]. Available from: <https://www.bbc.co.uk/news/uk-england-suffolk-51108800>.
- BBC News 2017. Man charged after lorry blown over on Forth Road Bridge. *BBC*. [Online]. [Accessed 21 May 2023]. Available from: <https://www.bbc.co.uk/news/uk-scotland-edinburgh-east-fife-39279342>.
- Berreby, D. 1992. The Great Bridge controversy. *Discover*.
- Browne, D. 2022. National Highways unveils big plans for SWIS 2. *Highwaysmagazine.co.uk*. [Online]. [Accessed 15 May 2023]. Available from: <https://www.highwaysmagazine.co.uk/National-Highways-unveils-big-plans-for-SWIS-2-/9630>.
- Chen, W.-F. and Duan, L. 1999. *Bridge Engineering Handbook* (W.-F. Chen & L. Duan, eds.). Boca Raton, FL, USA: CRC Press.
- Cho-Ming, C. 2021. Challenges in weather forecasting. *Hklaureateforum.org*. [Online]. [Accessed 23 May 2023]. Available from: <https://hklaureateforum.org/en/challenges-in-weather-forecasting>.
- Department of Transport 2014. Transport Resilience Review A review of the resilience of the transport network to extreme weather events. *Org.uk*. [Online]. [Accessed 15 May 2023]. Available from: <https://www.sasig.org.uk/wp-content/uploads/2014/07/DfT-transport-resilience-review.pdf>.
- Disclosure log*. (n.d.). Nationalhighways.co.uk. Retrieved May 21, 2023, from <https://foiform.nationalhighways.co.uk/request?id=DBE7392DA582B148ED8691C082747C21940E1B6234EFAD75>
- Elgee, E. 2020. Storm Ciara: M48 Severn Bridge closed as lorry overturns in high wind - live updates. *SomersetLive*. [Online]. [Accessed 15 May 2023]. Available from: <https://www.somersetlive.co.uk/news/somerset-news/storm-ciara-m48-severn-bridge-3830393>.
- England, H. 2018. Orwell Bridge closure protocol summary. *Gov.uk*. [Online]. [Accessed 15 May 2023]. Available from: [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/755947/Annex\\_A.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/755947/Annex_A.pdf).
- Fleet News 2016. Highways England launches severe weather information service. *Fleetnews.co.uk*. [Online]. [Accessed 15 May 2023]. Available from: <https://www.fleetnews.co.uk/news/fleet-industry-news/2016/10/26/highways-england-launches-severe-weather-information-service>.

- Kaufman, M. 2020. Why it's impossible to forecast the weather too far into the future. *Mashable*. [Online]. [Accessed 15 May 2023]. Available from: <https://mashable.com/feature/how-far-future-weather-forecast>.
- Keane, B.Y.O. n.d. An impact study of the closure of Hammersmith bridge'. *Ucl.ac.uk*. [Online]. [Accessed 15 May 2023]. Available from: [https://discovery.ucl.ac.uk/id/eprint/10160315/1/Keane\\_10160315\\_thesis.pdf](https://discovery.ucl.ac.uk/id/eprint/10160315/1/Keane_10160315_thesis.pdf).
- Keghouche, I. 2022. Improving offshore weather forecasting with machine learning. *StormGeo*. [Online]. [Accessed 15 May 2023]. Available from: <https://www.stormgeo.com/solutions/renewables-and-energy-markets/articles/improving-offshore-weather-forecasting-with-machine-learning/>.
- Kim, B., Shin, S. and Kim, D. 2018. Scenario-based economic impact analysis for bridge closures due to flooding: A case study of North Gyeongsang Province, South Korea. *Water*. **10**(8), p.981.
- Love, L. 2022. Tay Bridge locked down after lorry overturns amid Met Office wind warning. *Daily Record*. [Online]. [Accessed 21 May 2023]. Available from: <https://www.dailyrecord.co.uk/news/scottish-news/tay-road-bridge-lorry-crash-28393958>.
- Masters, A. 2020. *Itv.com*. [Online]. [Accessed 15 May 2023]. Available from: <https://www.itv.com/news/wales/2020-02-13/cctv-shows-the-moment-strong-winds-overturn-lorry-on-severn-bridge>.
- Met Office 2018. How we measure wind. *Met Office*. [Online]. [Accessed 23 May 2023]. Available from: <https://www.metoffice.gov.uk/weather/guides/observations/how-we-measure-wind>.
- Met Office 2016. Weather stations. *Met Office*. [Online]. [Accessed 23 May 2023]. Available from: <https://www.metoffice.gov.uk/weather/learn-about/how-forecasts-are-made/observations/weather-stations>.
- Met Office 2022. What are the National Severe Weather Warning Service Impact tables? *Met Office*. [Online]. [Accessed 15 May 2023]. Available from: <https://www.metoffice.gov.uk/weather/guides/severe-weather-advice>.
- Msaewe, H.A., Psimoulis, P.A., Hancock, C.M., Roberts, G.W. and Bonenberg, L. 2021. Monitoring the response of Severn Suspension Bridge in the United Kingdom using multi-GNSS measurements. *Structural control and health monitoring*. **28**(11).
- Nasr, A., Kjellström, E., Björnsson, I., Honfi, D., Ivanov, O.L. and Johansson, J. 2020. Bridges in a changing climate: a study of the potential impacts of climate change on bridges and their possible adaptations. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*. **16**(4), pp.738–749.
- National Highways 2022. Orwell Bridge closure protocol summary. *Amazonaws.com*. [Online]. [Accessed 21 May 2023]. Available from: <https://s3.eu-west-2.amazonaws.com/assets.nationalhighways.co.uk/orwell/Orwell+bridge+protocol+summary+2022+FINAL.PDF>.
- National Highways 2020a. The Orwell Bridge - national highways.
- National Highways 2020b. The Severn bridges - national highways.
- National Highways 2020c. Winter driving - how we help you on our roads - National Highways.
- Old 1997. The challenge of weather prediction. *Core.ac.uk*. [Online]. [Accessed 23 May 2023]. Available from: <https://core.ac.uk/download/pdf/291586648.pdf>.

- Orwell\_bridge\_incident\_data 2016\_09\_04 to 2019\_11\_30*. (n.d.). Gov.uk. Retrieved 21 May 2023, from [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/856162/Orwell\\_Bridge\\_Incident\\_Data\\_2016\\_09\\_04\\_to\\_2019\\_11\\_30.csv/preview](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/856162/Orwell_Bridge_Incident_Data_2016_09_04_to_2019_11_30.csv/preview)
- Owen, C. 2020. Severn Bridge remains closed after lorry blown over in the wind. *WalesOnline*. [Online]. [Accessed 21 May 2023]. Available from: <https://www.walesonline.co.uk/news/wales-news/severn-bridge-remains-closed-after-17726173>.
- Perry, A. and Symons, L. 1994. The wind hazard in Great Britain and its effects on road and air transport. *Journal of wind engineering and industrial aerodynamics*. **52**, pp.29–41.
- Phone, O. 2009. High wind strategy and national wind management guidelines. *Gov.scot*. [Online]. [Accessed 15 May 2023]. Available from: <https://www.transport.gov.scot/media/25393/j10783.pdf>.
- Poddaeva, O., Fedosova, A. and Gribach, J. 2019. The study of wind effects on the bridge constructions. *E3S web of conferences*. **97**, p.03030.
- Pritchard, O., Carluccio, S., Mian, J. and Patterson, D. 2016. Ensuring long-term resilience of Highways England's geotechnical assets to severe weather events *In: Asset Management Conference (AM 2016)*. Institution of Engineering and Technology, pp.1–8.
- Sillin, J. 2019. Model Mania: The Limitations of Weather Models. *Weather.us*. [Online]. [Accessed 15 May 2023]. Available from: <https://blog.weather.us/model-mania-the-limitations-of-weather-models/>.
- Smith, A.W., Argyroudis, S.A., Winter, M.G. and Mitoulis, S.A. 2021. Economic impact of bridge functionality loss from a resilience perspective: Queensferry Crossing, UK. *Engineering Sustainability*. **174**(4), pp.254–264.
- Smith, D.L., Zuckerberg, F.L., Schaefer, J.T. and Rasch, G.E. 1986. Forecast problems: The meteorological and operational factors *In: Mesoscale Meteorology and Forecasting*. Boston, MA: American Meteorological Society, pp.36–49.
- Stone, T. 2016. Highways England launches integrated weather information system. *Traffic Technology Today*. [Online]. [Accessed 15 May 2023]. Available from: <https://www.trafficechnologytoday.com/news/weather-systems/highways-england-launches-integrated-weather-information-system.html>.
- Storyful, S. 2016. Lorry blown over by high winds on Humber Bridge – video. *The guardian*. [Online]. [Accessed 21 May 2023]. Available from: <http://www.theguardian.com/uk-news/video/2016/apr/07/lorry-blown-over-by-high-winds-on-humber-bridge-video>.
- UKRI 2022. Innovative satellite tech set to improve weather forecasting. *Ukri.org*. [Online]. [Accessed 15 May 2023]. Available from: <https://www.ukri.org/news/innovative-satellite-tech-set-to-improve-weather-forecasting/>.
- Willyweather 2023. River Orwell - Orwell Bridge wind forecast, Suffolk - WillyWeather. *Willyweather.co.uk*. [Online]. [Accessed 15 May 2023]. Available from: <https://wind.willyweather.co.uk/ee/suffolk/river-orwell---orwell-bridge.html>.
- WindCrane n.d. Wind monitoring importance in bridge construction and operation. *Windcrane.com*. [Online]. [Accessed 15 May 2023]. Available from:

<https://www.windcrane.com/blog/construction/wind-monitoring-importance-bridge-construction-and-operation>.

Zhang, X., Connor, J.J. and Dpf, H.M. 2012. Wind effect on long span bridge. *Mit.edu*. [Online]. [Accessed 15 May 2023]. Available from: <http://dspace.mit.edu/bitstream/handle/1721.1/74418/812915230-MIT.pdf;sequence=2>.

## **8.0 Appendices**

### **8.2 Ethics Approval Form – Students**

Since this is purely a desk-based study an ethics approval form isn't needed.