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Manuscript title: Economic impact of road bridge functionality loss from a resilience perspective: Queensferry Crossing

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Abstract

Understanding the resilience of transport networks is critical for efficient asset management. This paper takes an innovative approach to studying the operability of the Queensferry Crossing (QFC) including cost-benefit aspects. A key driver for the QFC was to increase the resilience of the A90/M90 link by reducing weather-related closures. The first weather-related closure of the QFC was in February 2020, when ice formed on the superstructure cables and fell on the carriageway and vehicles, creating a safety risk for bridge users. The bridge was closed for 41 hours and in this paper, we compare the estimated monetary losses with those of past FRB closures. The costs of potential mitigation measures are then assessed in the context of closure costs, thus, improving the resilience of the QFC. Although the QFC has only been open for three years, it is already apparent that it is significantly more resilient than the largely replaced FRB, whether this is considered as the number, duration or costs of closures. It was also found that investing in adaptation measures to prevent similar events in the future is cost-effective, as the cost of a de-icing system is approximately equal to the daily cost of the QFC closure.

Keywords: Bridges; Infrastructure planning; Weather; Resilience

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1. Introduction

The objective of this study was to estimate the economic costs of the closure of the Queensferry Crossing (QFC) (Figure 1a) based on available methods, using existing data and making reasonable assumptions where required. This then allows a comparison of the costs of closure to its predecessor, the Forth Road Bridge (FRB) (Figure 1b), thus quantifying the change in resilience as a result of the construction of the QFC. The paper provides a baseline estimation of cost, and hence does not include a full economic appraisal considering the life-cycle costs of the asset, which would be the topic of another study. Bridges are critical components of a road network, linking communities and effecting the crossing of rivers, estuaries and other transport networks and in doing so facilitating economic activity. Resilience analysis is increasingly used to understand the impacts of closure on the efficient running of road, and other transport, networks (Ganin et al., 2017, Argyroudis et al., 2020a). Such closures can be due to a wide range of environmental factors including landslides, floods and, in the QFC case examined here, ice. Increased extreme weather incidents, resulting from climate change, place even greater emphasis on the importance of understanding resilience to support decision-making (Dong and Frangopol, 2016).

Resilience describes the attributes that a bridge or a network has, that allows them to withstand, respond and/or adapt to a range of disruptive events by preserving and even enhancing critical functionality (Ayyub, 2014). In this respect, resilience accounts for structural functionality and recovery planning after the occurrence of a hazard, to achieve acceptable levels of downtime according to the objectives of network operators. Resilience-based design and management are new principles that are gradually being adopted (Twumasi-Boakye and Sobanjo, 2018, Reeves et al., 2019).

The Queensferry Crossing (QFC) was the largest infrastructure project in Scotland for a generation, becoming the longest three-tower cable-stayed bridge in the world, reaching a total length of 2.7km (Curran et al., 2010). The structure is continuous from abutment to abutment with no intermediate expansion joints and notably, concrete resistant to the ingress of chlorides along with stainless steel rebar were used to ensure the 120-year design life within a saline environment (Climie and Shackman, 2019). One of the key issues of the Forth Road Bridge (FRB) was the lack of redundancy in the suspension cable system, thus resulting in its closure anytime maintenance was required (Colford and Clark, 2010). An internal cable inspection carried out in 2004/05 showed that the loss of strength due to corrosion in the main cables was around 8% and that the rate of deterioration would require loading restrictions to be instigated between 2014 to 2020 due to the lack of structural redundancy. In 2008 a second inspection indicated an increased strength loss to 10%. Acoustic monitoring systems were fitted on the cables to detect the rate of future wire breaks and dehumidification systems were fitted to stop or slow down the rate of deterioration (Cocksedge and Bulmer, 2009).

The 2004/08 inspections raised concerns over the future functionality of the FRB as significant and frequent repairs would be required, resulting in traffic restrictions for the then annual average daily traffic of around 70,000 vehicles, with substantial impacts. Therefore, it was determined that the bridge was no longer a viable option for the Firth of Forth crossing in the long-term (Shackman et al., 2019) and the QFC was conceived to provide a more resilient alternative. The QFC was designed to have greater structural redundancy by using a cable stayed system that involved 144 pairs of individually replaceable stays with a design life of 60 years and allowing the bridge to remain open during maintenance (Curran et al., 2018). The project valued at £1.35 billion and was opened in August 2017.

On the 10 February 2020, following storms Ciara and Dennis, ice and snow accumulated on the QFC cable stays falling to the deck below and damaging eight vehicles; the QFC was closed for the first time since its opening in August 2017 on safety grounds. The bridge remained closed until 12th February, a closure of approximately 41hours. The closure attracted significant news coverage as the bridge was reported to be able to remain open in all weather conditions due to its resilient design. For example, the bridge was fitted with 3.5m high barriers to significantly increase the resilience of the new crossing to the high winds that caused relatively frequent closures of the FRB. The closure resulted in a 56 km diversion to the Kincardine Bridge with reported additional journey times of 60 to 90 minutes (BBC News, 2020a) (Figure 2). The wider Forth Replacement Crossing scheme also incorporated emergency crossovers to the north and south of the QFC to allow traffic to be diverted relatively quickly back to the FRB in the event of a major incident occurrence on the QFC. While this option was not available in February 2020 due to major maintenance work being undertaken on the FRB at the time, this option would normally be available.

Following the closure, the question was raised, how “The bridge that should never close” (BBC News, 2020b) could be managed to ensure the asset was as resilient as intended? One mitigation measure the Scottish Government have proposed involves the installation of sensors to detect warning of ice build-up on the structure at an earlier stage. Although the build-up of ice and snow coupled with gusts of winds did not cause structural damage to the bridge, substantial consequences resulted from the closure affecting the economy, society and the environment. The QFC carries around 24 million journeys a year (BBC News, 2020a) and the costs incurred from such a closure are potentially significant. In the following, the economic impacts due to transport infrastructure closures in the framework of a quantitative risk analysis are described (section 2). Then, the costs for the 41hours closure of the QFC are evaluated (section 3), these costs are compared with those of past FRB closures (sections 4 and 5), and potential mitigation measures are discussed (section 6).

2. Economic impacts due to transport infrastructure closures

The economic impacts due to infrastructure closure can be classified as follows (Winter and Bromhead, 2012): *Direct economic impacts*, including the direct costs of clean-up and repair/replacement of lost/damaged infrastructure in the broadest sense. *Direct consequential economic impacts* related to 'disruption to infrastructure' and loss of service. The costs of partial or complete closure of a bridge for a given period with a given diversion can be estimated based on well-established models. *Indirect consequential economic impacts,* including longer-term impacts on businesses or tourism. These classifications have been used by Winter et al. (2014, 2019) and Milne et al. (2016) to develop the economic costs of landslide and flood (pluvial and coastal) events and their work typically identified the direct consequential economic impacts as the most important component of the overall impact. As the queues and delays at roadworks model was used for that work the current paper also serves the function of testing an alternative approach.

The estimation of direct consequential economic impacts inclusive of the traffic detour, social and environmental cost of the closure is based on Deco and Frangopol (2011) and Dong and Frangopol (2015). The original equations for the cost estimations were proposed by Stein et al. (1999), Kendall et al. (2008), and Padgett et al. (2009, 2010) and combine costed parameters relating to social, economic, and environmental emission factors. For a quantitative risk assessment these equations are combined with the damage probabilities derived from fragility functions for given hazard intensities, to calculate the expected 'weighted' consequential impact due to possible damage (Banerjee et al., 2019, Argyroudis et al., 2020b). The hazard intensity measures used for the fragility analysis are selected based on what the asset is subjected to such as accumulation of ice in the case of the QFC or scour depth for a bridge asset subjected to flooding (Yuan et al., 2019). Fragility functions are commonly developed based on numerical modelling, where the performance of the asset is estimated for increasing levels of intensity measures. The performance is measured through engineering demand parameters of critical components within the asset such as the bending moment across a bridge deck or settlement beneath a pier footing. The fragility functions demonstrate physical damage and give the probability that the asset component or whole system exceeds a defined limit state, for example this could be the

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serviceability threshold to cause cracking for a reinforced concrete bridge component. This limit state is associated with the relevant engineering demand parameters selected for the asset component and along with the uncertainties in their definitions and the results of the analysis undertaken, the fragility functions can be produced using a lognormal probability distribution (Argyroudis et al., 2019). An example of a conceptual fragility curve can be seen in Figure 3a.

Damage probabilities or vulnerability functions are commonly expressed in terms of damage repair costs usually being normalised by replacement cost, or even asset downtime normalised with days or fractions of the year (e.g. Figure 3b). The damage probabilities at each damage state are coupled with the associated damage ratios (reduced functionality at each damage state) and the relevant costed parameters. This is done with four levels of damage of increasing severity: minor, moderate, extensive, and complete (Banerjee et al., 2019). The 'weighted' damage ratio refers to the reduced functionality at each damage level; for example, at no damage the ratio would be 1.0 due to no impact on the functionality whereas at extensive or complete damage the ratio would be 0.75 and 0.0 respectively (Dong and Frangopol, 2015). The costed parameters can be for the *direct economic impacts, direct consequential economic impacts,* or *the indirect consequential economic impacts* as stated above. In the case of this paper, some of the parameters involve vehicle operation, the monetary value of transported goods and carbon dioxide emission costs as they relate to direct consequential impacts.

3. Costs of QFC closure

The bridge was completely closed and therefore had 0% functionality for 41 hours; the damage probability is not required in this case, as there is no reduced or partial operation and hence there is no need to use the 'weighted' average of the reduced functionality of the asset as described in the previous section. Therefore, the standard equations for estimating the direct consequential losses can be reduced to just the cost parameters multiplied by the restoration time.

The running (operational) cost (C_{Run}) associated with a detour on a bridge that has been closed can be expressed by Eq. (1) (Stein et al., 1999):

$$C_{Run} = \left[c_{Run,car} \left(1 - \frac{T}{100} \right) + c_{Run,truck} \frac{T}{100} \right] D \cdot AADT \quad (1)$$

where $c_{Run,car}$ and $c_{Run,truck}$ are the average costs for running cars and trucks per unit length (£/km), respectively; D is the length of the detour (km); AADT is the annual average daily traffic that takes the detour, i.e. the AADT for the bridge; and T represents the annual average daily truck traffic ratio (AADTT, %). AADT is related to the functionality level of a bridge under a given hazard event. For example, if the functionality equals 1.0 the bridge is fully open to traffic while if the functionality is equal to 0.0, the bridge is closed, and all traffic is detoured.

The monetary value of time loss for users and goods (C_{TL}) travelling through the detour and damaged link can be computed with Eq. (2) (Stein et al., 1999):

$$C_{TL}=\left[c_{AW}O_{car}\left(1-\frac{T}{100}\right)+(c_{ATC}O_{truck}+C_{goods})\frac{T}{100}\right]\cdot\left[AADT\cdot\frac{D}{S}+AADE\cdot\left(\frac{l}{S_D}-\frac{l}{S_0}\right)\right] \qquad (2)$$

Where c_{AW} is the average wage per hour (£/hour); c_{ATC} is the average total compensation per hour (£/hour); C_{goods} is the time value of the goods transported as cargo (£/hour); AADE is the annual average daily traffic remaining on the damaged link (zero in this case); O_{car} and O_{truck} are the average vehicle occupancies for cars and trucks, respectively; l is the route segment length, i.e. link, containing the bridge (km); S_0 and S_D represent the average speeds on the intact link and damaged link (km/hour), respectively; and S represents the average detour speed (km/hour).

The environmental cost (C_{EN}) associated with the closure is computed using the work done by Eq. (1). Due to the effects of the traffic detour on the bridge, additional carbon dioxide emissions are produced, and additional energy is consumed. In this case, factors $c_{Run,car}$ and $c_{Run,truck}$ are replaced and correspond to the environmental metric per unit distance for cars and trucks, respectively, e.g., carbon dioxide kg/mile. There were no repair actions required from the QFC closure and therefore the energy waste (embodied CO_2) from replacing structural material is not required in the assessment of the environmental costs.

The total economic consequences (C_{TOT}) is the sum of repair loss (C_{REP}), running loss of the detouring vehicles (C_{Run}), time loss due to the unavailability of the highway segment (C_{TL}), and environmental loss (C_{EN}) Eq. (3):

$$C_{TOT} = C_{REP} + C_{Run} + C_{TL} + C_{EN} \qquad (3)$$

Table 1 shows the direct consequential costs estimate for the 41-hour bridge closure as well as the corresponding daily cost and comparison ratio to the original project value.

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Although the 41hour QFC closure cost may seem extensive, there was no direct structural damage and thus only very limited Direct economic impacts, involving only clean-up and operational activities with, in context, negligible costs. It is also important to note that not all traffic will have completed the journey via the diversion route, which will also reduce the carbon and cost impacts relative to those calculated.

4. Costs of FRB closure

The most common cause of closure for the FRB was high wind speeds. Data obtained from Transport Scotland indicated that there were 55 occasions since the QFC opened when the FRB would have been closed to high-sided vehicles due to extreme weather conditions including the most recent storms, Ciara and Dennis. The wind barriers of the QFC are a key and integral feature in ensuring this improved resilience to extreme weather; since its opening in August 2017 it has been closed to high-sided vehicles on one occasion due to high winds but remained open to all other vehicles.

In February 2018, the FRB was closed completely to all vehicles as a result of snow accumulation on the carriageway during the ‘Beast from the East’ while the QFC remained open to traffic. It has also been highlighted that the reliability of the QFC compared to the FRB in terms of incident response has improved. This is a result of the hard shoulders provided over the full length of the QFC, allowing for emergency vehicle access and diverting traffic around an incident; this was a key design factor for added resilience of the new crossing (Hussain et al., 2019).

As stated in the Forth Crossing Bill (2010) “the full cost of the closure of the FRB bridge is likely to be of the order of £1.5 billion per annum”. This figure was derived as part of the feasibility studies for the QFC. This yields a pro-rate cost of £4.1M (million) per day and hence £7.0M for 41-hours of zero functionality as occurred for the QFC in February 2020. Comparing these figures is difficult; the £6.28M QFC closure cost includes economic, environmental and social costs, while the £1.5 billion per annum includes the ‘total’ cost to the economy, which encompasses job losses and loss of investment in the Scottish Economy. Notwithstanding this, the figures are broadly similar and give some comfort that the calculations detailed herein are robust.

The methodology used for estimating the *direct consequential economic impacts* of the QFC closure was used to determine the costs of the pre-2017 FRB closures for comparative purposes. Cost estimates of closure prior to the opening of the QFC in August 2017 are compared as any traffic diversion from the FRB after this date to the diversion route across the Kincardine and Clackmannanshire Bridges would be negligible. After August 2017 around 800, mainly public transport, vehicles a day used the FRB and the QFC was the primary closure diversion route.

In order to make a comparable cost estimate for closures of the FRB, data for 2015, 2016, and early-2017 closures were used. Data from the same traffic counter locations for the diversions to and across the Kincardine and Clackmannanshire Bridges as used for the QFC estimate. In some instances, there were temporal gaps in the traffic data and therefore, based on the available data and engineering judgment, assumptions were made for the total AADT of the closures. In Table 2, the *direct consequential economic impacts* of the FRB closures between 2015 and 2017 can be seen with a total cost of £6.08M and an average cost per day of £4.23M. This is comparable to the £4.1M cost per day as per Forth Crossing Bill (2010). The relevant parameters used for all the bridge closure cost estimates from Equations 1-3 are quantified in Table 3, along with corresponding data source(s).

5. Discussion

The *direct consequential economic impacts* resulting from the closure of critical infrastructure can be substantial, and in most cases are higher than the direct repair costs from structural damage. It has been shown in previous studies that highway bridges have yielded direct consequential economic losses 5-20 times greater than its repair costs (Venkittaraman et al., 2014). For this case the direct consequential economic impact of the QFC for a 41-hour closure was estimated at around £6.28M. This figure includes operational costs associated with the detour, cost of lost time of users and goods travelling through the detour, and the environmental cost due to additional CO_2 emissions. The outturn costs might benefit from adjustment of the values of some parameters if more specific data were available (e.g. the cost of the environmental metric).

Direct economic impacts related to clean-up of the bridge deck or to damage of cars due to falling ice have not been estimated but are considered to be negligible compared to the *direct consequential economic impacts*. Similarly, *indirect consequential economic impacts* have not been estimated but they are expected to be minimal due to the short duration of the closure. In comparing the QFC closure to the FRB, it can be observed that the average cost per day of closure for the FRB stands at £4.23M whereas the QFC closure came to £3.68M per day. Both figures are substantial and indicate how dependency on infrastructure assets that are fundamentally a backbone of the transportation network in Scotland for even short closure durations can cause significant social, economic, and environmental costs and impacts.

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The difference in these estimates for the QFC and FRB closures are related to varying volumes of traffic on the day(s) of closure, diversion speeds and different wages and compensation for road users in each year. For example, the AADT used for the FRB closure in 2015 was 39,851, which was significantly lower than the 2020 QFC of 64,319. This was because the 7-hour FRB closure was in the early hours of the morning when the diversion route had substantially less traffic than during peak times. The cost per day for the 2015 closure was , therefore, a lot lower than the £4.23M average for the FRB at £2.16M. Other closures of the FRB are associated with higher daily costs of up to £5.12M. The higher cost per day of closure for the FRB at £4.23M compared to the QFC £3.68M can be linked to the redundancy of the bridges and road network at the time of closure and the slower average diversion speeds round the Kincardine and Clackmannanshire bridges. For example, before the QFC opened in 2017 the FRB was the only direct route across the Firth of Forth and thus, the network was more reliant on the asset at that time and, in turn, causes a higher cost of closure due to its dependency, thus it was less resilient. This reflects the fact that closures vary with traffic flow throughout the day, and even when a full 24-hour period is covered there is variability due to traffic volume and the type and duration of the delays, and drivers' behaviours and decisions. Additionally, the QFC closure had an average diversion speed of 64km/h compared to an average of 46km/h for the FRB closures. This meaning that a slower diversion speed resulted in a longer and more costly diversion.

The icing incident that closed the QFC in February 2020 was quite specific and would have been unlikely to have closed the FRB; the FRB was partially closed for maintenance at the time and currently has a role dedicated to public transport. Notwithstanding this it is instructive to consider the impact of such events that would close the FRB but not the QFC in the future. In this context, the costs of the FRB closures can be broadly taken as the 'saving' in indirect consequential economic impacts as a result of its replacement by the QFC. This was not of course the primary reason for the change, which was driven by the substantial economic costs of full closure for major maintenance, but it does allow a monetised indication of the increased resilience achieved. Taking the £6.08M closure costs of the FRB for January 2015 to August 2017 the annual monetised improvement in resilience equates to around £2.3M.

In terms of closure frequency, the QFC can certainly be seen to have improved on the resilience of the FRB as the closure in February 2020 has been the first since its opening in 2017 and was related to very specific weather conditions. The estimate of the economic impacts of the QFC closure can be used to compare the cost of potential mitigation measures to prevent or reduce the likelihood of closure and inform cost-benefit analyses for mitigation measures.

6. Mitigation measures

Accumulation of ice on cable stays and suspension cables is an issue experienced by bridges around the world such as the Orresund Crossing that connects Sweden and Denmark, the Uddevalla Bridge in Sweden and the Second Severn Crossing in south-west England (BBC News, 2020d). In terms of structural vulnerability to ice accumulation, most suspension and cable-stayed bridges can cope with the additional load caused by the snow or ice. The issue comes after the accumulation, during the melting phase where large volumes of ice fall on the bridge below and therefore causing damage to infrastructure, cars, or even occupants (Matejicka et al., 2019). Recently developed digital technology and monitoring systems can enhance the responsiveness and thus improve the resilience of critical assets and networks exposed to multiple hazards (Achillopoulou et al., 2020).

There have been various solutions suggested around the world to try and combat the issue of ice/snow accumulation on bridge cables, however, as bridges vary in structural form and environmental exposure it is difficult to produce a standard solution. For example, the Port Mann Bridge in Vancouver, Canada has a developed solution involving the release of 'collars' or metal chains around the cables to clear ice accumulations. The success or otherwise of this approach is largely unknown, but it is important to note that the system relies on the collars being operated correctly and manually reloaded after use (Matejicka et al., 2019). Much like Scotland the climate of Vancouver tends to be wet, but 'ice storms' are more common in British Columbia and the Port Mann Bridge has experienced icing issues similar to that which affected the QFC.

For instance, the Port Mann Bridge has 8640 chain collars fitted to 288 cables (30 per cable). The collars are made from galvanised steel chains (Figure 4a) with varying weight and length depending on the inclination, diameter and length of the cable. The system involves the manual release (Figure 4b) of the collars and their descent under the action of gravity affecting ice-clearing under the action of gravity. These collars are used in conjunction with early weather warning systems to allow detection of snow and ice build-up on the stays (Robertson et al., 2018).

In the winter of 2016/17 significant snow and storms were experienced in the Vancouver area with a total of 22 days of snowfall. It was estimated to cost $5M Canadian Dollars (CA$) to operate the cable collar system during that period, whereas the year before the cost was only CA$300,000 (Vancouver Sun, 2017). This correlates to a cost per snow day of roughly CA$230,000, which is equivalent to £130,000 per day. The QFC has a total of 288 cable stays and similar operational costs could be inferred, but the lack of specific data for the system means that it is difficult to determine what installation costs. However, a rough estimate of the cost for preventing one major closure of the QFC can be inferred from the Port Mann Bridge operational costs for winter 2016/17. However, it is recognised that damage is introduced by mitigation measures and the potential closures of the bridge in the future to repair these damages were not included in the cost estimation. For example, the Port Mann Bridge has reported damage of the helical fillet through using the chain collars (Matejicka et al., 2019). Hence, the cost of replacement and/or the damper fatigue without the fillet are facts that can be incorporated into the economic assessment.

The authors understand that the feasibility of ice-clearing systems, which is offered simply as an example rather than as a specific recommendation or endorsement to be considered following the 2020 closure. Transport Scotland have reported to have considered many different solutions, including "*coatings on cables, heating systems, even helicopters to come and try to blow all the snow and ice off with downwash, but it is a very difficult problem*" (BBC News, 2020d).

7. Conclusions

The economic consequences of the QFC closure in February 2020 have been estimated and compared to the closures experienced by its predecessor, the FRB, both over a notional three-year period. The method used employs a quantitative risk assessment technique that combines the economic, social, and environmental costs of closure with the weighted damage probabilities of the bridge calculated through fragility and vulnerability functions. This approach gives plausible results when compared with those produced by Winter et al. (2019) using the queues and delays at roadworks model to estimate the direct consequential economic impacts of landslides and floods.

The average cost per day of closure for the FRB was found to be 15% higher than for the 2020 QFC closure. This is as a result of varying traffic volume and conditions, annual monetary parameter differences, and changes in redundancy of the bridge assets over time. However, this is what current data indicated, yet contains uncertainties, including the variability of traffic throughout the day and drivers' behaviours and decisions. Regardless of their differences, both figures are significant and represent an extensive opportunity cost that could be directed toward other important and demanding infrastructure if closure is prevented. The February 2020 QFC closure came two and a half years after its opening and was the first weather-related closure in its history. The authors are not aware of any bridges globally that have achieved full resilience (zero closures) over an extended period of operation in a challenging environment such as that of the Firth of Forth.

The annual savings in direct consequential economic impacts as a result of the replacement of the FRB by the QFC are estimated at over £2.0M. While this was not the driver for the construction of the QFC monetising the increased resilience to closure achieved is useful and this figure is likely to be an underestimate assuming that future icing incidents are mitigated against. The evidence suggests that deployment of mitigation measures will increase the resilience and hence reduce the maintenance costs by avoiding occasional closures, yet, it is recognised that further studies would be required in support of this statement.

It should also be mentioned that the improved resilience of the QFC is due to the design and structural form of the bridge. The wind barriers, hard shoulder and emergency crossovers all facilitate the improved resilience of the QFC. Additionally, the cable-stayed nature of the QFC in terms of improved redundancy compared to the suspension form of the FRB presents a massive contribution to the improved resilience of the crossing.

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List of notations

C_{Run} is the running (operational) cost

$c_{Run,car}$ is the average cost for running cars per unit length

$c_{Run,truck}$ is the average cost for running trucks per unit length

D is the length of the detour

AADT is the annual average daily traffic that takes the detour

T is the annual average daily truck traffic ratio

C_{TL} is the monetary value of time loss for users and goods travelling through the detour

c_{AW} is the average wage per hour

c_{ATC} is the average total compensation per hour

C_{goods} is the time value of the goods transported as cargo

AADE is the annual average daily traffic remaining on the damaged link

O_{car} is the average vehicle occupancies for cars

O_{truck} is the average vehicle occupancies for trucks l is the route segment length

S_0 is the average speed on the intact link

S_D is the average speed on the damaged link

S is the average detour speed

C_{EN} is the environmental cost

C_{TOT} is the total economic consequences

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Table 1. Estimated economic consequences for Queensferry Crossing closure

Cost	Total (1.7 days) [£]	Per day [£]
Operational cost associated with the detour, (C_{Run})	2,944,015	1,721,646
Cost of time loss for users and goods travelling through the detour, (C_{TL})	3,021,481	1,766,948
Environmental cost of CO_2 emissions, (C_{EN})	318,161	186,059
Total economic consequences, (C_{TOT})	6,283,656	3,674,653
Cost as a percentage of the project value		
Project value [£]	1,350,000,000	
Losses to project cost ratio	0.47%	

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Design life (years)	120	
Value per day [£]	30,822	

Table 2. Estimated economic consequences for Forth Road Bridge closures

Closure	09/01/2015		29/01/2016		01/02/2016		11/01/2017	
Duration	7 hours – 0.29 days		5 hours – 0.21 days		2.5 hours – 0.10 days		19 hours – 0.79 days	
Cost	Total [£]	Per day [£]	Total [£]	Per day [£]	Total [£]	Per day [£]	Total [£]	Per day [£]
Operational cost associated with the detour, (C_{Run})	308,951	1,065,348	409,546	1,950,220	203,173	2,031,729	1,702,637	2,155,237
Cost of time loss for users and goods travelling through the detour, (C_{TL})	283,394	977,220	518,331	2,468,242	286,810	2,868,103	2,087,641	2,642,583
Environmental cost of CO_2 emissions, (C_{EN})	33,386	115,126	44,257	210,748	21,956	219,556	183,993	232,903
Total economic consequences, (C_{TOT})	625,731	2,157,694	972,134	4,629,210	511,939	5,119,389	3,974,271	5,030,723
Total economic consequences from all closures (1.4 days) [£]	6,084,075							
Average total economic consequences from all closures per day [£]	4,234,254							
Project value [£]	19,500,000							
Losses to project cost ratio	3.21%		4.99%		2.63%		20.38%	

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Table 3. Parameters of the variables associated with the consequences of QFC and FRB closures

Parameter	Value					Reference				
	QFC 2020	FRB 2015	FRB 2016 (1)	FRB 2016 (2)	FRB 2017	QFC 2020	FRB 2015	FRB 2016 (1)	FRB 2016 (2)	FRB 2017
Restoration time (days)	1.71	0.29	0.21	0.1	0.79	BBC News (2020c)	Data provided by Transport Scotland for Forth Road Bridge closure durations			
$c_{Run,car}$ (£/km)	0.40					Average of: https://media.rac.co.uk/blog_posts/typical-vehicle-running-costs-for-petrol-engine-cars-42585 and converted from per mile to per km (Anon. 2016)				
$c_{Run,truck}$ (£/km)	1.01					Average of: http://www.transportengineer.org.uk/article-images/166209/Out_of_our_hands.pdf and converted from per mile to per km (Anon, 2018)				
D (km)	56					BBC News (2020a)				
ADTT (%)	11.5					Taken for motorways: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/808555/road-traffic-estimates-in-great-britain-2018.pdf (Anon, 2019a)				
AADT (vehicles/day)	64319	39851	72951	76000	80620	Data provided by Transport Scotland for Kincardine and Clackmannanshire diversion				
c_{AW} (£/hour)	14.54	12.98				WebTAG data values Table A1.3.5 for average car in week (Department for Transport, 2019b)				
c_{ATC} (£/hour)	19.06	17.02				WebTAG 2020 data values Table A1.3.5 for average OGV in week (Department for Transport, 2019b)				
c_{goods} (£/hour)	2.97	2.54	2.62	2.62	3.16	Value converted from $/hour to £/hour based on the average exchange rate at the time of closure. Deco and Frangopol (2015)				
O_{car}	2.243					Wong and Winter (2018)				
O_{truck}	1.000					Deco and Frangopol (2011)				
S (km/hour)	64	64	47	42	48	Data provided by Transport Scotland for Kincardine and Clackmannanshire diversion converted to km/hour				
$C_{run,car}$ (CO2	0.22					Dong et al. (2014)				

kg/km)		
$C_{run,truck}$ (CO_2kg/km)	0.56	Dong et al. (2014)
Cost value of environmental metric per unit weight (carbon dioxide) (£/kg), C_{Env}	0.2	See https://carbonpricingdashboard.worldbank.org/map_dataAnon (2020)

List of figure captions

Figure 1. (a) the Queensferry Crossing (Hussain et al., 2019), (b) the Forth Road Bridge (FRB), the Forth Rail Bridge is shown behind the FRB (Colford and Clark, 2010).

Figure 2. Diversion route across the Kincardine Bridge due to the closure of Queensferry Crossing

Figure 3. Conceptual fragility (a) and vulnerability (b) curves (Argyroudis et al., 2019)

Figure 4. Chain-link collar (a) and chain release device (CRD) (b) used on Port Mann Bridge (Robertson et al. 2018).

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Figure 1

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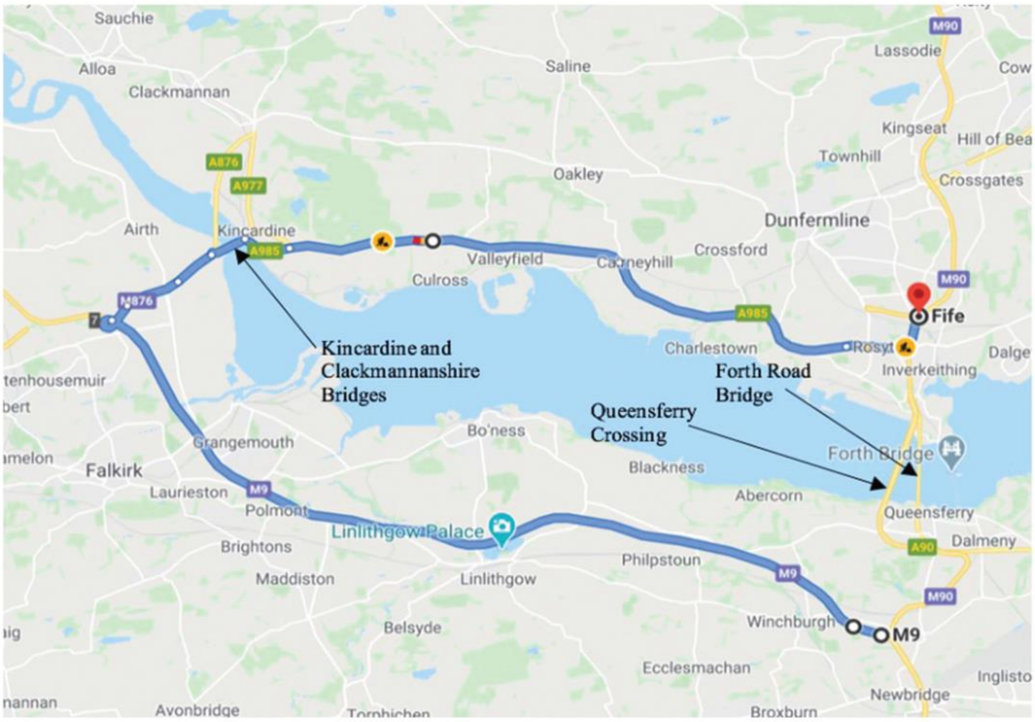

Figure 2

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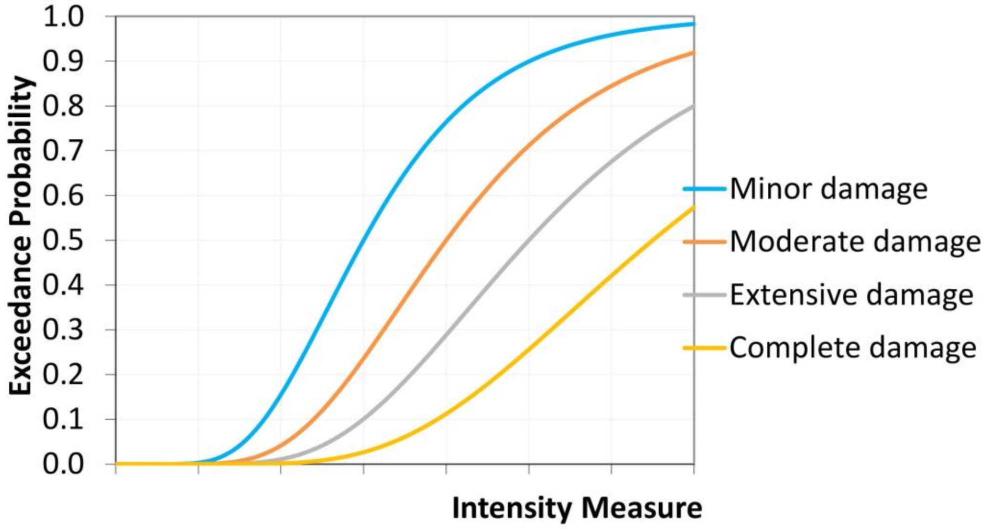

Figure 3a

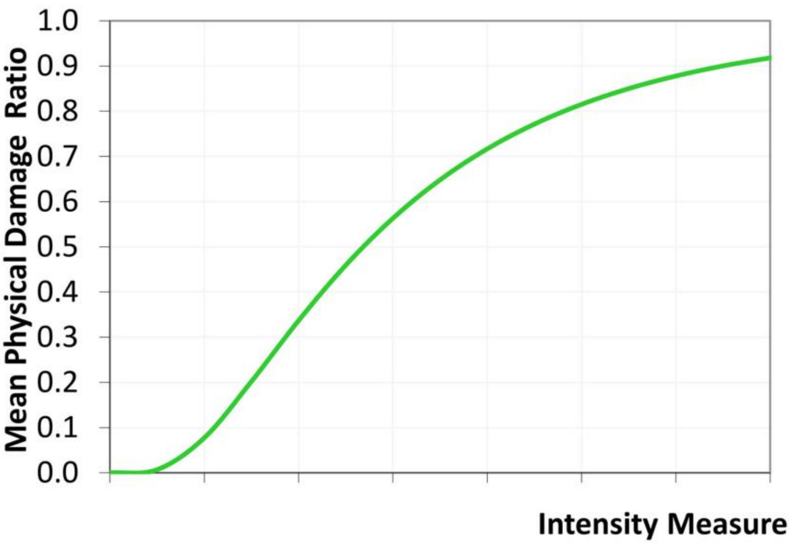

Figure 3b

Figure 3

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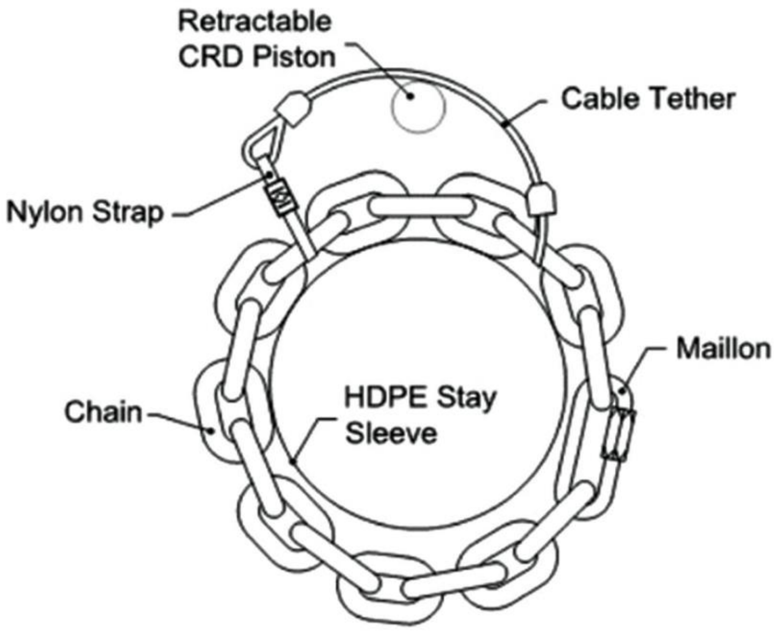
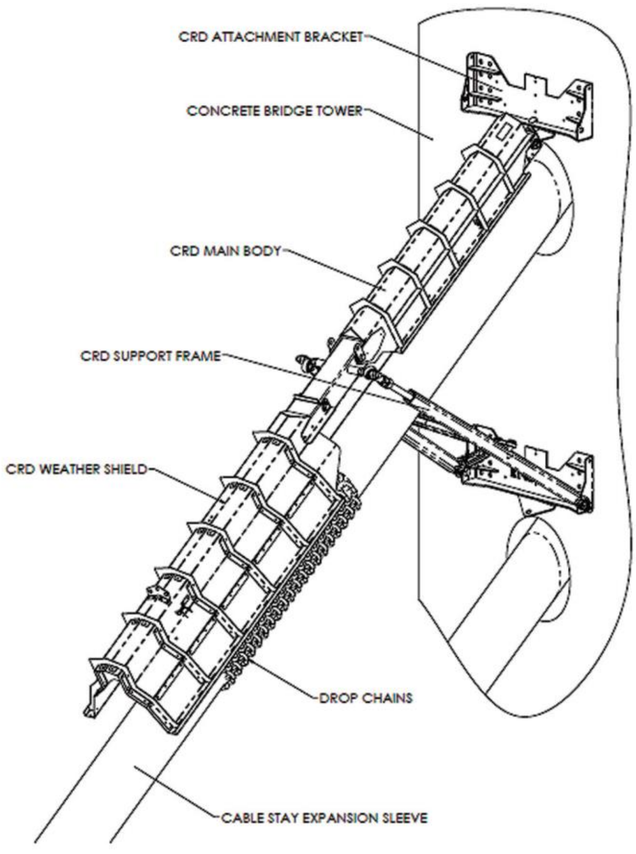


(a)



(b)

Figure 4