2. Low carbon

Carbon assessment – operation, maintenance and use of the Clifton Suspension Bridge

Sam Wood and Cameron Archer-Jones present the results from a recent carbon study of the historic Clifton Suspension Bridge and comment on how the use-stage carbon associated with the bridge can be most effectively managed.

Introduction

Isambard Kingdom Brunel's masterpiece, the iconic Clifton Suspension Bridge **(Figure 1)**, towers above the Avon Gorge and provides a vital transport link into Bristol, carrying approx. 10 000 vehicles each day. The bridge is a Grade 1 listed structure, completed in 1864, and is owned by the Clifton Suspension Bridge Trust (CSBT), an independent, not-for-profit charity.

The bridge is supported by two stone towers, which, in turn, support wrought iron chains, suspender rods, longitudinal and transverse girders. The carriageway deck **(Figure 2)** consists of 5in (approx. 12.5cm) timber baulks spanning longitudinally between the transverse girders, 2in (approx. 5cm) cross planks and approx. 40mm thickness of mastic asphalt. The bridge spans 702ft (approx. 214m) between the towers and has a total length of approx. 350m.

The civil engineering industry, which represents a significant portion of UK carbon emissions, has a responsibility to lead by example in the response to the climate emergency. This includes eliminating or reducing emissions in all phases of the asset lifecycle.

With this in mind, the CSBT Trustees asked COWI to conduct a study to better understand the operational and maintenance carbon 'costs' associated with the bridge. This article summarises the study and includes an estimate of the capital carbon (CapCarb) and a review of the annual in-use carbon linked with the operation, maintenance and use of the bridge. The lifecycle stages considered follow those defined in PAS 2080[1] **(Figure 3)**.

Capital carbon [A1–A5]

To provide some context for the operational carbon (OpCarb) associated with maintaining the bridge, it is useful to compare it with the theoretical CapCarb if an approximate like-for-like replacement were to be constructed tomorrow using current material manufacturing, transport and construction processes. This comparison can then be used to inform an assessment of the relative carbon costs of maintaining or replacing the asset.

This theoretical CapCarb has been derived using COWI's in-house CO_2e tool, which follows the methodology of the IStructE's *How to calculate embodied carbon* guide[2], unless otherwise described in this article. This assessment focuses on the bridge, as the approach roads are not owned or operated by CSBT.

As the bridge was built between 1831–64, material manufacture and construction methods have changed dramatically in the period since. No reliable carbon estimates exist from the 19th century. As a result, this CapCarb footprint is calculated assuming the bridge was built using material produced today to replicate its original form and arrangement.

While theoretically considering a like-for-like replacement is useful to provide some basis to compare with OpCarb and user carbon (UseCarb), it is noted that if the bridge were being replaced today, the maintenance demand would be anticipated to be reduced.

Average carbon factors associated with equivalent modern materials **(Table 1)** are used to prepare a present-day CapCarb estimate. This evaluation considers the superstructure (deck, hangers, chains), the substructure (towers, abutments, saddles), and ancillaries (e.g. protective coatings and drainage). The total embodied CapCarb estimated for the bridge is approx. 7760tCO_2e **(Figure 4)**.

Adopting a similar methodology to that described in the SCORS Rating System for Bridges proposal (or SCORBS)[3], the carbon intensity would be 3.1tCO_2e/m^2 (functional deck area), which would result in a rating of 'E/F' **(Figure 5)**.

Although higher than the average bridge in COWI's database (which currently has more than 100 bridges), it is less than most other suspension bridges, which are generally considerably greater than 3.5tCO_2e/m^2. Several factors are expected to contribute to the

Terminology

Carbon	=	Carbon dioxide equivalent emissions – a unit of global warming potential corresponding to 1kg of carbon dioxide (kgCO_2e)
CapCarb	=	Capital carbon associated with construction of the asset, the equivalent to upfront carbon for buildings (corresponding to lifecycle modules A1–A5). (Also referred to as embodied carbon)
OpCarb	=	Operational carbon associated with ongoing energy use, maintenance, refurbishment or replacement works (corresponding to lifecycle modules B1–B8)
UseCarb	=	In-use carbon associated with use of the asset by the public (corresponding to lifecycle module B9)

↙FIGURE 1: Clifton Suspension Bridge crossing River Avon Gorge in Bristol

relatively low embodied carbon of the Clifton Suspension Bridge **(Figure 6)** relative to other suspension bridges in COWI's database:

- The bridge was designed for lighter traffic loads (limited to 4 tons gross weight and 2.5 tons axle weight) compared with a modern suspension bridge; therefore, numerous elements of the structure are proportionately smaller.
- The span length is now quite modest in the context of modern suspension bridges.
- Concrete and steel represent much higher proportions of the structure and thus embodied carbon for a typical modern suspension bridge. Low-carbon materials, such as stone and timber, are widely used at Clifton but rarely used in modern suspension bridges.

Table 1: Principal A1–A3 carbon factors assuming replacement of bridge today

Material	Carbon factor
Fabricated steel plate	2.5kgCO_2e/kg
Rolled steel section	1.74kgCO_2e/kg
Mass concrete	166kgCO_2e/m^3
Stone masonry	0.08kgCO_2e/kg
Hardwood timber	0.31kgCO_2e/kg (neglecting sequestration)

NB Carbon steel rather than wrought iron assumed for modern estimate.
Refer to Appendix C of IStructE guide *How to calculate embodied carbon*[2] for details on A4 and A5 carbon estimates.

↘FIGURE 2: Cross-section of Clifton Suspension Bridge

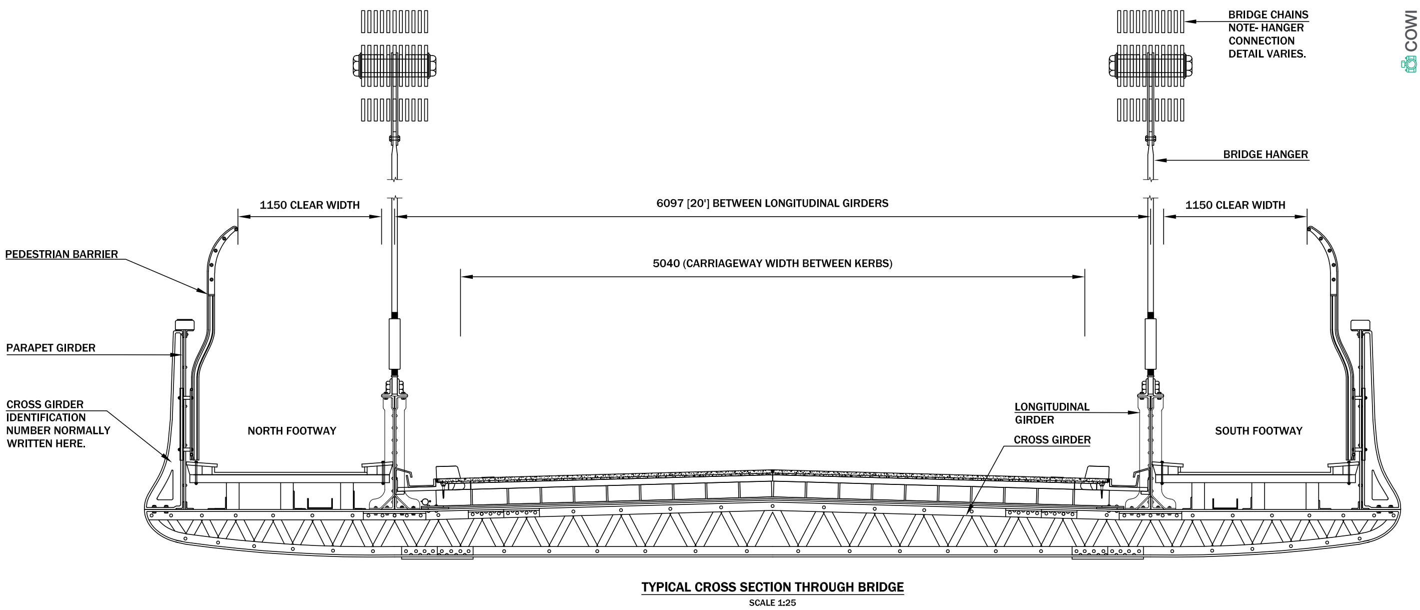


Table 2: OpCarb associated with energy consumption

	2019	2020
Energy consumption	151 400kWh	134 700kWh
Carbon equivalent	32tCO_2e	28.6tCO_2e

Table 3: Carbon costs associated with major routine maintenance projects

Project	Estimated frequency	Embodied carbon
Repainting	20 years	58tCO_2e
Re-decking	50 years	43tCO_2e
Resurfacing	25 years	15tCO_2e
Gantry replacement	25 years	20tCO_2e

Table 4: Estimated annual UseCarb of bridge

	Total crossings per annum	User-associated carbon
2019	2 484 861	153tCO_2e
2020	1 234 597	76tCO_2e

Table 5: Additional UseCarb arising from closure of bridge

Year	Total crossings per annum	Average daily crossings	Carbon impact per day
2019	2 484 861	6808	2.3tCO_2e
2020	1 234 597	3382	1.1tCO_2e

→| There is a historical tradition of increased material efficiency at the expense of additional labour.

Operational carbon

Energy consumption in use [B1 and B6]

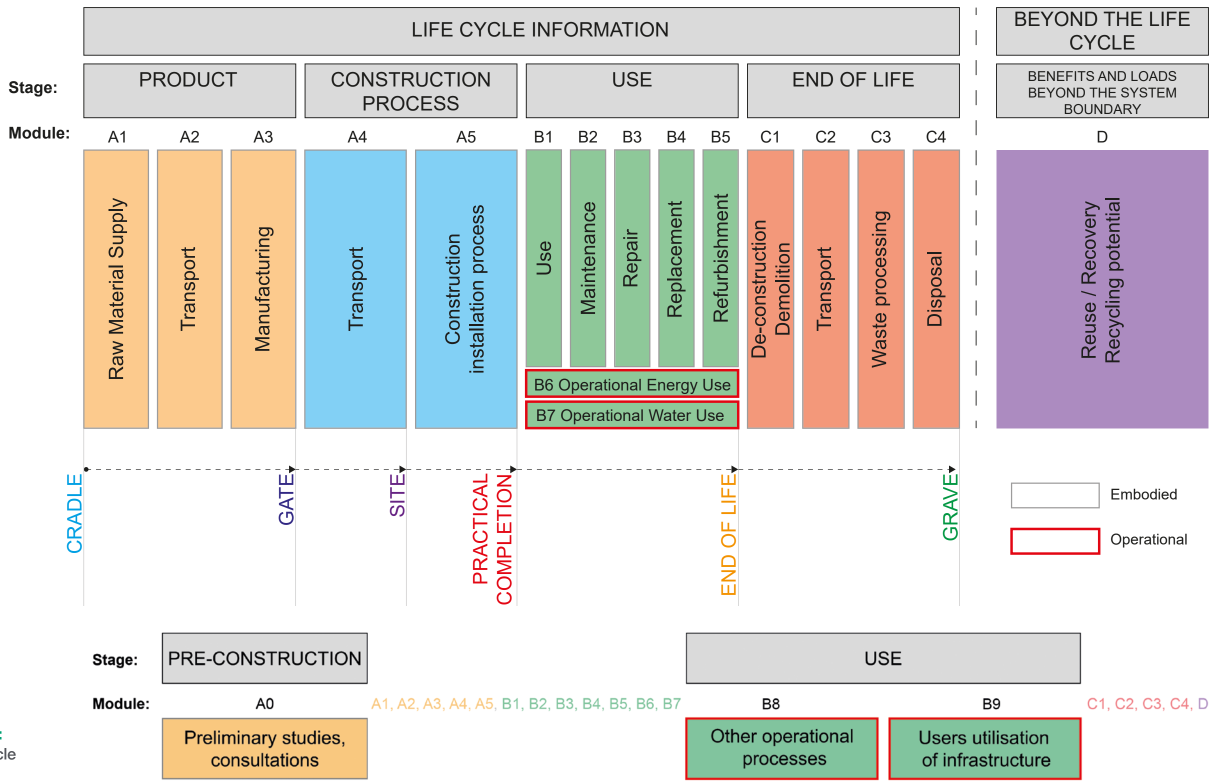
There are five main sources of energy consumption associated with operation of the bridge: Leigh Woods Toll House, Clifton Toll House, bridge illuminations, public toilets and the Visitor Centre and operations building.

Although the public toilets, Visitor Centre and operations building are not strictly part of the bridge 'asset', they are included to gain insight into the total OpCarb associated with the bridge.

CSBT provided electricity readings for 2019 and 2020. An electrical ground-source heat pump is used for heating and thus the electricity data provided covers all energy consumption for heating, lighting and power. Between 2019 and 2020, there was no significant change in electricity consumption associated with the toll houses and illuminations; however, the public toilets, Visitor Centre and operations building saw drops of around 25%. This is presumably because of their closure during the Covid-19 lockdowns.

Assuming that the Leigh Woods Toll House uses approximately the same amount of energy as the Clifton Toll House, the greatest users of energy are the operations building and Visitor Centre, followed by the bridge illuminations **(Figure 7)**.

The OpCarb of the Clifton Suspension Bridge due to energy consumption is detailed in **Table 2**. The carbon equivalent has been



↗FIGURE 3: Asset lifecycle modules[2]

calculated using the UK government's carbon conversion factors for energy from the National Grid (0.212kgCO_2e/kWh)[4].

CSBT currently procures its energy from an exclusively renewable tariff and thus the OpCarb associated with the bridge's energy consumption could be considered close to 0kgCO_2e. Nonetheless, CSBT is looking to reduce energy consumption further through various initiatives.

Staff and volunteer travel [B8]

CSBT has provided travel data for 51 staff and volunteers. The data provided for this assessment included the frequency of travel, distance travelled, and mode of transport. **Figure 8** shows the miles travelled using each mode of transport over a year and the associated total kgCO_2e produced by staff and volunteers annually; this total is dominated by car travel. The CO_2e has been calculated using the conversions factors from UK government guidance[4].

The total CO_2e production because of staff and volunteer travel is 20.5tCO_2e/year, which is comparable to that due to the energy consumption of the bridge (28.6tCO_2e in 2020). It was also found that 70% of trips by car are fewer than 10 miles in length and 30% fewer than five miles in length. Therefore, there is the potential for significant carbon savings for these shorter journeys.

Maintenance, repair, replacement and refurbishment [B2–B5]

During the course of the bridge's service life, maintenance projects are required from time to time. The majority of the bridge metalwork is original: the main items that have been replaced or are due to be replaced are summarised in **Table 3** (this considers manufacturing-related CapCarb only, i.e. modules A1–A3).

This maintenance/refurbishment summary is not exhaustive and major non-routine refurbishment/replacement activities have been carried out in the past. The embodied carbon was not quantified in detail during the study; however, CSBT intends to measure and record this information in future.

Simplistically adopting an average maintenance carbon per year, along with a nominal allowance of non-routine refurbishment, the annual maintenance-associated carbon is estimated to be approx. 7–10tCO_2e per annum.

User carbon

User utilisation of infrastructure (B9)

The UseCarb is the carbon associated with transport on the crossing. Calculating UseCarb requires three inputs:

1) number of vehicles crossing the bridge
2) fuel consumption and thus carbon production of those vehicles

↘FIGURE 4: CapCarb estimate for modern replacement

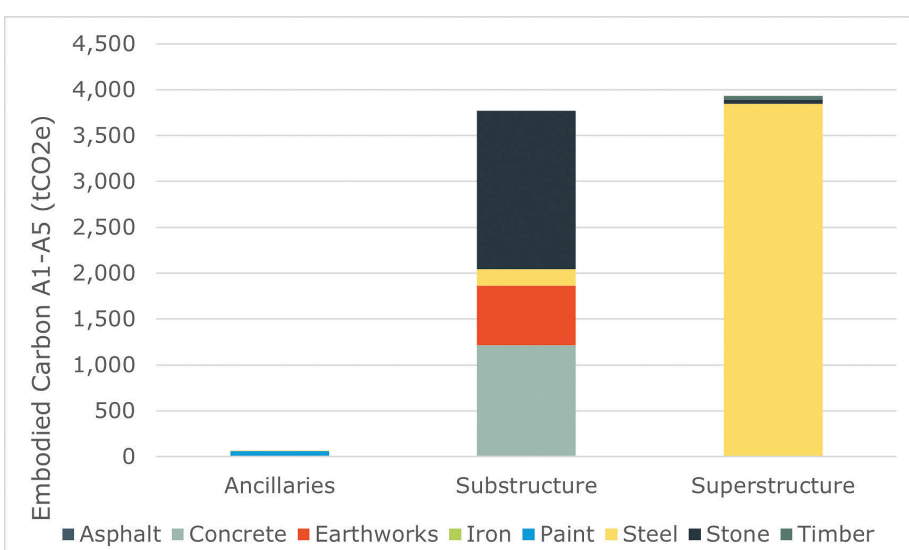


FIGURE 5: Proposed structural carbon rating system for bridges (SCORBS)

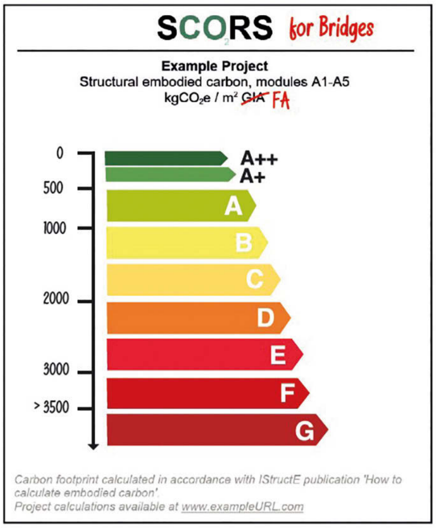
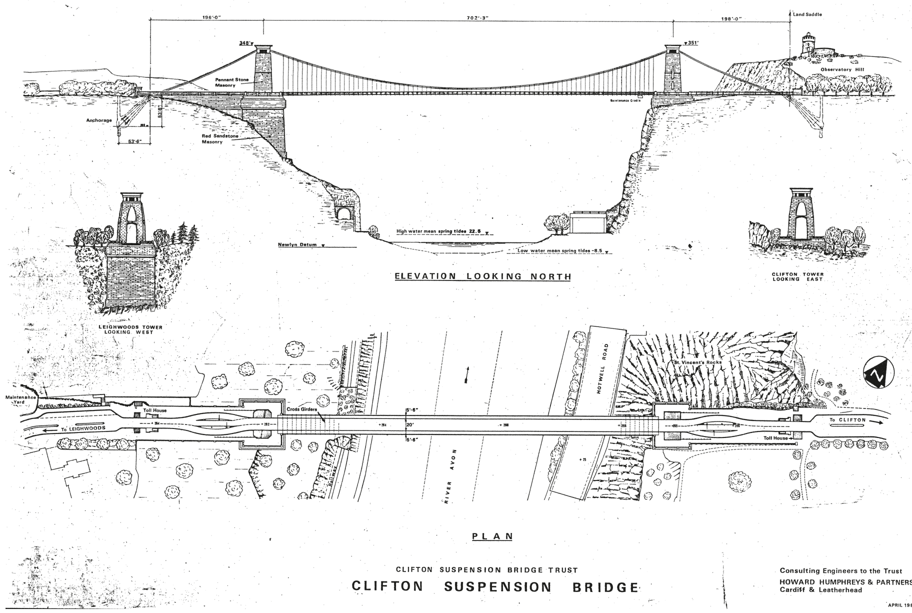


FIGURE 6: Howard Humphreys and partners record drawing of Clifton Suspension Bridge



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3) defined journey length associated with the bridge.

CSBT provided daily toll data for 2019 and 2020 and thus it is possible to determine the number of vehicles crossing the bridge **(Figure 9)**.

The effect of the Covid-19 pandemic is clear from the 2020 toll data, with a notable drop in crossings corresponding with the first national lockdown in the UK. With the rise in people working from home and therefore not needing to commute, it is unclear whether the number of crossings will eventually return to pre-pandemic levels.

An average carbon conversion factor of 0.28kgCO_2e/mile or 0.18kgCO_2e/km has been used – this is for a medium-sized passenger vehicle of unknown fuel type defined in the UK government's GHG conversion factors[4]. In reality, some crossings will also be motorbikes or small vans, but this is unlikely to be significant.

The defined journey length associated with use of the asset for the purpose of this comparison is restricted to the total bridge length: 0.22 miles or 350m. By combining these inputs it is possible to estimate the annual UseCarb **(Table 4)**.

Impact of bridge closure

Since closing the Clifton Suspension Bridge has a greater impact on journey lengths than just that corresponding to the length of the bridge, the impact of closing the bridge was considered with a broader network-level review.

In the event of a bridge closure, e.g. due to maintenance, based on a high-level origin-destination study, this would result in an additional 1.5 miles or 2.4km on average for those who still set out on their journey. Also, a 20% proportion of drivers are assumed to no longer carry out their journey, at least using a road vehicle, in the event that the bridge is closed.

The resulting user-associated carbon impact for closing the bridge is estimated for the average day in **Table 5**.

This demonstrates that keeping the crossing open has a significant role to play in minimising UseCarb and represents a 'saving' of approx. 840tCO_2e per annum compared with closing the bridge or if it was no longer in use.

This is also useful data when planning maintenance. Although it matches the intuitive approach to minimise disruption to traffic, it shows that the impact of closing a bridge during peak periods can be very significant in relation to the in-use stage emissions associated with transport infrastructure.

A typical road closure for bridge maintenance would take place from 08:00 to 18:00. However, if the Clifton Suspension Bridge must be closed for essential maintenance, CSBT generally conducts 'off-peak closures', which last from 09:30 to 15:30 – a four-hour reduction to the contractor's working day.

FIGURE 7: Energy usage of Clifton Suspension Bridge

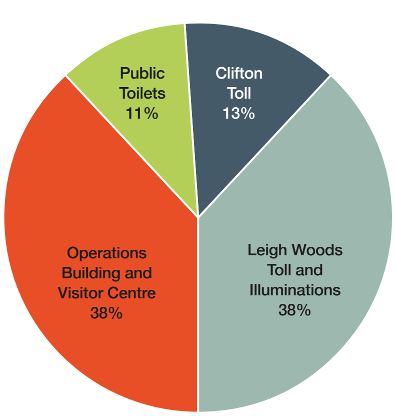
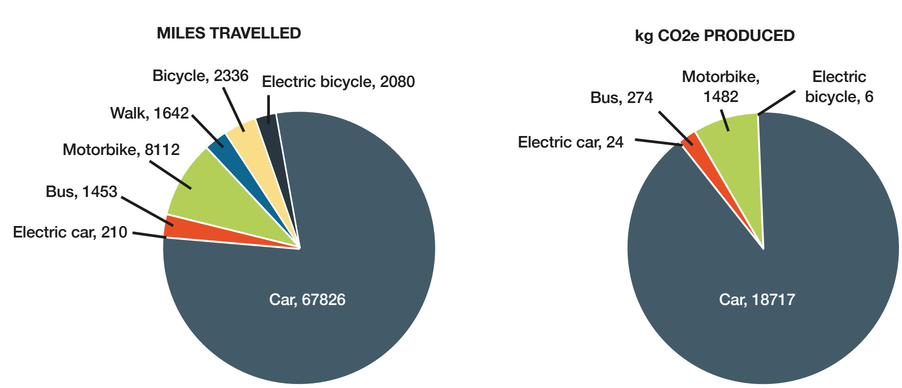
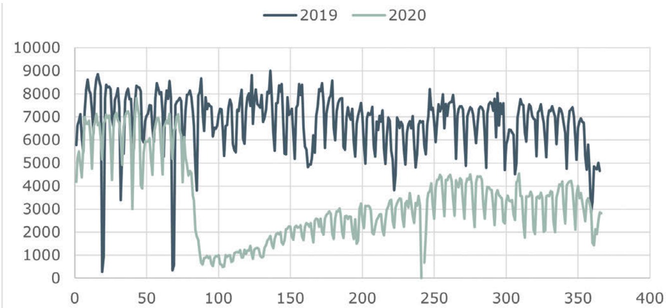
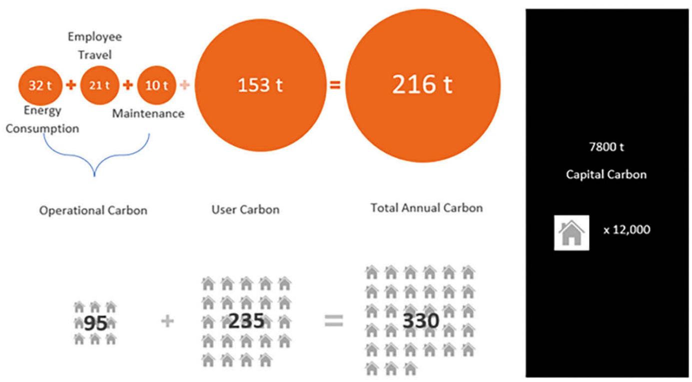


FIGURE 8: Miles travelled and CO_2e produced by staff and volunteer travel over a year





←FIGURE 9: Annual crossings measured daily (CSBT, 2019/20 data)



←FIGURE 10: Summary of CSBT's annual UseCarb and OpCarb (each house icon in chart represents annual emissions of 10 homes)

This enables the trust to continue collecting tolls during peak hours (when 40% of crossings occur). It also minimises disruption around the Cumberland Basin by allowing approx. 2300 cars to use the bridge during peak hours, rather than taking the longer diversionary route. Based on this data, it is possible to calculate the average carbon saving arising from the off-peak closure, which equates to approx. 1.1tCO_2e per day (based on 2019 crossing data).

Conclusions

This study has shown the considerable carbon benefit to the ongoing operation and maintenance of the Clifton Suspension Bridge compared with replacing it: OpCarb (approx. 60tCO_2e per annum) is dwarfed by the CapCarb associated with replacing the bridge (approx. 7800tCO_2e, excluding disruption to traffic) **(Figure 10)**.

Considering the impact of bridge closures linked to essential maintenance, these results support the importance of ensuring that maintenance operations minimise disruption to traffic. While this is generally the default approach to bridge maintenance, this study has quantified the magnitude of this impact with respect to embodied carbon for the Clifton Suspension Bridge, avoiding 2.3tCO_2e/day for a full-day closure, or 1.1tCO_2e/day if closed only during off-peak times (greater than 10% of the annual maintenance-related carbon per day).

Ongoing maintenance-related CO_2e for bridges is an area that would benefit from increased focus to understand what good maintenance looks like. This is one area of consideration within the Net Zero Bridges Group, and any parties willing to share data in this space are encouraged to contact info@netzerobridges.org.

The bridge has significant heritage and tourism value as well as providing a vital transport link for the City of Bristol **(Figure 11)**. This study considered the carbon associated with operation, maintenance and use of the Clifton Suspension Bridge, which reinforces the importance of the CSBT's role in maintaining the bridge in perpetuity. Purely with respect to carbon, ongoing maintenance of the structure, rather than replacement, provided that it minimises disruption to traffic, clearly has the greatest impact on minimising the carbon associated with this transport link.

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↖FIGURE 11: As well as providing important transport link for Bristol, Clifton Suspension Bridge has significant heritage and tourism value

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