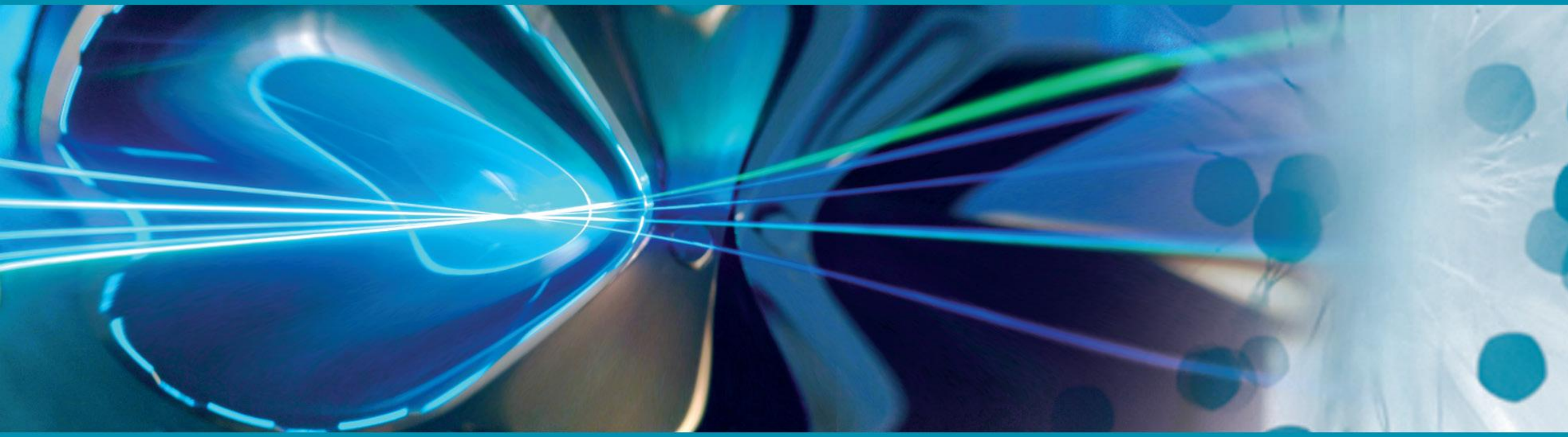

Mini-project report

Embedding sustainable development into structural design teaching using sustainability appraisal tools

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A Higher Education Academy Engineering Subject Centre Mini Project

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CONTENTS

SUMMARY

The Department of Civil, Environmental and Geomatic Engineering (CEGE) at University College London (UCL) was commissioned by the Higher Education Academy Subject Centre to undertake a mini-project entitled 'Embedding sustainable development into structural design teaching using sustainability appraisal tools' in 2008. The primary aims of the project were to develop teaching material and student exercises that would

1. Develop expertise in sustainability appraisal tools and methods
2. Help students enrolled on courses in civil and structural engineering develop a deeper understanding of sustainable development and its relevance to structural design
3. Introduce students to a new sustainability performance evaluation tool called SASS.

The Joint Board of Moderators in their accreditation guidelines, Annex C, note that engineers have been expected to be able to respond to societies' concerns about the impact of human activity on the environment for some years but that there is a growing desire from governments and the public that this environmental concern is now placed in the context of achieving the correct balance between environmental, societal and economic outcomes within the overarching concept of sustainable development. Nevertheless, currently structural design teaching at universities is mostly focused on technical and economic issues. Environmental factors such as global warming and social factors such as noise pollution are largely ignored. The choices of construction material, structural form and method of construction have a significant effect on the environment and society. This omission in the teaching syllabus chiefly arises for two main reasons

(i) it is not clear which factors should be considered
(ii) how individual impacts can be evaluated and accounted for in design.

Knowledge of sustainability appraisal tools would appear to offer a solution to both these problems and should also help develop some expertise in sustainability appraisal which is now increasingly being specified by clients.

There are a number of tools that can be used to evaluate the sustainability performance of various forms of construction such as BREEAM, CEEQUAL, SPeAR, Sustainability Accounting and SASS. Chapter 1 provides an overview of these tools and explains how they are used and discusses their merits. SASS has primarily been developed to help Engineers assess the sustainability performance of bridge structures. Unlike the other methods discussed in this report SASS is largely quantitative. This approach should appeal to engineering students used to precision and allow the effects of design decisions on sustainability to be readily evaluated. It also enables the effect of changes in the relative priority given to the environment, society and economy to be investigated.

In Chapter 2 SASS is used to compare the sustainability performance of three different design options for a new bridge over a dual two-lane motorway. Bridge 1 is a four span continuous steel beam and slab bridge with integrated bank seat foundations and three intermediate leaf piers. Bridge 2 is a two-span simply supported prestressed concrete beam and slab bridge with cantilever abutments and an intermediate leaf pier. Bridge 3 is a three span voided concrete slab bridge with a full height abutment at one end and a bank seat at the other and two intermediate portal piers. Two phases of bridge provision are considered, namely construction and in-service, to give the life-time sustainability. Details of the key appraisal parameters are provided. The way in which individual impacts are evaluated and combined to produce an overall sustainability score for individual structures is described. The study is concluded with a short discussion on the findings.

The output from this study has been used to develop a series of worked examples and related exercises for students, presented in Chapter 3 of the report, which are designed to

- test their understanding of the process involved in determining sustainability scores for bridges
- test their ability to calculate the scores for the three sustainability themes (environment, economy and society)
- test their ability in normalising these scores and applying weighting factors to find the sustainability scores
- use their results to establish whether construction or lifetime maintenance is the major contributor to poor sustainability
- use their results to rank environment, economy and society components in terms of their contribution to poor sustainability
- use their knowledge of bridge design/durability and maintenance strategies to suggest ways of improving the sustainability of bridges.

The commentary on these student exercises provided at the end of Chapter 3 suggests some ways in which environmental, economic and social impacts may be reduced. The commentary also highlights the interconnectedness of the three sustainability themes so that a change introduced in order to reduce, say, the environmental impact may have an adverse effect on the economics or social components. In a similar way the

use of more durable design materials aimed at reducing lifetime maintenance costs may have an adverse affect on the environment.

The importance of traffic delay costs is emphasised. On busy road the traffic delay costs resulting from maintenance work can be very high substantially increasing the economic impact, making it the critical sustainability component. Thus steps taken to minimise maintenance time can be especially sustainable.

The discounted cash flow technique is used for the calculation of lifetime costs allowing all costs to be compared at the same date (the year of construction).

The report is concluded with a short discussion on the outcome of a trial of the student exercises and some comments on perceived benefits, resource implications/prerequisites and future direction.

Chapter 1: Sustainability Appraisal Tools

1.1 Introduction

The Joint Board of Moderators requires that sustainable development be integrated into engineering education[1], a core component of which is design. Sustainable development is a complex concept and a universally accepted definition does not exist at this moment in time. The most often quoted description is that given in the Brundtland report[2]: 'development which meets the needs of the present without compromising the ability of future generations to meet their own needs'. This has been widely interpreted to mean the simultaneous pursuit of economic prosperity, environmental preservation and social equity, as depicted in the Venn diagram[3] shown in Fig. 1.

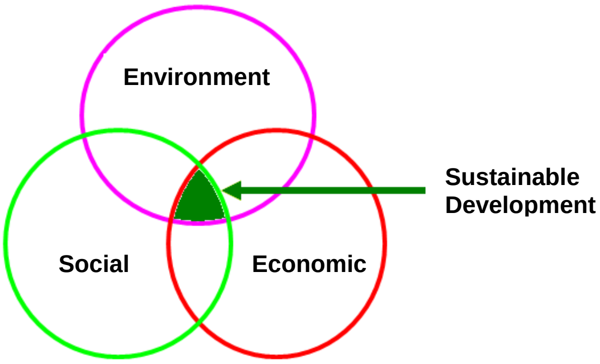


Fig. 1: Sustainable development model

Construction is a major sector of the UK national economy and accounts for around 10% gross domestic product. It employs around 3 million people, is estimated to consume about 6 tonnes of materials per person per year and generates large amounts of waste and emissions[4,5]. Construction activity can also have a significant effect on the local community[6]. It should be remembered too that significant environmental, social and economic impacts occur during the operational life of built facilities, which are directly related to decisions taken at the design stage. Nonetheless the construction industry is responsible for the provision and maintenance of much of the nation's infrastructure – transport, housing, hospitals, schools, water supply, effluent disposal, etc - and therefore provides an invaluable service. Moreover, the construction process lends itself to detailed measurements and thus provides an idea test bed to evaluate policy on sustainable development. It was for these reasons the industry was selected in 1998 by the UK Government – New Labour – as a suitable platform to develop a framework for sustainable development[5]. To achieve sustainable development, a number of legislative directives and acts have been passed over the past decade on waste, water, air, wildlife, land and climate change, many of which are aimed at curbing the adverse effects of construction activity whilst at the same time improving the quality, competitiveness and profitability of the industry. In recent years, because of the growing awareness of sustainable development, the push for sustainable construction has also come from the public and led some client organisations, research institutes and professional bodies to produce voluntary codes and standards on this subject[7,8].

To assist the construction industry act on the plethora of legislation, policy, codes, standards etc on sustainable development a number of appraisal tools have been proposed. Generally, these tools have been developed, singly or in combination, by professional bodies, private companies and academia. Some are relevant to urban planning e.g. regional LADF[9] and BEQUEST[10] whereas others are primarily applicable to building projects e.g. BREEAM[11], LEED[12] and Green Star[13]. Two are relatable to civil infrastructure: CEEQUAL[14] and SASS[15]. Generally speaking these tools all claim to act as both a guide to the inputs of sustainable design and as a measure of sustainability performance post-construction.

Ideally, a sustainability appraisal tool should allow the separate assessment of all relevant lifetime economic, environmental and social impacts in a straightforward, transparent, rigorous and repeatable manner. It should also include a means of combining the impacts to provide an overall assessment of sustainability.

Currently the use of appraisal tools is voluntary but may at some future date become mandatory. The purpose of this chapter is to provide an overview of the following typical appraisal tools and explains how they are used and discusses their merits.

- BREEAM
- CEEQUAL
- Sustainability Accounting[16]
- SPeAR[17]
- GSAP[18]
- SASS

Knowledge of these tools should help Civil and Structural Engineers extend their understanding of the issues relevant to sustainable design/construction as well as develop some expertise in sustainability appraisal which is now routinely specified by clients.

1.2 Building Research Establishment Environmental Assessment Method (BREEAM)

BREEAM is a popular and easy to understand tool developed by the UK Building Research Establishment to assess the environmental performance of building projects. It has been designed to evaluate the environmental performance of new builds as well as extensions, major refurbishments and fit-outs of existing buildings.

BREEAM Sections	Weighting (%)	
	New builds, extensions and major refurbishments	Building fit-out only
Management	12	13
Health and Wellbeing	15	17
Energy	19	21
Transport	8	9
Water	6	7
Materials	12.5	14
Waste	7.5	8
Land Use and Ecology	10	N/A
Pollution	10	11

Table 1.1: BREEAM Sections and weighting

Table 1.1 lists the nine major indicators (sections) used in BREEAM. The table also shows the recommended weightings applicable to each section. It can be seen that the weightings not only depend on the section but also on the nature of the work being assessed. The weightings in the Table have been derived by consulting a wide cross-section of stakeholders from the construction industry including designers, developers, end users, financiers, insurers, regulators, experts, etc.

Performance in each section is evaluated by addressing a number of questions. For example the questions addressed within the section on *Water* cover the following issues:

- *Wat 1*: Water consumption
- *Wat 2*: Water meter
- *Wat 3*: Major leak detection
- *Wat 4*: Sanitary supply shut off
- *Wat 5*: Water recycling
- *Wat 6*: Irrigation systems

Clearly the overall aim of this section is to appraise water consumption. Thus the use of fittings/equipment and features which reduce consumption of potable water such as low flush toilets or grey water for flushing, tap inserts, water meters, equipment which can monitor and shut off supplies of water when leaks are detected, the provision of low-water irrigation systems/strategies, etc, will achieve a high score and vice versa.

Scores (or credits) are awarded based on the responses obtained, in accordance with defined criteria, backed by various types of evidence considered acceptable such as copies of management plans, written statements, audits, correspondence, photographs, etc.

The credits are used to calculate a BREEAM rating for the project. In order to achieve a rating, however, it is necessary to achieve a certain minimum number of credits in some key issues within each section. Generally, the scores shown in Table 1.2 are used to classify performance. But this is subject to the condition that the minimum standards applicable to that rating have also been met. Table 1.3 shows the minimum BREEAM standards for educational buildings. If say the final BREEAM score is 75% the building could be awarded an EXCELLENT rating. However if the credits achieved for *Ene 1* (i.e. Reduction of CO_2 emissions) is 4 the BREEAM rating would be downgraded to VERY GOOD as the minimum standard necessary for an EXCELLENT rating is 6 credits (see Table 1.3). If the building is to achieve an OUTSTANDING rating there are additional conditions which must be met, details of which can be found in the BREEAM manual.

BREEAM rating	% score
UNCLASSIFIED	< 30
PASS	≥ 30
GOOD	≥ 45
VERY GOOD	≥ 55
EXCELLENT	≥ 70
OUTSTANDING	≥ 85

Table 1.2: BREEAM rating benchmarks

Various versions of BREEAM have been developed. Currently there are BREEAM assessments for the following building types:

- Courts
- Schools
- Industrial units
- Hospitals
- Offices
- Retail outlets
- Prisons

In recent years the scope of BREEAM has been extended to include some socio-economic factors in order to provide a more holistic measure of building performance. Nevertheless, BREEAM is heavily biased towards measuring environmental performance and use of this tool alone may not necessarily achieve sustainability in building construction.

BREEAM issues	BREEAM Rating / Minimum number of credits				
	PASS	GOOD	VERY GOOD	EXCELLENT	OUTSTANDING
Man 1: Commissioning	1	1	1	1	2
Man 2: Considerate Constructors				1	2
Man 4: Building user guide				1	1
Man 9: Publication of Building information					1
Man 10: Development as a learning resource					1
Hea 4: High frequency lighting	1	1	1	1	1
Hea 12: Microbial contamination	1	1	1	1	1
Ene 1: Reduction of CO_2 emissions				6	10
Ene 2: Sub-metering of substantial energy uses			1	1	1
Ene 5: Low zero carbon technologies				1	1
Wat 1: Water consumption		1	1	1	2
Wat 2: Water meter		1	1	1	1
Wst 3: Recyclable waste storage				1	1
LE 4: Mitigating ecological impact			1	1	1

Table 1.3: Minimum BREEAM standards for Educational buildings[11]

1.3 **Civil Engineering Environmental Quality Assessment and Award Scheme (CEEQUAL)**

CEEQUAL[14] is a tool developed by a team led by the UK Institution of Civil Engineers to assess the environmental performance of civil engineering projects based on the factors listed in Table 1.4.

CEEQUAL Sections	Maximum number of questions	Maximum available score
Project environmental management	23	120
Land use	15	82
Landscape issues	13	69
Ecology and biodiversity	14	85
Archaeological and cultural heritage	10	62
Water issues	14	89
Energy	13	85
Material use	21	95
Waste management	16	87
Transport	13	76
Nuisance to neighbours	17	73
Community relations	11	77
Total	180	1000

Table 1.4: CEEQUAL Sections, maximum question numbers and available scores

It is the civil engineering equivalent to BREEAM in that like BREEAM it aims to improve the environmental performance of construction projects. However, there are a number of differences in detail which are worth noting.

Firstly, there are more sections in CEEQUAL than BREEAM and sections which are seemingly the same are differently defined. For example, in CEEQUAL the aim of the section headed *Water issues* is to reduce the use of potable water as well as reduce the risk of pollution of groundwater and existing water features during construction. In BREEAM, the latter is covered within the section on *Pollution*. In BREEAM there is no equivalent to CEEQUAL's section on *Archaeology and cultural heritage*. Similarly there is no equivalent in CEEQUAL to BREEAM's section on *Health and wellbeing* because of differences in the nature of the projects covered by the two schemes. Thus *Health and wellbeing* addresses issues related to the comfort of occupants of building structures e.g. indoor air quality, thermal comfort, view-out, all of which generally have none or very little relevance to users of civil engineering structures. Nevertheless, where a predominantly civil engineering project includes individual building structures it may be appropriate to carry out both BREEAM and CEEQUAL assessments.

Like BREEAM, CEEQUAL assesses environmental performance by means of a number of questions. Table 1.4 shows the number of questions applicable to each section. From the associated scores it will be appreciated that the questions are differently weighted within and between sections, which reflects the relative importance of the issue to the overall performance of the project. However unlike BREEAM there is only one version of CEEQUAL. This means that not all the questions will be relevant in all cases and therefore the first stage of the assessment involves identifying relevant questions from each section, a process referred to as scoping, which are subsequently used to evaluate performance. Not all questions can be treated in this way as they are regarded as core and are therefore compulsory for all projects. Table 1.5 lists the questions which must be included in all CEEQUAL assessments within the section on *Energy*, for example

Like BREEAM, scores are awarded based on the responses obtained, in accordance with defined criteria, backed by various types of evidence considered appropriate during the scoping stage.

The scores are used to determine the CEEQUAL award for the project. The scores represent the percentage by which the project exceeds the statutory/regulatory minimum required for this type of project. If the project exceeds this minimum by 25% it is awarded a PASS. Higher scores attract higher awards in accordance with the criteria given in Table 1.6.

Question number	Question	Scores		
		Client	Design	Contraction
93	Is there evidence of appropriate measures having been incorporated to reduce energy consumption in use?	16		0
94	Is there evidence that the design has explored opportunities for the incorporation of energy from renewable sources?	4		0
95	Has energy from renewable sources been incorporated in the scheme where appropriate?	9		0
97	Is there evidence that the design has incorporated appropriate measures to reduce energy consumption during consumption where feasible?	4		0
98	Has an energy management plan or energy management section of SEMP or integrated project plan been drawn up and implemented?	0	0	5

Table 1.5: Compulsory questions within the Energy section

CEEQUAL award	score
PASS	> 25%
GOOD	> 40%
VERY GOOD	> 60%
EXCELLENT	> 75%

Table 1.6: CEEQUAL award benchmarks

Five award types are possible with this scheme:

- Whole project awards
- Design only awards
- Construction only awards
- Design and Build awards
- Client and Design awards

Whole project awards are applied for on behalf of the whole team i.e. clients, designers and contractors. The remainder are applied for by team members either to seek rewards for their individual effort or because one or more of the parties do not wish to participate in the application.

The CEEQUAL tool when conceived had a limited range of social and economic themes but newer releases of the tool are trying to address this drawback. Another drawback of this tool is that much of the input data is qualitative which can lead to inconsistencies in scoring.

1.4 Sustainability Accounting[16]

The method takes as its starting point the traditional financial information that is normally compiled for a project such as the cost of construction, cost of operation, revenues, taxes paid and grants received. This information is used to prepare a sustainability statement which details the direct financial impacts (costs and savings) of sustainability initiatives as well as the indirect environmental and social impacts (Table 1.7). Generally, the direct financial savings will accrue to clients but may be passed on to the construction company depending upon the contractual arrangements, whereas the indirect saving accrues to third parties such as the users and society.

The direct accounts provide details of the extra expenditure arising out of various environmental and social initiatives undertaken as part of the proposed works, which are recorded as *costs*. The benefits that accrue as a result of undertaking each of these initiatives over the design life of the project are recorded as *savings*. Both values will normally be expressed in monetary terms. For example, the use of ground granulated blast furnace slag (GGBS) in concrete bridges increases the cost of construction because of the need for improved curing (item X in Table 1.7). However it should also reduce the incidence of chloride-induced reinforcement corrosion, necessitating fewer and possibly less extensive repairs thereby resulting in a saving in maintenance expenditure (item Y).

Environmental & Social Features	**Direct**		**Indirect**		
	Costs (£)	**Savings (£)**	**Environmental**	**Social**	**Stakeholders Affected**
Environmental costs/benefits Additional expenditure for extra curing during construction Saving in maintenance expenditure	X	Y	Reduction in CO_2, SO_2 emissions, waste, etc		
Net Direct Savings (environment)					
Social cost/benefits Traffic Delay Costs				Z	
Net Direct Savings (social)					
Total Direct Savings					

Table 1.7**.** Sustainability Accounting statement

The indirect accounts provide details of the environmental and social benefits that will accrue to third parties as a result of proposed sustainability initiatives. These benefits should preferably be expressed in financial terms but where this is not possible a statement containing numerical estimates of the benefits should be provided. Thus continuing the above example, the indirect *environmental benefit* of using GGBS would include a reduction in the use of virgin materials and harmful emissions associated with manufacture of an equivalent amount of ordinary Portland cement. The indirect social benefits would include an overall reduction in delays to road user because of the need for fewer and less prolonged lane closures during repair work. This reduction in delays could be expressed in monetary terms as traffic delay costs and would be regarded as a *social benefit* as it accrues to users (item Z).

Sustainability accounting would appear to provide a very systematic method of comparing the impact of construction on clients, users and society. However, it would generally be quite difficult to optimise design options using this method as it makes no attempt to combine impacts in order to make an overall assessment of sustainability.

1.5 Sustainable Project Appraisal Routine (SPeAR)

SPeAR[17] is a Windows program which has been developed by Arup to appraise the sustainability of projects and products. The tool can be adapted for use on any development type irrespective of specialist sector - housing, transport, urban planning, vehicle design, etc – and has been designed to assess sustainability at all stages of development and operation.

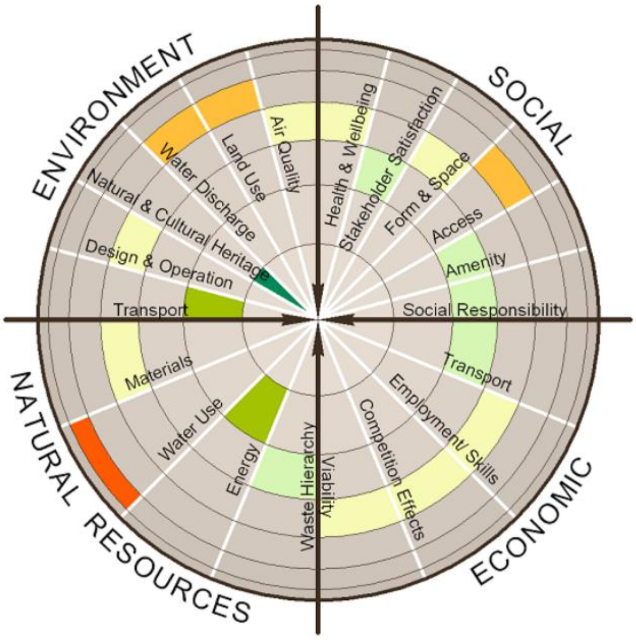


Fig. 2. SPeAR diagram for sustainability assessment

SPeAR is essentially based on the four broad objectives on which New Labour's vision of sustainable development was founded[5], namely:

- Environmental protection
- Social equity
- Economic viability
- Efficient use of natural resources

A set of indicators is used to measure performance in each of the four areas. Many of the indicators are core and must therefore be considered in the evaluation. A few (normally less than 10%) may be added or changed depending on the type of project under consideration.

The environmental indicators considered in SPeAR include air quality, water quality, land use and ecology. The objective is to encourage design and development which will keep the impacts on these indicators below the level required to allow the system to recover and continue to evolve. The purpose of the economic indicators is to consider financial viability and the wealth creation potential of the project and its distribution within and among communities. The aim of the social indicators is to increase the quality of life of all interested and affected parties to the project by for example enhancing the landscape, improving accessibility, minimising noise and vibration emanating during construction or operation of the scheme and strengthening social identity. The ambition of the natural resources indicators is to encourage more efficient usage of materials thereby reducing both the amount of raw material and the energy required for production and transportation, as well the overall amount of waste generated.

The appraisal process involves identifying relevant indicators and in each case assessing performance against a scale of "beyond best practice" and "worst case" (Fig. 3). The median line represents good practice. From the published literature it is not entirely clear how performance is rated and if the evaluations are repeatable.

The results are displayed on the four-quadrant model shown in Fig. 2 which provides a pictorial sustainability profile of the project and also highlights both strength and weaknesses of the design. It is noteworthy that since two of the four quadrants relate to environmental themes, the results from this model will be biased towards environmental objectives.

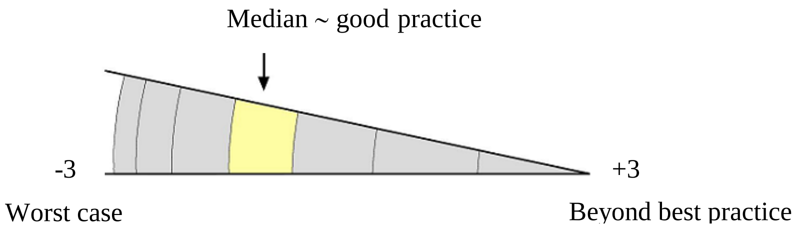


Fig. 3

In the full model shown in Fig. 2, some of the indicators appear in two places e.g. water, transportation and land use and care is need in using the model as there is a risk of double accounting. Some of the other limitations of this appraisal tool noted by the authors of the tool include

- Open to misuse/bias
- Involves a thinking process of a team not an individual
- Needs a diverse skills base team, many experts can be subjective, one person should co-ordinate and capture the balance and increase objectivity
- Oversimplification
- Key indicators could be lost
- Comparisons can only be made within a project not between different projects due to specificity of indicators
- Not an answer to sustainability, rather a tool to guide step change towards sustainability

1.6 Gifford Sustainability Appraisal Process (GSAP)

GSAP[18] is described as a process rather than an appraisal tool. This is because although within it there is an appraisal tool and a sustainability framework, it also incorporates a technique called Appreciative Inquiry (AI), whose aims are

- to identify the project-specific sustainability opportunities using the collective experience of the project team and client;
- to stretch the breadth of the sustainability opportunities available;
- to spread the shared understanding of sustainability aspirations to all members of the project team prior to formulation of design solutions.

The authors believe this feature makes to it superior to other appraisal methods which largely involve measuring the performance of a "prepared solution", with the expectation that some incremental improvement might then be engineered.

Fig. 4 shows the GSAP methodology. The first stage involves carrying out a literature review to gather background information on the project as well as relevant local, regional and national sustainability aspirations, opportunities and policies. The second stage involves presenting the findings at a sustainability workshop facilitated by sustainability specialists and the use of Appreciative Inquiry to search out and agree possible unconstrained sustainability aspirations and measures, on the following themes (categories):

- *Climate change & Energy*
- *Pollution*
- *Biodiversity, Heritage and Landscaping*
- *Waste & Resources*
- *Community*
- *Economics*

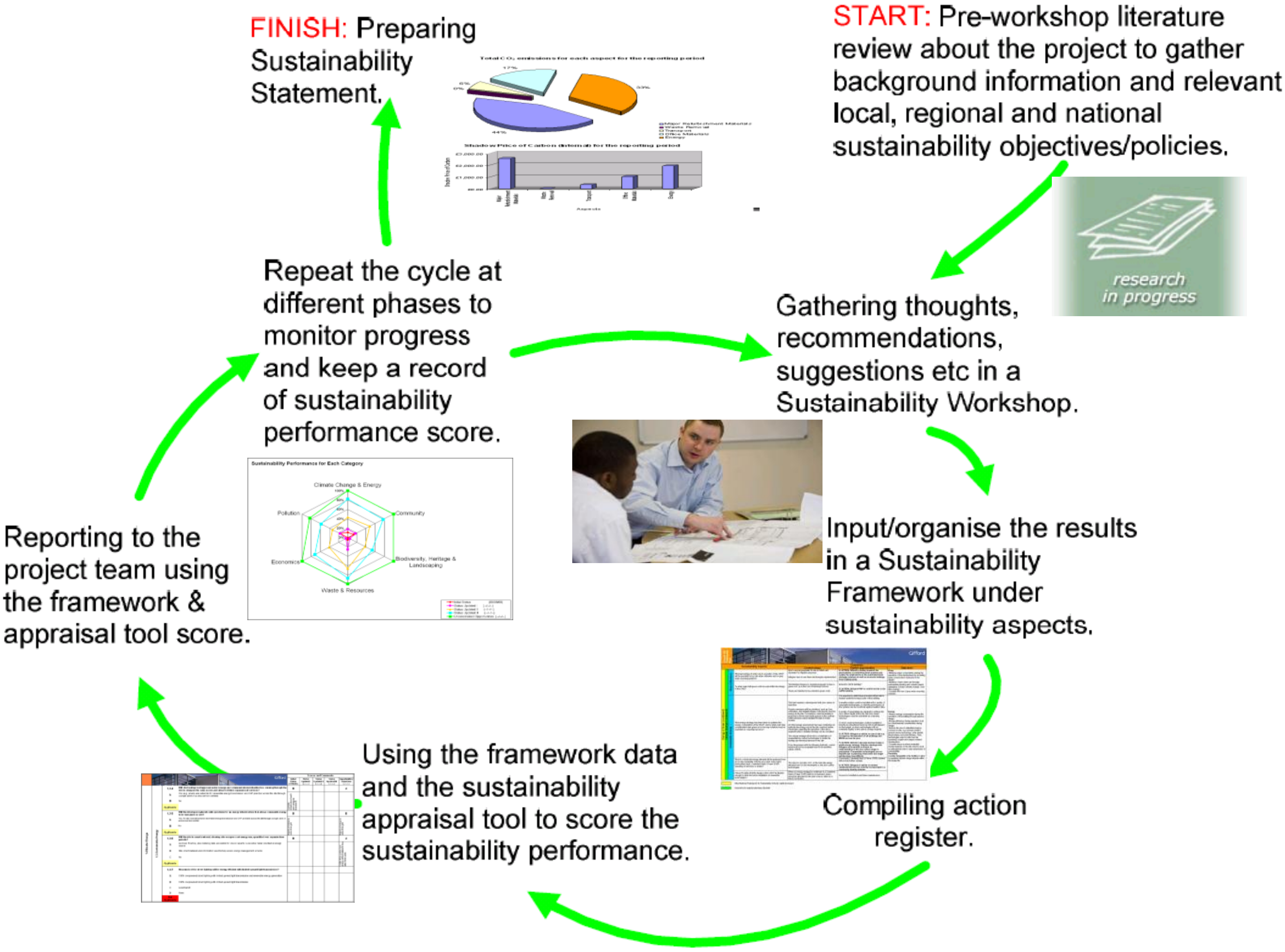


Fig. 4: GSAP process

They are similar to the indicators mentioned in *Opportunities for change: Consultation paper on a UK strategy for sustainable construction*, published by the Department of Environment, Transport and the Regions in 1998. Each category consists of a number of issues. *Climate change and energy*, for example, considers the following matters

- *flooding*
- *heat island*
- *sustainable energy*
- *climate change adaptation*

Their impacts are evaluated by addressing one or more questions. For example, the questions considered within *sustainable energy* may include

- What steps will the developer take to produce an energy strategy for the proposed development to optimise the energy consumption of the site?
- What % of total site energy demand will be produced from a renewable source (e.g. wind, solar, hydro, photovoltaic bank, etc)?
- To what extent will the development take into account the hierarchy for feasible heating system?

Some possible responses and associated scores are provided and used together with weighting factors to determine the project's current (initial) sustainability performance. The process is repeated as the design progresses and any changes to sustainability performance recorded. This not only allows sustainability performance to be monitored but also the decisions which resulted in the changed status recorded.

After each assessment has been carried out, the sustainability performance of each category as well as an overall sustainability performance score is determined and a comparison of current status and unconstrained opportunities illustrated by means of the spider graph shown in Fig. 5 produced, where the outer layers represent the highest attainable sustainability performance.

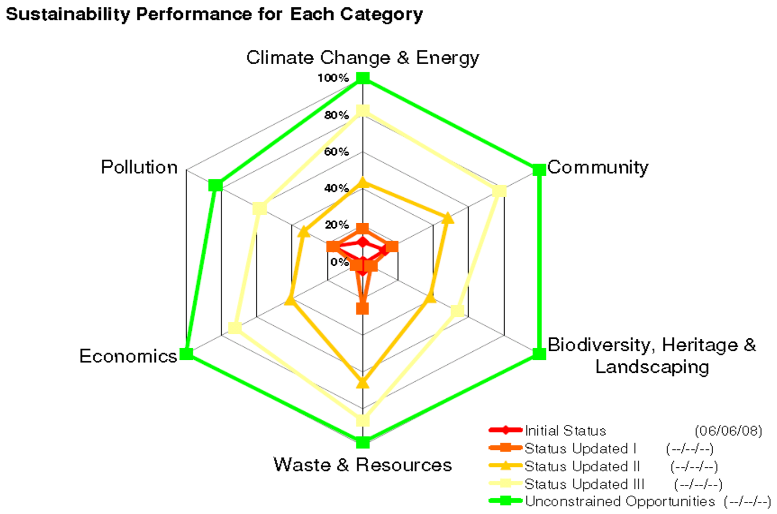


Fig. 5

1.7 **System for Appraising the Sustainability of Structures (SASS)**

SASS[15] is a quantitative method developed at UCL to appraise the sustainability of bridges. However, the methodology is sufficiently general that its use could be extended to other civil engineering structures. Unlike the other methods discussed in this chapter, SASS does not give an absolute measure of sustainability but is used to compare different design and maintenance strategies. Fig. 6 shows the indicators used to appraise sustainability. Note that *resource use* includes *energy*, *materials*, *land* and *water*. In all cases, performance is evaluated in numerical terms. The following briefly describes the scope of each factor and how individual impacts are scored and ultimately combined in order to obtain an overall sustainability score for the scheme.

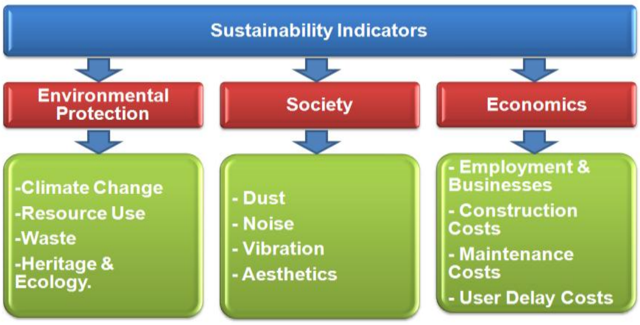


Fig. 6: SASS sustainability indicators

1.7.1 Climate change

SASS assumes climate change is directly related to carbon dioxide emissions. The model enables the CO_2 equivalent emissions associated with the following items/activities to be estimated:

- manufacture of materials for construction and maintenance work
- transport of materials from factory gate to building site
- plant required for construction
- transport of construction and demolition waste
- transport for employees from home to building site
- traffic congestion during maintenance work.

The impact is measured in tonnes of CO_2 emissions.

1.7.2 Energy

The aim is to promote energy efficiency. SASS enables the energy required for the following operations to be taken into account:

- manufacture of materials for construction and maintenance work
- transport of materials from factory gate to building site
- operation of plant/equipment
- transport of construction and demolition waste.
- transport for employees from home to building site
- traffic congestion during maintenance work.

The impact is measured in gigajoules of energy required.

1.7.3 Materials

This indicator takes account of both the amount and source of materials required for construction and maintenance work. Thus the use of virgin materials, especially those derived from non-renewable sources, is discouraged whereas the opposite is true of construction material reused on site.

The impact is assessed by multiplying the weight of material required by the corresponding resource impact factor (Table 1.8) and summing the scores.

Origin	Weight (t)	Resource impact factor	Score
% reused on site		× 1	
% reused transported off site		× 2	
% recycled onsite		× 2	
% recycled transported offsite		× 3	
% virgin responsibly sourced		× 4	
% virgin		× 5	
Total score			

Table 1.8 Material use impact

1.7.4 Land

The aim is to minimise the area of land required for the project as well as any adverse effect of construction and/or maintenance work at or below ground level or to adjacent property. SASS recommends that the impact of land is determined taking account of

- total land take
- quality of land at end of project
- % brown-field
- % agricultural land
- adverse effect on surrounding properties due to proposed works e.g. increased risk of flooding and potential loss of mineral resources.

1.7.5 Water

The aim is to minimise water usage on the project and the risk of contamination of surface and ground water. On this basis, SASS recommends that the impact is based on the following factors:

- total volume of potable water required
- risk of contamination of water courses and mitigation measures
- risk of contamination of ground water and mitigation measures
- past performance.

1.7.6 Waste

The aim here is to minimise the amount of hazardous waste and the volume of material going to land fill. A further aim is to promote the greater use of waste materials during construction and maintenance operations and design for deconstruction. SASS recommends performance in this area should be evaluated by considering

- total volume of waste
- volume of waste going to land fill
- volume of waste reused/recycled
- volume of hazardous waste produced
- past performance ?????????.

The impact is assessed by multiplying the amount of waste in each category by the corresponding waste impact factor (Table 1.9) and summing the results.

Disposal	Weight (t)	Waste impact factor	Score
% reused on site		× 1	
% transported off site & reused		× 2	
% recycled onsite		× 2	
% recycled transported offsite & reused		× 3	
% landfill no hazard		× 4	
% land fill hazardous		× 5	
Total score			

Table 1.9 Waste impact

1.7.7 Heritage, Ecology and Biodiversity

The aim is to minimise use of land of high ecological or heritage/archaeological value. A further aim is to minimise any adverse effect on wildlife and artefacts of heritage/archaeological value during construction and maintenance operations. The impact is based on

- area of land of high ecological value required
- % of wildlife that will be adversely affected during construction and operation phases
- area of site on land of high heritage/archaeological value
- % of heritage/archaeological features that will be adversely affected during construction and operation phases

1.7.8 Aesthetics

Aesthetics is assessed using work presented by the Australian Roads and Traffic Authority and the Highways Agency. Aesthetics is based purely on a series of questions. The method involves making separate assessment of

- the bridge as a whole
- the bridge and its surroundings
- parts and details
- public consultation.

The responses are used to score the design.

1.7.9 Noise

Undesirable sound is referred to as noise. Noise can affect human being in several ways including annoyance, interference with various activities, hearing loss and stress leading to a number of health problems. SASS assesses noise impact based on

- net increase in noise level
- duration
- effect on neighbours
- public consultation and past performance
- mitigation measures.

1.7.10 Dust

Dust emissions from construction activity are a common and well recognised problem. Some of the harmful effects of dust include lung problems, eye irritation and carcinogenicity, nuisance due to surface soiling of property, damage to plant and aquatic life.

SASS assesses the impact based on a set of questions which examine

- net increase in dust level
- duration
- effect on neighbours
- public consultation and past performance.

1.7.11 Vibration

Site operations such as blasting, pile driving, dynamic compaction of loose soils and use of heavy equipment can cause ground and structural vibrations. Excessive vibrations can also result in nuisance to local communities, interference with sensitive equipment and decrease in serviceability and durability of structures.

Vibration is assessed in a similar fashion to noise and involves consideration of

- vibration dose
- duration
- effect on neighbours
- public consultation and past performance.

1.7.12 Constructions costs

The aim is to minimise the initial cost of construction. This principally involves estimating the cost of labour, equipment and materials. The impact is measured in monetary terms.

1.7.13 Maintenance costs

The aim is to minimise the cost of routine maintenance and repair work required over the life time of the structure. This principally involves estimating engineering as well traffic management costs in monetary terms.

1.7.14 Traffic delay costs

The aim is to minimise the amount of traffic disruption during maintenance operations. This involves principally taking account of

- number of maintenance interventions
- durability of the repair
- length of road closure
- duration of road closure
- timing of work
- traffic flow rate
- percentage of heavy goods vehicles.

This impact is also measured in monetary terms.

1.7.15 Employment and businesses

The aim is to minimise impacts and maximise opportunities for local communities/businesses. This is assessed by means of a series of questions which evaluate the potential to employ local labour and benefits for local businesses. Also considered are the potential adverse effects on local communities and mitigation measures.

1.7.16 Calculating the sustainability score

The scores for the various indicators are recorded in the column headed *Quantity* in Table 1.10. In order to obtain an overall sustainability score the individual values must be combined. In SASS this is achieved using a normalising technique in which the score for a given factor are reduced to a dimensionless value. This also allows comparison with similar normalized scores for other factors. The normalised scores may then be weighted and the weighted scores summed in order to arrive at an overall sustainability score for the scheme.

Indicators	Bridge 1				Bridge 2				Bridge 3			
	Weighting (W)	Quantity	Normalised Score (N)	Weighted Score (W × N)	Weighting	Quantity	Normalised Score	Weighted Score	Weighting	Quantity	Normalised Score	Weighted Score
Environment												
CO_2 emitted												
Energy consumed												
Material use												
Waste												
Heritage, Ecology & Biodiversity												
Water												
Land												
Society												
Dust												
Noise												
Vibration												
Aesthetic												
Safety & Accessibility												
Economy												
Construction cost												
Maintenance cost												
Traffic delay cost												
Employment & Business												
Sustainability score												

Table 1.10: Specimen table for use with SASS

1.8 Conclusions

This chapter has discussed the salient features of a number of appraisal tools which can be employed to measure the sustainability performance of various forms of construction such as buildings, civil infrastructure and even entire cities, at different stages of their life cycle. These tools are largely based on the indicators introduced by the UK government to define and monitor sustainable development. Use of these tools should assist the construction industry take account of the plethora of recent legislation, policy, codes of practice, voluntary standards, etc, on achieving sustainable development. Some of the tools discussed are well established such as BREEAM and CEEQUAL whereas others are perhaps less well-known e.g. SASS and GSAP, either because they are relatively new or have been developed by private organisations and are predominantly used in-house.

The review has also revealed that

- some of the tools are heavily biased towards evaluation of environmental impacts and do not in actual fact measure sustainability
- in some cases the method of assessment is not robust and the tool open to misuse/bias
- some tools do not combine impacts thus making it difficult to determine which solution is the most sustainable where several options exist and also to optimise designs
- it is important to identify and agree sustainability aspirations at the outset of the project before devising design solutions.

Tools such as BREEAM are largely concerned with measuring performance during operational life since this generally represents the major impact associated with building structures. However this can make it difficult for civil and structural engineers to readily appreciate their role in achieving sustainable construction. Road traffic is one of the major sources of carbon dioxide emissions in the UK[19] and beyond. It reduces air quality and also adds significantly to noise and dust pollution. The emissions/pollution from road traffic will no doubt increase still further in future years as population levels rise and the world becomes more affluent. Some of the major initiatives used to reduce road traffic impact include

- implementation of tighter emission standards for new vehicles,
- the development of cleaner fuels,
- encouraging less car usage
- greater use of public transport.

Another important initiative which appears to have been overlooked thus far is to reduce the idle time experienced by drivers during repair and maintenance of highways, in particular bridge structures. Lane closures or other forms of traffic management during maintenance work invariably leads to a reduction in traffic speeds and sometimes stop-start driving. This increases both fuel consumption and CO_2 emissions. SASS can be used to appraise the impact of alternative bridges designs on these and other environmental as well as societal and economic factors. The following chapter provides detailed guidance on this method of sustainability appraisal and will hopefully assist students of civil and structural engineering appreciate the effect of design decisions pertaining to choice of construction material, structural form and method of construction on sustainability and thus show how they can fully contribute to the vision of sustainable development.

Chapter 2: A comparison of bridge options

2.1 Introduction

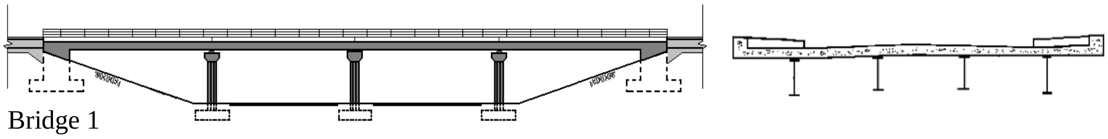
In order to demonstrate the SASS methodology three outline bridge designs were prepared. All were intentionally overbridges carrying a two-way access road, with a total carriageway width of 7.3 m and 2.5 m wide footpaths on both sides, across a dual two lane motorway. Both the road and the motorway were assumed to be regularly salted in winter which would lead to corrosion of embedded reinforcing steel.

The motorway was assumed to have an AADT (Average Annual Daily Traffic Flow) of approximately 80,000 vehicles in both directions of which 20% are heavy goods vehicles (HGV). The AADT for the access road was taken as 6,000 vehicles of which 10% are HGV. It was further assumed that the motorway and bridge would open to traffic at the same time.

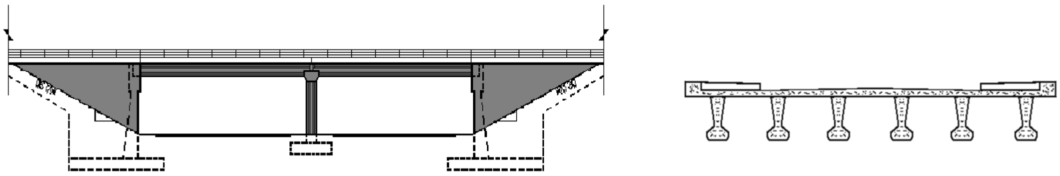
The scheme is situated in an area of ‘outstanding natural beauty’ and any structure at the proposed location will be highly visible, therefore an aesthetically pleasing design was deemed necessary. Moreover it was assumed that the bridge is sited close to a hospital.

2.2. Bridge options

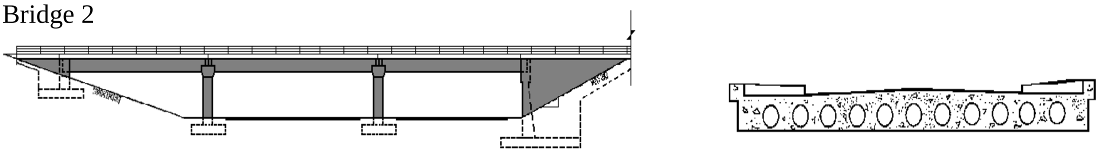
Details of three proposed bridge options are shown in Fig. 7[20]. Bridge 1 is a four span continuous steel beam and slab bridge with integrated bank seat foundations and three intermediate leaf piers. Bridge 2 is a two-span simply supported prestressed concrete beam and slab bridge with cantilever abutments and an intermediate leaf pier. Bridge 3 is a three span voided concrete slab bridge with a full height abutment at one end and a bank seat at the other and two intermediate portal piers. Further construction details can be found in Chapter 3. It should be noted that these options are not necessarily typical of designs that would be used in practice but were selected for various practical reasons and also provide sufficient scope to demonstrate the versatility of the appraisal method. The evaluation considered two phases of bridge provision, namely construction and in-service, to give the life time sustainability.



(a) Bridge 1



(b) Bridge 2



(c) Bridge 3

Figure 7 - Bridge design options

2.3 Sustainability Appraisal

The measurement of sustainability involves combining the effects of an activity on the environment, the economy and society. The following discusses how SASS was used to evaluate the individual themes of sustainability and how they are combined to give a measure of sustainability.

2.3.1 *Environmental Impact Assessment*

As discussed in section 1.7, SASS recommends use of the following set of indicators to measure environmental performance:

- Climate change
- Energy consumption
- Materials usage
- Waste
- Heritage, Biodiversity and Ecology
- Water
- Land

In this exercise only the first three indicators were considered. It was assumed that the other indicators would have similar impacts across all schemes. The way in which each indicator was assessed is discussed below.

2.3.1.1 CLIMATE CHANGE

SASS assumes climate change is directly related to carbon dioxide emissions. In this exercise the CO_2 equivalent emissions associated with the following items/activities were calculated:

- manufacture of materials for construction and repair work
- transport of materials from factory gate to building site
- traffic congestion due to repair and maintenance work.

The other items/activities recommended by SASS were assumed to be the same for all schemes and were therefore excluded from consideration.

(a) CO_2 for production and transportation of materials

(i) Embodied CO_2

Table 2.1 shows for selected materials the embodied tons of CO_2 produced per tonne of material production and per tonne.km of material transported to the construction site. The values in the table are based on inventories/guidance produced by a number of bodies including the University of Bath[21], DEFRA (Department for Environment, Food and Rural Affairs)[22] and the Environment Agency[23]. The transport emission factor (i.e. 1.32×10^{-4}) is for an average heavy goods vehicle (HGV).

Material	Tons of CO_2 Production emission factor (tonne)	Transport emission factor (tonne.km)
OPC	0.97	1.32×10^{-4}
Aggregate	0.008	〃
Stainless steel	6.15	〃
Steel beams	1.79	〃
Steel reinforcement	1.72	〃
Parapets	2.82	〃
Water proofing	8.28	〃
Paint	6.10	〃

Table 2.1: Embodied tonnes of CO_2 per ton of construction material for production and transportation

(ii) Weights of materials

The weights of materials required for construction and lifetime maintenance of the three bridge structures are shown in Table 2.2. The weights of materials necessary for construction were estimated from the working drawings. The weights of materials required for repair were obtained using the information in Table 2.3. This is based on DMRB BD36[24] and assumes that, because of deterioration, a percentage of the relevant surface area of material/item will need to be replaced at given intervals of time.

(iii) Transportation

The CO_2 produced during transportation of materials from factory gate to building site was calculated assuming the transport distance for all materials was 25 km.

	Bridge 1		Bridge 2		Bridge 3	
Material	Construction (tonnes)	Lifetime repairs (tonnes)	Construction (tonnes)	Lifetime repairs (tonnes)	Construction (tonnes)	Lifetime repairs (tonnes)
OPC	357	19	341	42	417	49
Aggregate	1386	72	1327	163	1618	190
Stainless steel reinforcement	140	-	-	-	296	-
Steel beams	65	-	-	-	-	-
High Yield reinforcement	340	-	482	-	204	-
Parapets	17	6	17	6	17	6
Water proofing	1.2	0.36	0.4	1.2	0.6	1.8
Paint	0.08	0.03	-	-	-	-
Asphaltic joints	-	-	3	-	4	-
Total weights	2306.3	97.4	2170.4	212.2	2556.6	246.8

Table 2.2: Materials required for construction and lifetime maintenance of Bridges 1-3

Maintenance activity	Frequency (years)	Defect repair area
Concrete repairs - E2	30	10%
Concrete repairs – E3	30	50%
Stainless steel	120	-
Steel beams	120	-
Steel reinforcement	120	-
Parapet replacement	30	10%
Water proofing	30	100%
Steelwork painting	25	10%

Table 2.3: Frequency of repair work and defect area

(iv) CO_2 emissions: production and transportation

The CO_2 produced during manufacture of materials was obtained from

$$\text{Mass of material} \times \text{Production emission factor} \quad \text{--------------(1)}$$

The CO_2 produced during transport of materials was obtained from

$$\text{Mass of material} \times \text{Transport distance} \times \text{Transport emission factor} \quad \text{--------------(2)}$$

The results for Bridges 1-3 are summarise in respectively Tables A1-A3 (Appendix A).

(b) CO_2 due to traffic congestion

Lane closures or other forms of traffic management during maintenance work invariably leads to a reduction in traffic speeds and sometimes stop-start driving. This increases both fuel consumption and CO_2 emissions.

The quantities of extra CO_2 produced as a result of traffic congestion during maintenance operations depend on

- duration of maintenance work over life time in days
- length of road with traffic management
- flow of HGV per day and the normal kg of CO_2 per km produced
- flow of other vehicles per day and the normal kg of CO_2 per km produced
- kg of CO_2 emitted per km by HGV and other vehicles[22] i.e. vehicle emission factor (respectively, 0.906 and 0.2042)
- additional emissions during maintenance work[25] i.e. congestion emission factor (assumed to be 30% of normal values)
- whether or not the work is carried out at night or during off-peak hours i.e. road user delay influence factor

(i) Lifetime duration of maintenance work

This principally depends on

- Type of maintenance activity
- Frequency of repair work
- Extent of repair
- Rate of repair
- Lifetime number of treatments

Table 2.4 shows the various maintenance activities required for Bridge 1. Note that waterproofing renewal, parapet repair and joint replacement were not considered as it was assumed that these operations will be carried out from the top surface of the bridge where traffic volumes are comparatively low and would therefore cause negligible congestion. The table also shows the expected frequency of each maintenance activity, the associated extent of deterioration as well as the rates of repair. The latter were used to calculate the works duration time. The total number of treatments required over the life of the structure was estimated using the design life, which for bridges is normally taken as 120 years. For example, in the case of concrete repairs a total of three maintenance interventions will be necessary in order that the structure remains serviceable throughout its design life i.e. in years 30, 60 and 90. Finally the lifetime duration of each maintenance action is obtained by multiplying the time required to undertake a single action by the total number of actions required during the life of the structure.

Maintenance Activity	Frequency (years)	Total extent	Extent of inspection/repair	Rate of inspection/repair	Duration of work	Lifetime number of treatments	Lifetime duration (days)
Inspection	5	4 spans	100%	1 span/day	4 days	23	4 × 23 = 92
Drain cleaning	2	4 spans	100%	½ span/day	2 days	59	2 × 59 = 118
Concrete repairs – E2	30	500 m^2	10% × 500 = 50 m^2	2 m^2 per wk	25 wks (175 days)	3	175 × 3 = 525
Steelwork painting	25	800 m^2	10% × 800 = 80 m^2	25 m^2 per wk	3.2 wks (23 days)	4	23 × 4 = 92

Table 2.4: Maintenance data for Bridge 1

(ii) Length of lane closures

Table 2.5 shows the assumed lengths of lane closures required for maintenance of Bridge 1. It was assumed that bridge inspection would be carried out from a mobile elevated platform and would require short lengths of lane closures in order to complete. Concrete repairs and steelwork painting are both substantive operations however and would both require a full carriageway closure and the provision of a contraflow. Since the central reservation crossover points are 2 km apart a minimum traffic management length of 3 km was judged appropriate.

Maintenance Activity	Length of traffic management (km)
Inspection	0.2
Concrete repair	3
Painting	3

Table 2.5: Length of the closure required for maintenance work

(iii) Road user delay influence factor

Some maintenance activities such as bridge inspections can be carried out over short periods of time. Thus, it would be reasonable to assume that this work would be scheduled at weekends or other off peak times when traffic volumes are low, thus minimising the disruption to road users. Under these circumstances it would be appropriate to use the road user delay influence factor to calculate CO_2 emissions (Table 2.6). However, it should be remembered that off-peak and particularly night working will also increase labour costs.

	Road user delay influence factor
Day working	1.0
Off peak / Night working	0.25

Table 2.6: Road user delay influence factor[22]

(iv) CO_2 emissions: traffic congestion

The CO_2 emissions due to traffic congestion were determined using the following expression

Lifetime duration of maintenance work × length of lane closure required ×
average daily vehicle flow × vehicle emission factor × congestion emission factor ×
road user delay influence factor (where relevant) -------------(3)

Tables A4-A6 summarise the CO_2 emissions due to traffic congestion for Bridges 1-3 respectively.

(c) Lifetime CO_2 emissions

Table 2.7 summarises the lifetime CO_2 emissions for the three bridge structures.

Bridge	CO_2 for production and transport (tonnes)	CO_2 due to congestion (tonnes)	Lifetime CO_2 emissions (tonnes)
1	2,025	15,245	17,270
2	1,299	12,522	13,821
3	2,732	14,616	17,348

Table 2.7: Lifetime CO_2 emissions for Bridges 1, 2 and 3

2.3.1.2 **ENERGY CONSUMPTION**

In this exercise the energy consumed during the following operations was considered:

- manufacture of materials for construction and repair
- transport of materials from factory gate to building site
- traffic congestion occurring during repair work due to any enabling works e.g. lane closures.

The other items/activities recommended by SASS (see Section 1.7.2) were assumed to be the same for all schemes and were therefore excluded from consideration.

(a) Energy for production and transportation of materials

(i) Embodied energy

Table 2.8 shows for selected materials the energy consumed per tonne of material for production and per tonne.km of material transported to the construction site. This data is principally based on inventories produced by the University of Bath[21], DEFRA (Department for Environment, Food and Rural Affairs)[22] and the Environment Agency[23]. The transport energy factor is based on the DEFRA transport emission factor for an average heavy goods vehicle (HGV) and the DEFRA GHG (green house gas) conversion factor which gives respectively the average diesel consumption per ton.km for an HGV and the CO_2 produced per ton.km. The energy consumed per ton.km is based on the diesel consumption and the calorific value of diesel.

Material	Gj of energy	
	Production energy factor (tonne)	Transport energy factor (tonne.km)
OPC	6.1	2.0×10^{-3}
Aggregate	0.15	〃
Stainless steel	51.5	〃
Steel beams	22.7	〃
Steel reinforcement	22.7	〃
Parapets	35.8	〃
Water proofing	140	〃
Paint	80	〃

Table 2.8: Gj of energy per ton of construction material for production and transportation

(ii) Weights of materials

The weights of materials required for construction and lifetime maintenance are shown in Table 2.2 above.

(iii) Transportation

The energy required for transportation of construction and repair materials from factory gate to building site was calculated assuming the transport distance for all materials was 25 km.

(iv) Embodied energy: production and transportation

The energy required for production was determined from

Mass of material × Production energy factor ------------------(4)

The calculation of energy required for the transportation of materials to site was obtained from

Mass of material × Transport distance × Transport energy factor --------------(5)

Tables A7-A9 summarise the energy required for production and transportation of materials obtained for Bridges 1-3 respectively.

(b) Extra energy consumption due to traffic congestion

The quantities of extra energy used as a result of traffic congestion during maintenance operations depends on

- duration of maintenance work over lifetime in days (Table 2.4)
- length of road with traffic management (Table 2.5)
- flow of HGV per day and the normal fuel consumption
- flow of other vehicles per day and the normal fuel consumption
- additional fuel consumption during maintenance work i.e. congestion energy factor (assumed to be 30%[25] of normal values)
- whether or not the work is carried out during off-peak hours (Table 2.6)
- kg of CO_2 emitted per km by HGV and other vehicles (respectively, 0.906 and 0.2042)
- kg of CO_2 emitted per litre of fuel (2.63 kg and 2.33 kg for respectively diesel and petrol)
- calorific value of fuel (46 Mj/kg and 44.8 Mj/kg for respectively diesel and petrol
- density of fuel (0.885 kg/l and 0.737 kg/l for respectively diesel and petrol)

The last four quantities were used to calculate the *energy consumption factor* as follows:

Energy consumption factor for HGVs = $\frac{0.906}{2.63} \times 46 \times 0.885 = 14\ Mj / km$

Energy consumption factor for HGVs = $\frac{0.2042}{2.33} \times 45.85 \times 0.737 = 3 Mj / km$

(ii) Energy consumption: Traffic congestion

The extra energy consumption due to traffic congestion during maintenance work was determined using the following expression

Total duration of maintenance work × length of lane closure required × average daily vehicles flow × energy consumption factor × congestion energy factor × road user delay influence factor (where relevant) --------------(6)

Tables A10-A12 show the results of this analysis for Bridges 1-3 respectively.

(c) Lifetime energy consumption

Table 2.9 summarises the lifetime energy consumption for the three bridges.

Bridge	Energy for production and transport (Gj)	Energy due to congestion (Gj)	Lifetime energy consumption (Gj)
1	20,055	230,080	250,135
2	14,676	188,985	203,661
3	24,299	220,578	244,877

Table 2.9: Lifetime energy consumption for Bridges 1, 2 and 3

2.3.1.3 **MATERIALS USAGE**

This represents the sum of the materials needed for construction and lifetime maintenance of the structure (see Table 2.2) and was simply obtained by summing the weights of all the materials required for each bridge. The results are summarised in Table 2.10.

Bridge	Weight of materials for construction (tonnes)	Weight of materials for maintenance (tonnes)	Lifetime material use (tonnes)
1	2,306	98	2,404
2	2,171	212	2,383
3	2,556	247	2803

Table 2.10: Lifetime material use for Bridges 1, 2 and 3

2.3.2 *Economic Impacts Assessment*

SASS assesses lifetime economic impacts in terms of

- cost of construction
- cost of maintenance
- cost of traffic delays caused by maintenance work.

The latter two costs are discounted to take account of when, during the life of the structure, the costs occurred. As noted in the introduction it was assumed that the motorway and bridge would open to traffic at the same time and therefore no traffic delay costs would occur during construction.

2.3.2.1 COST OF CONSTRUCTION

The initial cost of construction can be obtained using standard surveying techniques. This involves preparing bills of quantities which itemise the types of work and the quantities required. An estimate of the price of unit item of work can be obtained from past contracts or via the SPON's Price Book[26] and used to calculate the total cost of the structure. However in this work, the cost of construction was simply based on a rate per m^2 of deck, assumed to £1000/m^2, thus giving the values shown in Table 2.11.

Bridge	Area of bridge deck (m^2)	Cost (£)
1	64 × 12.3 = 787.2	787,200
2	32 × 12.3 = 393.6	393,600
3	48 × 12.3 = 590.4	590,400

Table 2.11: Cost of construction of Bridges 1, 2 and 3

2.3.2.2 COST OF MAINTENANCE WORK

SASS assumes that the cost of maintenance work principally depends on:

- Engineering costs
- Access cost
- Traffic management costs
- Overheads

The way in which these costs are estimated is outlined below.

(i) Engineering costs

Engineering costs depend on

- Type of maintenance work
- Extent of work
- Rate of repair

Table 2.12 lists common maintenance options for bridges together with some information necessary for estimating the engineering costs of the various treatments. The data has been taken from Design Manual for Roads and Bridges BD36[24] issued in draft form in 2002. The maintenance costs in this document are at 1998 prices and have been updated to 2009 values using the Price Index Factor given by

$$\text{Price Index Factor} = \frac{\text{The current Retail Price Index}}{160.2} \quad \text{--------------(7)}$$

Also included in the table is information on the frequency of maintenance work. In some cases e.g. inspection and drain clearing, the figures quoted are based on recommended practice. In other cases e.g. joint replacement and steelwork painting, the frequency may be based on past experience and/or manufacturer's recommendations. Yet in other case e.g. deck waterproofing replacement, it would make sense if this work coincided with pavement renewal, in order to minimise traffic disruption.

The service life of the element or maintenance option also depends on the exposure. Table 2.12 gives details of exposure classes relevant to bridge structures. The values for concrete subjected to E2 exposure shown in Table 2.12 assume that concrete will be repaired every 30 years which will result in 10% of the existing surface area needing replacement. From Table 2.14 it can be seen that if the work was carried out sooner it would be cheaper and quicker to complete as both the severity and extent of the defective concrete would be smaller. However, a greater number of maintenance intervention would be required, which could well increase lifetime costs due to higher traffic management and traffic delay costs (see below).

Generally it will be economical to combine maintenance activities e.g. repainting the steelwork and carrying out concrete repairs, as this should reduce overall disruption to road traffic and hence reduce traffic delay costs.

Maintenance options	Frequency (years)	Defect repair area	Cost (£)	Rate
Inspection	5		£1,100/span	1 span/day
Drain cleaning	2		£300/span	½ span/day
Water proofing	30	100%	n/a	n/a
Buried joint replacement	10		£100/m	60m/wk
Steelwork painting - E2	25	10%	£35/m^2	25 m^2/wk
Concrete repairs - E2	30	10%	£1,600/m^2	2 m^2/wk
Concrete repairs – E3	30	50%	£1,600/m^2	2 m^2/wk
Parapet replacement	30	10%	n/a	n/a

Table 2.12: Maintenance options and access

Exposure class	Corrosion Environment	Typical element location
E1 Protected	Low	Element protected from slat spray with silane or enhanced durability measures
		Elements protected from salt spray by a protective enclosure.
E2 Sheltered Exposure	Medium	Bridge soffit subject to light vehicle spray from salted road.
		Top of roadside bridge pier or abutment subject to light vehicle spray from salted road.
E3 Severe	High	Roadside bridge abutment, parapet upstand or deck edge beam subject to heavy vehicle spray from salted road.
		Section of bridge deck of leaking expansion joint or gutter e.g. deck end crosshead
		Top surface of unwaterproofed bridge decks.
		Areas where corrosion or spalling of surface concrete is evident.

Table 2.13: Exposure classes

Exposure class	Time to Maintenance (years)	Defect repair area	Cost (£ per m^2)	Rate (m^2 per week)
Reinforced concrete decks and main members, including substructures				
E1	No defects			
E2	10	2%	300	8
	20	5%	600	4
	30	10%	1200	2
E3	10	10%	1200	2
	20	20%	1200	2
	30	50%	1200	2
Pre-stressed decks and main members				
E1	No defects			
E2	10	-	-	-
	20	5%	1200	2
	30	10%	1200	2
E3	10	5%	1200	2
	20	10%	1200	2
	30	20%	1200	2

Table 2.14: Concrete repairs to reinforced concrete and prestressed elements (DMRB BD 36[24])

(ii) Access cost

Table 2.15 shows two methods which are used to gain access to bridges during maintenance work. The costs have been taken from DMRB BD36[24] and updated to 2009 values by multiplying by the Price Index Factor (equation 7).

Methods	**Cost**
Scaffolding	£1.50 m^2/day
Mobile elevated platform	£400/day

Table 2.15 Access costs

(iii) Traffic management costs

Traffic management costs depends on

- type of maintenance work
- method of maintenance
- element to be maintained
- density and mix of traffic
- extent, duration and length of the lane closure required.

Table 2.16 shows various traffic management systems applicable to bridge maintenance contracts. Again, the costs have been taken from DMRB BD36[24] and updated to 2009 values by multiplying by the Price Index Factor (equation 7).

Type of traffic management	**Cost**
Single lane closure	£600 per day
Two lane closure	£700 per day
*Two lane closure with contraflow	£1800 per day
**Full carriageway closure	£1100 per day
Automatic traffic control	£1100 per day

* For a two lane dual motorway ** For a two-lane dual carriageway road

Table 2.16 Traffic management costs

(iv) Overheads

DMRB BD36 recommends that the cost of contract overheads should be based on the value of preventative maintenance work but excluding the cost of traffic management and access. Preventative maintenance is defined as work that is not essential now but may be justified on economic grounds. It includes items such as joint replacement, steelwork painting and concrete repairs. In this work overhead costs were estimated using the figures shown in Table 2.17 which have been taken from DMRB BD36 and updated to 2009 values by multiplying by the Price Index Factor.

Value of preventative maintenance work	**Weekly cost (£)**
< £50,000	700
£50,000 – £250,000	1,300
£250,000 - £1,000,000	6,500
> £1,000,000	13,000

Table 2.17 Overhead costs

(v) Discount rates

Expenditure on construction and maintenance (including the effects of traffic delays) will occur at different stages during the life of the structure, which means that cost estimates should take account of the time value of money. Costs arising in different years may be reduced to their present values by a process known as discounting. Normally this is achieved using the following formula

$$\text{Discounted cost} = \frac{Undiscounted\ \cos t}{(1+i)^{n}} \quad \text{------------------(8)}$$

where
i is the discount rate
n is the age of the bridge when the maintenance activity is carried out.

The discount rates for highway structures used in this work are shown in Table 2.18 and were obtained from the Treasury Green Book[27].

Age (years)	Discount rate (%)
0 - 30	3.5
31 - 75	3.0
76 -125	2.5

Table 2.18: Discount rates for different ages

Example 1: <u>Cost of inspecting Bridge 1</u>

<u>Labour/equipment</u>
Cost = £1100/span (Table 2.10)
Assuming work will be carried out at weekends, increase cost by 1.5 ⇒ cost = £1100 × 1.5 = £1,650/span
Total number of spans = 4 (Fig. 2.1)
∴Total cost = £1,650 × 4 = £6,600

<u>Gaining Access</u>
Assume access will be from a mobile working platform
Cost of mobile platform = £400 / day (Table 2.14)
Rate of inspection = 1 span/day
Since bridge has four spans, work duration = 4 days
∴**Total** cost = £400 × 4 = £1,600

<u>Traffic management</u>
Assume two lanes will be closed while the inspection work is carried out.
Cost = £700/day (Table 2.11). Since work will be carried out at weekends, increase cost by 1.5 = £700 × 1.5 = £1,050/day
Cost of traffic management = £1050 × 4 = £4,200

<u>Overheads</u>
Not applicable since this is routine maintenance

<u>Engineering cost</u>
Engineering cost = Labour/equipment + Gaining access + Traffic management + Overheads
= £6,600 + £1,600 + £4,200 + 0 = £12,400
Lifetime number of treatments = 23 (Table 2.3)
Lifetime engineering cost = Cost of treatment × Lifetime number of treatments = £12,400 × 23 = £285,200

Discounted lifetime engineering cost = $\sum_{i=1}^{6} \frac{12,400}{(1+0.035)^{5i}} + \sum_{j=7}^{15} \frac{12,400}{(1+0.03)^{5j}} + \sum_{k=16}^{23} \frac{12,400}{(1+0.025)^{5k}}$ = £76,935.46

2.3.2.2 TRAFFIC DELAY COST

Some types of maintenance activity cause traffic congestion as a result of lane closures to provide access to parts of the bridge or for the protection of workers. The extent of this disruption depends on

- the number of lanes closed
- the total number of lanes
- whether or not there is contraflow working
- the length of the lane closure
- the average daily traffic flow
- the proportion of the traffic that are HGVs.

The Department for Transport's (DfT) computer program called Queues and Delays at Roadworks (QUADRO) takes these factors into account to calculate the monetary consequences of the delays caused by the disruption to traffic for each day the disruption lasts. The DfT has also produced tables which can be used in lieu of running QUADRO (see Appendix B). Note that the costs in these tables are given at 1998 prices and should be updated to 2009 prices using the Price Index Factor discussed earlier, prior to use.

As previously noted it was assumed that drain cleaning, parapet repair and joint replacement will be undertaken from above deck. This should result in minimal traffic disruption because the vehicle flow rate on the bridge is relatively small and therefore the associated traffic delay costs would also be quite small.

It is further assumed that waterproofing will be carried out at the same as time as pavement reconstruction. In all likelihood the reconstruction operation would be part of a much wider road resurfacing scheme and not just confined to the bridge. Therefore, no allowance for traffic management and user delay costs regarding waterproofing was made in this work.

The delay cost for an activity is given

Daily delay cost × number of days the activity takes-----------------(9)

The lifetime delay cost is obtained by multiplying the values obtained from equation (9) by the number of treatments needed during the life of the bridge.

Like the engineering costs, delay costs must also be discounted which is carried out using equation (8). The lifetime discounted costs for a maintenance activity are obtained by summing the discounted lifetime cost for each activity.

Example 2: <u>Traffic delay cost of inspecting Bridge 1</u>

For a two lane dual motorway with 80,000 AADT and 20% HGV, one primary and two secondary lanes unaffected, Table 32 (TRRM Vol. 1 Annex 5.5.2)[28] gives a traffic delay cost of £103,000/day at 1998 prices over a length of 0.2km (Table 2.4).

Price Index Factor = 1.316 ⇒ Traffic delay cost at 2009 prices = 1.316 × £103,000 ≈ £135,600/day
Work will be carried out at weekends ⇒ Road user delay influence factor = 0.25 (Table 2.5)
Modified traffic delay cost = £135,600 × 0.25 = £33,900/day

From above, work duration = 4 days

$\therefore$ Traffic delay cost per inspection = £33,900 × 4 = £135,600

Total number of inspections required = 23 (Table 2.3)

$\therefore$ Lifetime undiscounted delay cost = £135,600 × 23 = £3,118,800

$$\text{Discounted lifetime delay costs} = \sum_{i=1}^{6} \frac{135{,}600}{\left(1+0.035\right)^{5i}} + \sum_{j=7}^{15} \frac{135{,}600}{\left(1+0.03\right)^{5j}} + \sum_{k=16}^{23} \frac{135{,}600}{\left(1+0.025\right)^{5k}} = £841{,}326.42$$

Details of the engineering and traffic delay costs of the other maintenance options for Bridge 1 can be found in Appendix C. Appendix C also provides full details of the engineering and traffic delay costs for the various maintenance actions required for Bridges 2 and 3.

Tables 2.19 and 2.20 summarises respectively the lifetime engineering and traffic delay costs for the maintenance activities required on Bridge 1.

Maintenance Activity	Frequency (years)	Cost of single application (£)	Age of bridge at each application	Life time cost (£)	Discounted life time cost (£)
Inspection	5	12,400	5, 10, 15, etc…… 115	285,200	76,935.46
Drain cleaning	2	1,200	2, 4, 6, 8, etc … 118	70,800	19,278.67
Painting	25	58,000	25, 50, 75, 100	232,000	49,001.10
Concrete repair	30	655,000	30, 60, 90	1,965,000	415,510.57
Total					£ 560,725.80

Table 2.19: Engineering costs of maintenance activities for Bridge 1

Maintenance activity	Length of lane closure (km)	Delay cost per day (£)	Duration of closure for each activity (days)	Delay cost for each activity (£)	Lifetime delay cost (£)	Discounted lifetime delay cost (£)
Inspection	0.2	33,900	4	135,600	3,118,800	841,326.42
Painting	3	201,400	23	4,632,000	18,528,800	3,913,498.40
Concrete repair	3	36,100	175	6,317,500	18,952,500	4,007,614.80
Total						£ 8,762,439.62

Table 2.20: Traffic delay costs of maintenance activities for Bridge 1

Tables 2.21 and 2.22 summarises respectively the lifetime engineering and traffic delay costs for the maintenance activities required on Bridge 2.

Maintenance Activity	Frequency (years)	Cost of single application (£)	Age of bridge at each application	Life time cost (£)	Discounted life time cost (£)
Inspection	5	6,200	5, 10, 15, etc…… 115	142,600	38,467.73
Drain cleaning	2	600	2, 4, 6, 8, etc … 118	35,400	9,639.34
Concrete repair	30	1,156,700	30, 60, 90	3, 470,100	733,772.64
Total					£ 781,879.71

Table 2.21: Engineering costs of maintenance activities for Bridge 2

Maintenance activity	Length of lane closure (km)	Delay cost per day (£)	Duration of closure for each activity (days)	Delay cost for each activity (£)	Lifetime delay cost (£)	Discounted lifetime delay cost (£)
Inspection	0.2	33,900	2	67,800	1,559,400	420,663.21
Concrete repair	3	36,100	322	11,624,200	34,872,600	7,374,011.20
Total						£ 7,794,674.40

Table 2.22: Traffic delay costs of maintenance activities for Bridge 2

Tables 2.23 and 2.24 summarises respectively the lifetime engineering and traffic delay costs for the maintenance activities required on Bridge 3.

Maintenance Activity	Frequency (years)	Cost of single application (£)	Age of bridge at each application	Life time cost (£)	Discounted life time cost (£)
Inspection	5	9,300	5, 10, 15, etc…… 115	213,900	57,701.59
Drain cleaning	2	900	2, 4, 6, 8, etc … 118	53,100	14,459.01
Concrete repair	30	1,360,800	30, 60, 90	4,082,400	863,246.89
Total					£ 935,407.49

Table 2.23: Engineering costs of maintenance activities for Bridge 3

Maintenance activity	Length of lane closure (km)	Delay cost per day (£)	Duration of closure for each activity (days)	Delay cost for each activity (£)	Lifetime delay cost (£)	Discounted lifetime delay cost (£)
Inspection	0.2	33,900	3	101,700	2,339,100	630,994.81
Concrete repair	3	36,100	371	13,393,100	40,179,300	8,496,143.30
Total						£ 9,127,138.11

Table 2.24: Traffic delay costs of maintenance activities for Bridge 3

2.3.3 **Societal Impact Assessment**

SASS takes account of the following issues

- aesthetic
- dust
- noise
- vibration

The following describes how these factors are measured.

2.3.3.1 **Aesthetics**

This impact is measured by considering the following

- percentage of guidelines followed
- past performance and the provision of a liaison officer

The guidelines recommended for bridge aesthetics are shown in Tables 2.25-2.27 and refer respectively to the following features

The bridge as a whole	8 guidelines
The bridge and its surroundings	23 guidelines
The parts and details of a bridge	36 guidelines

They are based on guidance prepared by the Austrian Roads and Transport Authority[29] and the Highways Agency[30] on Bridge Aesthetics/Appearance.

Each aspect contributes 25% to the total score for this provision of sustainability (Table 2.28).

The remaining 25% is obtained from past performance/provision of liaison officer in accordance with the scores shown in Table 2.29.

Individual aspects	Score	Justifications/Actions for the scores (text or drawing no.)
1,1,1 - Excessive imbalanced proportions between significant elements should be avoided as much as possible.		
1,1,2 - Similar proportions or ratios throughout the structure can create a harmony.		
1,1,3 - The ratio of Deck to Parapet Depth is also considered a significant aesthetic proportion and guidelines have been developed by Cardiff University School of Engineering		
1,1,4 - the Span to Depth ratio is determined by the structural design. The value of the span-to-depth ratio can be an indicator of aesthetic design. The general agreement among bridge design experts states that span-to-depth ratio between 15 and 30 provi		
1,2,1 - it must be considered as an important aesthetic indicator because symmetrical bridges are often more aesthetically pleasing than non symmetricals.		
1,3,1 - to achieve a consistent order, bridge spans should match where possible. Also, the interaction of bridge elements like lighting columns, barrier supports and piers should be considered.		
1,4,1 - The complexity of a bridge should be minimized especially in natural landscape settings as it tends to attract the eye and competes with views of the landscape.		
1,4,2 - Honesty of form is about the materials and structures to look like what they are.		

Table 2.25: Guidelines for Bridge as a whole

2,1,1 - Make the bridge as invisible as possible to hide it in the landscape. (suits to smaller bridges)		
2,1,2 - Make the bridge as simple and elegant as possible to complement the landscape: This approach is a practical, cost effective objective for overpasses and larger bridges and can lead to good looking bridge solutions.		
2,1,3 - Maximize views of the landscape through the bridge: By minimizing the profile of the bridge, the landscape setting will dominate the view and be appreciated from all viewpoints.		
2,1,4 - Bridges with a horizontal form are generally preferable to bridges on a grade over flat simple landscapes and significant expanses of water		
2,1,5 - Significant stands of existing vegetation should be retained		
2,1,6 - Footprint of the bridge (e.g. pile caps, abutments) should be minimized so that the retention of local vegetations maximized.		
2,1,7 - The presence and extent of intermediate structures and hard surfaces between the bridge and landscape should be minimized.		
2,1,8 - Careful design of earthworks and planting and the selection of endemic species grown from locally collected seed.		
2,2,1 - A landmark structure should be created in a way that complements or contrasts with its visual catchments.		
2,2,2 - Maximizing views from the bridge of the local urban setting		
2,2,3 - Maximizing views through the bridge from the urban setting		
2,2,4 - Respecting locally valued structures and their cartilages by complementing local styles and materials		
2,2,5 - Ensuring the space under the bridge is not dark, degraded and unsafe.		
2,3,1 - In such cases plants should be located to the outside of the space and irrigation may be required.		
2,3,2 - Combining planting with a hard paved or gravel surface is often appropriate.		
2,3,3 - Clean uncluttered surfaces, neat connections and simple layout of girders will help to give a neat appearance.		
2,3,4 - When designing the soffit, consider bracing, when it is required, and ensure an orderly and regular pattern where possible.		
2,4,1 - Short span (up to approximately 18m): prestressed concrete plank bridges. **2,4,2 - Short to medium span (approximately 18-40m): pre-stressed concrete girders or pre-stressed concrete voided slabs.** **2,4,3 - Medium span (approximately 40-80m): ste**		

Table 2.26: Guidelines for Bridge and its surroundings

3,1,1 - They should appear as continuous uninterrupted lines, extending the full length of the bridge with a generous overlap of the abutments.		
3,1,2 - A neat, sharp edge will help define them against the background.		
3,1,3 - Maximizing the shadow cast on the superstructure will further accentuate and express their form.		
3,1,4 - The outer face should be a smooth single plane surface, slanted slightly outwards towards the bottom, to better catch the sunlight.		
3,1,5 - The top should angle towards the road, to channel rainwater onto the bridge, minimizing staining of the outside face.		
3,1,6 - If the deck soffit is visually complex, consideration should be given to hiding this complexity, by extending the parapet soffit below the deck soffit.		
3,2,1 - In the elevation, hunched girders are expressive and responsive to the forces in the bridge. They can often be more distinctive and elegant than single depth beams.		
3,2,2 - Three or five span haunches are aesthetically very elegant balanced structures.		
3,2,3 - In cross section, if the girder is right angled it can catch the light and a double line may be visible. Maximizing the overhang will increase the shadow. A curved soffit will provide a gradation of tone and minimize a sharp line at the base of th		
3,3,1 - In an urban area that vertical forms are present and only close views available, headstock may provide a reassuring sense of strength and durability, as well as visual interest.		
3,3,2 - In a rural area where horizontal forms predominate, headstock can be overly complex and should be carefully considered and designed with their visual impact in mind, or avoided.		
3,3,3 - If possible headstocks should not extend across the outer face of the girder. This introduces unnecessary complexity and appears in elevation as if the headstock is supporting the deck rather than the girder.		
3,4,1 - Bridges which have pier spacings or spans which are roughly proportional to the bridge's height above ground level are more aesthetically pleasing than bridges which do not follow this proportion. They seem more responsive to their context.		
3,4,2 - Collecting multiple piers into pairs or clusters can open up views below the deck and also give rhythm and elegance to the supports.		
3,4,3 - Rounding off the corners of rectangular piers provides a softer form, which may be preferable in certain contexts. For example where the presence of the pier needs to be down played so that superstructure is dominant, e.g. in a rural setting.		
3,4,4 - Pier shapes which have a slight taper (A taper of around 1:80) are desirable.		
3,4,5 - The reverse taper should only be used where the appearance of rigidity is required between superstructure and pier. Otherwise the appearance of the top heavy pier can be imbalanced and does not reflect the forces acting on the pier well.		
3,5,1 - The proportion of pier size to pile cap size should be considered. Imbalanced proportions should be avoided.		
3,5,2 - In a tidal watercourse, if the view of the piles is to be minimised, the pile cap may require a skirt as they need to be visible to boats and shipping as a safety measure.		
3,6,1 - If using of wall abutments is unavoidable the use of planting should be considered to screen the abutment walls.		
3,6,2 - Reducing the abutments can create a more refined and better looking bridge. It does however increase the span and therefore depth of beam.		
3,6,3 - Continuing the superstructure or the parapet allows the shadow line to reduce the dominance of the abutment, and makes the bridge appear longer and more elegant.		
3,6,4 - Angling the abutments provides a more open sleek look and helps visually anchor the span.		
3,6,5 - Spill through abutments allow open views to the landscape and better visibility to the road beyond.		
3,6,6 - slight angle on the taper can make the wall appear less dominating especially if next to a footpath. This avoids visual crowding.		
3,7,1 - With the exception of name plates and navigation signs, signage should be kept off bridges as far as possible. They add clutter and complexity and detract from the structure. They also obstruct views from the bridge.		
3,8,1 - An outward curving screen creates a more open feeling for bridge users. However it presents a greater apparent depth of structure for onlookers.		
3,8,2 - The screens should extend to the ends of the bridge span and consideration should be given to integrating the bridge barrier and safety screens.		
3,9,1 - Where possible lighting on bridges should be minimized or avoided.		
3,9,2 - If necessary lighting should be used in the median as far from the parapet as possible to reduce clutter or designed into the parapet structure.		
3,9,3 - If considerable effort is put into the design of the appearance of the bridge it is better value for money to allow the bridge to be viewed at night (dependent on context, cost, safety and environmental issues).		
3,10,1 - The colour and grade of the pipe system must be considered as these aspects can jar with the overall bridge design.		
3,11,1 - Where possible avoid the use of noise walls on bridges.		
3,11,2 - The use of transparent panels should be considered so that the apparent slenderness of the superstructure is not affected.		
3,12,1 - Landscape tones are generally subdued and dark; therefore light colours and textures (for bridge primary elements) provide a good contrast. (the exception is when they are culturally appropriate such as traditional Chinese bridges or unique icon		
3,12,2 - A neutral palette of black, gray and white tend to give a clear definition of the bridge as an object in the landscape.		

Table 2.27: Guidelines for Bridges: The parts and details

Aesthetic Aspects	Max Score
Bridges as whole	25%
Bridge & its surroundings	25%
Parts & Details	25%
Past performance/Public consultation	25%

Table 2.28: Weighting factors for aesthetics

Past performance	Liaison officer allocated	Impact score out of 10
Poor	Yes	5
Good	Yes	1
None	Yes	3
Poor	No	10
Good	No	7
None	No	9

Table 2.29: Impact scores for past performance and liaison officer

Aesthetic impact is obtained from

$$\left(\frac{No\ of\ guidelines\ satisfied}{No\ of\ relevant\ guidelines\ for\ bridge\ as\ a\ whole}\right)25\% + \left(\frac{No\ of\ guidelines\ satisfied}{No\ of\ relevant\ guidelines\ for\ bridge\ and\ its\ surroundings}\right)25\% + \left(\frac{No\ of\ guidelines\ satisfied}{No\ of\ relevant\ guidelines\ for\ parts\ and\ details}\right)25\% + \left(1-\frac{Impact\ score}{10}\right)25\% \quad \text{--------------------}(10)$$

Example 3: Aesthetics - Bridge 1

With the aid of Fig. 7 estimate the aesthetic impact score for Bridge 1. Assume the designer has no past performance but has appointed a liaison officer to consult with the public.

(i) Guidelines

Appendix D1 shows completed copies of Tables 2.24-2.26 for Bridge 1. The results are summarised in the table below and used in conjunction with the weighting factors included in Table 2.28 to score the guidelines.

Guidelines	Relevant guidelines	Guidelines observed	% observed	Score (%)
Bridge as a whole	8	8	100	25
Bridge and its surroundings	9	8	88.9	22.2
Parts and details	31	25	80.6	20.1
Total				67.3

(ii) Past performance/liaison officer

From Table 2.29 it can be seen that the score is 7 out of 10 giving an impact of

$$\left(1-\frac{7}{10}\right)25\% = 7.5$$

(iii) Aesthetics score

The aesthetics impact score for Bridge 1 is

67.3 + 7.5 = 74.8%

Aesthetics - Summary

Table 2.30 shows the aesthetics impact scores for Bridge 1. Also included are the impact scores for Bridges 2 and 3. Full details of the supporting calculations can be found in Appendices D1-2 and D1-3.

Bridge	Guidelines	Past performance/liaison officer	Aesthetics score
1	67.3	7.5	74.8
2	64.7	7.5	72.2
3	39.1	7.5	46.6

Table 2.30

2.3.3.2 **Dust**

This impact is evaluated by considering the following[31]

- the net increase in dust level
- the presence of sensitive buildings nearby
- public consultation and past performance of contractor
- duration of dust nuisance

(i) Net increase in dust level (μg)

This is given by

Predicted maximum dust level – Ambient dust level

(ii) Sensitive premises

This impact is assessed using Table 2.31.

Type of Premises	**Working Time/Period**			
	Weekday		**Weekend**	
	Day	**Night**	**Day**	**Night**
Hospitals, care homes & similar	**10** (Hazardous for patients.)	**10** (Hazardous for patients.)	**10** (Hazardous for patients.)	**10** (Hazardous for patients.)
Offices & similar	**8** (Hazardous for staff & extra cleaning required.)	**6** (Extra cleaning required.)	**6** (Extra cleaning required.)	**6** (Extra cleaning required.)
Commercial/business & similar	**8** (Hazardous for shoppers, staff & extra cleaning required.)	**6** (Extra cleaning required.)	**8** (Hazardous for shoppers/staff & extra cleaning required.)	**6** (Extra cleaning required.)
Schools/colleges & similar	**10** (Hazardous for students, staff & extra cleaning required.)	**6** (Extra cleaning required.)	**6** (Hazardous for students, staff & extra cleaning required.)	**6** (Extra cleaning required.)
Residential & similar	**10** (Hazardous for residents & extra cleaning required.)	**8** (Extra cleaning required.)	**10** (Hazardous for residents & extra cleaning required.)	**8** (Extra cleaning required.)
Others	**8** (assumed)	**6** (assumed)	**8** (assumed)	**6** (assumed)

Table 2.31: Sensitive premises

(iii) Public consultation and past performance

This impact is assessed using the data in Table 2.29.

(iv) Duration

This is the total number of days during construction and maintenance work when the dust level is expected to reach the declared value.

(v) Impact assessment

Dust impact is obtained from

Net increase in dust level × Presence of sensitive buildings nearby ×
Public consultation/past performance × Duration -------------------(11)

Example 4: Dust score for Bridge 1

Calculate the dust score for Bridge 1assuming the following

- ambient dust level = 150 µg
- declared maximum dust level = 170 µg
- hospital nearby
- dust producing activities occur throughout the week during daytime hours
- contractor has no past performance but has appointed a liaison officer to consult with the public
- duration of dust nuisance : construction period - 90 days
  : maintenance period – 175 days per treatment.

Thus the scores are as follows

(i) Dust level

170 – 150 = 20 µg

(ii) Sensitive premises

From Table 2.31 the score is 20

(iii) Public consultation and contractor performance

From Table 2.29 it can be seen that the score is 3

(iv) Duration

No of maintenance treatments = 3

∴ Total duration of dust nuisance = 90 + 3 × 175 = 615 days

(v) Sustainability score

The overall sustainability score for dust is

20 × 20 × 3 × 615 = 738,000

Table 2.32 summarises the dust scores for Bridge 1. Also included are the results for Bridges 2 and 3. Further details of the assumptions for these bridges can be found in Appendices D2-1 and D2-2.

Bridge	Dust level	Sensitive premises	Public consultation/contracto performance	Duration	Score
1	20	20	3	615	738,000
2	10	20	3	580	348,000
3	10	20	3	678	406,000

Table 2.32

2.3.3.3 **Noise**

Noise impact is measured by considering the following[32]

- net increase in noise level
- duration of nuisance
- presence of sensitive buildings nearby
- public consultation and past performance
- measures taken to mitigate the effect of noise.

(i) Net increase in noise level

This is given by

Maximum declared noise level - Ambient noise level

(ii) Duration

This is total number of days during construction and maintenance work the noise nuisance is likely to persist.

(iii) Presence of sensitive buildings

See Table 2.29

(iv) Public consultation and past performance

See Table 2.30

(v) Measures taken to mitigate the effect of noise

Possible measures include use of

- low noise surfaces
- noise walls

The mitigation factor is 1/10 for each measure employed.

(vi) Impact assessment

Noise impact is given by

Net increase in noise level × Duration × Presence of sensitive buildings nearby ×
Public consultation/past performance × Mitigation measures ------------(12)

Example 5: Noise score for Bridge 1

Calculate the dust impact score for Bridge 1assuming the following

- ambient noise level = 60 dBA
- declared maximum noise level = 90 dBA
- duration of noise nuisance : construction period – 90 days
  : maintenance period - 175 days per treatment
- hospital nearby
- contractor has no past performance but has appointed a liaison officer to consult with the public
- noise walls deployed

(i) Net increase in noise level

$$90 - 60 = 30 \text{ dBA}$$

(ii) Duration

No of maintenance treatments = 3

$\therefore$ Total duration of dust nuisance = $90 + 3 \times 175 = 615$ days

(iii) Sensitive premises

From Table 2.29 the score is 20

(iv) Public consultation and contractor performance

From Table 2.28 it can be seen that the score is 3

(v) Mitigation measures

Since noise walls are to be deployed mitigation factor = 1/10.

(vi) Sustainability score

Noise impact

$$= 30 \times 615 \times 20 \times 3 \times 1/10 = 110{,}700$$

Table 2.33 summarises the noise scores for Bridge 1. Also included are the results for Bridges 2 and 3. Further details of the assumptions for these bridges can be found in Appendices C3-1 and C3-2.

Bridge	Noise level (dBA)	Duration (days)	Sensitive premises	Public consultation / past performance	Mitigation measure factor	Score
1	30	615	20	3	0.1	110,700
2	30	580	20	3	0.1	104,400
3	30	678	20	3	0.1	122,040

Table 2.33

2.3.3.4 **Vibration**

This impact on society is quantified by considering the following four factors

- vibration dose
- duration of nuisance
- presence of sensitive premises nearby
- public consultation/contractor past performance

Vibration dose

The total vibration dose for a day is given by the formula taken from BS 6472-1[33]

$$1.4at^{0.25} \text{------------(13)}$$

where

a is the rms (root mean square) acceleration

t is the duration of vibration occurrence in seconds multiplied by average number of occurrences per day

Duration

This is the number of days during construction and during maintenance work the vibration level is expected to reach the maximum level declared.

Sensitive buildings

See Table 2.29

Public consultation and past performance

See Table 2.28

Impact assessment

The noise impact is obtained from

$$\text{Vibration dose} \times \text{Duration} \times \text{Presence of sensitive buildings} \times$$
$$\text{Public consultation and past performance of contractor} \quad \text{------------(14)}$$

Example 6: Vibration score for Bridge 1

Calculate the vibration score for Bridge 1 assuming the following

- the root mean square acceleration is 0.5
- the duration of vibration occurrence in seconds is 1200 sec and the average number of occurrences per day is 6
- duration of nuisance: construction period – 90 days
  : maintenance period - 175 days per treatment
- hospital nearby
- the contractor has no past performance but has appointed a liaison officer to consult with the public

Vibration dose

The vibration dose is given by

$$= 1.4at^{0.25} = 1.4 \times 0.5 \times (1200 \times 6)^{0.25} = 6.45$$

Duration

No of maintenance treatments = 3

$\therefore$ Total duration of nuisance = 90 + 3 × 175 = 615 days

Sensitive premises

From Table 2.29 the score is 20

Public consultation and past performance

From Table 2.28 it can be seen that the score is 3

Sustainability score

Vibration impact

$$= 6.45 \times 615 \times 20 \times 3 = 238{,}005$$

Table 2.34 summarises the vibration scores for Bridge 1. Also included are the results for Bridges 2 and 3. Further details of the assumptions for these bridges can be found in Appendices D4-1 and D4-2.

Bridge	Vibration dose	Duration (days)	Sensitive premises	Public consultation / past performance	Score
1	6.45	615	20	3	238,005
2	6.45	580	20	3	224,460
3	6.45	678	20	3	262,386

Table 2.34

2.3.4 Calculating the sustainability score for a bridge

Table 2.35 could be used to summarise the impacts of each of the above factors for the three bridge structures.

Indicators	Bridge 1		Bridge 2		Bridge 3	
	Quantity	Normalised score	Quantity	Normalised score	Quantity	Normalised score
Environment						
CO_2 emitted	X	$\left(1-\frac{X}{X+Y+Z}\right)100$	Y	$\left(1-\frac{Y}{X+Y+Z}\right)100$	Z	$\left(1-\frac{Z}{X+Y+Z}\right)100$
Energy consumed						
Materials consumed						
Society						
Dust						
Noise						
Vibration						
Aesthetic						
Economy						
Construction cost						
Maintenance cost						
Traffic delay cost						

Table 2.35 Normalised scores

In order to obtain an overall sustainability score we have to combine the scores. This is problematical because they are measured in different units. SASS, unlike other the appraisal methods discussed in Chapter 1, is designed to give a relative measure of sustainability rather than an absolute measure. It is used to compare the sustainability of a number of design options or maintenance strategies.

Each environmental factor such as CO_2 emitted, energy consumed or tonnage of materials consumed is compared for each design/maintenance strategy. The comparison is carried out by a normalization technique.

Assuming the scores for a particular factor for Bridges 1, 2 and 3 are X, Y and Z respectively then the normalized score for Bridge 1 is given by

$$\left(1-\frac{X}{X+Y+Z}\right)100 \text{ ------------(15)}$$

Using this approach the bridge with the highest impact will have the lowest score.

These normalized scores are dimensionless and therefore can be compared with similar normalized scores for other factors.

SASS also permits the relative weightings between the three sustainability themes (environment, economy and society) to be varied. It also permits the relative weightings of the different factors within a sustainability theme to be varied. Normally an equal weighting is applied to both sustainability themes and factors, however sometimes constraints may justify non-equal weightings.

Thus, if we assume equal weightings apply to both themes and factors, the weighting factor for each of the three themes is 1/3 or 0.33. For the economy themes there are three factors so these will have a weighting factor of 0.33/3 = 0.11 (Table 2.36).

If we assume the ratio of weighting factors for the sustainability themes is Environment 1: Society 1: Economy 2, the weighting factor for each theme is

Environment	0.25
Society	0.25
Economy	0.5

Table 2.37 shows the effect of these weightings on sustainability.

Indicators	Bridge 1				Bridge 2				Bridge 3			
	Weighting (W)	Quantity	Normalised Score (N)	Weighted Score (W × N)	Weighting	Quantity	Normalised Score	Weighted Score	Weighting	Quantity	Normalised Score	Weighted Score
Environment												
CO$_2$ emitted	0.11	17,267	64.35	7.08	0.11	13,821	71.47	7.86	0.11	17,348	64.18	7.06
Energy consumed	0.11	250,135	64.20	7.06	0.11	203,661	70.85	7.79	0.11	244,877	64.95	7.14
Materials consumed	0.11	2,404	68.33	7.52	0.11	2383	68.60	7.55	0.11	2803	63.07	6.94
Society												
Dust	0.0833	738,000	50.54	4.21	0.0833	348,000	76.68	6.39	0.0833	406,000	72.79	6.06
Noise	0.0833	110,700	67.17	5.60	0.0833	104,400	69.03	5.75	0.0833	122,040	63.80	5.32
Vibration	0.0833	238,005	67.17	5.60	0.0833	224,460	69.03	5.75	0.0833	262,386	63.80	5.32
Aesthetic	0.0833	-	74.8	6.23	0.0833	-	72.2	6.01	0.0833	-	46.6	3.88
Economy												
Construction cost	0.11	787,200	55.56	6.11	0.11	393,600	77.78	8.56	0.11	590,400	66.67	7.33
Maintenance cost	0.11	560,726	75.39	8.29	0.11	781,880	65.68	7.22	0.11	935,407	58.94	6.48
Traffic delay cost	0.11	8,762,440	65.88	7.25	0.11	7,794,674	69.65	7.66	0.11	9,127,138	64.46	7.09
Sustainability score				64.95				70.54				62.62

Table 2.36: Sustainability scores for Bridges 1, 2 and 3 - Weighting for Environment 1, Society 1, Economy 1.

Indicators	Bridge 1				Bridge 2				Bridge 3			
	Weighting	Quantity	Normalised Score	Weighted Score	Weighting	Quantity	Normalised Score	Weighted Score	Weighting	Quantity	Normalised Score	Weighted Score
Environment												
CO$_2$ emitted	0.0833	17,267	64.35	5.36	0.0833	13,821	71.47	5.95	0.0833	17,348	64.18	5.35
Energy consumed	0.0833	250,135	64.20	5.35	0.0833	203,661	70.85	5.90	0.0833	244,877	64.95	5.41
Materials consumed	0.0833	2,404	68.33	5.69	0.0833	2383	68.60	5.72	0.0833	2803	63.07	5.25
Society												
Dust	0.0625	738,000	50.56	3.16	0.0625	348,000	76.69	4.79	0.0625	406,000	72.79	4.55
Noise	0. 0625	110,700	67.17	4.20	0. 0625	104,400	69.03	4.32	0. 0625	122,040	63.80	3.99
Vibration	0. 0625	238,005	67.17	4.20	0. 0625	224,460	69.03	4.32	0. 0625	262,386	63.80	3.99
Aesthetic	0. 0625	-	74.8	4.68	0. 0625	-	72.2	4.51	0. 0625	-	46.6	2.91
Economy												
Construction cost	0.1666	787,200	55.56	9.26	0.1666	393,600	77.78	12.96	0.1666	590,400	66.67	11.11
Maintenance cost	0.1666	560,726	75.39	12.54	0.1666	781,880	65.68	10.94	0.1666	935,407	58.94	9.82
Traffic delay cost	0.1666	8,762,440	65.88	10.98	0.1666	7,794,674	69.65	11.60	0.1666	9,127,138	64.46	10.74
Sustainability score				65.44				71.01				63.12

Table 2.37: Sustainability scores for Bridges 1, 2 and 3 - Weighting for Environment 1, Society 1, Economy 2

2.4 Discussion

Sustainability is a concept that is presently not precisely defined. It is not directly measurable in the same way that for example temperature can be measured. The three sustainability themes namely environment, economics and society can be individually calculated but they have different units so it is not possible to combine them in a simple way to give a measure of sustainability. In SASS the values of the component parts are normalised to give three unitless values that can be easily combined. Before carrying out this combination it is necessary to decide the relative importance of the three components. This is best done using engineering judgement by consensus of a group of experts yielding a weighting factor for each component. In a similar way the constituent parts of each of the three themes can be combined using normalisation and weighting factors.

Using this approach the normalised scores, weighting factors and sustainability scores for the three bridges described in Chapter 2 are reported in Tables 2.36 and 2.37. The methodology described in Chapter 2 for determining sustainability means that it is a comparative measure rather than an absolute measure. Therefore a sustainability score for a particular structure has no significance. It is only when the sustainability scores for different bridges are compared that a meaningful interpretation of the results is achieved. Thus we can say that the three bridges are ranked in order of increasing sustainability. It is in this way that the sustainability of bridges with different structural forms/material or different maintenance strategies may be compared. Thus on the basis of Table 2.36 the following comments can be made:

- Overall Bridge 2 is the most sustainable and Bridge 3 is the least sustainable overall

- In terms of the environmental theme, Bridge 3 was the least sustainable and Bridge 2 the most sustainable

- In terms of the social theme, Bridge 3 was the least sustainable and Bridge 2 the most sustainable

- In terms of the economic theme, Bridge 2 was the most sustainable and Bridge 3 was the least sustainable

- For each bridge the environmental factor (CO_2 emitted, energy consumed and materials required) scores were similar

- For each bridge there were significant differences in the economic factors (construction, maintenance and traffic delay cost) scores. In particular Bridge 2 has the lowest construction cost and Bridge 1 the highest construction cost. Bridge 1 conversely has the lowest maintenance cost whereas Bridge 3 has the highest maintenance cost. Bridge 2, however, has the lowest traffic delay cost and Bridge 3 the highest traffic delay cost. The traffic delay costs on Bridge 1 are higher than on Bridge 2 because Bridge 1 requires a full carriageway closure for the painting work.

- Bridge 2 is clearly the most sustainable because it scores best for each of the three sustainability themes

- Bridge 3 is clearly the least sustainable as it scores lowest for each of the three sustainability themes

- The design of Bridge 1 has a continuous reinforced concrete deck supported on steel beams, with two integral bank seat abutments and three piers. Bridge 2 consists of two spans of prestressed concrete deck beams, two wall abutments and one pier. Bridge 3 has three voided reinforced concrete spans, one wall and one bank seat abutment and two piers. These bridges are all overbridges so the dual two-lane motorway passes under the bridge with a minor road passing over the bridge. Both roads are de-iced with rock salt during the winter and the top surface of the bridge decks are protected from salt with water proofing membranes. Thus the areas of concrete exposed to salt and hence vulnerable to corrosion of reinforcing steel are (a) the lower parts of the piers and abutments facing the road and exposed to traffic spray and (b) the deck ends and tops of piers/abutments under deck joints that have a tendency to leak salt water from the deck. Bridges 1, 2 and 3 each have four faces of pier/abutments facing the traffic. Bridge 1 has no joints since it has a continuous deck with integral abutments, Bridge 2 has three joints (two over abutments and one over a pier) and Bridge 3 has four joints (two over abutments and two over piers). Therefore Bridge 1 would be expected to need the least maintenance since only the lower parts of the piers/abutments would need maintenance. Bridge 3 would be expected to need more maintenance than Bridge 2 because whilst both these bridges need a similar amount of maintenance to their piers/abutments, Bridge 3 has one more deck joint than Bridge 2. The advantage of Bridge 1 is partly countered by the requirement of its steel beams for maintenance painting, a procedure that is also very disruptive to traffic. The above reasoning explains why maintenance cost scores within the economy theme are ranked Bridge 1(highest), Bridge 2, Bridge 3 (lowest). It also explains why the traffic delay cost scores within the economy theme are ranked Bridge 2 (highest), Bridge 1, Bridge 3 (lowest).

From Table 2.37 (different weightings)

- The overall sustainability ranking is unchanged by giving the economy twice the weighting of the environment and society factors

- Comparing the economy scores for each bridge in Table 2.36 and Table 2.37 it can be seen that changing the weighting factors has increased the differences. Thus the economy scores for Bridge 2 that were the highest in Table 2.36 are comparatively even better in Table 2.37 when the economy weighting factor has been increased.

Chapter 3: Sustainability appraisal of bridges by the SASS method – Student exercises

Introduction

Bridge construction and maintenance costs the UK economy several hundreds of millions of pounds annually and can have significant social and environmental impacts. However design decisions continue to be dominated by initial costs although in recent years decisions have also been based on life time costs. None or very little account is taken of the environmental and social factors relevant to sustainable development. This is largely due to the fact that few structural engineers know what sustainable development actually is and the lack of a clear methodology for sustainability appraisal of civil engineering structures.

The measurement of sustainability involves combining the effects of an activity, in our case the provision of a bridge crossing, on the environment, the economy and society. The exercises that follow deal with the calculation of the individual themes of sustainability namely

- environment
- economy
- society

and how they are combined to give a measure of sustainability. The way the relative priorities given to the environment, economy and society for a particular bridge scheme affect the overall sustainability is also investigated.

For each situation a worked example is provided as a teaching aid together with related exercises to test understanding.

In these exercises and worked examples two phases of bridge provision are considered

- construction
- in-service

to give the life time sustainability.

The work presented is based on research carried out at UCL to develop a model called SASS (System for Appraising the Sustainability of Structures) to evaluate the sustainability of civil engineering structures.

Problem

A new road bridge is required to cross a dual two lane motorway, the cross-section of which is shown in Fig. E1.

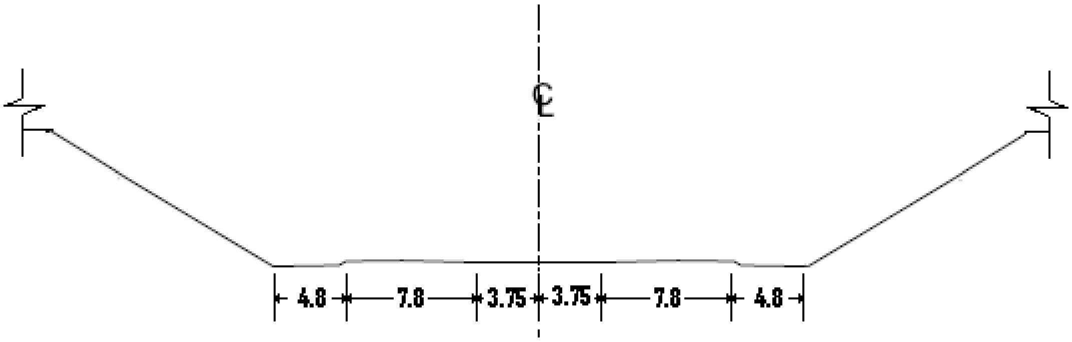


Fig. E1 Cross-section of motorway

It is to be designed to carry a two-way access road, with a total carriageway width of 7.3 m and 2.5 m wide footpaths on both sides.

The motorway has an AADT (Average Annual Daily Traffic Flow) of approximately 80,000 vehicles in both directions of which 20% are heavy goods vehicles (HGV). The AADT for the access road is 6,000 vehicles of which 10% are HGV. The motorway is assumed to be closed to traffic during construction of the bridge.

The scheme is located in an area of ‘outstanding natural beauty’ and since the bridge will be highly visible an aesthetically pleasing solution is necessary. Also, the bridge site is close to a hospital.

Fig. E2 shows three possible design solutions for the bridge.

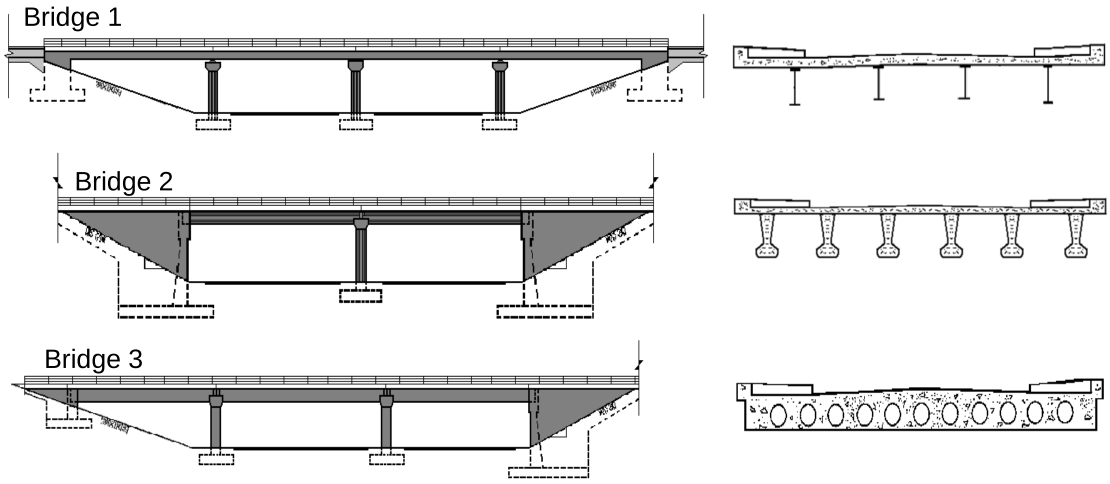


Figure E2 - Bridge design options

Bridge 1 is 64 m long and has a 225 mm thick continuous reinforced concrete deck which acts compositely with four steel UBs (914 × 305 × 253). The substructure comprises integrated bank-seat abutments (Fig. 3) and three intermediate wall piers (Fig. 4). The parapets are type N2 (Fig. 5).

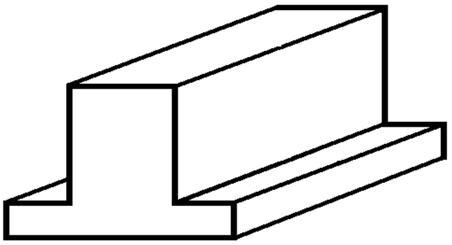


Fig. E3: Bank-seat abutment

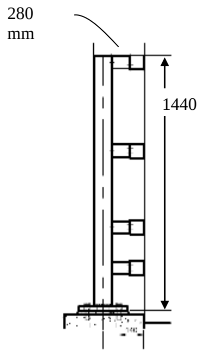


Fig. E5: Bridge parapet

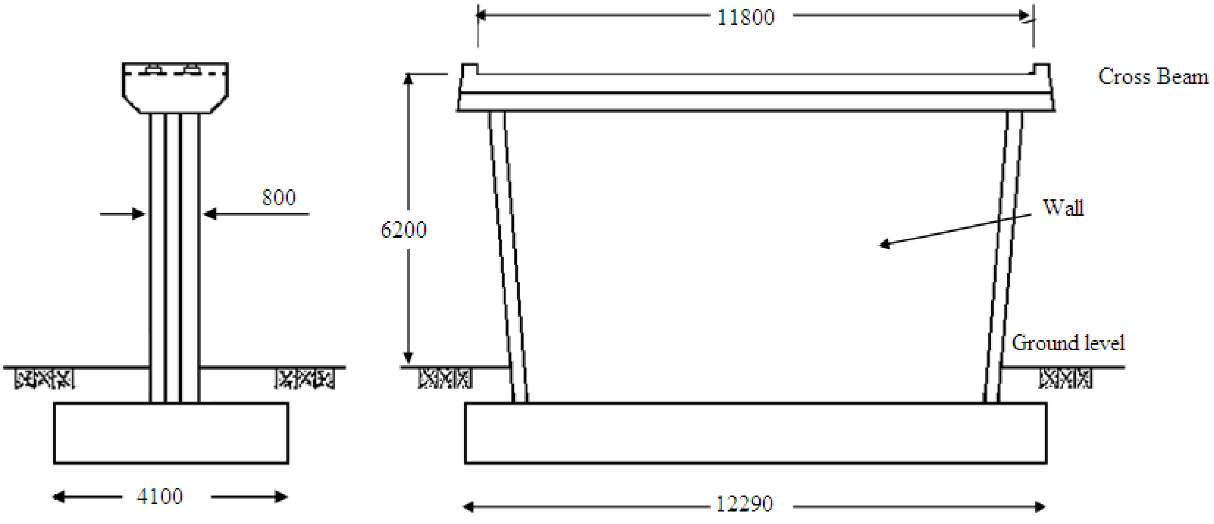


Fig. E4: Wall pier

Bridge 2 is a 32 m long two span simply supported composite prestressed concrete beam and slab bridge. It has closed end cantilever abutments with wing walls (Fig. 6) and an intermediate wall pier, similar to Bridge 1.

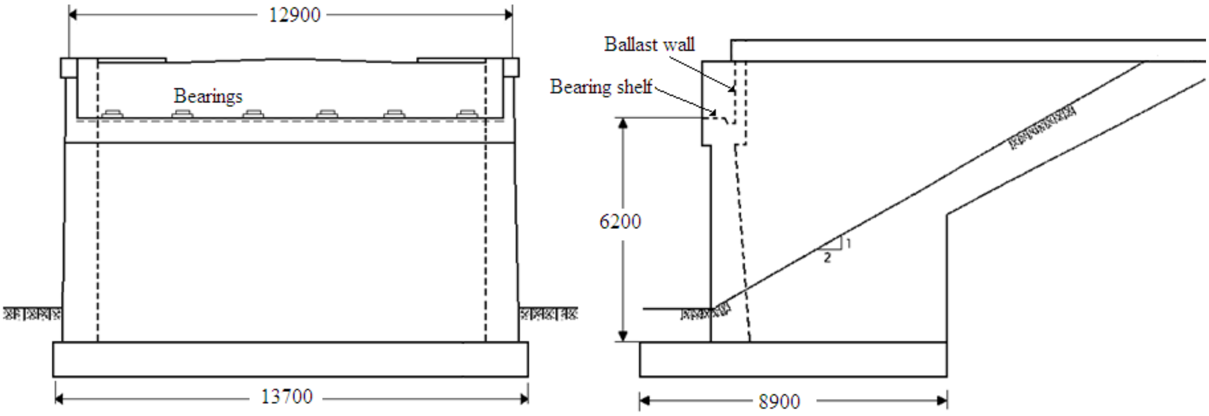


Fig. E6: Cantilever abutment with wing walls

Bridge 3 is 48 m long. The deck is a three span simply supported reinforced concrete voided slab. The right hand support is a cantilever abutment with wing walls (Fig. 6) and the left hand support is a bank seat (Fig. 7). The intermediate supports consist of columns and crossbeam (Fig. 8).

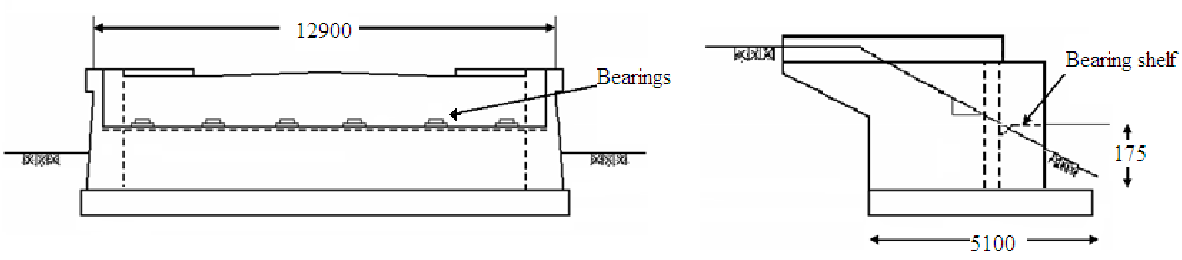


Fig. E7: Bank seat

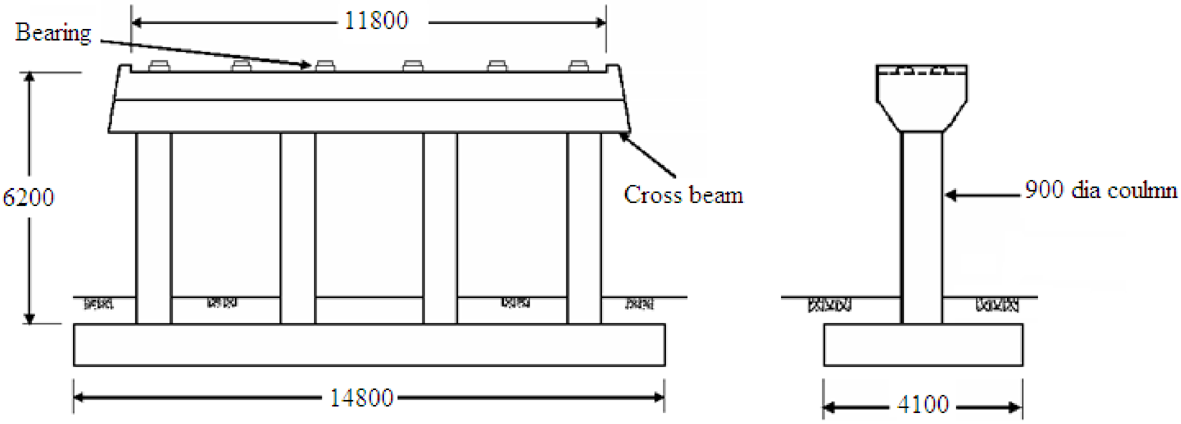


Fig. E8: Intermediate support for Bridge 3

The problem is to determine which of these three options is the most sustainable. The following exercises consider how to calculate the impacts of the three sustainability themes (environment, economy, society) and how to combine the impacts to obtain the overall sustainability score.

Ex. 1: Environmental Impact

As noted above, Bridge 1 has steel beams and a reinforced concrete deck slab giving a composite action superstructure that is continuous across the piers and integrated with bank seat pads made from reinforced concrete (Fig. E2). The deck is reinforced with stainless steel bars; the remaining elements of the bridge are reinforced with high yield steel bars.

In the example it is assumed that the effect of constructing this bridge on the environment is principally based on the embodied tons of carbon dioxide (CO_2) produced and the gigajoules (Gj) of energy consumed in the production of the construction materials and similar quantities for the transportation of materials to the construction site.

Table Ex1.1 lists the quantities of the different materials required for the construction of this bridge. Table Ex1.2 gives the embodied tons of CO_2 produced and Gj of energy consumed per unit mass of each of these materials for production and transport to the construction site.

The values of tons of CO_2 produced and Mj consumed in transport are based on the DEFRA (Department for Environment, Food and Rural Affairs) Emission Factor for an average heavy goods vehicle (HGV) and the DEFRA GHG (green house gas) conversion factor which gives the average diesel consumption per ton.km for an HGV and the CO_2 produced per ton.km. The energy consumed per ton.km is based on the diesel consumption and the calorific value of diesel. In this example it is assumed that all the materials are transported 25 km to site.

Material	Tonnage
OPC	357
Aggregate	1386
Stainless steel reinforcement	140
Steel beams	65
High Yield Steel reinforcement	340
Parapets	17
Water proofing	1.2
Paint	0.08

Table Ex 1.1: Construction materials

Material	Production		Transport (per km)	
	ton of CO_2	Gj of energy	ton of CO_2	Gj of energy
OPC	0.97	6.1	1.32×10^{-4}	1.66×10^{-3}
Aggregate	0.008	0.15	〃	〃
Stainless steel	6.15	51.5	〃	〃
Steel beams	1.79	22.7	〃	〃
Steel reinforcement	1.72	22.7	〃	〃
Parapets	2.82	35.8	〃	〃
Water proofing	8.28	140	〃	〃
Paint	6.10	80	〃	〃

Table Ex. 1.2: Embodied tons of CO_2 and Gj of energy per ton of each construction material for production and transportation

The calculation of the tons of CO_2 produced and Gj of energy consumed for each material used in the bridge is straightforward involving the multiplication of the mass of material from Table Ex1.1 by the embodied CO_2 per ton of material. For example for OPC we have

$$357 \times 0.97 = 346.29 \text{ tons of } CO_2$$
$$357 \times 6.1 = 2177.70 \text{ Gj}$$

The calculation of similar quantities for the transportation of materials to site is also straightforward involving the multiplication of the relevant figures from Tables Ex1.1 and 1.2 by the transport distance, assumed to be 25 km in this example, thus giving

$$357 \times 1.32 \times 10^{-4} \times 25 = 1.18 \text{ tons of } CO_2$$
$$357 \times 1.66 \times 10^{-3} \times 25 = 14.82 \text{ Gj}$$

Exercise 1

Repeat the above calculations for the other materials listed in Table Ex1.1 and then complete the spaces in Table Ex1.3 to 2 decimal places.

Material	Production		Transport	
	ton of CO_2	Gj of energy	ton of CO_2	Gj of energy
OPC	346.29	2177.70	1.18	14.82
Aggregate				
Stainless steel				
Steel beams				
Steel reinforcement				
Parapets				
Water proofing				
Paint				

Table Ex 1.3: Embodied tons of CO_2 and Gj for production and transportation of construction materials

In order to calculate the tons of CO_2 produced and Gj of energy consumed in providing this bridge crossing for 120 years (the nominal design life of a bridge) we need to make a number of assumptions about maintenance and inspection frequency

steel work painting	every 25 years
bridge inspection	every 5 years
clean drainage system	every 2 years
replace waterproofing	every 30 years
concrete repairs to E2 concrete	every 30 years
repairs to E3 concrete	every 30 years

E1, E2 and E3 are exposure classes as shown in Table Ex1.4. It is assumed that when maintenance work is done 10% of the relevant surface area is replaced.

Exposure class	Corrosion Environment	Typical element location
E1 Protected	Low	Element protected from slat spray with silane or enhanced durability measures
		Elements protected from salt spray by a protective enclosure.
E2 Sheltered Exposure	Medium	Bridge soffit subject to light vehicle spray from salted road.
		Top of roadside bridge pier or abutment subject to light vehicle spray from slated road.
E3 Severe	High	Roadside bridge abutment, parapet upstand or deck edge beam subject to heavy vehicle spray from salted road.
		Section of bridge deck of leaking expansion joint or gutter e.g. deck end crosshead
		Top surface of unwaterproofed bridge decks.
		Areas where corrosion or spalling of surface concrete is evident.

Table Ex 1.4: Exposure classes

There are two components to the tons of CO_2 and Gj of energy that accrue during the service life

- repair materials used and their transportation to site
- traffic congestion occurring during repair work due to traffic management operations e.g. lane closures.

Material	Tonnage
OPC	19
Aggregate	72
Parapets	6
Water proofing	0.36
Paint	0.03

Table Ex. 1.5: Life time quantities of repair materials

The second of these components arises because fuel consumption of the vehicles using the bridge increases at low speeds with stop-start driving.

The quantities of materials needed over the life time of the bridge are given in Table Ex1.5.

Inspection and drain cleaning do not consume materials. Stainless steel is maintenance free. The values of service life production of CO_2 and energy consumption for the repair materials are calculated as before using Tables Ex1.2 and 1.5.

Exercise 2

Calculate the values of CO_2 emissions and energy consumption for each repair material and insert your answers in Table Ex1.6.

Material	Embodied		Transport	
	ton of CO_2	Gj of energy	ton of CO_2	Gj of energy
OPC				
Aggregate				
Parapets				
Water proofing				
Paint				

Table Ex. 1.6: Tons of CO_2 emitted and Gj of energy consumed in providing repair materials

The quantities of extra CO_2 produced and energy consumed as a result of traffic congestion during maintenance work depends on

- duration of maintenance work over life time in days
- length of road with traffic management
- flow of HGV per day and the normal kg of CO_2 per km produced
- flow of other vehicles per day and the normal kg of CO_2 per km produced
- additional emissions and fuel consumption during maintenance work (assumed to be 30% of normal values)
- whether or not the work is carried out during off-peak hours
- kg of CO_2 emitted per km by HGV and other vehicles (respectively, 0.906 and 0.2042)
- kg of CO_2 emitted per litre of fuel
- calorific value of the fuel
- density of fuel

The last four quantities are used to calculate the energy consumption factor for HGV's as 14 Mj per km and for other vehicles it is 3 Mj per km.

Waterproofing and parapet work will cause negligible congestion because they are carried out from the top surface of the bridge where traffic flows are comparatively low.

We use the information in Table Ex1.7 and the figures for energy consumption per km for HGV and other vehicles to calculate the traffic congestion component of the effect on the environment of providing the bridge for 120 years.

Consider bridge inspections, for example, the extra HGV emissions as a result of the congestion caused by inspections is calculated as follows

> 92 (Table Ex1.7) × 0.2 (Table Ex1.7) × 0.3 (extra fuel consumption) × 0.25 (off-peak coefficient) × 16,000 (Average HGV flow per day) × 0.906 (kg of CO_2 per HGV per km)
> = 20,004 kg of CO_2

The extra energy consumed by HGVs as a result of traffic congestion during maintenance work is calculated as follows

> 92 days × 0.2 km × 0.3 (extra fuel consumption) × 0.25 (off-peak coefficient) × 16,000 vehicles per day × 14 Mj per km (average energy consumption of an HGV) × 10^{-3} = 309.12 Gj

Maintenance Activity	Lifetime duration (days)	Length of traffic management (km)
Inspection	92	0.2
Concrete repair	525	3
Painting	88	3

Table Ex. 1.7: Duration and length of the closure required for maintenance work

Exercise 3

(i) Repeat the above calculations for the other maintenance activities and enter your results in Table Ex1.8.

Activity	HGVs		Other vehicles		Total	
	kg of CO_2	Gj of energy	kg of CO_2	Gj of energy	kg of CO_2	Gj of energy
Inspection	20,004	309.12				
Concrete repair						
Painting						

Table Ex. 1.8: Tons of CO_2 emitted and Gj of energy consumed in providing repair materials

(ii) Compare the results in your completed versions of Tables Ex1.3, Ex1.6 and Ex1.8 and

a) decide whether construction and maintenance has most effect on the environment over the life time of the bridge
b) whether the use of repair materials or the congestion resulting from traffic management has the greater effect on the environment, which materials and maintenance activities have the greatest effect on the environment and make suggestions about how to reduce the impact on the environment
c) find the total tonnage of materials used over the lifetime of the bridge from Tables Ex1.1 and Ex1.5
d) list other key factors associated with construction and maintenance operations which could adversely affect the environment and in each case discuss how the impact might be evaluated.

Ex 2. Economic Impact

The total cost of a bridge over its lifetime comprises three main components

- cost of construction
- cost of maintenance
- cost of traffic delays caused by maintenance work.

The latter two costs are discounted to take account of when, during the life of the bridge, the costs occurred.

The construction cost is relatively straightforward to calculate and in this exercise is given as £ 787,200.

The maintenance cost is more complicated to calculate as it depends on the type of maintenance and the frequency of its application.

Exercise 4

In Table Ex2.1 you are given

- the maintenance activities for this bridge
- the frequency at which they need to be applied
- the cost of a single maintenance treatment.

You are required to calculate the total maintenance cost for each activity to achieve a 120 years life for the bridge. This involves finding the age of the bridge when each activity is needed and then discounting the cost of the single maintenance activity based on this age. The discount rates for different ages are given in Table Ex2.2 taken from the Treasury's Green Book. The total lifetime cost for all the maintenance activities is then obtained by summing the single application costs over the lifetime both with and without discounting. You should use the following formula and Table Ex2.2 to carry out the discounting

$$\text{Discount cost} = \frac{\textit{Undiscounted cost}}{(1+i)^n} \quad \text{-----------(E1)}$$

where
i is the discount rate
n is the age of the bridge when the maintenance activity is carried out.

For example the discounted cost of the inspection carried out when the bridge is 40 years old is given by

$$\text{Discount cost} = \frac{12.4\times10^3}{(1+3.0\%)^{40}} = £3801.30$$

The inspection row in Table Ex2.1 has been completed for you. You are required to complete the rest of the Table.

Activity	Frequency (years)	Cost of single application (£)	Age of bridge at each application	Life time cost (£)	Discounted life time cost (£)
Inspection	5	12,400	5, 10, etc ….. 115	285,200	76,935
Concrete repair	30	655,000			
Painting	25	58,000			
Drain cleaning	2	1,200			

Table Ex. 2.1: Cost and frequency of application of maintenance activity

Age (years)	Discount rate (%)
0 - ≤ 30	3.5
30 - ≤ 75	3.0
75 - ≤ 125	2.5

Table Ex. 2.2: Discount rates for different ages

Some types of maintenance activity cause traffic congestion as a result of lane closures to provide access to parts of the bridge or for the protection of workers. The extent of this disruption depends on

- the number of lanes closed
- the total number of lanes
- whether or not there is contraflow working
- the length of the lane closure
- the average daily traffic flow
- the proportion of the traffic that are HGVs.

The Department for Transport's computer program called QUADRO takes these factors into account to calculate the monetary consequences of the delays caused by the disruption to traffic for each day the disruption lasts. The DfT has also produced tables which can be used in lieu of running QUADRO (see Appendix B). As the costs in these tables are based on 1998 prices, however, the values should be increased in line with inflation. Thus, the delay cost for painting shown in Table Ex 2.3 is based on Table 31 and has been adjusted for inflation. Concrete repairs will cause traffic disruption on and below the bridge. The delay cost for concrete repair shown in Table 2.3 has been obtained using, respectively, Tables 42 and 28, and adjusted for inflation. It is assumed that inspection work will be carried out during off-peak hours and therefore the delay cost for inspection given in the table has been obtained from Table 32 and adjusted for inflation and off-peak working.

For this bridge it is assumed that drain cleaning can be carried out from the top of the deck which causes little disruption because of the relatively low flow of traffic over the bridge compared with under the bridge.

Table Ex2.3 gives the duration in days of the lane closures for each maintenance activity, the length of the lane closure in km and the user delay cost per day assuming an average daily traffic flow of 80,000 under the bridge of which 20% are HGVs.

Maintenance activity	Length of lane closure (km)	Delay cost per day (£)	Duration of closure for each activity (days)	Delay cost for each activity (£)	Lifetime delay cost (£)	Discounted lifetime delay cost (£)
Inspection	0.2	33,900	4	135,600	3,118,800	841,326
Concrete repair	3	36,100	175			
Painting	3	201,400	23			

Table Ex. 2.3: Traffic delay costs

The delay cost for each activity is obtained by multiplying the delay cost per day by the number of days each activity takes and the lifetime delay cost by further multiplying by the number of treatments needed in the 120 years life of the bridge. The discounted delay costs are calculated as before (Exercise 4) on the basis of age of the bridge when maintenance is carried out using equation (E1) and Table Ex2.2. The discounted costs for a maintenance activity carried out at different ages are then summed to give the discounted lifetime cost for this activity.

Exercise 5

(i) Row 1 of Table Ex2.3 has been completed for you and now you are required to complete the rest of the Table.

(ii) From your result

a) sum the construction cost, maintenance cost and traffic delay cost for each activity over the 120 year life (discounted and non-discounted cost)
b) calculate the grand total lifetime cost for the bridge (discounted and non-discounted)
c) comment on the contributions to the total made by construction, maintenance and traffic delay
d) comment on the contributions made to service life costs of maintenance and traffic delay costs
e) suggest ways of reducing the lifetime cost of a bridge and whether or not they may influence environmental and social aspects of sustainability.

(iii) List any other economic factors which should be considered and in each case discuss how the impact on sustainability might be measured.

(iv) The discounted lifetime delay costs in Table Ex 2.3 assume that the base year for discounting is 2009. However, the Highways Agency recommends that the base year for discounting should be the Department for Transport's standard base year which is currently 2002. Recalculate the discounted delay cost for inspection assuming the base year is 2002.

Ex3. Societal Impact

The construction and maintenance of a bridge over its lifetime can have an impact on people living nearby. The main impacts are due to

- dust
- noise
- vibration
- aesthetic

The following describes how these impacts are quantified.

(i) Aesthetics

This impact is measured by considering the following

- percentage of guidelines followed
- past performance and the provision of a liaison officer

The guidelines recommended for bridge aesthetics are shown in Tables Ex3.1-3.3 and refer respectively to the following features

The bridge as a whole	8 guidelines
The bridge and its surroundings	23 guidelines
The parts and details of a bridge	36 guidelines

Note that not all guidelines will be relevant to a particular scheme and should therefore not influence the assessment.

Each aspect contributes 25% to the total score for this provision of sustainability (Table Ex 3.4).

The remaining 25% is obtained from past performance/provision of liaison officer in accordance with the scores shown in Table Ex3.5. Note that in this case the lower the score the smaller the impact, hence the score is subtracted from 1 to give a score such that the higher the score the smaller the impact.

Example: Aesthetics

Determine the aesthetics score for the bridge assuming the following

bridge as a whole	6 out of 8 guidelines observed
bridge and its surroundings	20 out of 23 guidelines observed
parts and details of a bridge	30 out of 36 guidelines observed

- the designer has no past performance but has appointed a liaison officer to consult with the public the scores are as follows

Guidelines

Design feature	Number of guidelines observed	Percentage of guidelines observed	Score
Bridge as a whole	6	(6/8)100 = 75	75 × 25% = 18.75
Bridge and its surroundings	20	(20/23)100 = 87	87 × 25% = 21.75
Parts and details of a bridge	30	(30/36)100 = 83	83 × 25% = 20.75

Past performance and public consultation

From Table Ex3.5 it can be seen that the score is 3 out of 10 giving an impact of $\left(1-\frac{3}{10}\right)25\% = 17.5$

The overall sustainability score for aesthetics is obtained by adding the score for each aspect, giving

18.75 + 21.75 + 20.75 + 17.5 = 78.75

<u>Exercise 6</u>

For Bridge 1 (see Fig. E2)

(i) Determine which, if any, of the guidelines in Tables Ex3.1-Ex 3.3 should be excluded from consideration.

(ii) Provisionally establish the guidelines which will be observed in the final design and during the construction phase of the bridge.

(iii) Assuming the designer has a good record of past performance but that there are no specific provisions to liaise with the public, calculate the overall sustainability score for aesthetics. List any assumptions.

Individual aspects	Score	Justifications/Actions for the scores (text or drawing no.)
1,1,1 - Excessive imbalanced proportions between significant elements should be avoided as much as possible.		
1,1,2 - Similar proportions or ratios throughout the structure can create a harmony.		
1,1,3 - The ratio of Deck to Parapet Depth is also considered a significant aesthetic proportion and guidelines have been developed by Cardiff University School of Engineering		
1,1,4 - the Span to Depth ratio is determined by the structural design. The value of the span-to-depth ratio can be an indicator of aesthetic design. The general agreement among bridge design experts states that span-to-depth ratio between 15 and 30 provi		
1,2,1 - it must be considered as an important aesthetic indicator because symmetrical bridges are often more aesthetically pleasing than non symmetricals.		
1,3,1 - to achieve a consistent order, bridge spans should match where possible. Also, the interaction of bridge elements like lighting columns, barrier supports and piers should be considered.		
1,4,1 - The complexity of a bridge should be minimized especially in natural landscape settings as it tends to attract the eye and competes with views of the landscape.		
1,4,2 - Honesty of form is about the materials and structures to look like what they are.		

Table Ex3.1: Guidelines for Bridge as a whole

2,1,1 - Make the bridge as invisible as possible to hide it in the landscape. (suits to smaller bridges)		
2,1,2 - Make the bridge as simple and elegant as possible to complement the landscape: This approach is a practical, cost effective objective for overpasses and larger bridges and can lead to good looking bridge solutions.		
2,1,3 - Maximize views of the landscape through the bridge: By minimizing the profile of the bridge, the landscape setting will dominate the view and be appreciated from all viewpoints.		
2,1,4 - Bridges with a horizontal form are generally preferable to bridges on a grade over flat simple landscapes and significant expanses of water		
2,1,5 - Significant stands of existing vegetation should be retained		
2,1,6 - Footprint of the bridge (e.g. pile caps, abutments) should be minimized so that the retention of local vegetations maximized.		
2,1,7 - The presence and extent of intermediate structures and hard surfaces between the bridge and landscape should be minimized.		
2,1,8 - Careful design of earthworks and planting and the selection of endemic species grown from locally collected seed.		
2,2,1 - A landmark structure should be created in a way that complements or contrasts with its visual catchments.		
2,2,2 - Maximizing views from the bridge of the local urban setting		
2,2,3 - Maximizing views through the bridge from the urban setting		
2,2,4 - Respecting locally valued structures and their cartilages by complementing local styles and materials		
2,2,5 - Ensuring the space under the bridge is not dark, degraded and unsafe.		
2,3,1 - In such cases plants should be located to the outside of the space and irrigation may be required.		
2,3,2 - Combining planting with a hard paved or gravel surface is often appropriate.		
2,3,3 - Clean uncluttered surfaces, neat connections and simple layout of girders will help to give a neat appearance.		
2,3,4 - When designing the soffit, consider bracing, when it is required, and ensure an orderly and regular pattern where possible.		
2,4,1 - Short span (up to approximately 18m): prestressed concrete plank bridges. **2,4,2 - Short to medium span (approximately 18-40m): pre-stressed concrete girders or pre-stressed concrete voided slabs.** **2,4,3 - Medium span (approximately 40-80m): ste**		

Table Ex3.2: Guidelines for Bridge and its surroundings

3,1,1 - They should appear as continuous uninterrupted lines, extending the full length of the bridge with a generous overlap of the abutments.		
3,1,2 - A neat, sharp edge will help define them against the background.		
3,1,3 - Maximizing the shadow cast on the superstructure will further accentuate and express their form.		
3,1,4 - The outer face should be a smooth single plane surface, slanted slightly outwards towards the bottom, to better catch the sunlight.		
3,1,5 - The top should angle towards the road, to channel rainwater onto the bridge, minimizing staining of the outside face.		
3,1,6 - If the deck soffit is visually complex, consideration should be given to hiding this complexity, by extending the parapet soffit below the deck soffit.		
3,2,1 - In the elevation, hunched girders are expressive and responsive to the forces in the bridge. They can often be more distinctive and elegant than single depth beams.		
3,2,2 - Three or five span haunches are aesthetically very elegant balanced structures.		
3,2,3 - In cross section, if the girder is right angled it can catch the light and a double line may be visible. Maximizing the overhang will increase the shadow. A curved soffit will provide a gradation of tone and minimize a sharp line at the base of th		
3,3,1 - In an urban area that vertical forms are present and only close views available, headstock may provide a reassuring sense of strength and durability, as well as visual interest.		
3,3,2 - In a rural area where horizontal forms predominate, headstock can be overly complex and should be carefully considered and designed with their visual impact in mind, or avoided.		
3,3,3 - If possible headstocks should not extend across the outer face of the girder. This introduces unnecessary complexity and appears in elevation as if the headstock is supporting the deck rather than the girder.		
3,4,1 - Bridges which have pier spacings or spans which are roughly proportional to the bridge's height above ground level are more aesthetically pleasing than bridges which do not follow this proportion. They seem more responsive to their context.		
3,4,2 - Collecting multiple piers into pairs or clusters can open up views below the deck and also give rhythm and elegance to the supports.		
3,4,3 - Rounding off the corners of rectangular piers provides a softer form, which may be preferable in certain contexts. For example where the presence of the pier needs to be down played so that superstructure is dominant, e.g. in a rural setting.		
3,4,4 - Pier shapes which have a slight taper (A taper of around 1:80) are desirable.		
3,4,5 - The reverse taper should only be used where the appearance of rigidity is required between superstructure and pier. Otherwise the appearance of the top heavy pier can be imbalanced and does not reflect the forces acting on the pier well.		
3,5,1 - The proportion of pier size to pile cap size should be considered. Imbalanced proportions should be avoided.		
3,5,2 - In a tidal watercourse, if the view of the piles is to be minimised, the pile cap may require a skirt as they need to be visible to boats and shipping as a safety measure.		
3,6,1 - If using of wall abutments is unavoidable the use of planting should be considered to screen the abutment walls.		
3,6,2 - Reducing the abutments can create a more refined and better looking bridge. It does however increase the span and therefore depth of beam.		
3,6,3 - Continuing the superstructure or the parapet allows the shadow line to reduce the dominance of the abutment, and makes the bridge appear longer and more elegant.		
3,6,4 - Angling the abutments provides a more open sleek look and helps visually anchor the span.		
3,6,5 - Spill through abutments allow open views to the landscape and better visibility to the road beyond.		
3,6,6 - slight angle on the taper can make the wall appear less dominating especially if next to a footpath. This avoids visual crowding.		
3,7,1 - With the exception of name plates and navigation signs, signage should be kept off bridges as far as possible. They add clutter and complexity and detract from the structure. They also obstruct views from the bridge.		
3,8,1 - An outward curving screen creates a more open feeling for bridge users. However it presents a greater apparent depth of structure for onlookers.		
3,8,2 - The screens should extend to the ends of the bridge span and consideration should be given to integrating the bridge barrier and safety screens.		
3,9,1 - Where possible lighting on bridges should be minimized or avoided.		
3,9,2 - If necessary lighting should be used in the median as far from the parapet as possible to reduce clutter or designed into the parapet structure.		
3,9,3 - If considerable effort is put into the design of the appearance of the bridge it is better value for money to allow the bridge to be viewed at night (dependent on context, cost, safety and environmental issues).		
3,10,1 - The colour and grade of the pipe system must be considered as these aspects can jar with the overall bridge design.		
3,11,1 - Where possible avoid the use of noise walls on bridges.		
3,11,2 - The use of transparent panels should be considered so that the apparent slenderness of the superstructure is not affected.		
3,12,1 - Landscape tones are generally subdued and dark; therefore light colours and textures (for bridge primary elements) provide a good contrast. (the exception is when they are culturally appropriate such as traditional Chinese bridges or unique icon		
3,12,2 - A neutral palette of black, gray and white tend to give a clear definition of the bridge as an object in the landscape.		

Table Ex3.3: Guidelines for Bridges: The parts and details

Aesthetic Aspects	**Max Score**	**Score gained**
Bridges as whole	25%	
Bridge & its surroundings	25%	
Parts & Details	25%	
Past performance/Public consultation	25%	
Total		

Table Ex 3.4: Weighting factors for aesthetics

Past performance	**Liaison officer allocated**	**Impact score out of 10**
Poor	Yes	5
Good	Yes	1
None	Yes	3
Poor	No	10
Good	No	7
None	No	9

Table Ex 3.5: Impact scores for past performance and liaison officer

(ii) **Dust**

This impact is quantified by considering the following four factors

- the net increase in dust level
- the presence of sensitive buildings nearby (Table Ex3.6)
- public consultation and past performance of contractor (Table Ex3.7)
- duration of dust nuisance

The relevant assumptions for this bridge are

- the ambient dust level is 150 μg and the maximum expected dust level during construction and maintenance does not exceed 170 μg
- it is in the vicinity of a hospital
- dust producing activities are carried out during the daytime during weekdays and at weekends
- the contractor has no past performance but has appointed a liaison officer to consult with the public
- duration of dust nuisance : construction period - 90 days
  : maintenance period – 175 days per treatment.

Thus the scores are as follows

- <u>Dust level</u>

  $$170 - 150 = 20$$

- <u>Sensitive premises</u>

  From Table Ex3.6 the score is 20

- <u>Public consultation and contractor performance</u>

  From Table Ex3.7 it can be seen that the score is 3

- <u>Duration</u>

  No of maintenance treatments = 3

  The score is (90 + 3 × 175 =) 615 being equal to the total duration of dust nuisance.

Type of Sensitive Premises	**Working Time/Period**			
	Weekday		**Weekend**	
	Day	**Night**	**Day**	**Night**
Hospital, Caring homes & Similar premises	**10** (Hazardous for patients.)	**10** (Hazardous for patients.)	**10** (Hazardous for patients.)	**10** (Hazardous for patients.)
Offices & Similar premises	**8** (Hazardous for staff & extra cleaning required.)	**6** (Extra cleaning required.)	**6** (Extra cleaning required.)	**6** (Extra cleaning required.)
Commercial / Businesses & Similar premises	**8** (Hazardous for shoppers, staff & extra cleaning required.)	**6** (Extra cleaning required.)	**8** (Hazardous for shoppers/staff & extra cleaning required.)	**6** (Extra cleaning required.)
Schools/ Colleges & Similar premises	**10** (Hazardous for students, staff & extra cleaning required.)	**6** (Extra cleaning required.)	**6** (Hazardous for students, staff & extra cleaning required.)	**6** (Extra cleaning required.)
Residential & Similar premises	**10** (Hazardous for residents & extra cleaning required.)	**8** (Extra cleaning required.)	**10** (Hazardous for residents & extra cleaning required.)	**8** (Extra cleaning required.)
Others:	**8** (assumed)	**6** (assumed)	**8** (assumed)	**6** (assumed)

Table Ex3.6: Sensitive premises

Past performance	**Liaison officer allocated**	**Impact score out of 10**
Poor	Yes	5
Good	Yes	1
None	Yes	3
Poor	No	10
Good	No	7
None	No	9

Table Ex3.7: Past performance and public consultation

(ii) Noise

This impact on society is quantified by considering five factors as follows

1) the net increase in noise level
2) the time the impact is present
3) the presence of sensitive buildings nearby
4) public consultation and past performance
5) measures taken to mitigate the effect of noise.

Factors (2), (3) and (4) are the same as for dust and are calculated in the same way. Thus the scores for these factors are respectively 615, 20 and 3.

<u>Net increase in noise level</u>

Assuming the ambient noise level is 60 dBA and the maximum expected noise level is 90 dBA during construction and maintenance work, the score is

$$90 - 60 = 30$$

<u>Measures taken to mitigate the effect of noise</u>

Two measures are commonly used

- low noise surfaces
- noise walls

The score for this factor is obtained by allowing one tenth for each of the above measures. For this bridge it is assumed that only low noise surfaces are used to mitigate the effect of noise so the score is 1/10.

(iii) Vibration

This impact on society is quantified by considering four factors

- vibration dose
- duration
- presence of sensitive premises nearby
- public consultation/contractor past performance

The scores for the last three factors are the same as for dust and noise. The scores are respectively 615, 20 and 3.

The total vibration dose for a day is given by the formula

$$1.4at^{0.25} \text{ ------------(2)}$$

where

a is the rms (root mean square) acceleration

t is the duration of vibration occurrence in seconds multiplied by average number of occurrences per day (respectively, 1200 sec and 6 in this case).

Thus the vibration dose is

$$1.4 \times 0.5 \times (1200 \times 6)^{0.25} = 6.45$$

Exercise 7

(i) From the above information calculate the overall impact scores for dust, noise and vibration.

(ii) Compare the impacts of aesthetics, dust, noise and vibration and comment on how the impacts could be reduced and what consequences this may have for the environmental and economic impacts.

Ex4. Calculating the sustainability score for a bridge

Exercises 1-3 have determined the impact scores of providing a bridge for 120 years on the environment, economy and society. In order to obtain an overall sustainability score we have to combine these three scores. This is problematical because they are measured in different units. SASS, unlike other appraisal methods such as BREEAM and CEEEQUAL, is designed to give a relative measure of sustainability rather than an absolute measure. It is used to compare the sustainability of a number of bridge designs or maintenance strategies.

Each environmental factor such as CO_2 emitted, energy consumed or tonnage of materials consumed is compared for each design/maintenance strategy. The comparison is carried out by a normalization technique.

Assuming the cost of construction of the three bridge designs 1, 2 and 3 to be £787 200, £393 600 and £590 400 respectively then the normalized score for Bridge 1 is given by

$$\left(1-\frac{787\,200}{787\,200+393600+590\,400}\right)100 = 55.6\ \%$$

Using this approach the bridge with the highest cost of construction will have the lowest score.

These normalized scores are dimensionless and therefore can be compared with similar normalized scores for other economy, environment and society factor.

<u>Exercise 8</u>

(i) Enter your results for Bridge 1 in Table Ex 4.1
(ii) Using the information in Table Ex4.1 calculate the normalized score for the other factors using the method above and insert the values in Table Ex 4.1 for Bridges 1, 2 and 3.

Indicators	Bridge 1		Bridge 2		Bridge 3	
	Quantity	Normalised score	Quantity	Normalised score	Quantity	Normalised score
Environment						
CO_2 emitted			13,821		17,348	
Energy consumed			203,661		244,877	
Materials consumed			2383		2803	
Society						
Dust			348,000		406,800	
Noise			104,400		122,040	
Vibration			224,460		262,386	
Aesthetic			62.2		46.5	
Economy						
Construction cost	787,200	55.6	393,600		590,400	
Maintenance cost			781,880		935,407	
Traffic delay cost			7,794,674		9,127,138	

Table Ex4.1: Normalized scores for Bridges 1, 2 and 3

SASS also permits the relative weightings between the three sustainability themes (environment, economy and society) to be varied. It also permits the relative weightings of the different factors within a sustainability theme to be varied. Normally an equal weighting is applied to both sustainability themes and factors, however sometimes constraints may justify non-equal weightings.

In the example given in Table Ex4.1 we will initially assume equal weightings apply to both themes and factors. Thus the weighting factor for each of the three themes is 1/3 or 0.33. For the economy themes there are three factors so these will have a weighting factor of 0.33/3 = 0.11.

Exercise 9

(i) Determine the weighting factors for the environment and society factors and insert them in Table Ex4.2.

(ii) Determine the weighted score for each factor by multiplying the normalized score by the weighting factor, for example the weighted score for cost of construction is given by

$$55.6 \times 0.11 = 6.1 \text{ for Bridge 1}$$

and insert your values in Table Ex4.2.

(iii) Sum all the weighted scores to give a sustainability score for each bridge and rank the three bridges in order of decreasing sustainability.

Exercise 10

Assume the economy is constrained and hence has a higher weighting factor compared with the other themes. Assume the ratio of weighting factors for the sustainability themes is environment 1: society 1: Economy 2. Therefore the weighting factor for each theme is

Environment	0.25
Society	0.25
Economy	0.5

You should now determine

- the weighting factors for each bridge as before
- the weighted score for each bridge
- the sustainability score for each bridge

Enter your values in a revised version of Table Ex4.2 and comment on how the weighting factors have changed the sustainability ranking of the three bridges.

Indicators	Bridge 1				Bridge 2				Bridge 3			
	Weighting	Quantity	Normalised Score	Weighted score	Weighting	Quantity	Normalised Score	Weighted score	Weighting	Quantity	Normalised Score	Weighted score
Environment												
CO_2 emitted												
Energy consumed												
Materials consumed												
Society												
Dust												
Noise												
Vibration												
Aesthetic												
Economy												
Construction cost												
Maintenance cost												
Traffic delay cost												

Table Ex. 4.2: Normalised scores for Bridges 1, 2 and 3

Commentary on exercises

The commentary provided below on these student exercises suggests some ways in which environmental, economic and social impacts may be reduced. The commentary also highlights the interconnectedness of the three sustainability components so that a change introduced in order to reduce, say, the environmental impact may have an adverse effect on the economics or social components. In a similar way the use of more durable design materials aimed at reducing lifetime maintenance costs may have an adverse affect on the environment.

It is important to know whether construction or maintenance is the major contributor to environment degradation. If construction was the major contributor then alternative design materials could be considered. For example carbon fibre type reinforcement may be less harmful for the environment; steel bridges may be more harmful than concrete bridges. Masonry bridges may be the least harmful. Different materials may influence the cost of construction, maintenance frequency and design characteristics such as span length. Thus all these factors must be considered.

If maintenance was the major contributor to environmental degradation then more durable design materials could be considered. These would reduce the maintenance frequency and associated traffic delays. Corrosion of steel is the main cause of bridge deterioration requiring maintenance work. The onset of corrosion can be delayed and its subsequent rate of progress reduced by modifying the design materials or incorporating protective measures. For example using better quality concrete with lower water/cement ratio or a greater depth of concrete cover will slow the rate of chloride ion ingress, increase the time to corrosion and reduce the number of maintenance treatments. The use of stainless steel instead of mild steel will prevent corrosion and eliminate maintenance work resulting from corrosion. Dosing the concrete with corrosion inhibitors can have a similar effect. The reduction in maintenance achieved by using these modifications of the design materials would have to be balanced against their higher embodied CO_2, energy and cost. The use of more efficient maintenance treatments with longer lives will also reduce maintenance frequency. For example cathodic protection could be compared with the traditional method, concrete repair. The impact of more durable materials or repair methods on lifetime cost would also have to be taken into account.

If traffic delay costs are the major contributor to poor sustainability attempts would be needed to reduce maintenance frequency and the time for which traffic lanes are closed to traffic or diversions are in operation. This could be achieved by using more durable materials, improved repair methods and faster methods for repair work. Night time working is a useful way of limiting traffic delay costs. Traffic delay costs may increase over the life of the bridge due to increased traffic flows or proportion of HGV’s, although discounting costs will have the opposite effect. The impact of traffic diversions as opposed to lane closures could be compared with respect to costs and environmental impact. For example if a suitable alternative route is available it may be better to divert some or all of the traffic thereby allowing the repairs to be made more quickly. Diverted traffic, especially if it includes HGV’s, can cause problems such as noise, fumes and vibrations to buildings and people on the alternative route. This may be important if there are sensitive buildings such as hospitals or schools on the alternative route. Slow moving traffic caused by lane closures during maintenance work also results in a higher level of exhaust pollutants such as oxides of nitrogen and sulphur as the fuel is burnt less efficiently in the internal combustion engine. The higher frequency of accidents of traffic passing through maintenance work or on diversions also needs to be taken into account.

The availability of natural resources for bridge construction materials is not a major problem. There are adequate supplies of iron ore, coal, clay and aggregates. In densely populated built environments such as the UK the extraction of gravel aggregates is a problem not because of an insufficient supply but owing to the land take involved in its extraction. This has resulted in the use of recycled and sea dredged aggregates. The latter requires washing to remove sea salts that could cause corrosion of the reinforcing steel and this places a heavy demand on clean water, a limited resource in many countries.

Lifecycle costs may be reduced by using more durable materials, as previously discussed, since this will reduce the maintenance frequency. This is particularly relevant on heavily trafficked roads where maintenance work cannot be undertaken without using traffic management schemes that often cause delays. Costs are compared at the date of construction by using the discounted cash flow technique. This means that maintenance and traffic delay costs that accrue later in the life of the bridge are substantially reduced. For example if the discount rate is 3% then costs incurred after age 80 are reduced by more than 90% and could be neglected on the calculations of lifetime cost.

The procedure for assessing aesthetics is fundamentally different to that used for the other social factors considered namely noise, dust and vibration. Generally, measures which reduce construction time and increase the time to maintenance will result in lower social impacts. Reductions in construction time could be achieved by for example increasing the percentage of off-site fabrication. The time to maintenance could be increased by using more durable materials. Off-site fabrication could reduce both environmental as well as economic impacts because of reduced waste and reduced labour, the need for less plant, tools and materials storage, quicker installation, fewer quality difficulties and guaranteed delivery. Improving durability may increase the initial cost of construction but should reduce maintenance costs with a concomitant reduction in environmental costs due to reduced material use, CO_2 emissions, energy and waste.

The calculation of sustainability inevitably involves a number of estimates and assumptions so the results will lack precision. Therefore when comparing the sustainability scores for the alternative bridges we are looking for distinct differences in value in order to reliably rank the bridges in terms of increasing sustainability. If the values are similar a reliable ranking may not be possible so all we can say is that the bridges have similar sustainability scores. In order to decide on the most sustainable bridge we can consider the relative contributions of environment, cost and social factors as well as the overall score. In most cases we would probably prefer these contributions to be similar instead of one of the factors being particularly poor.

The calculation of the lifetime sustainability scores usually employs equal weighting for the environment, cost and society themes. Sometimes, however, one of the factors will be more important than the others. For example if the funds available are limited then costs will be more important and this is often the case. The weighting factors can be varied to take account of this, although the actual value to use is best decided by a consensus of experts. Similarly in some situations the environment or social factors can be the most important.

It is clear that almost any change to the construction and maintenance of a bridge will have far reaching and diverse effects on its lifetime sustainability. This is why it is not intuitively possible to know how such changes affect sustainability and therefore why a standard method for calculating sustainability is essential.

Chapter **4: Evaluation**

The examples and exercises were trialled on a group of third year students enrolled on the BEng/MEng programme in civil engineering at University College London. Students were asked to carry out the work in groups of three and given approximately four weeks to complete the task, which was ample. So as to achieve consistency of marking and feedback to students the assessment form in Appendix E was used. The feedback session consisted of a short talk on sustainable development and a review of common sustainability appraisal tools such as those discussed in chapter 1 to help put SASS into context. This was followed by a detailed discussion on the work submitted: common mistakes/omissions and to highlight any interesting points raised in individual submissions.

It was clear from the submissions that students had not experienced any difficulties understanding the questions or completing Exercises 1 and 2.

Exercise 3 required students to calculate CO_2 emissions and energy consumed due to various maintenance activities. The example in the brief was for inspection which, unlike the other maintenance activities considered, could be carried out during off-peak hours. Unfortunately, most students did not realise this fact and therefore underestimated the quantities of CO_2 and energy involved. Nonetheless, this did not invalidate the rest of the analysis. Exercise 3ii(b) asked students to make recommendations on how to reduce the impact of maintenance activity on the environment. Possible measures included enhanced concrete quality and cover, stainless steel rebar in the substructure and the provision of a protective enclosure system. Many, but by no means all, students made quite a poor attempt at this question which was partly attributable to the fact that durability, which is a topic in Engineering Materials, was covered after the hand-in date for the assignment.

Exercise 5 focused on traffic delay costs for various maintenance treatments. Students did not experience any difficulties calculating costs but a few were rather sceptical of the order of values obtained and were eager to learn more about this technique. Having correctly identified which maintenance treatment has the largest impact, some students made quite poor attempts at suggesting ways of reducing lifetime costs and discussing possible influences on environmental and social factors (i.e. Ex 5(ii)(e)). Again the mismatch with the timetable for Engineering Materials may have contributed to this problem.

Except for the part on bridge aesthetics (Ex 6) the section on social impact assessment was generally well attempted (Ex 7).

The students did not seem to experience any difficulty calculating the overall sustainability scores for the three bridge designs but the discussion of results (Ex 9(iv) and Ex 10) could have been more thorough. It appeared that while the students had a good understanding of modes of deterioration such as corrosion they showed less appreciation of which parts of bridges are vulnerable to deterioration. The lack of this practical knowledge probably demonstrates that their training has been dominated by design to the detriment of maintenance.

One group of students only attempted those exercises requiring numerical answers.

Some students felt that they would have performed better if they had received more instructions at the outset of this work, this being the only negative feedback received, whereas others felt that the assignment had provided good context for the talk on sustainability and sustainability appraisal tools at the feedback session.

Overall the students made a good attempt at the work and unlike previous years' seemed to have enjoyed this element of the design course. Equally important was the fact that they had gained some understanding of the implications of sustainable development on structural design, construction and maintenance.

Chapter 5: Reflections

Previous attempts at teaching sustainable development to students of structural design on degree courses were found to be rather passive and somewhat ineffective. Generally, two one hour lectures were devoted to the topic. Aspects discussed included the definition of sustainable development, implications for civil engineering and current approaches to achieving sustainable development such as performance indicators, economic instruments and sustainability appraisal tools. Some examples of sustainable construction practices were also provided. Students' understanding of the subject matter was assessed either via an essay or a question on the end of year examination paper. Although the students performed well on these assessments, the feedback received from some students suggested that the lectures were not actually very useful as they were already aware of many of the issues highlighted. Worse was the fact that they didn't really understand how they would take account of these issues in scheme design. Experience of teaching engineering students suggested that worked examples are a good way of clarifying principles and procedures and it was with this thought in mind that the assignment presented in chapter 3 was developed.

Since this assignment has only been trialled once it is perhaps a little premature to draw firm conclusions about this style of teaching and learning sustainable design. Nevertheless, based on the submissions and feedback received from students it would seem reasonable to conclude that the approach was largely successful in that it

(a) helped develop an awareness of the impact of design decisions on the environment, society and economy
(b) raised awareness of the inter-relationships between the various issues relatable to sustainable development
(c) developed some expertise in appraisal tools and how they can assist the production of sustainable designs
(d) provided first-hand experience of the processes involved in sustainability appraisal.

Furthermore it was found that this project-based, analytical approach seemed to appeal to engineering students as evidenced in their general level of interest in the topic as well as specific aspects of the work such as traffic delay costs and bridge aesthetics. Another advantage was the fact that it was quite easy to distinguish between those students who had applied themselves and thought deeply about the work and others who had adopted a more mechanical approach. To further encourage students to address the more challenging parts of the assignment perhaps a marking scheme could be added.

From the comments made in Chapter 4 it might be concluded that students should have prior knowledge of the following topics

- Bridges e.g. construction, modes of deterioration and maintenance methods
- Whole life cost analysis e.g. principles, assumptions, methodology and key input parameters
- Bridge aesthetics

However, this is not absolutely necessary since these topics could be discussed either when requested by students or during the feedback session, when they are fully engaged.

From a resource point of view it was found that the coursework is largely self-explanatory and actually required very little time to administer. This approach to teaching and learning sustainable development could be extended to other types of structures but the basic data would have to be collated. To prevent the risk of plagiarism in future years some alternative design options will be developed. This will not entail too much extra work as it should be possible to mix and match various elements from the existing designs in order to obtain new options. Thus a fourth option could be a two span continuous steel beam and slab bridge with two full height abutments and one pier. Option 5 could be a four span simply supported prestressed concrete beam and slab bridge with bank seats and three intermediate piers. Further developments of this work might include the provision of spreadsheets to eliminate the tedium of performing a large number of hand calculations and perhaps an oral component.

Chapter 6: Conclusions

Courses in structural design have traditionally focused on technical and economic issues and largely ignored environmental and social factors. Civil infrastructure can have a significant impact on the environment, society and economy and it is important therefore that civil engineers develop sustainable designs. But the problem is that currently it is not clear how this can be achieved in practice.

The work presented in this report is an attempt to address this problem. It consists of a series of examples and related exercises which involve carrying out a sustainability appraisal on a four span continuous steel beam and slab bridge with integrated bank seat foundations and three intermediate leaf piers. Initially, students are asked to assess the impact of the scheme on various sustainability factors, including CO_2 emissions, energy use, maintenance costs, traffic delay costs, noise and dust. Subsequently they are asked to propose measures to reduce the impact on each of the three main sustainability themes in turn (i.e. environment, economy and society) and consider the consequences on the remaining themes, with the aim of minimising the overall impact.

The impact on the various factors is measured in different units and must be combined in order to establish which of the proposed measures or, in our case, alternative bridge schemes is the most sustainable. This is achieved using a normalising technique which converts the scores into dimensionless values. However, before carrying out this combination it is necessary to decide the relative importance of the three sustainability themes. This is best done using engineering judgement by consensus of a group of experts yielding a weighting factor for each theme.

The work presented in this report shows that choices of construction material, structural form and method of maintenance can have far reaching and diverse effects on the lifetime sustainability of structures. It is not intuitively possible to know how these factors affect sustainability performance and that judicious use of sustainability appraisal tools present a way forward.

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Appendix A

A.1 CO_2 for production and transport of materials

Material	Construction (tonnes of CO_2)		Lifetime repairs (tonnes of CO_2)	
	Production	Transport	Production	Transport
OPC	346.29	1.18	18.43	0.06
Aggregate	11.09	4.57	0.58	0.24
Stainless steel	861.00	0.46		
Steel beams	116.35	0.21		
Steel reinforcement	584.80	1.12		
Parapets	47.94	0.06	16.92	0.02
Water proofing	9.94	-	2.98	-
Paint	0.73	-	0.18	-
Total	1978.14	7.60	39.09	0.32

Σ 2,025.15 t

Table A1: Embodied tonnes of CO_2 for production and transportation of construction and repair materials for Bridge 1

Material	Construction (tonnes of CO_2)		Lifetime repairs (tonnes of CO_2)	
	Production	Transport	Production	Transport
OPC	330.77	1.13	40.74	0.14
Aggregate	10.62	4.38	1.31	0.54
Stainless steel	-	-	-	-
Steel beams	-	-	-	-
Steel reinforcement	830	1.6	-	-
Parapets	47.9	0.06	16.9	0.02
Water proofing	3	-	10	-
Paint	-	-	-	-
Asphaltic joints	0.14	-	-	-
Total	1222.43	7.17	68.95	0.70

Σ 1,299.25 t

Table A2: Embodied tonnes of CO_2 for production and transportation of construction and repair materials for Bridge 2

Material	Construction (tonnes of CO_2)		Lifetime repairs (tonnes of CO_2)	
	Production	Transport	Production	Transport
OPC	404.5	1.38	47.53	0.16
Aggregate	12.94	5.34	1.52	0.63
Stainless steel	1820.4	0.98	-	-
Steel beams	-	-	-	-
Steel reinforcement	350.9	0.67	-	-
Parapets	47.9	0.06	16.9	0.02
Water proofing	5	0	15	-
Paint	-	-	-	-
Asphaltic joints	0.19	0	-	-
Total	2641.83	8.43	80.95	0.81

Σ 2,732.02 t

Table A3: Embodied tonnes of CO_2 for production and transportation of construction and repair materials for Bridge 3

A.2 CO_2 emissions due to maintenance

Activity	HGVs	Other vehicles
	(tonnes of CO_2)	
Inspection	20	18
Concrete repair	6,849	6,175
Painting	1,148	1, 035
	8,017	7,228

Σ 15,245 t

Table A4: CO_2 emissions due to maintenance of Bridge 1

Activity	HGVs	Other vehicles
	(tonnes of CO_2)	
Inspection	10	9
Concrete repair	6,575	5,928
	6,585	5,937

Σ 12,522 t

Table A5: CO_2 emissions due to maintenance of Bridge 2

Activity	HGVs	Other vehicles
	(tonnes of CO_2)	
Inspection	15	14
Concrete repair	7,671	6,916
	7,686	6,930

Σ 14,616 t

Table A6: CO_2 emissions due to maintenance of Bridge 3

A3. Energy for production and transport of materials

Material	Construction (Gj)		Lifetime repairs (Gj)	
	Production	Transport	Production	Transport
OPC	2177.70	17.85	115.90	0.95
Aggregate	207.90	69.30	10.80	3.60
Stainless steel	7210.00	7.00		
Steel beams	1475.50	3.25		
Steel reinforcement	7718.00	17.00		
Parapets	608.60	0.85	182.58	0.30
Water proofing	168.00	0.05	50.40	0.12
Paint	9.60	-		-
Total	19,575.30	115.30	359.68	5.03

Σ 20,055.31 Gj

Table A7: Energy required for production and transport of materials for Bridge 1

Material	Construction (Gj)		Lifetime repairs (Gj)	
	Production	Transport	Production	Transport
OPC	2080	17.05	256.2	2.10
Aggregate	200	66.35	24.5	8.17
Stainless steel	-	-	-	-
Steel beams	-	-	-	-
Steel reinforcement	10,941.4	24.10	-	-
Parapets	608.60	0.85	214.8	0.30
Water proofing	168.00	0.02	50.4	0.06
Paint	-	-	-	-
Asphaltic joints	7.8	0.15	-	-
Total	14005.80	108.52	545.9	10.63

Σ 14,675.59 Gj

Table A8: Energy required for production and transport of materials for Bridge 2

Material	Construction (Gj)		Lifetime repairs (Gj)	
	Production	Transport	Production	Transport
OPC	2543.7	20.85	298.9	2.45
Aggregate	242.7	80.90	28.5	9.50
Stainless steel	15,244	14.80	-	-
Steel beams	-	-	-	-
Steel reinforcement	4,630.8	10.20	-	-
Parapets	608.6	0.85	214.8	0.30
Water proofing	84	0.03	252	0.09
Paint	-	-	-	-
Asphaltic joints	10.4	0.20	-	-
Total	23,364.20	127.83	794.20	12.34

Σ 24,298.57 Gj

Table A9: Energy required for production and transport of materials for Bridge 3

A.4 Energy for maintenance

Activity	HGVs (Gj)	Other vehicles (Gj)
Inspection	309	265
Concrete repair	105,840	90,720
Painting	17,740	15,206
Total	123,889	106,191

Σ 230,080 Gj

Table A10: Energy for maintenance of Bridge 1

Activity	HGVs (Gj)	Other vehicles (Gj)
Inspection	155	133
Concrete repair	101,606	87,091
Total	101,761	87,224

Σ 188,985 Gj

Table A11: Energy for maintenance of Bridge 2

Activity	HGVs (Gj)	Other vehicles (Gj)
Inspection	232	199
Concrete repair	118,541	100,606
Total	118,773	101,805

Σ 220,578 Gj

Table A12: Energy for maintenance of Bridge 3

A5. Maintenance costs

Activity	Frequency (years)	Cost of single application (£)	Age of bridge at each application	Life time cost (£)	Discounted life time cost (£)
Inspection	5	12,400	5, 10, 15 ……115	285,200	76,935.46
Concrete repair	30	655,000	30, 60, 90	1,965,000	415,510.57
Painting	25	58,000	25, 50, 75, 100	232,000	49,001.10
Drain cleaning	2	1,200	2, 4, 6 ……. 118	70,800	19,278.67
Total					£ 560,725.80

Table A13: Lifetime discounted and undiscounted maintenance costs for Bridge 1

Activity	Frequency (years)	Cost of single application (£)	Age of bridge at each application	Life time cost (£)	Discounted life time cost (£)
Inspection	5	6,200	5, 10, 15 ……115	142,600	38,467.73
Concrete repair	30	1,156,900	30, 60, 90	3,470,100	733,772.64
Drain cleaning	2	600	2, 4, 6 ……. 118	35,400	9,639.34
Total					£ 781,879.71

Table A14: Lifetime discounted and undiscounted maintenance costs for Bridge 2

Activity	Frequency (years)	Cost of single application (£)	Age of bridge at each application	Life time cost (£)	Discounted life time cost (£)
Inspection	5	9,300	5, 10, 15 ……115	213,900	57,701.59
Concrete repair	30	1,360,800	30, 60, 90	4,082,400	863,246.89
Drain cleaning	2	900	2, 4, 6 ……. 118	53,100	14,459.01
Total					£ 935,407.49

Table A15: Lifetime discounted and undiscounted maintenance costs for Bridge 3

A6. Traffic delay costs

Maintenance activity	Length of lane closure (km)	Delay cost per day (£)	Duration of closure for each activity (days)	Delay cost for each activity (£)	Lifetime delay cost (£)	Discounted lifetime delay cost (£)
Inspection	0.2	23,900	4	135,600	3,118,800	841,326.42
Concrete repair	3	36,100	175	6,137,500	18,952,500	4,007,614.80
Painting	3	201,400	23	4,632,200	18,528,800	3,913,498.70
Total						£ 8,762,439.90

Table A16: Traffic delay costs for Bridge 1

Maintenance activity	Length of lane closure (km)	Delay cost per day (£)	Duration of closure for each activity (days)	Delay cost for each activity (£)	Lifetime delay cost (£)	Discounted lifetime delay cost (£)
Inspection	0.2	33,900	2	67,800	1,559,400	420,663.21
Concrete repair	3	36,100	322	11,624,200	34,872,600	7,374,011.20
Total						£ 7,794,674.40

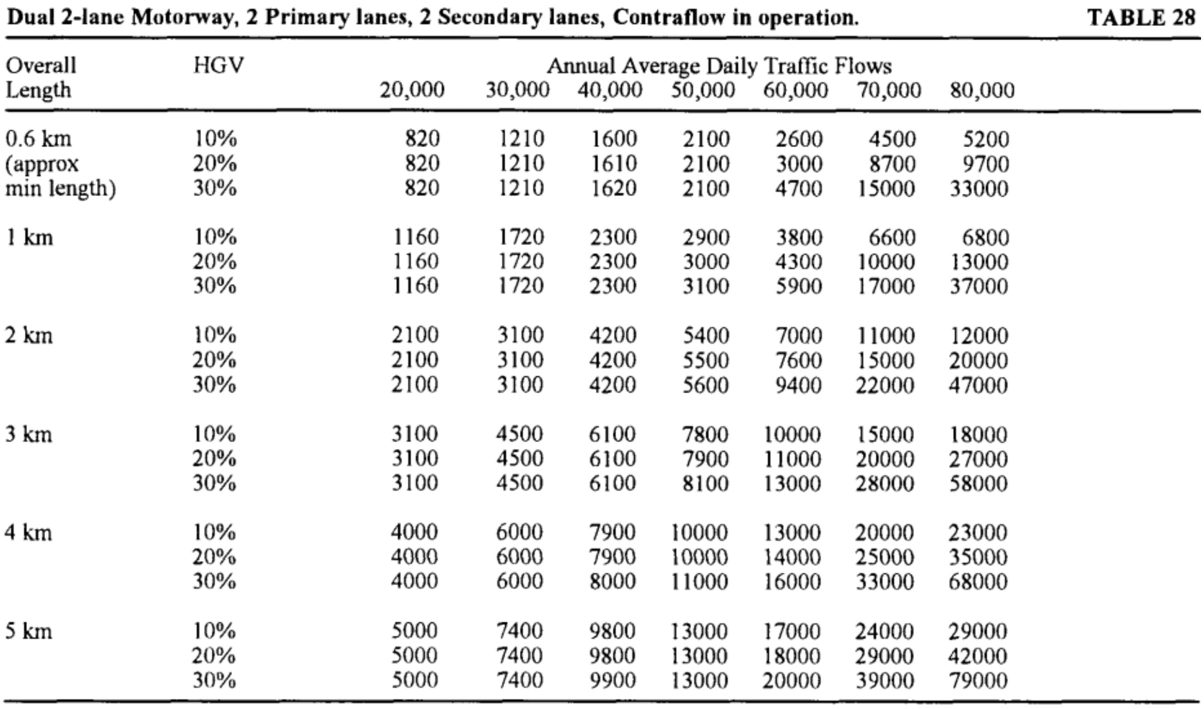
Table A17: Traffic delay costs for Bridge 2

Maintenance activity	Length of lane closure (km)	Delay cost per day (£)	Duration of closure for each activity (days)	Delay cost for each activity (£)	Lifetime delay cost (£)	Discounted lifetime delay cost (£)
Inspection	0.2	33,900	3	101,700	2,339,100	630,994.81
Concrete repair	3	36,100	371	13,393,100	40,179,300	8,496,143.30
Total						£ 9,127,138.10

Table A18: Traffic delay costs for Bridge 3

Appendix B: Quadro Tables

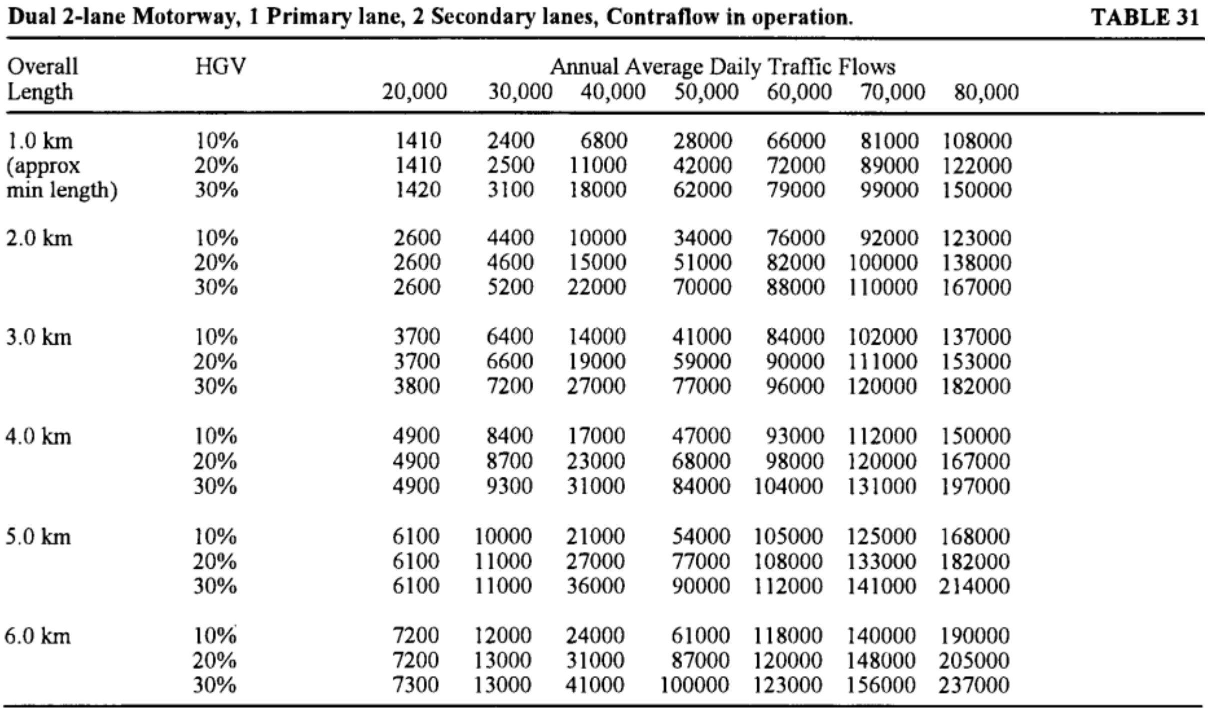
QUADRO Table 28



Dual 2-lane Motorway, 2 Primary lanes, 2 Secondary lanes, Contraflow in operation. **TABLE 28**

Overall Length	HGV	Annual Average Daily Traffic Flows						
		20,000	30,000	40,000	50,000	60,000	70,000	80,000
0.6 km (approx min length)	10%	820	1210	1600	2100	2600	4500	5200
	20%	820	1210	1610	2100	3000	8700	9700
	30%	820	1210	1620	2100	4700	15000	33000
1 km	10%	1160	1720	2300	2900	3800	6600	6800
	20%	1160	1720	2300	3000	4300	10000	13000
	30%	1160	1720	2300	3100	5900	17000	37000
2 km	10%	2100	3100	4200	5400	7000	11000	12000
	20%	2100	3100	4200	5500	7600	15000	20000
	30%	2100	3100	4200	5600	9400	22000	47000
3 km	10%	3100	4500	6100	7800	10000	15000	18000
	20%	3100	4500	6100	7900	11000	20000	27000
	30%	3100	4500	6100	8100	13000	28000	58000
4 km	10%	4000	6000	7900	10000	13000	20000	23000
	20%	4000	6000	7900	10000	14000	25000	35000
	30%	4000	6000	8000	11000	16000	33000	68000
5 km	10%	5000	7400	9800	13000	17000	24000	29000
	20%	5000	7400	9800	13000	18000	29000	42000
	30%	5000	7400	9900	13000	20000	39000	79000

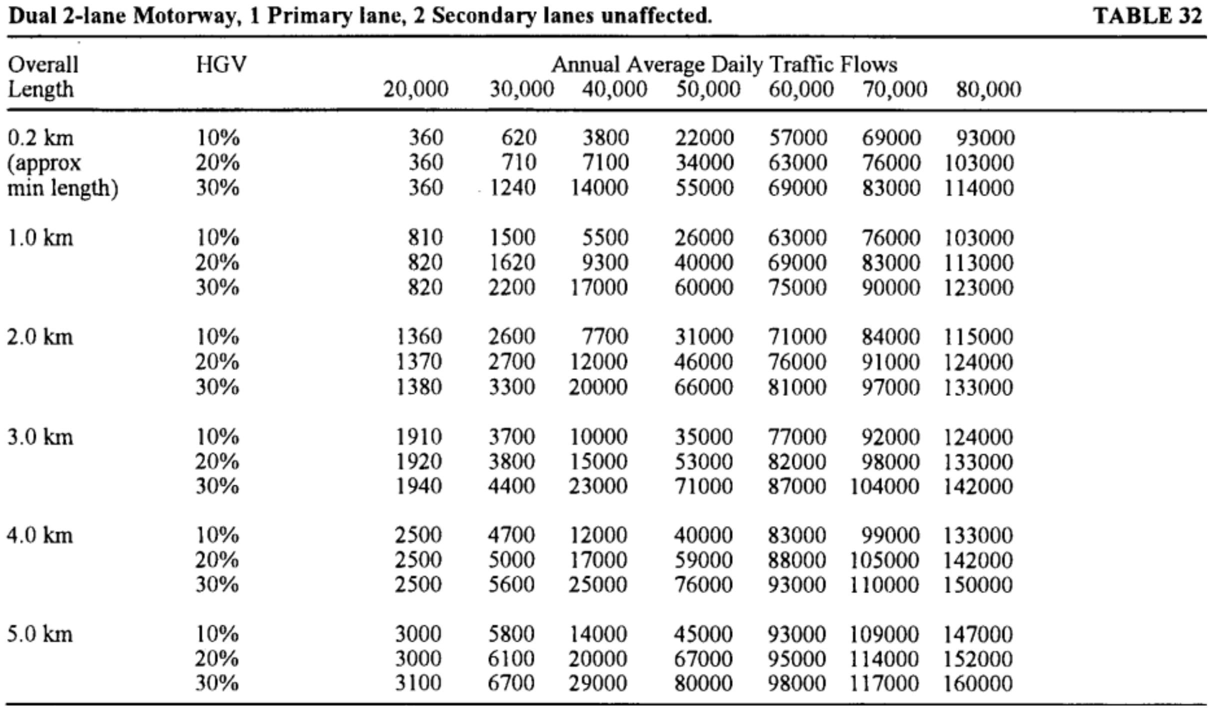
QUADRO Table 31



Dual 2-lane Motorway, 1 Primary lane, 2 Secondary lanes, Contraflow in operation. **TABLE 31**

Overall Length	HGV	Annual Average Daily Traffic Flows						
		20,000	30,000	40,000	50,000	60,000	70,000	80,000
1.0 km (approx min length)	10%	1410	2400	6800	28000	66000	81000	108000
	20%	1410	2500	11000	42000	72000	89000	122000
	30%	1420	3100	18000	62000	79000	99000	150000
2.0 km	10%	2600	4400	10000	34000	76000	92000	123000
	20%	2600	4600	15000	51000	82000	100000	138000
	30%	2600	5200	22000	70000	88000	110000	167000
3.0 km	10%	3700	6400	14000	41000	84000	102000	137000
	20%	3700	6600	19000	59000	90000	111000	153000
	30%	3800	7200	27000	77000	96000	120000	182000
4.0 km	10%	4900	8400	17000	47000	93000	112000	150000
	20%	4900	8700	23000	68000	98000	120000	167000
	30%	4900	9300	31000	84000	104000	131000	197000
5.0 km	10%	6100	10000	21000	54000	105000	125000	168000
	20%	6100	11000	27000	77000	108000	133000	182000
	30%	6100	11000	36000	90000	112000	141000	214000
6.0 km	10%	7200	12000	24000	61000	118000	140000	190000
	20%	7200	13000	31000	87000	120000	148000	205000
	30%	7300	13000	41000	100000	123000	156000	237000

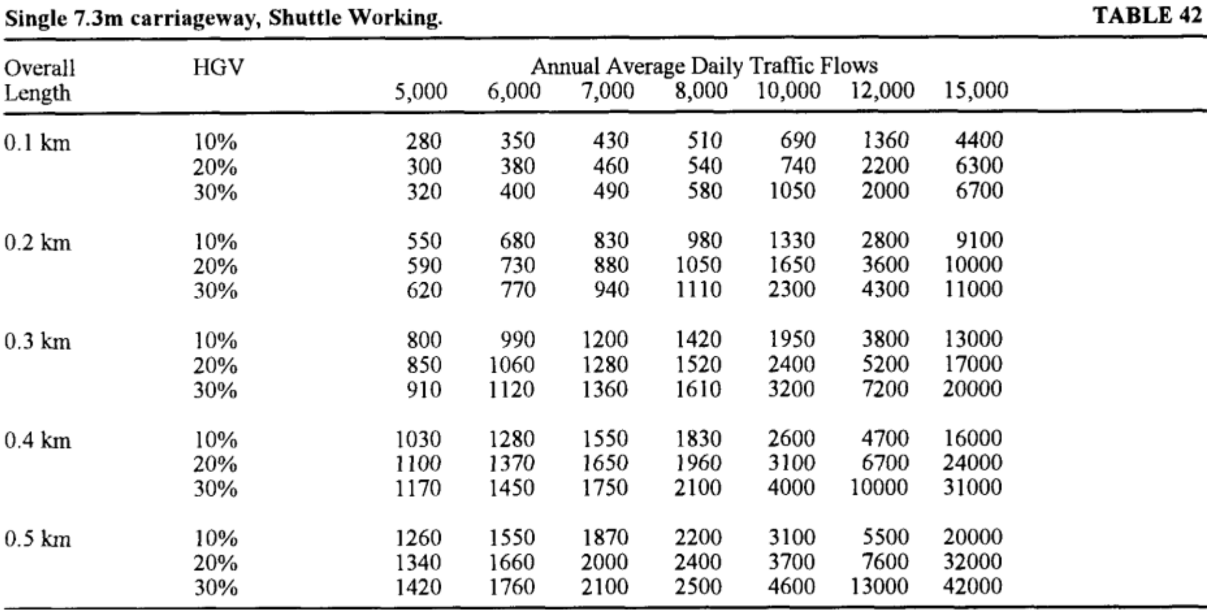
QUADRO Table 32



Dual 2-lane Motorway, 1 Primary lane, 2 Secondary lanes unaffected. **TABLE 32**

Overall	HGV	Annual Average Daily Traffic Flows						
Length		20,000	30,000	40,000	50,000	60,000	70,000	80,000
0.2 km	10%	360	620	3800	22000	57000	69000	93000
(approx	20%	360	710	7100	34000	63000	76000	103000
min length)	30%	360	1240	14000	55000	69000	83000	114000
1.0 km	10%	810	1500	5500	26000	63000	76000	103000
	20%	820	1620	9300	40000	69000	83000	113000
	30%	820	2200	17000	60000	75000	90000	123000
2.0 km	10%	1360	2600	7700	31000	71000	84000	115000
	20%	1370	2700	12000	46000	76000	91000	124000
	30%	1380	3300	20000	66000	81000	97000	133000
3.0 km	10%	1910	3700	10000	35000	77000	92000	124000
	20%	1920	3800	15000	53000	82000	98000	133000
	30%	1940	4400	23000	71000	87000	104000	142000
4.0 km	10%	2500	4700	12000	40000	83000	99000	133000
	20%	2500	5000	17000	59000	88000	105000	142000
	30%	2500	5600	25000	76000	93000	110000	150000
5.0 km	10%	3000	5800	14000	45000	93000	109000	147000
	20%	3000	6100	20000	67000	95000	114000	152000
	30%	3100	6700	29000	80000	98000	117000	160000

QUADRO Table 42



Single 7.3m carriageway, Shuttle Working. **TABLE 42**

Overall	HGV	Annual Average Daily Traffic Flows						
Length		5,000	6,000	7,000	8,000	10,000	12,000	15,000
0.1 km	10%	280	350	430	510	690	1360	4400
	20%	300	380	460	540	740	2200	6300
	30%	320	400	490	580	1050	2000	6700
0.2 km	10%	550	680	830	980	1330	2800	9100
	20%	590	730	880	1050	1650	3600	10000
	30%	620	770	940	1110	2300	4300	11000
0.3 km	10%	800	990	1200	1420	1950	3800	13000
	20%	850	1060	1280	1520	2400	5200	17000
	30%	910	1120	1360	1610	3200	7200	20000
0.4 km	10%	1030	1280	1550	1830	2600	4700	16000
	20%	1100	1370	1650	1960	3100	6700	24000
	30%	1170	1450	1750	2100	4000	10000	31000
0.5 km	10%	1260	1550	1870	2200	3100	5500	20000
	20%	1340	1660	2000	2400	3700	7600	32000
	30%	1420	1760	2100	2500	4600	13000	42000

Appendix C: Maintenance and Traffic delay costs

C1 - Bridge 1

C1-1 Drain cleaning

Labour/equipment

Cost = £300/span (Table 2.11)
No of spans = 4
∴Total **c**ost = £300 × 4 = £1,200

Gaining Access

Assume drain cleaning is carried out from the top surface of the deck and therefore are no access costs.

Traffic management

No carriageway closures required.
∴Cost of traffic management = 0

Overheads

Not applicable since this is routine maintenance

Cost of treatment

Engineering cost of treatment = Labour/equipment + Gaining access + Traffic management + Overheads
= £1,200 + £0 + £0 + 0 = £1,200

Lifetime number of treatments = 59 (Table 2.3)
Lifetime engineering cost = Cost of treatment × Lifetime number of treatments = £1,200 × 59 = £70,800

Discounted lifetime cost = $\sum_{i=1}^{15} \frac{1,200}{\left(1+0.035\right)^{2i}} + \sum_{j=16}^{37} \frac{1,200}{\left(1+0.03\right)^{2j}} + \sum_{k=38}^{59} \frac{1,200}{\left(1+0.025\right)^{2k}}$ = £19,278.67

Traffic delay cost

No lane closure required
∴Traffic delay cost = £0.

C1-2 Steelwork painting

Labour/equipment

Total area of steelwork = 800 m^2.
From Table 2.11 assume 10% area of steelwork to repaint every 25 years.
Steelwork painting to 80 m^2.
Price = £35 / m^2.

∴Cost of single treatment = £35 × 80 = £2,800

Gaining Access

Assume access by scaffolding and that full carriageway closure is required.
Scaffold over half deck area = 64 × 12.3 × ½ ≈ 400 m^2
Scaffold cost £1.5/ m^2/day
Steelwork painting to 80 m^2 @ 25 m^2/wk (Table 2.5) = 3.2 wk ≈ 23 days

∴Cost of scaffolding = 400 × £1.5 × 23 = £13,800

Traffic management

Carriageway closure with contraflow = £1,700/day

Cost of traffic management = £1,700 × 23 = £39,100

Overheads

Cost of contract = £2,800
Since contract < £50,000 ⇒ overhead rate = £700/wk (Table 2.16)

∴Total overhead cost = £700 × 3.2 ≈ £2,300

Cost of treatment

Engineering cost of treatment = Labour/equipment + Gaining access + Traffic management + Overheads
= £2,800 + £13,800 + £39,100 + £2,300 = £58,000

Lifetime number of treatments = 4 (Table 2.3)
Lifetime cost of treatment = £58,000 × 4 = £232,000

Discounted lifetime cost of treatment = $\frac{58,000}{(+0.035)^{25}} + \frac{58,000}{(+0.03)^{50}} + \frac{58,000}{(+0.03)^{75}} + \frac{58,000}{(+0.025)^{100}}$ = £49,001.10

Traffic delay cost

Assume steelwork painting will require a full carriageway closure. The central reservation crossover points are 2km apart giving a minimum traffic management length of 3km. For a two lane dual motorway with 80,000 AADT and 20% HGV, one primary and two secondary lanes with contraflow, Table 31 (TRRM Vol. 1 Annex 5.5.2) gives a traffic delay cost of £153,000/day at 1998 prices over a length of 3km.

RPI factor = 1.316 ⇒ Traffic delay cost at 2009 prices = 1.316 × £153,000 ≈ £201,400/day
Traffic delay cost per treatment = £201,400 × 23 = £4,632,200

Lifetime traffic delay cost = 4 × £4,632,200 = £ 18,528,800

Undiscounted lifetime delay costs = $\frac{4,632,200}{(+0.035)^{25}} + \frac{4,632,200}{(+0.03)^{50}} + \frac{4,632,200}{(+0.03)^{75}} + \frac{4,632,200}{(+0.025)^{100}}$ = £3,913,498.40

C1-3: Concrete repairs

Some of this work will be undertaken from a mobile platform positioned on the bridge whereas other work will be carried out from scaffolding erected on the motorway. Therefore both costs were determined for this maintenance action. Repairs to the deck slab will require shuttle working and a load restriction to HGVs. For moderate and major repairs much of the deck repair work will be carried out from above deck.

(I) ON THE ROAD BELOW

Cost of treatment

Total surface area of concrete = 500 m^2.
From Table 2.7 assume 10% of surface area of concrete to repair every 30 years.
Concrete repair to 50 m^2.
Price = £1600 / m^2.

∴Cost of single treatment = £1600 × 50 = £80,000

Gaining Access

Assume access by scaffolding and that repairs will be undertaken using two closed lanes for the duration of the works.

Scaffold over quarter of deck area = 64 × 12.3 × ¼ ≈ 200 m^2
Scaffold cost £1.5/ m^2/day
Concrete repair to 50 m^2 @ 2 m^2/wk (Table 2.7) = 25 wk = 175 days

∴Cost of scaffolding = 200 × £1.5 × 175 = £52,500

Traffic management

Two lane carriageway closure with contraflow = £1,700/day

(II) ON THE ROAD ABOVE

Gaining Access

Not applicable

Traffic management

Automatic traffic control = £1,100/day
Total works cost = £80,000
Cost of gaining access = £52,500

Total cost of traffic management = (£1,700 + £1,100) × 175 = £490,000

Overheads

Since cost of work (= £80,000) is between £50,000 and £250,000 $\Rightarrow$ overhead rate = £1300/wk (Table 2.16)

$\therefore$ Total overhead cost = £1,300 × 25 = £32,500

Cost of treatment

Total cost of single treatment = Labour/equipment + Gaining access + Traffic management + Overheads
= £80,000 + £52,500 + £490,000 + £32,500 = £655,000

Lifetime number of treatment = 3 (Table 2.3)
Lifetime cost of concrete repairs = £655,000 × 3 = £1,965,000

$$\text{Discounted lifetime cost of concrete repairs} = \frac{655{,}000}{(1+0.035)^{30}} + \frac{655{,}000}{(1+0.03)^{60}} + \frac{655{,}000}{(1+0.025)^{90}} = £415{,}510.57$$

Traffic delay cost

(I) ON THE ROAD BELOW

For a two lane dual motorway with 80,000 AADT and 20% HGV, two primary and two secondary lanes with contraflow, Table 28 (TRRM Vol. 1 Annex 5.5.2) gives a traffic delay cost of £27,000/day at 1998 prices over a length of 3km.

RPI factor = 1.316 $\Rightarrow$ Traffic delay cost at 2009 prices = 1.316 × £27,000 ≈ £35,600/day

(II) ON THE ROAD ABOVE

For shuttle working on a single 7.3m road with 6,000 AADT and 10% HGV, Table 42 gives a value of £350/day.
RPI factor = 1.316 $\Rightarrow$ Traffic delay cost at 2009 prices = 1.316 × £350 ≈ £500/day
Total traffic delay cost per treatment = (£35,600 + £500) × 175 = £6,317,500

Lifetime traffic delay cost = 3 × £6,317,500 = £18,952,500

$$\text{Lifetime delay costs} = \frac{6{,}317{,}500}{(1+0.035)^{30}} + \frac{6{,}317{,}500}{(1+0.03)^{60}} + \frac{6{,}317{,}500}{(1+0.025)^{90}} = £4{,}007{,}614.80$$

C2 - Bridge 2

C2-1 Cost of inspection

Labour/equipment
Cost = £1100/span (Table 2.10)
Assuming work will be carried out at weekends, increase cost by 1.5 ⇒ cost = £1100 × 1.5 = £1,650/span
Total number of spans = 2 (Fig. 2.1)
∴Total cost = £1,650 × 2 = £3,300

Gaining Access
Assume access will be from a mobile working platform
Cost of mobile platform = £400 / day (Table 2.14)
Rate of inspection = 1 span/day
Since bridge has two spans, work duration = 2 days

∴**Total** cost = £400 × 2 = £800

Traffic management
Assume two lanes will be closed while the inspection work is carried out.
Cost = £700/day (Table 2.11). Since work will be carried out at weekends, increase cost by 1.5 = £700 × 1.5 = £1,050/day

Cost of traffic management = £1050 × 2 = £2,100

Overheads
Not applicable since this is routine maintenance

Engineering cost
Engineering cost = Labour/equipment + Gaining access + Traffic management + Overheads
= £3,300 + £800 + £2,100 + 0 = £6,200

Lifetime number of treatments = 23 (Table 2.3)
Lifetime engineering cost = Cost of treatment × Lifetime number of treatments = £6,200 × 23 = £142,600

Discounted lifetime engineering cost = $\sum_{i=1}^{6} \frac{6,200}{(1+0.035)^{5i}} + \sum_{j=7}^{15} \frac{6,200}{(1+0.03)^{5j}} + \sum_{k=16}^{23} \frac{6,200}{(1+0.025)^{5k}}$ =£38,467.73

Traffic delay cost of inspecting

For a two lane dual motorway with 80,000 AADT and 20% HGV, one primary and two secondary lanes unaffected, Table 32 (TRRM Vol. 1 Annex 5.5.2) gives a traffic delay cost of £103,000/day at 1998 prices over a length of 0.2km (Table 2.4).

Price Index Factor = 1.316 ⇒ Traffic delay cost at 2009 prices = 1.316 × £103,000 ≈ £135,600/day
Work will be carried out at weekends ⇒ Road user delay influence factor = 0.25 (Table 2.5)
Modified traffic delay cost = £135,600 × 0.25 = £33,900/day

From above, work duration = 2 days
∴Traffic delay cost per inspection = £33,900 × 2 = £67,800

Total number of inspections required = 23 (Table 2.3)
∴Lifetime undiscounted delay cost = £67,800 × 23 = £1,559,400

Discounted lifetime delay costs = $\sum_{i=1}^{5} \frac{67,800}{(1+0.035)^{5i}} + \sum_{j=6}^{15} \frac{67,800}{(1+0.03)^{5j}} + \sum_{k=16}^{23} \frac{67,800}{(1+0.025)^{5k}}$ =£420,663.21

C2-2 Drain cleaning

Labour/equipment
Cost = £300/span (Table 2.11)

No of spans = 2

∴Total cost = £300 × 2 = £600

Gaining Access

Assume drain cleaning is carried out from the top surface of the deck and therefore are no access costs.

Traffic management

No carriageway closures required.
∴Cost of traffic management = 0

Overheads

Not applicable since this is routine maintenance

Cost of treatment

Engineering cost of treatment = Labour/equipment + Gaining access + Traffic management + Overheads
= £600 + £0 + £0 + 0 = £600

Lifetime number of treatments = 59 (Table 2.3)
Lifetime engineering cost = Cost of treatment × Lifetime number of treatments = £600 × 59 = £35,400

Discounted lifetime cost = $\sum_{i=1}^{15} \frac{600}{(1+0.035)^{2i}} + \sum_{j=16}^{37} \frac{600}{(1+0.03)^{2j}} + \sum_{k=38}^{59} \frac{600}{(1+0.025)^{2k}}$ = £9,639.34

Traffic delay cost

No lane closure required ∴traffic delay cost = £0.

C2-3: Concrete repairs

Some of this work will be undertaken from a mobile platform positioned on the bridge whereas other work will be carried out from scaffolding erected on the motorway. Therefore both costs were determined for this maintenance action. Repairs to the deck slab will require shuttle working and a load restriction to HGVs. For moderate and major repairs much of the deck repair work will be carried out from above deck.

(I) ON THE ROAD BELOW

Cost of treatment

(i) E2 concrete repairs

Total surface area of concrete = 480 m^2.
From Table 2.7 assume 10% of surface area of concrete to repair every 30 years.
∴Concrete repair to 48 m^2.

Rate of repair = 2 m^2/week
Work duration = 48/2 = 24 weeks = 168 days

(ii) E3 concrete repairs

Total surface area of concrete = 220 m^2.
From Table 2.7 assume 20% of surface area of concrete to repair every 30 years.
∴Concrete repair to 44 m^2.

Rate of repair = 2 m^2/week
Work duration = 44/2 = 22 weeks = 154 days

Price = £1600 / m^2.

∴Cost of single treatment = (48 + 44) × £1600 = £147,200

Gaining Access

(I) ON THE ROAD BELOW

Assume access by scaffolding and that repairs will be undertaken using two closed lanes for the duration of the works.

Scaffold over quarter of deck area = 32 × 12.3 × ¼ ≈ 100 m^2
Scaffold cost £1.5/ m^2/day

Total duration of concrete repairs = 168 + 154 = 322 days

∴Cost of scaffolding = 100 × £1.5 × 322 = £48,300

(II) ON THE ROAD ABOVE

Not applicable

Traffic management

(I) ON THE ROAD BELOW

Two lane carriageway closure with contraflow = £1,700/day

(II) ON THE ROAD ABOVE

Automatic traffic control = £1,100/day

Cost of traffic management = (£1,700 + £1,100) × 322 = £901,600

Total works cost = £147,200
Cost of gaining access = £48,300
Cost of traffic management = £901,600

Overheads

Since cost of work (= £147,200) is between £50,000 and £250,000 ⇒ overhead rate = £1300/wk (Table 2.16)

∴Total overhead cost = £1,300 × 46 = £59,800

Cost of treatment

Total cost of single treatment = Labour/equipment + Gaining access + Traffic management + Overheads
= £147,200 + £48,300 + £901,600 + £59,800= £1,156,700

Lifetime number of treatment = 3 (Table 2.3)
Lifetime cost of concrete repairs = £1,156,700 × 3 = £3,470,100

Discounted lifetime cost of concrete repairs = $\frac{1{,}156{,}700}{(1+0.035)^{30}}+\frac{1{,}156{,}700}{(1+0.03)^{60}}+\frac{1{,}156{,}700}{(1+0.025)^{90}}$ = £733,772.64

Traffic delay cost

(I) ON THE ROAD BELOW

For a two lane dual motorway with 80,000 AADT and 20% HGV, two primary and two secondary lanes with contraflow, Table 28 (TRRM Vol. 1 Annex 5.5.2) gives a traffic delay cost of £27,000/day at 1998 prices over a length of 3km.

RPI factor = 1.316 ⇒ Traffic delay cost at 2009 prices = 1.316 × £27,000 ≈ £35,600/day

(II) ON THE ROAD ABOVE

For shuttle working on a single 7.3m road with 6,000 AADT and 10% HGV, Table 42 gives a value of £350/day.

RPI factor = 1.316 ⇒ Traffic delay cost at 2009 prices = 1.316 × £350 ≈ £500/day

Total traffic delay cost per treatment = (£35,600 + £500) × 322 = £11,624,200
Lifetime traffic delay cost = 3 × £11,624,200 = £34,872,600

Lifetime delay costs = $\frac{11{,}624{,}200}{(1+0.035)^{30}} + \frac{11{,}624{,}200}{(1+0.03)^{60}} + \frac{11{,}624{,}200}{(1+0.025)^{90}}$ = £7,374,011.20

C3 - *Bridge 3*

C3-1 Cost of inspection

Labour/equipment

Cost = £1100/span (Table 2.10)

Assuming work will be carried out at weekends, increase cost by 1.5 ⇒ cost = £1100 × 1.5 = £1,650/span

Total number of spans = 3 (Fig. 2.1)

∴Total **c**ost = £1,650 × 3 = £4,950

Gaining Access

Assume access will be from a mobile working platform

Cost of mobile platform = £400 / day (Table 2.14)

Rate of inspection = 1 span/day

Since bridge has three spans, work duration = 3 days

∴**Total c**ost = £400 × 3 = £1,200

Traffic management

Assume two lanes will be closed while the inspection work is carried out.

Cost = £700/day (Table 2.11). Since work will be carried out at weekends, increase cost by 1.5 = £700 × 1.5 = £1,050/day

Cost of traffic management = £1050 × 3 = £3,150

Overheads

Not applicable since this is routine maintenance

Engineering cost

Engineering cost = Labour/equipment + Gaining access + Traffic management + Overheads
= £4,950 + £1,200 + £3,150 + 0 = £9,300

Lifetime number of treatments = 23 (Table 2.3)

Lifetime engineering cost = Cost of treatment × Lifetime number of treatments = £9,300 × 23 = £213,900

Discounted lifetime engineering cost $= \sum_{i=1}^{6} \frac{9{,}300}{(1+0.035)^{5i}} + \sum_{j=7}^{15} \frac{9{,}300}{(1+0.03)^{5j}} + \sum_{k=16}^{23} \frac{9{,}300}{(1+0.025)^{5k}}$ = £ 57,701.59

Traffic delay cost of inspecting

For a two lane dual motorway with 80,000 AADT and 20% HGV, one primary and two secondary lanes unaffected, Table 32 (TRRM Vol. 1 Annex 5.5.2) gives a traffic delay cost of £103,000/day at 1998 prices over a length of 0.2km (Table 2.4).

Price Index Factor = 1.316 ⇒ Traffic delay cost at 2009 prices = 1.316 × £103,000 ≈ £135,600/day

Work will be carried out at weekends ⇒ Road user delay influence factor = 0.25 (Table 2.5)

Modified traffic delay cost = £135,600 × 0.25 = £33,900/day

From above, work duration = 3 days

∴Traffic delay cost per inspection = £33,900 × 3 = £101,700

Total number of inspections required = 23 (Table 2.3)

∴Lifetime undiscounted delay cost = £101,700 × 23 = £2,339,100

Discounted lifetime delay costs $= \sum_{i=1}^{6} \frac{101{,}700}{(1+0.035)^{5i}} + \sum_{j=7}^{15} \frac{101{,}700}{(1+0.03)^{5j}} + \sum_{k=16}^{23} \frac{101{,}700}{(1+0.025)^{5k}}$ = £630,994.81

C3-2 Drain cleaning

Labour/equipment

Cost = £300/span (Table 2.11)
No of spans = 3

$\therefore$Total cost = £300 × 3 = £900

Gaining Access

Assume drain cleaning is carried out from the top surface of the deck and therefore are no access costs.

Traffic management

No carriageway closures required.
$\therefore$Cost of traffic management = 0

Overheads

Not applicable since this is routine maintenance

Cost of treatment

Engineering cost of treatment = Labour/equipment + Gaining access + Traffic management + Overheads
= £900 + £0 + £0 + 0 = £900

Lifetime number of treatments = 59 (Table 2.3)
Lifetime engineering cost = Cost of treatment × Lifetime number of treatments = £900 × 59 = £53,100

$$\text{Discounted lifetime cost} = \sum_{i=1}^{15}\frac{900}{\left(1+0.035\right)^{2i}}+\sum_{j=16}^{37}\frac{900}{\left(1+0.03\right)^{2j}}+\sum_{k=38}^{59}\frac{900}{\left(1+0.025\right)^{2k}} = £\ 14{,}459.01$$

Traffic delay cost

No lane closure required $\therefore$traffic delay cost = £0

C3-3: Concrete repairs

Some of this work will be undertaken from a mobile platform positioned on the bridge whereas other work will be carried out from scaffolding erected on the motorway. Therefore both costs were determined for this maintenance action. Repairs to the deck slab will require shuttle working and a load restriction to HGVs. For moderate and major repairs much of the deck repair work will be carried out from above deck.

(I) ON THE ROAD BELOW

Cost of treatment

(i) E2 concrete repairs

Total surface area of concrete = 560 m^2.
From Table 2.7 assume 10% of surface area of concrete to repair every 30 years.
$\therefore$Concrete repair to 56 m^2.

Rate of repair = 2 m^2/week
Work duration = 56/2 = 28 weeks = 196 days

(ii) E3 concrete repairs

Total surface area of concrete = 250 m^2.
From Table 2.7 assume 20% of surface area of concrete to repair every 30 years.
$\therefore$Concrete repair to 50 m^2.

Rate of repair = 2 m^2/week
Work duration = 50/2 = 25 weeks = 175 days

Price = £1600 / m^2.

$\therefore$Cost of single treatment = (56 + 50) × £1600 = £169,600

Gaining Access

(I) ON THE ROAD BELOW

Assume access by scaffolding and that repairs will be undertaken using two closed lanes for the duration of the works.

Scaffold over quarter of deck area = 48 × 12.3 × ¼ ≈ 150 m^2
Scaffold cost £1.5/ m^2/day

Total duration of concrete repairs = 196 + 175 = 371 days

∴Cost of scaffolding = 150 × £1.5 × 371 ≈ £83,500

(I) ON THE ROAD ABOVE

Not applicable

Traffic management

(I) ON THE ROAD BELOW

Two lane carriageway closure with contraflow = £1,700/day

(II) ON THE ROAD ABOVE

Automatic traffic control = £1,100/day

Total works cost = £169,600
Cost of gaining access = £83,500
Cost of traffic management = (£1,700 + £1,100) × 371 = £1,038,800

Overheads

Since cost of work (= £169,600) is between £50,000 and £250,000 ⇒ overhead rate = £1300/wk (Table 2.16)
∴Total overhead cost = £1,300 × 53 = £68,900

Cost of treatment

Total cost of single treatment = Labour/equipment + Gaining access + Traffic management + Overheads
= £169,600 + £83,500 + £1,038,800 + £68,900 = £1,360,800

Lifetime number of treatment = 3 (Table 2.3)

Lifetime cost of concrete repairs = £1,360,800 × 3 = £4,082,400

$$\text{Discounted lifetime cost of concrete repairs} = \frac{1{,}360{,}800}{(1+0.035)^{30}} + \frac{1{,}360{,}800}{(1+0.03)^{60}} + \frac{1{,}360{,}800}{(1+0.025)^{90}} = £\ 863{,}246.89$$

Traffic delay cost

(I) ON THE ROAD BELOW

For a two lane dual motorway with 80,000 AADT and 20% HGV, two primary and two secondary lanes with contraflow, Table 28 (TRRM Vol. 1 Annex 5.5.2) gives a traffic delay cost of £27,000/day at 1998 prices over a length of 3km.

RPI factor = 1.316 ⇒ Traffic delay cost at 2009 prices = 1.316 × £27,000 ≈ £35,600/day

(II) ON THE ROAD ABOVE

For shuttle working on a single 7.3m road with 6,000 AADT and 10% HGV, Table 42 gives a value of £350/day.

RPI factor = 1.316 ⇒ Traffic delay cost at 2009 prices = 1.316 × £350 ≈ £500/day

Total traffic delay cost per treatment = (£35,600 + £500) × 371 = £13,393,100

Lifetime traffic delay cost = 3 × £13,393,100   = £40,179,300

Lifetime delay costs = $\frac{13{,}393{,}100}{(1+0.035)^{30}}+\frac{13{,}393{,}100}{(1+0.03)^{60}}+\frac{13{,}393{,}100}{(1+0.025)^{90}}$ = £ 8,496,143.30

APPENDIX D

D1-1) Aesthetics – Bridge 1

1,1,1 - Excessive imbalanced proportions between significant elements should be avoided as much as possible.	**Yes**	Elegant design.
1,1,2 - Similar proportions or ratios throughout the structure can create a harmony.	**Yes**	Can be seen from the drawing.
1,1,3 - The ratio of Deck to Parapet Depth is also considered a significant aesthetic proportion and guidelines have been developed by Cardiff University School of Engineering	**Yes**	Assumed to be considered.
1,1,4 - the Span to Depth ratio is determined by the structural design. The value of the span-to-depth ratio can be an indicator of aesthetic design. The general agreement among bridge design experts states that span-to-depth ratio between 15 and 30 provi	**Yes**	Assumed to be considered.
1,2,1 - it must be considered as an important aesthetic indicator because symmetrical bridges are often more aesthetically pleasing than non symmetricals.	**Yes**	Can be seen from the drawing.
1,3,1 - to achieve a consistent order, bridge spans should match where possible. Also, the interaction of bridge elements like lighting columns, barrier supports and piers should be considered.	**Yes**	Can be seen from the drawing.
1,4,1 - The complexity of a bridge should be minimized especially in natural landscape settings as it tends to attract the eye and competes with views of the landscape.	**Yes**	It is an integral bridge therefore simpilified in terms of bearings etc. and looks as a solid object. (???)
1,4,2 - Honesty of form is about the materials and structures to look like what they are.	**Yes**	Assumed to be considered.

Table D1.1.1: Bridge as a whole

2,1,1 - Make the bridge as invisible as possible to hide it in the landscape. (suits to smaller bridges)	**Yes**	See-through abutments and slender design allows for this.
2,1,2 - Make the bridge as simple and elegant as possible to complement the landscape: This approach is a practical, cost effective objective for overpasses and larger bridges and can lead to good looking bridge solutions.	**Yes**	Can be seen from the drawing.
2,1,3 - Maximize views of the landscape through the bridge: By minimizing the profile of the bridge, the landscape setting will dominate the view and be appreciated from all viewpoints.	**Yes**	See-through abutments and slender design allow for this.
2,1,4 - Bridges with a horizontal form are generally preferable to bridges on a grade over flat simple landscapes and significant expanses of water	**Yes**	Can be seen from the drawing.
2,1,5 - Significant stands of existing vegetation should be retained	**Yes**	Assumed to be considered.
2,1,6 - Footprint of the bridge (e.g. pile caps, abutments) should be minimized so that the retention of local vegetations maximized.	**Yes**	Assumed to be considered.
2,1,7 - The presence and extent of intermediate structures and hard surfaces between the bridge and landscape should be minimized.	**Yes**	Assumed to be considered.
2,1,8 - Careful design of earthworks and planting and the selection of endemic species grown from locally collected seed.	**No**	This hasn't been considered.
2,2,1 - A landmark structure should be created in a way that complements or contrasts with its visual catchments.		Not Applicable
2,2,2 - Maximizing views from the bridge of the local urban setting		Not Applicable
2,2,3 - Maximizing views through the bridge from the urban setting		Not Applicable
2,2,4 - Respecting locally valued structures and their cartilages by complementing local styles and materials		Not Applicable
2,2,5 - Ensuring the space under the bridge is not dark, degraded and unsafe.		Not Applicable
2,3,1 - In such cases plants should be located to the outside of the space and irrigation may be required.		Not Applicable
2,3,2 - Combining planting with a hard paved or gravel surface is often appropriate.		Not Applicable
2,3,3 - Clean uncluttered surfaces, neat connections and simple layout of girders will help to give a neat appearance.		Not Applicable
2,3,4 - When designing the soffit, consider bracing, when it is required, and ensure an orderly and regular pattern where possible.		Not Applicable
2,4,1 - Short span (up to approximately 18m): prestressed concrete plank bridges. **2,4,2 - Short to medium span (approximately 18-40m): pre-stressed concrete girders or pre-stressed concrete voided slabs.** **2,4,3 - Medium span (approximately 40-80m): ste**	**Yes**	

Table D1.1.2: Bridge and its surroundings

3,1,1 - They should appear as continuous uninterrupted lines, extending the full length of the bridge with a generous overlap of the abutments.	Yes	Can be seen from the drawing.
3,1,2 - A neat, sharp edge will help define them against the background.	Yes	Assumed to be considered.
3,1,3 - Maximizing the shadow cast on the superstructure will further accentuate and express their form.	Yes	Assumed to be considered.
3,1,4 - The outer face should be a smooth single plane surface, slanted slightly outwards towards the bottom, to better catch the sunlight.	Yes	Assumed to be considered.
3,1,5 - The top should angle towards the road, to channel rainwater onto the bridge, minimizing staining of the outside face.	Yes	Assumed to be considered.
3,1,6 - If the deck soffit is visually complex, consideration should be given to hiding this complexity, by extending the parapet soffit below the deck soffit.	Yes	Assumed to be considered.
3,2,1 - In the elevation, hunched girders are expressive and responsive to the forces in the bridge. They can often be more distinctive and elegant than single depth beams.	No	This hasn't been considered.
3,2,2 - Three or five span haunches are aesthetically very elegant balanced structures.	Yes	Can be seen from the drawing.
3,2,3 - In cross section, if the girder is right angled it can catch the light and a double line may be visible. Maximizing the overhang will increase the shadow. A curved soffit will provide a gradation of tone and minimize a sharp line at the base of th	Yes	Assumed to be considered.
3,3,1 - In an urban area that vertical forms are present and only close views available, headstock may provide a reassuring sense of strength and durability, as well as visual interest.		Not Applicable
3,3,2 - In a rural area where horizontal forms predominate, headstock can be overly complex and should be carefully considered and designed with their visual impact in mind, or avoided.	Yes	Assumed to be considered.
3,3,3 - If possible headstocks should not extend across the outer face of the girder. This introduces unnecessary complexity and appears in elevation as if the headstock is supporting the deck rather than the girder.	Yes	Assumed to be considered.
3,4,1 - Bridges which have pier spacings or spans which are roughly proportional to the bridge's height above ground level are more aesthetically pleasing than bridges which do not follow this proportion. They seem more responsive to their context.	Yes	Assumed to be considered.
3,4,2 - Collecting multiple piers into pairs or clusters can open up views below the deck and also give rhythm and elegance to the supports.	Yes	Assumed to be considered.
3,4,3 - Rounding off the corners of rectangular piers provides a softer form, which may be preferable in certain contexts. For example where the presence of the pier needs to be down played so that superstructure is dominant, e.g. in a rural setting.	No	This hasn't been considered.
3,4,4 - Pier shapes which have a slight taper (A taper of around 1:80) are desirable.	No	This hasn't been considered.
3,4,5 - The reverse taper should only be used where the appearance of rigidity is required between superstructure and pier. Otherwise the appearance of the top heavy pier can be imbalanced and does not reflect the forces acting on the pier well.	No	This hasn't been considered.
3,5,1 - The proportion of pier size to pile cap size should be considered. Imbalanced proportions should be avoided.		Not Applicable
3,5,2 - In a tidal watercourse, if the view of the piles is to be minimised, the pile cap may require a skirt as they need to be visible to boats and shipping as a safety measure.		Not Applicable
3,6,1 - If using of wall abutments is unavoidable the use of planting should be considered to screen the abutment walls.	Yes	Assumed to be considered.
3,6,2 - Reducing the abutments can create a more refined and better looking bridge. It does however increase the span and therefore depth of beam.	Yes	Can be seen from the drawing.
3,6,3 - Continuing the superstructure or the parapet allows the shadow line to reduce the dominance of the abutment, and makes the bridge appear longer and more elegant.	Yes	Assumed to be considered.
3,6,4 - Angling the abutments provides a more open sleek look and helps visually anchor the span.	No	This hasn't been considered.
3,6,5 - Spill through abutments allow open views to the landscape and better visibility to the road beyond.	Yes	Can be seen from the drawing.
3,6,6 - slight angle on the taper can make the wall appear less dominating especially if next to a footpath. This avoids visual crowding.	No	This hasn't been considered.
3,7,1 - With the exception of name plates and navigation signs, signage should be kept off bridges as far as possible. They add clutter and complexity and detract from the structure. They also obstruct views from the bridge.	Yes	Assumed to be considered.
3,8,1 - An outward curving screen creates a more open feeling for bridge users. However it presents a greater apparent depth of structure for onlookers.		Not Applicable
3,8,2 - The screens should extend to the ends of the bridge span and consideration should be given to integrating the bridge barrier and safety screens.		Not Applicable
3,9,1 - Where possible lighting on bridges should be minimized or avoided.	Yes	Assumed to be considered.
3,9,2 - If necessary lighting should be used in the median as far from the parapet as possible to reduce clutter or designed into the parapet structure.	Yes	Assumed to be considered.
3,9,3 - If considerable effort is put into the design of the appearance of the bridge it is better value for money to allow the bridge to be viewed at night (dependent on context, cost, safety and environmental issues).	Yes	Assumed to be considered.
3,10,1 - The colour and grade of the pipe system must be considered as these aspects can jar with the overall bridge design.	Yes	Assumed to be considered.
3,11,1 - Where possible avoid the use of noise walls on bridges.	Yes	Assumed to be considered.
3,11,2 - The use of transparent panels should be considered so that the apparent slenderness of the superstructure is not affected.	Yes	Assumed to be considered.
3,12,1 - Landscape tones are generally subdued and dark; therefore light colours and textures (for bridge primary elements) provide a good contrast. (the exception is when they are culturally appropriate such as traditional Chinese bridges or unique icon	Yes	Assumed to be considered.
3,12,2 - A neutral palette of black, gray and white tend to give a clear definition of the bridge as an object in the landscape.	Yes	Assumed to be considered.

Table D1.1.3: Parts and details

D1-2) Aesthetics - Bridge 2

With the aid of Fig. E2 (chapter 3) estimate the aesthetics impact score for Bridge 2. Assume the designer has no past performance but has appointed a liaison officer to consult with the public.

(i) Guidelines

Completed copies of Tables 2.25-2.27 for Bridge 2 are shown below. The results are summarised in the table and used in conjunction with the weighting factors given in Table 2.28 to score the guidelines.

Guidelines	Relevant guidelines	Guidelines observed	% observed	Score (%)
Bridge as a whole	8	8	100	25
Bridge and its surroundings	9	4	44.4	11.1
Parts and details	31	23	74.2	18.6
Total				64.7

(ii) Past performance/liaison officer

From Table 2.29 it can be seen that the score is 7 out of 10 giving an impact of

$$\left(1-\frac{7}{10}\right)25\% = 7.5$$

(iii) Sustainability score

The sustainability score for aesthetics is

$$64.7 + 7.5 = 72.2$$

1,1,1 - Excessive imbalanced proportions between significant elements should be avoided as much as possible.	**Yes**	Can be seen from the drawing.
1,1,2 - Similar proportions or ratios throughout the structure can create a harmony.	**Yes**	Can be seen from the drawing.
1,1,3 - The ratio of Deck to Parapet Depth is also considered a significant aesthetic proportion and guidelines have been developed by Cardiff University School of Engineering	**Yes**	Assumed to be considered.
1,1,4 - the Span to Depth ratio is determined by the structural design. The value of the span-to-depth ratio can be an indicator of aesthetic design. The general agreement among bridge design experts states that span-to-depth ratio between 15 and 30 provi	**Yes**	Assumed to be considered.
1,2,1 - it must be considered as an important aesthetic indicator because symmetrical bridges are often more aesthetically pleasing than non symmetricals.	**Yes**	Can be seen from the drawing.
1,3,1 - to achieve a consistent order, bridge spans should match where possible. Also, the interaction of bridge elements like lighting columns, barrier supports and piers should be considered.	**Yes**	Can be seen from the drawing.
1,4,1 - The complexity of a bridge should be minimized especially in natural landscape settings as it tends to attract the eye and competes with views of the landscape.	**Yes**	it's symmetrical and simple.
1,4,2 - Honesty of form is about the materials and structures to look like what they are.	**Yes**	Assumed to be considered.

Table D1.2.1: Bridge as a whole

2,1,1 - Make the bridge as invisible as possible to hide it in the landscape. (suits to smaller bridges)	**No**	Bridge abutments do not allow for this.
2,1,2 - Make the bridge as simple and elegant as possible to complement the landscape: This approach is a practical, cost effective objective for overpasses and larger bridges and can lead to good looking bridge solutions.	**No**	Bridge abutments do not allow for this.
2,1,3 - Maximize views of the landscape through the bridge: By minimizing the profile of the bridge, the landscape setting will dominate the view and be appreciated from all viewpoints.	**No**	Bridge abutments do not allow for this.
2,1,4 - Bridges with a horizontal form are generally preferable to bridges on a grade over flat simple landscapes and significant expanses of water	**Yes**	Can be seen from the drawing.
2,1,5 - Significant stands of existing vegetation should be retained	**Yes**	Assumed to be considered.
2,1,6 - Footprint of the bridge (e.g. pile caps, abutments) should be minimized so that the retention of local vegetations maximized.	**Yes**	Assumed to be considered.
2,1,7 - The presence and extent of intermediate structures and hard surfaces between the bridge and landscape should be minimized.	**No**	Bridge abutments do not allow for this.
2,1,8 - Careful design of earthworks and planting and the selection of endemic species grown from locally collected seed.	**No**	This hasn't been considered.
2,2,1 - A landmark structure should be created in a way that complements or contrasts with its visual catchments.		Not Applicable
2,2,2 - Maximizing views from the bridge of the local urban setting		Not Applicable
2,2,3 - Maximizing views through the bridge from the urban setting		Not Applicable
2,2,4 - Respecting locally valued structures and their cartilages by complementing local styles and materials		Not Applicable
2,2,5 - Ensuring the space under the bridge is not dark, degraded and unsafe.		Not Applicable
2,3,1 - In such cases plants should be located to the outside of the space and irrigation may be required.		Not Applicable
2,3,2 - Combining planting with a hard paved or gravel surface is often appropriate.		Not Applicable
2,3,3 - Clean uncluttered surfaces, neat connections and simple layout of girders will help to give a neat appearance.		Not Applicable
2,3,4 - When designing the soffit, consider bracing, when it is required, and ensure an orderly and regular pattern where possible.		Not Applicable
2,4,1 - Short span (up to approximately 18m): prestressed concrete plank bridges. **2,4,2 - Short to medium span (approximately 18-40m): pre-stressed concrete girders or pre-stressed concrete voided slabs.** **2,4,3 - Medium span (approximately 40-80m): ste**	**Yes**	

Table D1.2.2: Bridge and its surroundings

3,1,1 - They should appear as continuous uninterrupted lines, extending the full length of the bridge with a generous overlap of the abutments.	**Yes**	Can be seen from the drawing.
3,1,2 - A neat, sharp edge will help define them against the background.	**Yes**	Assumed to be considered.
3,1,3 - Maximizing the shadow cast on the superstructure will further accentuate and express their form.	**Yes**	Assumed to be considered.
3,1,4 - The outer face should be a smooth single plane surface, slanted slightly outwards towards the bottom, to better catch the sunlight.	**Yes**	Assumed to be considered.
3,1,5 - The top should angle towards the road, to channel rainwater onto the bridge, minimizing staining of the outside face.	**Yes**	Assumed to be considered.
3,1,6 - If the deck soffit is visually complex, consideration should be given to hiding this complexity, by extending the parapet soffit below the deck soffit.	**Yes**	Assumed to be considered.
3,2,1 - In the elevation, hunched girders are expressive and responsive to the forces in the bridge. They can often be more distinctive and elegant than single depth beams.	**No**	This hasn't been considered.
3,2,2 - Three or five span haunches are aesthetically very elegant balanced structures.	**Yes**	Can be seen from the drawing.
3,2,3 - In cross section, if the girder is right angled it can catch the light and a double line may be visible. Maximizing the overhang will increase the shadow. A curved soffit will provide a gradation of tone and minimize a sharp line at the base of th	**Yes**	Assumed to be considered.
3,3,1 - In an urban area that vertical forms are present and only close views available, headstock may provide a reassuring sense of strength and durability, as well as visual interest.		Not Applicable
3,3,2 - In a rural area where horizontal forms predominate, headstock can be overly complex and should be carefully considered and designed with their visual impact in mind, or avoided.	**Yes**	Assumed to be considered.
3,3,3 - If possible headstocks should not extend across the outer face of the girder. This introduces unnecessary complexity and appears in elevation as if the headstock is supporting the deck rather than the girder.	**Yes**	Assumed to be considered.
3,4,1 - Bridges which have pier spacings or spans which are roughly proportional to the bridge's height above ground level are more aesthetically pleasing than bridges which do not follow this proportion. They seem more responsive to their context.	**Yes**	Assumed to be considered.
3,4,2 - Collecting multiple piers into pairs or clusters can open up views below the deck and also give rhythm and elegance to the supports.	**Yes**	Assumed to be considered.
3,4,3 - Rounding off the corners of rectangular piers provides a softer form, which may be preferable in certain contexts. For example where the presence of the pier needs to be down played so that superstructure is dominant, e.g. in a rural setting.	**No**	This hasn't been considered.
3,4,4 - Pier shapes which have a slight taper (A taper of around 1:80) are desirable.	**No**	This hasn't been considered.
3,4,5 - The reverse taper should only be used where the appearance of rigidity is required between superstructure and pier. Otherwise the appearance of the top heavy pier can be imbalanced and does not reflect the forces acting on the pier well.	**No**	This hasn't been considered.

Table D1.2.3: Parts and details

3,5,1 - The proportion of pier size to pile cap size should be considered. Imbalanced proportions should be avoided.		Not Applicable
3,5,2 - In a tidal watercourse, if the view of the piles is to be minimised, the pile cap may require a skirt as they need to be visible to boats and shipping as a safety measure.		Not Applicable
3,6,1 - If using of wall abutments is unavoidable the use of planting should be considered to screen the abutment walls.	**No**	This hasn't been considered.
3,6,2 - Reducing the abutments can create a more refined and better looking bridge. It does however increase the span and therefore depth of beam.	**No**	Bridge abutments do not allow for this.
3,6,3 - Continuing the superstructure or the parapet allows the shadow line to reduce the dominance of the abutment, and makes the bridge appear longer and more elegant.	**Yes**	Assumed to be considered.
3,6,4 - Angling the abutments provides a more open sleek look and helps visually anchor the span.	**No**	This hasn't been considered.
3,6,5 - Spill through abutments allow open views to the landscape and better visibility to the road beyond.	**Yes**	Can be seen from the drawing.
3,6,6 - slight angle on the taper can make the wall appear less dominating especially if next to a footpath. This avoids visual crowding.	**No**	This hasn't been considered.
3,7,1 - With the exception of name plates and navigation signs, signage should be kept off bridges as far as possible. They add clutter and complexity and detract from the structure. They also obstruct views from the bridge.	**Yes**	Assumed to be considered.
3,8,1 - An outward curving screen creates a more open feeling for bridge users. However it presents a greater apparent depth of structure for onlookers.		Not Applicable
3,8,2 - The screens should extend to the ends of the bridge span and consideration should be given to integrating the bridge barrier and safety screens.		Not Applicable
3,9,1 - Where possible lighting on bridges should be minimized or avoided.	**Yes**	Assumed to be considered.
3,9,2 - If necessary lighting should be used in the median as far from the parapet as possible to reduce clutter or designed into the parapet structure.	**Yes**	Assumed to be considered.
3,9,3 - If considerable effort is put into the design of the appearance of the bridge it is better value for money to allow the bridge to be viewed at night (dependent on context, cost, safety and environmental issues).	**Yes**	Assumed to be considered.
3,10,1 - The colour and grade of the pipe system must be considered as these aspects can jar with the overall bridge design.	**Yes**	Assumed to be considered.
3,11,1 - Where possible avoid the use of noise walls on bridges.	**Yes**	Assumed to be considered.
3,11,2 - The use of transparent panels should be considered so that the apparent slenderness of the superstructure is not affected.	**Yes**	Assumed to be considered.
3,12,1 - Landscape tones are generally subdued and dark; therefore light colours and textures (for bridge primary elements) provide a good contrast. (the exception is when they are culturally appropriate such as traditional Chinese bridges or unique icon	**Yes**	Assumed to be considered.
3,12,2 - A neutral palette of black, gray and white tend to give a clear definition of the bridge as an object in the landscape.	**Yes**	Assumed to be considered.

Table D1.2.3: Parts and details (Cont'd)

D1-3) Aesthetics - Bridge 3

With the aid of Fig. E2 (chapter 3) determine the aesthetics impact score for Bridge 3. Assume the designer has no past performance but has appointed a liaison officer to consult with the public.

(i) Guidelines

Completed copies of Tables 2.25-2.27 for Bridge 3 are shown below. The results are summarised in the table and used in conjunction with the weighting factors shown in Table 2.28 to score the guidelines.

Guidelines	Relevant guidelines	Guidelines observed	% observed	Score (%)
Bridge as a whole	8	3	37.5	9.4
Bridge and its surroundings	9	4	44.4	11.1
Parts and details	31	23	74.2	18.6
Total				39.1

(ii) Past performance/liaison officer

From Table 2.29 it can be seen that the score is 7 out of 10 giving an impact of

$$\left(1-\frac{7}{10}\right)25\% = 7.5$$

(iii) Sustainability score

The overall sustainability score for aesthetics is

$$39.1 + 7.5 = 46.6$$

1,1,1 - Excessive imbalanced proportions between significant elements should be avoided as much as possible.	No	Abutments are not in the same prportion.
1,1,2 - Similar proportions or ratios throughout the structure can create a harmony.	No	Abutments are not in the same prportion.
1,1,3 - The ratio of Deck to Parapet Depth is also considered a significant aesthetic proportion and guidelines have been developed by Cardiff University School of Engineering	Yes	Assumed to be considered.
1,1,4 - the Span to Depth ratio is determined by the structural design. The value of the span-to-depth ratio can be an indicator of aesthetic design. The general agreement among bridge design experts states that span-to-depth ratio between 15 and 30 provi	Yes	Assumed to be considered.
1,2,1 - it must be considered as an important aesthetic indicator because symmetrical bridges are often more aesthetically pleasing than non symmetricals.	No	Can be seen from the drawing.
1,3,1 - to achieve a consistent order, bridge spans should match where possible. Also, the interaction of bridge elements like lighting columns, barrier supports and piers should be considered.	No	Abutments and the deck are not in harmony.
1,4,1 - The complexity of a bridge should be minimized especially in natural landscape settings as it tends to attract the eye and competes with views of the landscape.	No	Unnecessary implication by having abutment wall on one side and bankseat on the other.
1,4,2 - Honesty of form is about the materials and structures to look like what they are.	Yes	Assumed to be considered.

Table D1.3.1: Bridge as a whole

2,1,1 - Make the bridge as invisible as possible to hide it in the landscape. (suits to smaller bridges)	**No**	Bridge abutments do not allow for this.
2,1,2 - Make the bridge as simple and elegant as possible to complement the landscape: This approach is a practical, cost effective objective for overpasses and larger bridges and can lead to good looking bridge solutions.	**No**	Bridge abutments do not allow for this.
2,1,3 - Maximize views of the landscape through the bridge: By minimizing the profile of the bridge, the landscape setting will dominate the view and be appreciated from all viewpoints.	**No**	Bridge abutments do not allow for this.
2,1,4 - Bridges with a horizontal form are generally preferable to bridges on a grade over flat simple landscapes and significant expanses of water	**Yes**	Can be seen from the drawing.
2,1,5 - Significant stands of existing vegetation should be retained	**Yes**	Assumed to be considered.
2,1,6 - Footprint of the bridge (e.g. pile caps, abutments) should be minimized so that the retention of local vegetations maximized.	**Yes**	Assumed to be considered.
2,1,7 - The presence and extent of intermediate structures and hard surfaces between the bridge and landscape should be minimized.	**No**	Bridge abutments do not allow for this.
2,1,8 - Careful design of earthworks and planting and the selection of endemic species grown from locally collected seed.	**No**	This hasn't been considered.
2,2,1 - A landmark structure should be created in a way that complements or contrasts with its visual catchments.		Not Applicable
2,2,2 - Maximizing views from the bridge of the local urban setting		Not Applicable
2,2,3 - Maximizing views through the bridge from the urban setting		Not Applicable
2,2,4 - Respecting locally valued structures and their cartilages by complementing local styles and materials		Not Applicable
2,2,5 - Ensuring the space under the bridge is not dark, degraded and unsafe.		Not Applicable
2,3,1 - In such cases plants should be located to the outside of the space and irrigation may be required.		Not Applicable
2,3,2 - Combining planting with a hard paved or gravel surface is often appropriate.		Not Applicable
2,3,3 - Clean uncluttered surfaces, neat connections and simple layout of girders will help to give a neat appearance.		Not Applicable
2,3,4 - When designing the soffit, consider bracing, when it is required, and ensure an orderly and regular pattern where possible.		Not Applicable
2,4,1 - Short span (up to approximately 18m): prestressed concrete plank bridges. **2,4,2 - Short to medium span (approximately 18-40m): pre-stressed concrete girders or pre-stressed concrete voided slabs.** **2,4,3 - Medium span (approximately 40-80m): ste**	**Yes**	

Table D1.3.2: Bridge and its surroundings

3,1,1 - They should appear as continuous uninterrupted lines, extending the full length of the bridge with a generous overlap of the abutments.	**Yes**	Can be seen from the drawing.
3,1,2 - A neat, sharp edge will help define them against the background.	**Yes**	Assumed to be considered.
3,1,3 - Maximizing the shadow cast on the superstructure will further accentuate and express their form.	**Yes**	Assumed to be considered.
3,1,4 - The outer face should be a smooth single plane surface, slanted slightly outwards towards the bottom, to better catch the sunlight.	**Yes**	Assumed to be considered.
3,1,5 - The top should angle towards the road, to channel rainwater onto the bridge, minimizing staining of the outside face.	**Yes**	Assumed to be considered.
3,1,6 - If the deck soffit is visually complex, consideration should be given to hiding this complexity, by extending the parapet soffit below the deck soffit.	**Yes**	Assumed to be considered.
3,2,1 - In the elevation, hunched girders are expressive and responsive to the forces in the bridge. They can often be more distinctive and elegant than single depth beams.	**No**	This hasn't been considered.
3,2,2 - Three or five span haunches are aesthetically very elegant balanced structures.	**Yes**	Can be seen from the drawing.
3,2,3 - In cross section, if the girder is right angled it can catch the light and a double line may be visible. Maximizing the overhang will increase the shadow. A curved soffit will provide a gradation of tone and minimize a sharp line at the base of th	**Yes**	Assumed to be considered.
3,3,1 - In an urban area that vertical forms are present and only close views available, headstock may provide a reassuring sense of strength and durability, as well as visual interest.		Not Applicable
3,3,2 - In a rural area where horizontal forms predominate, headstock can be overly complex and should be carefully considered and designed with their visual impact in mind, or avoided.	**Yes**	Assumed to be considered.
3,3,3 - If possible headstocks should not extend across the outer face of the girder. This introduces unnecessary complexity and appears in elevation as if the headstock is supporting the deck rather than the girder.	**Yes**	Assumed to be considered.
3,4,1 - Bridges which have pier spacings or spans which are roughly proportional to the bridge's height above ground level are more aesthetically pleasing than bridges which do not follow this proportion. They seem more responsive to their context.	**Yes**	Assumed to be considered.
3,4,2 - Collecting multiple piers into pairs or clusters can open up views below the deck and also give rhythm and elegance to the supports.	**Yes**	Assumed to be considered.
3,4,3 - Rounding off the corners of rectangular piers provides a softer form, which may be preferable in certain contexts. For example where the presence of the pier needs to be down played so that superstructure is dominant, e.g. in a rural setting.	**No**	This hasn't been considered.
3,4,4 - Pier shapes which have a slight taper (A taper of around 1:80) are desirable.	**No**	This hasn't been considered.
3,4,5 - The reverse taper should only be used where the appearance of rigidity is required between superstructure and pier. Otherwise the appearance of the top heavy pier can be imbalanced and does not reflect the forces acting on the pier well.	**No**	This hasn't been considered.
3,5,1 - The proportion of pier size to pile cap size should be considered. Imbalanced proportions should be avoided.		Not Applicable
3,5,2 - In a tidal watercourse, if the view of the piles is to be minimised, the pile cap may require a skirt as they need to be visible to boats and shipping as a safety measure.		Not Applicable
3,6,1 - If using of wall abutments is unavoidable the use of planting should be considered to screen the abutment walls.	**No**	This hasn't been considered.
3,6,2 - Reducing the abutments can create a more refined and better looking bridge. It does however increase the span and therefore depth of beam.	**No**	Bridge abutments do not allow for this.
3,6,3 - Continuing the superstructure or the parapet allows the shadow line to reduce the dominance of the abutment, and makes the bridge appear longer and more elegant.	**Yes**	Assumed to be considered.
3,6,4 - Angling the abutments provides a more open sleek look and helps visually anchor the span.	**No**	This hasn't been considered.
3,6,5 - Spill through abutments allow open views to the landscape and better visibility to the road beyond.	**Yes**	Can be seen from the drawing.
3,6,6 - slight angle on the taper can make the wall appear less dominating especially if next to a footpath. This avoids visual crowding.	**No**	This hasn't been considered.
3,7,1 - With the exception of name plates and navigation signs, signage should be kept off bridges as far as possible. They add clutter and complexity and detract from the structure. They also obstruct views from the bridge.	**Yes**	Assumed to be considered.
3,8,1 - An outward curving screen creates a more open feeling for bridge users. However it presents a greater apparent depth of structure for onlookers.		Not Applicable
3,8,2 - The screens should extend to the ends of the bridge span and consideration should be given to integrating the bridge barrier and safety screens.		Not Applicable
3,9,1 - Where possible lighting on bridges should be minimized or avoided.	**Yes**	Assumed to be considered.
3,9,2 - If necessary lighting should be used in the median as far from the parapet as possible to reduce clutter or designed into the parapet structure.	**Yes**	Assumed to be considered.
3,9,3 - If considerable effort is put into the design of the appearance of the bridge it is better value for money to allow the bridge to be viewed at night (dependent on context, cost, safety and environmental issues).	**Yes**	Assumed to be considered.
3,10,1 - The colour and grade of the pipe system must be considered as these aspects can jar with the overall bridge design.	**Yes**	Assumed to be considered.
3,11,1 - Where possible avoid the use of noise walls on bridges.	**Yes**	Assumed to be considered.
3,11,2 - The use of transparent panels should be considered so that the apparent slenderness of the superstructure is not affected.	**Yes**	Assumed to be considered.
3,12,1 - Landscape tones are generally subdued and dark; therefore light colours and textures (for bridge primary elements) provide a good contrast. (the exception is when they are culturally appropriate such as traditional Chinese bridges or unique icon	**Yes**	Assumed to be considered.
3,12,2 - A neutral palette of black, gray and white tend to give a clear definition of the bridge as an object in the landscape.	**Yes**	Assumed to be considered.

Table D1.3.3: Parts and details

D2-1) **Dust - Bridge 2**

Assuming the following determine the dust score for Bridge 2

- the ambient dust level is 150 μg and the maximum expected dust level during construction and maintenance does not exceed 160 μg
- it is in the vicinity of a hospital
- dust, noise and vibrating producing activities are carried out during the daytime during weekdays and at weekends
- the contractor has no past performance but has appointed a liaison officer to consult with the public
- duration of dust nuisance : construction period – 76 days
  : maintenance period – 168 days

Thus the scores are as follows

Dust level

$$160 - 150 = 10$$

Sensitive premises

From Table 2.29 the score is 20

Public consultation and contractor performance

From Table 2.28 it can be seen that the score is 3

Duration

The score is (76 + 3 × 168 =) 580 being equal to the number of days required for construction and maintenance.

Sustainability score

The overall sustainability score for dust is

$$10 \times 20 \times 3 \times 580 = 348{,}000$$

D2-2) **Dust - Bridge 3**

Assuming the following determine the dust score for Bridge 3

- the ambient dust level is 150 μg and the maximum expected dust level during construction and maintenance does not exceed 160 μg
- it is in the vicinity of a hospital
- dust, noise and vibrating producing activities are carried out during the daytime during weekdays and at weekends
- the contractor has no past performance but has appointed a liaison officer to consult with the public
- duration of dust nuisance : construction period – 90 days
  : maintenance period – 196 days

Thus the scores are as follows

Dust level

$$160 - 150 = 10$$

Sensitive premises

From Table 2.29 the score is 20

Public consultation and contractor performance

From Table 2.28 it can be seen that the score is 3

Duration

The score is (90 + 3 × 196 =) 678 being equal to the number of days required for construction and maintenance.

Sustainability score

The overall sustainability score for dust is

$$10 \times 20 \times 3 \times 678 = 406{,}000$$

D3-1) Noise score for Bridge 2

Assuming the following calculate the dust score for Bridge 2

- the ambient noise level is 60 dBA and the maximum expected noise level during construction and maintenance is 90 dBA
- duration of noise nuisance : construction period – 76 days
  : maintenance period – 168 days
- it is in the vicinity of a hospital
- the contractor has no past performance but has appointed a liaison officer to consult with the public
- the design incorporates a low noise road surface

Net increase in noise level
Assuming the ambient noise level is 60 dBA and the maximum expected noise level is 90 dBA during construction and maintenance work, the score is

$$90 - 60 = 30$$

Duration
The score for this factor is

$$76 + 3 \times 168 = 580$$

Sensitive premises
From Table 2.29 the score is 20

Public consultation and contractor performance
From Table 2.28 it can be seen that the score is 3

Mitigation measures
Modify score by 1/10.

Sustainability score
The overall sustainability score for noise is

$$30 \times 580 \times 20 \times 3 \times 1/10 = 104{,}400$$

D3-2) Noise score for Bridge 3

Assuming the following calculate the dust score for Bridge 3

- the ambient noise level is 60 dBA and the maximum expected noise level during construction and maintenance is 90 dBA
- duration of noise nuisance : construction period – 90 days
  : maintenance period – 196 days
- it is in the vicinity of a hospital
- the contractor has no past performance but has appointed a liaison officer to consult with the public
- the design incorporates a low noise road surface

Net increase in noise level
Assuming the ambient noise level is 60 dBA and the maximum expected noise level is 90 dBA during construction and maintenance work, the score is

$$90 - 60 = 30$$

Duration
The score for this factor is

$$90 + 3 \times 196 = 678$$

Sensitive premises
From Table 2.29 the score is 20

Public consultation and contractor performance
From Table 2.28 it can be seen that the score is 3

Mitigation measures
Modify score by 1/10.

Sustainability score
The overall sustainability score for noise is

$$30 \times 678 \times 20 \times 3 \times 1/10 = 122{,}040$$

D4-1) Vibration score for Bridge 2

Assuming the following calculate the vibration score for Bridge 2

- the root mean square acceleration is 0.5
- the duration of vibration occurrence in seconds is 1200 sec and the average number of occurrences per day is 6
- duration of vibration nuisance : construction period – 76 days
  : maintenance period – 168 days
- the bridge is in the vicinity of a hospital
- the contractor has no past performance but has appointed a liaison officer to consult with the public

Vibration dose
The vibration dose is given by

$$= 1.4at^{0.25} = 1.4 \times 0.5 \times (1200 \times 6)^{0.25} = 6.45$$

Duration
The score for this factor is

$$76 + 3 \times 168 = 580$$

Sensitive premises
From Table 2.29 the score is 20

Public consultation and contractor performance
From Table 2.28 it can be seen that the score is 3

Sustainability score
The overall sustainability score for vibration is

$$6.45 \times 580 \times 20 \times 3 = 224, 460$$

D4-2) Vibration score for Bridge 3

Assuming the following calculate the vibration score for Bridge 3

- the root mean square acceleration is 0.5
- the duration of vibration occurrence in seconds is 1200 sec and the average number of occurrences per day is 6
- duration of vibration nuisance : construction period – 90 days
  : maintenance period – 196 days
- the bridge is in the vicinity of a hospital
- the contractor has no past performance but has appointed a liaison officer to consult with the public

Vibration dose
The vibration dose is given by

$$= 1.4at^{0.25} = 1.4 \times 0.5 \times (1200 \times 6)^{0.25} = 6.4$$

Duration
The score for this factor is

$$90 + 3 \times 196 = 678$$

Sensitive premises
From Table 2.29 the score is 20

Public consultation and contractor performance
From Table 2.28 it can be seen that the score is 3

Sustainability score
The overall sustainability score for vibration is

$$6.45 \times 678 \times 20 \times 3 = 262, 386$$

Appendix E: Assessment form

Project Assessment Sheet: Sustainability Appraisal of Bridges

NAME ………………………………………………

	v. good			poor/not attempted	
Exercise 1	☐	☐	☐	☐	☐
Exercise 2	☐	☐	☐	☐	☐
Exercise 3					
- Table Ex 1.8	☐	☐	☐	☐	☐
- (a)	☐	☐	☐	☐	☐
- (b)	☐	☐	☐	☐	☐
- (c)	☐	☐	☐	☐	☐
- (d)	☐	☐	☐	☐	☐
Exercise 4	☐	☐	☐	☐	☐
Exercise 5					
- Table Ex 2.3	☐	☐	☐	☐	☐
- (ii) (a)	☐	☐	☐	☐	☐
- (ii) (b)	☐	☐	☐	☐	☐
- (ii) (c)	☐	☐	☐	☐	☐
- (ii) (d)	☐	☐	☐	☐	☐
- (ii) (e)	☐	☐	☐	☐	☐
- (iii)	☐	☐	☐	☐	☐
- (iv)	☐	☐	☐	☐	☐
Exercise 6					
- Scoping	☐	☐	☐	☐	☐
- Scoring	☐	☐	☐	☐	☐
- Assessment	☐	☐	☐	☐	☐
Exercise 7					
- Dust	☐	☐	☐	☐	☐
- Noise	☐	☐	☐	☐	☐
- Vibration	☐	☐	☐	☐	☐
- Comparison	☐	☐	☐	☐	☐
Exercise 8	☐	☐	☐	☐	☐
Exercise 9					
- (i)	☐	☐	☐	☐	☐
- (ii)	☐	☐	☐	☐	☐
- (iii)	☐	☐	☐	☐	☐
Exercise 10					
- Table Ex 4.2	☐	☐	☐	☐	☐
- Comment	☐	☐	☐	☐	☐
Overall Appreciation	☐	☐	☐	☐	☐
Appearance and Layout	☐	☐	☐	☐	☐

Other comments

Grade ………………..

Appendix F: PowerPoint presentation – Sustainability Appraisal Tools

A Higher Education Academy Engineering Subject Centre Mini Project