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Vehicle Restraint Systems on the A55 and A483 Trunk Roads

Whole Life Cycle Cost Benefit Analysis

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Figure 1 E42 Belgium, Froyennes © Febelcem

This study has been presented by John Elystan Richards during EUPAVE's Concrete Safety Barriers workshop on Friday, 2nd March 2018.

Following a strong interest in the topic, EUPAVE decided to share this study as a EUPAVE publication.

ACKNOWLEDGEMENTS

I would like to thank my employers YGC (Ymgynhoriaeth Gwynedd Consultancy), for their continued support during my studies, and for allowing me this opportunity to further myself. I am also grateful for the assistance from the members of YGC structures department during my studies and this research project.

I would also like to thank the Alan Owen and the other members of the North Mid Wales Trunk Road Agent that were instrumental in assisting me with the access to data, which otherwise I would not have been able to conduct this research.

I am grateful to my degree supervisor Denise Lee of Liverpool John Moores University for her assistance, and for providing excellent advice throughout the year.

I would also like to acknowledge and thank the advice and assistance of my brother Sion Richards who provided me with so much help with the Python programme that was used for this research.

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PREFACE BY EUPAVE

The EU Directives on Public Procurement and Concessions are applicable since 18 April 2016.

One of the goals of this legislation is to have bids assessed on the basis of the best price-quality ratio using tools such as life-cycle costing.

Life-cycle costing is unfortunately rarely applied today in Europe for procurement of transport infrastructure, despite the savings it can offer over the life of an asset of infrastructure, such as a road or a safety barrier. Thanks to the new Directives, there is an opportunity for Member States to update their procurement practices and save tax-payers' money, while also benefiting the environment.

EUPAVE is committed to providing guidance by offering its technical expertise and know-how to its members and to contracting authorities in the European Union who wish to use cost-effectiveness approaches to provide better value for money and more sustainable infrastructure.

ABSTRACT

A 50 year Life Cycle Analysis has been undertaken on the safety barriers currently in use on the A55 and A483 dual carriageway trunk roads, in North West Wales, in order to ascertain the best performing and most economical safety barrier system. The accident severity of the safety barriers in use was compared and a comparison of installation, maintenance costs and, related socio-economic costs for road accidents were also calculated for current safety barrier systems. Due to the low number of impacts recorded, the accident severity data for the A55 and A483 was inconclusive. Accounting for installation and maintenance costs, concrete barriers were found to be the most cost effective solution when considering the installation and maintenance costs over a 50 year period for all lengths. When taking into account the accident severity, and the related socio-economic costs, the data gathered when compared with accident data of other European countries proved inconclusive. Similar studies from Sweden and France provided contradictory conclusions in regards to accident severity of different barrier types; this is thought to be due to a combination of factors; such as weather, driver behaviour, and popular vehicle type. Whole Life Cycle costs using French highway data showed all barriers to be roughly comparable (Approximately £15,000,000 to £18,000,000 over 50 years for a 5km length), whereas Swedish highway data show concrete barriers to have a Whole Life Cycle cost of £11,072,590.00 for a 5km length, which is approximately half the cost of a steel corrugated barrier at £23,106,860.00. A 2007 TRL (Transport Research Laboratory) report states that accident severity between concrete barriers and steel barriers on the UK road network is comparable, and as such the installation and maintenance costs are the deciding factors, therefore, concrete barriers are recommended due to lower overall costs, reduced maintenance requirements and higher containment performance.

1. INTRODUCTION

1.1 INTRODUCTION

A significant number of vehicles in the United Kingdom use the Trunk Road network, and the continual maintenance and upgrading of the network is vital to the transport of goods and people throughout the UK. In order that the network is safe and fit for purpose, a programme of routine and steady state maintenance is continually underway throughout the various trunk road authorities.

Safety Barriers can be defined as structures "which are intended to contain and redirect errant vehicles safely for the benefit of the occupants and other road users on certain section of road and at particular locations" (British Standards, 2009). These safety barriers may be permanent or temporary installations, and are typically made of timber, steel or concrete, and along dual carriageways and motorways they are usually placed along the length of the central reservation, as well as on the verge when environmental hazards are present.

A typical safety barrier has an estimated life span of 25 years for steel, or 50 years for concrete barriers (Williams, 2007), during this time an installed system is exposed to the elements, and may receive damage from either vehicle impacts, road debris or routine maintenance activities; such as salt gritting, snow ploughing, or grass or tree cutting, because of the long life of barrier systems they are typically designed to have replaceable components in the event of damage.

In 2007 GL Williams of the TRL (Transport Research Laboratory Ltd) published a report on behalf of the Highways Agency (Now known as Highways England) which reviewed median barrier accidents which resulted in casualties, and the costs associated with steel and concrete barriers. The finished report also included a whole life costing for barriers in use at the time. As the report was published in 2007, the report makes reference to the superseded standards TD 19/85, where currently TD 19/06 is in use. The TRL report also makes no mention of proprietary safety barrier systems, such as those manufactured by Tata and Hill & Smith, a whole list of approved Road Restraint Systems, and suppliers are available from the Standards for Highways website (Standards for Highways, 2015).

The Interim Advice Note IAN 44/05, notes that the use of Non-Proprietary Safety Barrier Systems (NPSBS, and NPSBS Rev 1) are withdrawn as of 2005 for new contracts for Highways Agency (now Highways England) roads, and are only to be used for reference purposes in regards to maintenance, inspections and repairs and replacement works (Standards for Highways, 2005). The 2007 TRL report has not produced a whole life cycle costing on any proprietary steel barrier, which is the preferred choice for new installations. This report will include installation costs for proprietary systems that are currently in use on the North Mid Wales Trunk Road network, as any recommendations for replacements must include the current approved systems.

The purpose of this work is to perform a cost benefit analysis on the installation, maintenance and removal of the different safety barrier systems currently in use on the network, and propose improvements to the current safety barrier inventory along the A55 and A483. It is expected that this work would be applicable to roads throughout the UK, which share similar features. The report will analyse and compare the level of injuries that are typically received from impacts with safety barriers (also referred to as VRS or RRS; Vehicle Restraint Systems and Road Restraint Systems respectively), and compare whole life costs of these barriers. A whole life cycle cost benefit analysis would allow the maintaining authorities to consider which system would provide the best value as a function of performance, installation/removal cost and overall maintenance cost. Because the life of a steel barrier is given as 25 years and the life of a concrete barrier is given as 50 years, (Williams, 2007) the report will use the same method as the TRL report, and include the cost of two complete installations for steel systems, and compare the cost over a 50 year life cycle.

The analysis will use the A55 and A483; two sections of dual carriageway located within North Wales, and are maintained by the North Mid Wales Trunk Road Agent (NMWTRA). The combined length of both sections is 71 miles (114km), and share similar alignment and environments.

1.2 AIM OF THE RESEARCH

The aim of the research is to analyse the performance of EN1317 certified safety barrier systems that are currently in use along the A55 and A483 trunk roads, and compare their performance in order that the Trunk Road agency can make educated choices in regards to the long term cost choices on barrier renewals and installation on new projects. The accident severity performance, installation costs and maintenance costs will be compared for all available barrier types, and other ancillary costs, such as lost economic productivity from different accident severities or from maintenance programs and lane closures will be taken into account when possible.

The research will make use of publically available accident data and safety barrier inventory data from NMWTRA in order to identify accidents that have resulted in an impact with safety barriers, and compare accident severity of the accidents with safety barrier types that are in use on the A55 and A483 dual carriageways from the years 2005 to 2014.

A comparison on the whole life cycle costs of different barrier systems will attempt to take into account the installation and maintenance costs, as well as the lost economic productivity resulting from lane closures that would result from accidents, repair activities due to accidents and from routine maintenance activities, such as safety barrier inspections and re-tensioning of tensioned safety barriers.

The cost comparison will be conducted over a life cycle of 50 years, which is the design life of a concrete barrier. Steel barriers have a design life of 25 years, and the cost of steel barriers over 50 years will include installations, as well as the removal of the first barrier after the first 25 years. (Williams, 2007)

1.3 OBJECTIVES

- A comparison of the accident severity of safety barrier systems currently in use on the A55 and A483 trunk roads provided primary data. Similar studies on appropriate highways provided additional secondary data in order to recommend the best performing barrier system currently available.
- Installation and maintenance costs over a 50 year period were calculated for the different barrier types that are currently used on the A55 & A483 trunk roads. Comparisons of these barrier types were performed for lengths from 100m to 5000km which includes the typical range of installed lengths.
- Whole Life Cycle costs over a 50 year period were calculated, and included accident related and socio-economic costs such as hospital stays, insurance claims, lost economic output from delayed traffic etc. The Whole Life Cycle Costs for barriers were further compared with these additional costs.

2. RESEARCH METHODOLOGY

The research started by conducting a preliminary feasibility study, by contacting NMWTRA and consulting engineers YGC (Gwynedd Council Consultancy) (that are currently employed to inspect the North and Mid Wales safety barrier inventory) in regards to access to inspection and cost data of the sections under investigation.

Quantitative data analysis has been used for primary and secondary data. Calculation of primary data involved the manipulation of freely available STATS 19 road safety data covering the years 2005 to 2014 from the data.gov.uk website which are available as comma separated value files (Department for Transport, 2014). The accident data and vehicle data has been filtered to remove data that was not required (such as accidents that occurred on other roads, or accidents that did not impact barriers). A Python script has been used to cross reference both accident and vehicle data, and compile a separate .csv file that incorporated accidents along the A55 and A483 that resulted in a barrier impact. The finished spreadsheet included Ordnance Survey Grid Co-ordinates, and was imported into the QGIS open source Geographical Information Software mapping program.

The NMWTRA safety barrier inventory and inspection data is currently maintained by YGC, which uses the Bridgestation asset management software, of which the author can access as part of his employment by YGC. The current safety barrier inventory is available as a QGIS compatible spreadsheet; this allows the visual plotting of safety barrier locations and barrier impacts along the A55 and A483 (this could be expanded in future to include other roads on the network).

Further quantitative analysis has been undertaken using the GIS mapping software which created a map of all reported safety barrier impacts, as well as the location of all safety barriers on the A55 and A483, the map was used to compare the locations of the impacts with the safety barrier locations, and therefore allowed the identification of which safety barrier type was involved in each accident. The STATS 19 road accident data provided by the Department of Transport lists accident severity of all recorded accidents (severity is recorded as Slight, Serious or Fatal), which was compared with the type of safety barrier that was involved. This data was compared with other similar studies that have been undertaken in the expectation that larger data sets will provide a better estimation of barrier impact performance. Secondary data from other studies was compared and used only if the roads and barriers were comparable (EN1317 barrier systems on dual carriageway/ motorway type highways were preferred).

Further quantitative data analysis has been done on the cost comparisons between barrier systems using data from safety barrier providers, the NMWTRA, and YGC. The cost comparison includes the cost of the annual inspection and re-tensioning programmes, as well as the average repair cost of barriers undertaken by NMWTRA. Britpave have published a cost comparison study undertaken by Arup (Britpave, 2008), which details individual pricing points of components including proprietary steel barriers, while the study states the costs should not be used for pricing of works, it should be sufficient to give a general idea on the costs of safety barriers.

A further set of quantitative data has been calculated for the whole life cycle costs, secondary data, in the form of average socio-economic costs per accident were used to calculate the effect a single accident would have on the economy of the UK on a whole. Comparisons on the whole life cycle and socio-economic costs utilised primary and secondary safety barrier accident severity data.

3. BACKGROUND INFORMATION

3.1 THE A55 AND A483 TRUNK ROADS

The A55 Trunk Road (Fig. 3) was built as the road exists now from the 1960's to the present day (NMWTRA, 2015), with the process of turning the road into a dual carriageway mainly occurring during the 1980's. The A55 is 129km long and handles approximately 43,000 vehicles a day (NMWTRA, 2015), and with a speed limit of 70 mph throughout the majority of the route, with an exception being a 50mph restriction exists on the A55 along a 5.2km (3.25 mile) section where the A55 cuts through the town of Colwyn Bay. The A55 is also a part of the E22 Trans European Route, connecting Holyhead with Ishim in Russia (via Denmark, Sweden and Latvia) (UNECE, 2007).

The A483 road exists as a dual carriageway that bypasses the County town of Wrexham and has an approximate section length of 18.24km (11.4 miles). The A483, in 2014 had an AADT (Annual Average Daily Traffic) of approximately 42,000 motor vehicles (Department for Transport, 2015).

From correspondence with safety barrier inspectors that inspect the A55 and the A483, it seems that there are a significant number of steel safety barriers that exist on the A55 date from the 1980's, and are beyond their 25 year design life (Jones, 2015) *(personal communication, 11th November, 2015)*. Like for like replacements of these systems have been undertaken when damage is catastrophic in accordance with IAN 44/05, but this does not address safety barriers that have been incorrectly installed, or are defective due to deterioration. The current system of inspections and maintenance is a reactive solution to problems, and does not address the inadequate systems already in place. These defective systems do not provide the users of the trunk road with the safety provision that they should, and in the event of an accident, there is no guarantee that the safety barriers will perform in a way that is beneficial to the vehicle user or others nearby.

The safety barriers on the A55 are primarily placed to protect vehicles from hazards that are located near the highway, such as walls, bridges or highway furniture (Signs, lighting columns etc). Open Box Beam barriers are typically used when working widths are limited, but their enclosed design are believed by the inspector teams to lead to increased corrosion risk when installed near bridges and walls. A life cycle assessment would aim to prove a case for increased maintenance on these barriers, or replacement with a more suitable solution.

THE A55 AND A483 TRUNK ROADS AS A PART OF THE NMWTRA NETWORK

Figure 2 The A55 and A483 Trunk Roads as a part of the NMWTRA network (NMWTRA, 2015)

3.2 THE EN1317 CERTIFICATION

All new safety barrier installations on UK roads must be compliant with the European wide standard EN1317, and a list of these compliant systems can be found on the Standards for Highways website (Standards for Highways, 2015). Some of the systems on the approved list are unlikely to be encountered in the UK, due to list encompassing approved systems from other European countries, which would probably not be chosen because of cost, supply and maintenance issues.

EN1317-1 describes the test criteria methods, such as methods for measuring acceleration of impacting vehicles, test vehicle specifications *etc*. while EN1317-2 describes the performance classes, impact test acceptance criteria and test methods for safety barriers. These tests require that for a certain containment level classification (Table 2), the safety barrier must be subjected to impacts from certain vehicle types with a specific mass, which must collide with the barrier at a specific speed and angle (Table 1). A conventional steel safety barrier has a containment level of N2, which is certified to contain a 1500kg car travelling at 68mph, with an impact angle of 20 degrees. A typical concrete barrier has a containment level of H2, which is certified for a 13000kg bus with a speed of 43mph and an impact angle of 20 degrees. Higher containment levels (H4 & H4a) are available for both steel and concrete barriers, which are designed to contain HGV impacts.

VEHICLE IMPACT TEST CRITERIA

Test	Impact Speed		Impact angle degrees	Total Vehicle Mass kg	Type of Vehicle
	km/h	mph			
TB11	100	62	20	900	Car
TB21	80	50	8	1300	Car
TB22	80	50	15	1300	Car
TB31	80	50	20	1500	Car
TB32	110	68	20	1500	Car
TB41	70	43	8	10000	Rigid HGV
TB42	70	43	15	10000	Rigid HGV
TB51	70	43	20	13000	Bus
TB61	80	50	20	16000	Rigid HGV
TB71	65	40	20	30000	Rigid HGV
TB81	65	40	20	38000	Articulated HGV

Table 1. EN1317 Vehicle Test Criteria (British Standards, 2009)

CONTAINMENT LEVELS

Containment Levels	Acceptance Test
Low Angle Containment	
T1	TB21
T2	TB22
T3	TB41 and TB21
Normal Containment	
N1	TB31
N2	TB32 and TB11
Higher Containment	
H1	TB42 and TB11
H2	TB51 and TB11
H3	TB61 and TB11
Very High Containment	
H4a	TB71 and TB11
H4b	TB81 and TB11

Table 2. EN1317 Containment Levels (British Standards, 2009)

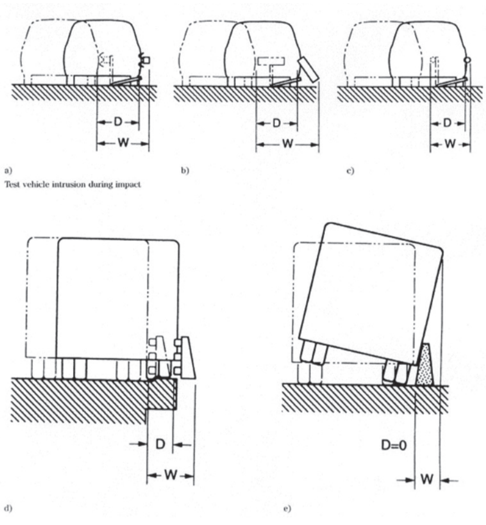


Figure 3 Working Width and Deflection as defined by EN1317 (British Standards, 2009)

"Several levels of performance are given for the three main criteria relating to the restraint of a road vehicle:

- The containment level, i.e. T1, T2, etc.
- The impact severity level, i.e. A, B or C;
- The deformation as expressed by working width, i.e. W1, W2 etc." (British Standards, 2009)

The EN1317-2 describes the tests necessary for a certain containment level, and the Working Width and Impact Severity Level that result from those tests (Fig. 2). For roads with a speed limit of 50mph or more (The A55, A483 and nearly all major roads in the UK) a minimum containment level of N2 is required, with England requiring a H1 concrete barrier for the central reservation on high traffic carriageways, corresponding to an AADT of 25,000 (Standards for Highways, 2006).

Safety Barriers that were installed before the adoption of EN1317, and TD 19/06 have been re-certified with appropriate performance levels.

3.3 SAFETY BARRIER TYPES USED ON THE A55 AND A483

Non-Proprietary Safety Barrier Systems

The NPSBS were certified for use on UK roads before the introduction of TD19/06, and were designed by the UK government, allowing multiple companies to manufacture NPSBS components.

Prior to the release of IAN 44/05 and TD 19/06 (Standards for Highways, 2006), the Non-Proprietary Safety Barrier System and TD 19/85 were accepted standards for highways which provided drawings, installation and maintenance information on the Non-Proprietary Safety Barrier Systems which are still the dominant barrier systems on UK roads. The NPSBS are a selection of barrier designs, designed by the UK government, and the designs are freely available, allowing a number of manufacturers to produce compatible designs. Paragraph 1.5 of IAN 44/05 states "The Highways Agency have previously allowed the use of the Non-Proprietary Safety Barrier Systems (NPSBS) on the Trunk

Road Network through the departure from standard submission process. The reason for this was because there were insufficient approved EN 1317 compliant Proprietary road restraint systems to fulfil the needs of the Highway Agency. Recently, however, the number of approved EN1317 compliant road restraint systems have increased to such an extent that the use of the NPSBS is now no longer required. Therefore the NPSBS dated June 2002 and the NPSBS (Revision 1) dated July 2005 are now withdrawn for new Contracts on Highways Agency Roads. Consequently, the NPSBS (Revision 1) is only to be used for reference purposes, maintenance inspections, minor maintenance replacement works, and repair works for accident damage. The Containment Performance Classes and Working Widths stated in the NPSBS (Revision 1) are still deemed to be appropriate for existing safety barriers including 'like for like' repairs." There are still uses for the NPSBS, in transitioning between differing systems, where different companies cannot accept liabilities between competing systems, even if the profiles are compatible.

The following section describes the different barrier systems that are in use throughout the A55 and A483, and are also common throughout the UK road network.

Open Box Beam - N2 containment

Open Box Beam (OBB) barriers (Fig. 4) are another non-proprietary system designed by the UK Government, available as single sided, double sided and double rail (for higher containment, H1) and they may also be fastened to walls or piers via hexagonal brackets (Standards for Highways, 1986). Due to the deployment of the OBB as a higher containment barrier, working width is typically limited, after the introduction of IAN44/05 and EN1317 the OBB barriers no longer provide the previously designed working width because of the rigidity of modern vehicles (Standards for Highways, 2005). The increased working width may result in the errant vehicles impacting with the protected structures, and as such OBB barriers may not currently provided adequate protection to structures or the occupants of errant vehicles.

Figure 4 Open Box Beams protecting a bridge pier
© John Elystan Richards

Interviews with the YGC safety barrier inspectors have revealed a strong belief that the insides of Open Box Beams are significantly more prone to corrosion, especially when located under bridges, or near walls, the cause of the increase in corrosion is unknown, and affects OBB barriers as well as the post bases (Jones, 2015) *(personal communication, 11th November, 2015)*.

Tensioned Corrugated Beams - N2 containment

The Tensioned Corrugated Beams TCB "consists of 'W' section beams, used single or double sided, attached to 'Z' section posts by shear bolts and tensioned between anchorages (Fig. 5). These safety fences may also be attached to angled brackets. This type of safety fence shall be used on central reserves and where other than short lengths are necessary on verges." (Standards for Highways, 1986)

The Tensioned Corrugated Beam has a tensioning mechanism, which requires regular re-tensioning due to seasonal temperature fluctuations and other factors, interviews with highway maintenance teams reveals that the tensioning method for double sided beams is difficult to accomplish, due to the small gap between beams that is used for wrench access (Jones, 2015) *(personal communication, 19th November, 2015)*. Because of this, and time constraints during night-time maintenance lane closures, the re-tensioning of significant lengths of Double Sided TCB is not time or cost effective. Proprietary corrugated beam systems are un-tensioned, and this introduces a time and cost savings during routine maintenance.

A number of proprietary un-tensioned steel barriers that are now certified for use share the same profile as the TCB, and there are similarities with a number of European and American systems (Commonly referred to as W-Beam Guardrails). The proprietary systems do not require re-tensioning, and are available in greater choice of working widths, making them suitable as replacements for Open Box Beam.

Figure 5 Double Sided TCB with tensioning assembly © John Elystan Richards

Proprietary Safety Barrier Systems Corrugated Beams (Vetex and Flexbeam) – N2 containment

Proprietary corrugated beams were industry replacements for the Tensioned Corrugated Beams, and are designed for EN1317 performance levels. The systems are slowly replacing the TCB installations on the UK road network, and new schemes require the installation of proprietary safety barriers. These safety barriers are relatively simple to maintain, and replacement parts are readily available. There is a requirement for qualified workers to perform maintenance which incurs a one-time training cost on the maintaining authority, but also it is uneconomical for a local authority to maintain spare components for multiple systems, therefore a local authority is likely to favour one product over others, which can depend on a number of factors, such as price or availability.

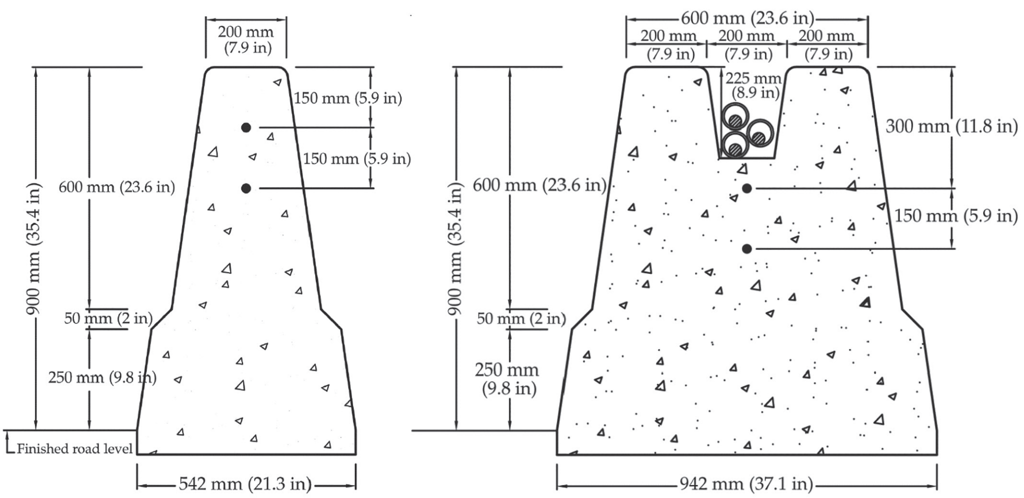
There are a number of corrugated safety barriers (also called W-beam guard rails) that are of a similar profile and performance to the TCB available throughout the EU, and elsewhere. The two main proprietary corrugated beams in use on the A55 and A483 roads (as well as the rest of the UK network) are the Tata Steel Vetex and the Hill & Smith Flexbeam systems.

The proprietary corrugated beams share the same profile as the tensioned corrugated beam, and can therefore be directly connected to existing TCB without the use of special transition pieces. These systems are un-tensioned, which reduces maintenance and installation requirements when compared with the TCB. Both systems share the N2 containment level as the TCB, but are capable of having smaller working widths when post spacing is reduced, thereby being capable of replacing OBB in the protection of structures or embankments. The proprietary corrugated systems are also available as H1 and H2 containment, which utilise a double rail (one above the other).

Concrete Barrier – H2 Containment

The proprietary concrete step barriers (Fig. 6), have now replaced the non-proprietary Vertical Concrete Barrier and the Higher Vertical Concrete Barrier since the introduction of IAN44/05. All concrete barriers have a guaranteed design life of 50 years, and are likely to last longer if properly installed and maintained. The proprietary concrete barriers as well as the barriers used abroad are externally similar, but internal reinforcement may differ, leading to different performance in the event of a collision. Concrete barriers are usually installed as a single barrier as shown on the left of Fig 6, or as a wide barrier for the allowances of median lighting columns or other services, shown of the right.

Figure 6 Extrudakerb Surface Mounted Concrete Barriers: Standard and Wide (GOMACO Corporation, 2009)



Concrete barriers differ from steel barriers in many ways; concrete barriers will not rust, and also do not deflect in an accident, except under the most extreme of circumstances. Concrete barriers are unlikely to need repairs following an impact with a vehicle, with the exception of HGVs, and to date there have been no crossover incidents from impacts with concrete barriers. Concrete barriers have a working width relating to the tipping of large vehicles, but the deflection is zero in the event of an impact. Because most barrier impacts are certified to incorporate a low angle impact the concrete step barriers are designed to redirect rather than contain the errant vehicle.

In-situ cast concrete barriers have an initial start-up cost relating to the casting machine, which does not apply to steel barriers; this initial cost can make short lengths more expensive than steel barriers, and concrete barriers cannot be installed soft verges, and because of this an additional cost relating to hardening of the verge are applicable to concrete barrier installations. Concrete barriers can also be cast next to existing structures such as bridge piers or retaining walls, but initial costs of special structures may be initially more expensive than a low working width steel barrier.

Protect 365 Beams – N2 containment

Manufactured by Tata Steel, the Protect 365 system is not widely used on the A55 and A483 and no impacts have been recorded against the system. The design is a rectangular hollow section and is certified for either N2W1 or N2W3 system (Tata Steel, 2011); such a design would be used in areas where the Open Box Beam would previously be used. No impacts were recorded against Protect 365 barriers.

Wire Rope Safety Barrier – N2 containment

Also referred to as a cable barrier, these types of barriers are in use throughout the UK road network, and are also found internationally. Constructed of tensioned cables, they are more flexible under impact than other barriers mentioned (Karim 2011). The sections of the A55 and A483 maintained by NMWTRA do not have cable barriers installed; they are however installed on the Anglesey section of the A55, and along some single carriageway trunk road in North and Mid Wales.

Figure 7 Concrete Step Barrier - N49 © Febelcem

4. LITERATURE REVIEW

An initial literature review was undertaken, and several pieces of literature were identified as being of interest. The *Whole Life Cost-Benefit Analysis for Median Safety Barriers* report was published on behalf of the Transport Research Laboratory in 2007; the report carried out an analysis of median barrier impacts throughout the years 1990 to 2002. The report also conducted a case study of the M25 motorway, correlating accidents with specific safety barrier types, and producing a whole life cycle cost benefit analysis of the barriers in use.

There were a number of conclusions from the report relating to both accident severity of barrier impacts and cost effectiveness of different barrier systems. "The number of serious accidents per kilometre is comparable between steel safety fencing and concrete safety barriers" and "Concrete barriers result in a lower rate of slight casualties and total accidents per kilometre than metal safety fences" (Williams 2007). The report also concluded that the concrete step barrier provided the lowest whole life cycle cost, as well as providing H2 containment, also a double sided TCB was the most economical steel barrier.

The report details the cost benefit analysis of existing non-proprietary safety barriers, and includes a 50 year cost benefit analysis of these systems. However it is likely the main portion of the report would have been done before the introduction of IAN 44/05 which does not allow for the installation of non-proprietary safety barrier Systems on new installations, and TD 19/06 where paragraph 3.59 requires the installation of H1 or higher concrete barrier on the central reserves on high traffic dual carriageways and motorways in England (It is not mandatory for Scotland and Wales), paragraph 3.60 provides allowances to this requirement if it not practicable, where a departure from standard may be provided for the installation of a barrier other than a concrete barrier. With the exception of the concrete step barrier, proprietary corrugated safety barriers (Vetex and Flexbeam etc.) are not mentioned in the 2007 report, and as such the cost benefit analysis of non-proprietary barriers is unlikely to provide significant benefit for new barrier installations, which do not require tensioning, or regular re-tensioning).

In 2011 a thesis "Road Design for Future Maintenance – Life Cycle Cost Analyses for Road Barriers" (Karim, 2011) was published. The paper was similar to the 2007 TRL report in that it correlated accident severity with specific safety barrier types, and compared whole life cycle costs to the barriers in use on the Swedish road network. Due to Sweden being an EN1317 compliant country, it is possible to compare performance levels of the barriers used in Sweden and those in the UK. The scope of 2011 study incorporated a number of motorways, dual carriageways as well as a type of dual carriageway referred to as "Collision Free Roads" from the years 2005 to 2008 (When EN1317 was already adopted). The research reached a number of conclusions and recommendations for safety barriers that may be applicable to the UK road network. The research points out that reactive cost management can result in a reduction of maintenance programmes, leading to reduced standards and quality of highway infrastructure.

In relation to accident severity due to barrier collisions Karim concludes that concrete barriers are seen to have the lowest injury rate, and cable barriers have the highest rate of injuries, which in turn incurs costs relating to emergency response, traffic management, and barrier repair costs etc. Karim states that for roads with AADT higher than 15,000 vehicles, the high initial cost is offset by a much lower life cycle cost when compared with steel barriers due to lower maintenance requirements and lower overall traffic disturbance.

From a repair cost standpoint, the use of concrete barriers is more favourable than for steel, which matches the conclusion of the 2007 TRL Study. Karim notes that "The repair rates and the average repair cost per vehicle kilometre for median cable barriers is higher than for median w-beam (corrugated) barriers, regardless of road type" A similar conclusion is drawn from Williams where cable barriers are the most expensive double sided steel barrier in whole life cycle cost. This does not necessarily concern the

A55 or the A483, but as cable barriers are an EN1317 compliant system, and are already installed on a number of UK roads it may be of use to future scheme planners when choosing a safety barrier system.

In 2013 a paper was published in the Accident Analysis and Prevention journal which analysed accidents along 2000km of French motorways between 1996 and 2010 (J.L. Martin, 2013). The highways in question are of motorway standard and include 2 lane and 3 lane motorways. The barriers in question are similar in design and performance to the non-proprietary barrier systems and concrete barriers that are in use along the UK road network. The paper concentrates on accident severity of barrier impacts, and does not go into any detail in regards to installation, repair or other life cycle costs, as such any recommendations in regards to safety barriers that should be used concentrate purely on vehicle occupant safety. Martin *et al.* concludes that for verge hazards a corrugated w-beam barrier with four metre post spacing is the safest option (similar to the TCB, Flexbeam, or Vetex), except where working width is limited and a concrete barrier would be required. From a purely accident severity standpoint Martin *et al.* concludes that a 2m spaced corrugated w-beam barrier (similar to the TCB, Flexbeam, or Vetex) is the overall safest option for use on the central reserve, but acknowledges the advantages in concrete barriers in eliminating crossover incidents; which are potentially much more severe than a conventional accident.

The study by Martin *et al.* does not take life cycle costs into account, and neither does it take into the account that concrete barriers typically do not require repair after an impact. After an impact a steel barrier would usually require a lane closure as well as a repair team and traffic management closure, this incurs a risk for the repair workers and vehicle occupants entering and leaving the traffic management area.

Karim and Williams both conclude that concrete barriers are the most cost effective safety barrier over an entire life cycle, as well as providing a higher protection level to prevent crossover incidents by HGVs. Karim concludes that concrete barriers have the lowest accident severity of barriers (including corrugated w-beam barriers) the disparity between the conclusions of Karim and Martin *et al.* are not known, and a number of factors may be responsible, such as weather, road geometry or traffic behaviour.

Figure 8 Concrete Step Barriers © Febelcem

5. DATA ANALYSIS OF BARRIER TYPES ON INJURY SEVERITY

5.1 PRIMARY DATA

The first portion of the quantitative data research compared how different safety barrier types affected the injury severity of accidents that involved safety barrier collisions on the NMWTRA managed portions of the A55 and A483 dual carriageways. The United Kingdom Government publishes reported road accident data annually; the STATS 19 files are published in a comma separated value file, and currently span the years 2005 to 2014. Two data files contained relevant data, one file contained info on the actual accident, with data on location, time and date, accident severity, road type, speed limit etc. The vehicle data file contained another set of data, including if the vehicle impacted a safety barrier. Both the accident and vehicle data was filtered to remove data that was not required, in order to reduce file size and improve performance of the correlation Python script.

A Python script was used to compare accident index numbers of both vehicle and accident data, and write a new combined .csv file, which contained coordinates and details of safety barrier impacts on the chosen roads from the years 2005 to 2014. The safety barrier inventory data (provided by YGC), and the combined accident data file were imported into an open source GIS (Geographical Information System) program (Fig. 9).

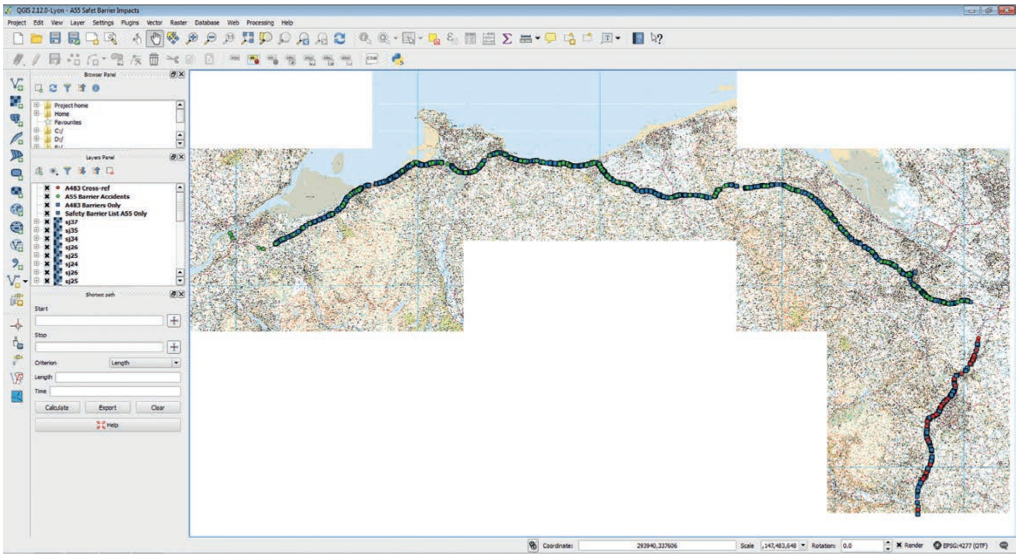


Figure 9 Mapped accident and barrier data on QGIS program

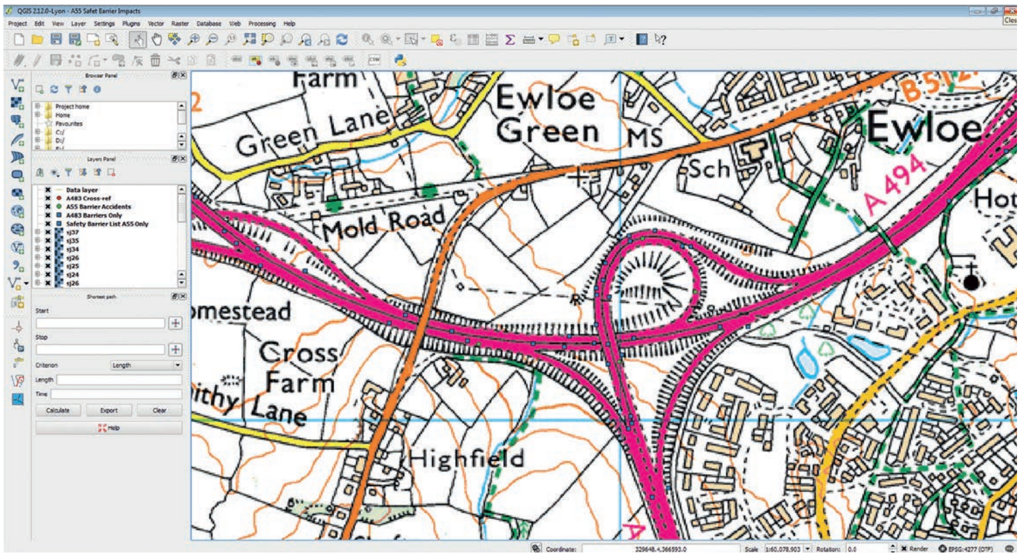


Figure 10 Barrier impacts at Ewloe Interchange.

The QGIS program with imported barrier and accident data was primarily used to locate accidents and identify the barrier that was involved in the accident (Fig. 10). In areas where multiple barrier are located close together, or otherwise the QGIS software and reported GPS data was not accurate enough, the Bridgestation asset management service and Google Streetview was used to make a best judgement on the likely barrier impact.

The STATS 19 accident data records accident severity on a three point scale which was used for the accident severity comparison. Accident severity classifications are defined in the STATS 20 document (Department for Transport, 2005):

"Fatal injury: 'fatal' injury includes only those cases where death occurs in less than 30 days as a result of the collision. 'Fatal' does not include death from natural causes or suicide.

Serious injury: examples of 'serious' injury are: fracture, internal injury, severe cuts, crushing, burns (excluding friction burns) concussion, severe general shock requiring hospital treatment, detention in hospital as an in-patient, either immediately or later, injuries to casualties who die 30 or more days after the collision from injuries, sustained in that collision.

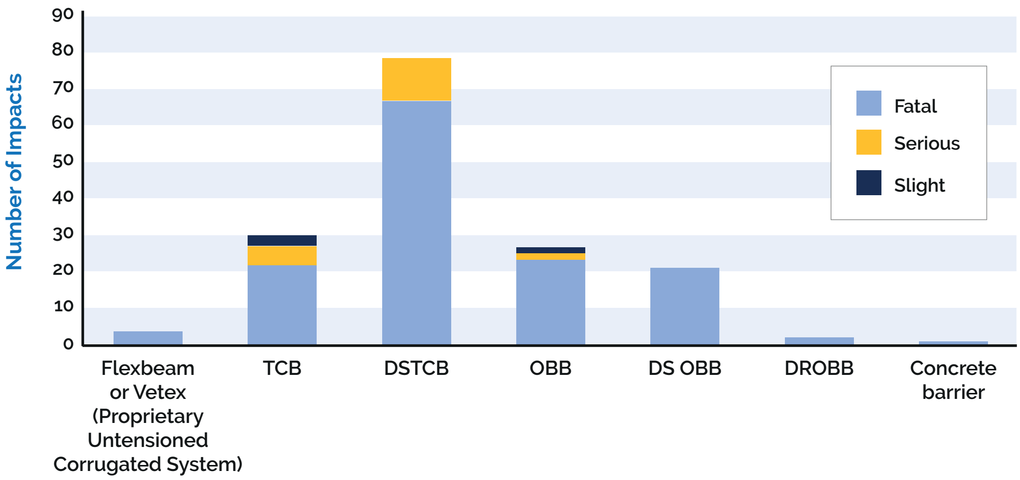
Slight injury: examples of 'slight' injury are: sprains, not necessarily requiring medical treatment, neck whiplash injury bruises, slight cuts, slight shock requiring roadside attention."

A55 AND A483 BARRIER IMPACTS YEARS 2005 – 2014

Table 3 A55 and A483 Barrier Impacts years 2005 – 2014

					Percentage of Accidents		
Barrier Type	**Slight**	**Serious**	**Fatal**	**Total**	**Slight %**	**Serious %**	**Fatal %**
Single Sided Corrugated (TCB)	26	5	3	34	76.5	14.7	8.8
Double Sided Corrugated (DSTCB)	66	12	0	78	84.6	15.4	0.0
Open Box Beam (OBB)	23	2	1	26	88.5	7.7	3.8
Double Sided Box Beam (DS OBB)	21	0	0	21	100.0	0.0	0.0
Double Rail Open Box Beam (DROBB)	2	0	0	2	100.0	0.0	0.0
Concrete Barrier	1	0	0	1	100.0	0.0	0.0
Total	139	19	4	162			

Graph 1 A55 and A483 Barrier Impacts years 2005 - 2014



Throughout 2005 to 2014 there were 162 barrier impacts that were reported in the STATS 19 data sets, (Table 3 and Graph 1). The data shows that Double Sided Tensioned Corrugated Beams account for the majority of barrier impacts, and concrete, double rail open box and proprietary systems accounting for a very small number of impacts. There is a relatively small number of these systems deployed on the network, with concrete median barriers only installed in one location on the A55 (at Jcn 27, St. Asaph). Double-sided tensioned corrugated beams account for the majority of installed barriers on the A55; the DSTCB is almost exclusively installed on the central reserve, and is installed on the majority of the length of the A55 and A483 central reserves. From the data it can be seen that despite the relatively large number of accidents that involve a double sided TCB impact, none of these have resulted in a fatality. The only barriers that are involved in a fatality are three single sided TCBs and the single-sided Open Box Beam. At the three fatalities connected to the TCBs the barriers were connected to, or were close to significantly more rigid vehicle restraint structures, resulting in a rapid halting of the vehicle, rather than the gradual deceleration or redirection of the vehicle. Two TCB impacts may have also impacted a bridge parapet, and the other may have also impacted a rigid full height anchorage, which could have resulted in more severe accidents. The Open Box Beam fatality was located on the western end of the Conwy tunnel, where central reserve and verge width are limited. The open box beams on the verges are connected to retaining walls, which depending on the direction of travel may have been detrimental to the performance of the barrier and safety of the vehicle occupants.

Because of the small number of concrete, double rail open box beams and proprietary corrugated beams the A55 and A483 data should not be used on its own to compare accident severity performance of barrier types.

5.2 SECONDARY DATA

The 2011 paper by Karim, and the 2013 paper by J.L Martin *et al.* have also investigated how different barrier types affected injury severity of road accidents that involve barrier impacts. Both studies were conducted on highways that possess a central reserve, and are built to dual carriageway or motorway standard. The standard of highway is similar to the A55 and A483, and both France and Sweden are EN 1317 compliant countries, therefore a comparative analysis of the Sweden and French accident data was undertaken to improve the performance of barrier impact data, especially with regards to the low number of concrete barriers found on the A55 and A483.

Figure 11 Location of fatal OBB impact © Google Maps

DATA ON ACCIDENT SEVERITY OF BARRIER IMPACTS FROM 2005 TO 2008 (KARIM, 2011)

Barrier Type	Barrier Length (km)	None / Slight Injuries	Severe Injuries	Fatal Injuries	Total	Slight %	Serious %	Fatal %
W-Beam (N2W4 - W5)	1439	549	96	11	656	83.7	14.6	1.7
Cable (N2W4 - W6)	1027	439	22	4	465	94.4	4.7	0.9
Pipe (N2W4)	87	68	15	0	83	81.9	18.1	0.0
Concrete (H2)	117	79	9	0	88	89.8	10.2	0.0
Total	2553	1056	133	15	1204			

Table 4. Data on Accident Severity of Barrier Impacts from 2005 to 2008 (Karim, 2011)

DATA ON ACCIDENT SEVERITY OF BARRIER IMPACTS (J.L. MARTIN, 2013)

J.-L. Martin *et al.* 2013	Long term analysis of the impact of longitudinal barrier of motorway safety					
Combined	N	Injuries	Fatalities	% Slight/None	% Injuries	% Fatalities
Single Sided Corrugated	17568	1775	91	89.4	10.1	0.5
Double Sided Corrugated	4164	508	11	87.5	12.2	0.3
Box Beam	1389	169	6	87.4	12.2	0.4
Concrete Barrier	5742	1124	30	79.9	19.6	0.5

Table 5. Data on Accident Severity of Barrier Impacts (J.L. Martin, 2013)

It is assumed that because corrugated W-beams are of similar shape, material and performance level that they are comparable to the TCB and Proprietary systems such as the Flexbeam and Vetex barriers in behaviour during impact. The concrete barriers are also assumed to be comparable in construction and performance when compared with concrete barriers in use in the UK, with minimal deflection under impact.

Martin *et al.* show similar fatality rate between single sided corrugated beams and concrete barriers, but concrete barriers show a higher injury rate, a conclusion that is not shared by Karim (Table 4 & 5), it is not known why this is, and may be due to factors not investigated. However differences between Swedish and French road users, vehicle types which behave differently under impact, and weather could account for this discrepancy.

From the A55 and A483 data the single sided corrugated beam is the worst overall performer, and the double sided TCB displaying the best performance, having no fatalities recorded against the barrier type despite a much greater number of impacts when compared with other barriers. Concrete barriers display favourable statistics in both studies, Karim shows concrete has having a lower rate of serious accidents compared with corrugated beam barrier, but Martin *et al.* show a significantly higher rate of injury when compared with all steel barrier types.

It should be noted that accident statistics on the Mouchel Parkman M25 Sphere Case Study, that there were no fatalities from concrete barrier impacts, and that "The number of serious casualties per kilometre is comparable between steel safety fencing and concrete safety barriers." And also "Concrete Barriers result in a lower rate of slight casualties and total accidents per kilometre than metal safety fencing" (Williams, 2007). But also it notes that these areas are typically of a lower traffic speed than the rest of the UK motorway network.

6. LIFE CYCLE COST BENEFIT ANALYSIS OF SAFETY BARRIERS

6.1 INITIAL COST DATA

Cost data on safety barrier installation can vary widely depending on site conditions; multiple site specific factors can have major impacts on the price of a scheme. The available verge width necessitates a certain containment level, as do any hazards that are already present. Local drainage or lighting may also impact in the location and containment level of the barrier, as would underground services. Local road geometry also has a major effect on the level of containment required, where junctions or interchanges where merging traffic can increase the risk of accidents. Because these factors vary to such a great degree, and the dangers are very site specific this study has not included provisions for installation of barrier near lighting columns, bridge piers, parapets or drainage features. For cost comparison the study has assumed a featureless highway of varying length.

Britpave have published a series of cost comparison reports identifying basic individual component costs for steel and concrete barrier installation (Table 6), along with typical daily outputs for concrete barriers, which have been used to further improve the accuracy of scheme prices as a factor of length. Installation of concrete barriers and steel barriers are vastly different, and while a concrete barrier can be installed as complete units in a length, a steel barrier may be installed in sections. The length of socketed posts of a barrier can be installed on one day, and the beam itself on another day, making daily output per linear metre difficult to estimate, also because steel barriers do not require significant mobilisation costs compared to concrete barriers. Because of these factors the price per linear metre of steel barriers is a nominal flat rate. Initial costing on the installation of corrugated steel barrier were made using pricing figures provided by YGC, with average costs based on previous schemes (Jones, 2015)*(personal communication, 02 November, 2015)*. A single sided N2W4 steel barrier at approximately £100 per linear metre, and a higher containment N2W2 barrier costs approximately £110 per li.m, a single sided barrier would likely also be installed with a P4 impact head terminal which costs approximately £4500. Double sided barriers use an additional beam, but maintain the single post, as such a double sided N2W2 system is approximately £150 per li.m, and a N2W4 double sided barrier is approximately £140 per li.m, but would likely transition to barriers that are already on the A55, and would not have a P4 terminal.

6.2 BASIC MAINTENANCE COSTS

During a period spanning from 2009 to 2015 the NMWTRA recorded 564 separate safety barrier repairs, of which at least 347 repairs were due to road traffic accidents, the remainder were made in response to either unreported road traffic accident damage, deterioration of existing systems (such as rusting of beams or posts), replacement of defective installations, or upgrading works,

TYPICAL COSTS FOR A CONCRETE STEP BARRIER

Britpave CSB Costs - Britpave Barrier Cost Comparison Study 1 of 3

Mobilisation/ Demobilisation			£2,500.00	once
Gang Cost			£5,500.00	daily
Concrete	£90 per m³	0.5m³ per li.m	£45.00	per li.m
Steel	£1000 per 1000kg	2 reinforcement bars; H20 bars	£5.02	per li.m
Hardened Central Reserve	4.5m wide at £9 per m²		£40.50	per li.m
Output	100m³ daily	200 li.m per day	£23,604.80	Daily (per 200m)

Table 6. Typical Costs for a Concrete Step Barrier

(Owen, 2015) *(personal communication, 02 November, 2015)*. Note that this is a significantly larger number than that reported by police in the STATS 19 accident statistics, he disparity in numbers may be explained by either:

- Under-reporting of minor accidents – barrier impacts not causing major damage to a vehicle, allowing vehicle to re-enter traffic before and accident report can be undertaken.
- Miscategorisation of accidents in the STATS 19 reports.

NMWTRA and the TRL 2007 report have noted that under-reporting of road accidents due to perceived triviality exist (Williams, 2007). It is probable that the under-reported accidents result in minor or no damage to the vehicle (allowing the vehicle to re-enter traffic without assistance), and due to the lack of emergency response the injuries of the vehicle occupants are either non-existent or very minor. Due to the lack of STATS 19 data on these incidents it is not possible to use the data in estimating the accident severity of the impact, and as such they have not been used in the previous chapter, even though they are likely low severity impacts because no emergency response was present.

Even though the barrier impacts are not reported at the time of the accident, the damage to the barrier is usually detected within a short period of time due to daily patrols by NMWTRA traffic officers and highway inspectors along the trunk road network. During 2010 – 2014 (records for 2009 and 2015 were partial records) there was an average of 95 safety barrier repairs conducted annually on the A55. NMWTRA do not have records on individual repair costs, but the average barrier repair cost over the period 2009 -15 was £4500 (Owen, 2015) *(personal communication, 02 November, 2015)*, therefore the average annual safety barrier repair cost for the A55 is £427,500. NMWTRA also undertake annual safety barrier inspection and re-tensioning programmes, which takes two years to complete i.e. each safety barrier is inspected or re-tensioned every two years, but the network is split into two biennial programmes. NMWTRA have reported that safety barrier inspections cost approximately £215,000 annually and re-tensioning has a yearly cost of approximately £403,750. Combined costs in maintaining the safety barrier network on the A55 is about £1,050,000 annually. It is immediately apparent that there are major cost savings to be had if the network only contained proprietary un-tensioned steel barriers, eliminating the need for biennial re-tensioning, inspection costs are assumed to remain constant for both steel barriers and concrete barriers, and are not considered.

During an accident a steel barrier is designed to deform under impact, and the posts are designed to fold down. After the accident these components will have to be replaced, which incurs costs due to traffic management, repair crews and the cost of replacement components. There are also socio-economic costs, when traffic speed is reduced, and a lane is closed to accommodate repairs teams. This is in addition to the routine maintenance that is undertaken, such as re-tensioning. In comparison a concrete barrier does not deform under impact and does not require repair except under major impact forces (Britpave, 2008), which provides cost savings in that there is no need for traffic management, repair teams, reduced speeds beyond the initial emergency response.

6.3 INSTALLATION AND BASIC LIFE CYCLE COSTS

For the purposes of this research a 50 year life cycle is assumed for the installation and maintenance costs for all safety barrier installations. A steel barrier will typically have a guaranteed design life of approximately 25 years, and concrete barriers are guaranteed for 50 years (Williams, 2007). Therefore a 50 year WLC analysis will take into account a re-installation of the steel barrier at the 25 year midpoint to accommodate comparative costing of both types of barrier. Removal or relocating of services, lighting columns *etc.* have not been taken into account, as well as concrete bifurcations for bridge piers, such costs are site specific.

COST OF CONCRETE BARRIER AS A FUNCTION ON LENGTH

Britpave Concrete Step Barrier - Scheme Costs

Length of Scheme (m)	Initial Scheme Cost	Basic 50 Year Cost	Basic Price per Li.m
50	£10,901.20	£10,901.20	£218.02
100	£16,802.40	£16,802.40	£168.02
250	£34,506.00	£34,506.00	£138.02
500	£64,012.00	£64,012.00	£128.02
750	£93,518.00	£93,518.00	£124.69
1000	£123,024.00	£123,024.00	£123.02
2000	£241,048.00	£241,048.00	£120.52
3000	£359,072.00	£359,072.00	£119.69
4000	£477,096.00	£477,096.00	£119.27
5000	£595,120.00	£595,120.00	£119.02

Table 7. Cost of Concrete Barrier as a function on length.

From table 7 it can be seen for barrier lengths that are longer than 2km the cost per linear metre is comparable to the cost given by YGC of £120 per linear metre, depending on containment, and if a central reserve barrier is required, the cost for concrete barriers becomes more prohibitive at barrier lengths that are shorter than about 250m. This does not take into account other scheme related costs that may make concrete or steel barriers more prohibitive due to site specific restrictions, for example carriageway drainage, underground services, bridge piers, parapets, bridge movement joints, lighting columns, or gantries. These hazards may exist in multiple locations, but the individual location and setback from the carriageway may necessitate different solutions to vehicular restraint, as such it is difficult to generalise these issues for the entire A55 and A483.

TYPICAL COSTS FOR A N2W4 DOUBLE SIDED BARRIER

N2W4 Double Sided Steel Corrugated Barrier

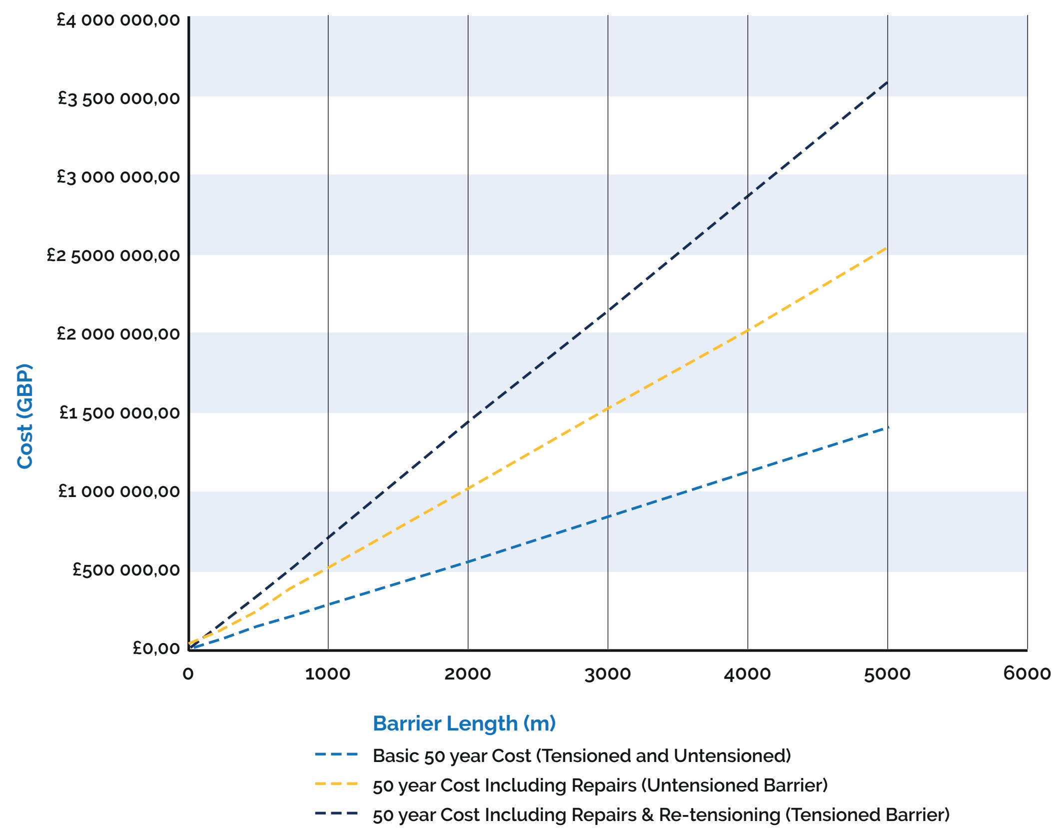
Length of Scheme (m)	Basic Price per Li.m	Initial Scheme Cost (25 yr)	Basic 50 year Cost	50 year Cost Including Repairs	50 year Cost Including Repairs & Re-tensioning
50	£140.00	£7,000.00	£14,000.00	£25,250.00	£35,875.00
100	£140.00	£14,000.00	£28,000.00	£50,500.00	£71,750.00
250	£140.00	£35,000.00	£70,000.00	£126,250.00	£179,375.00
500	£140.00	£70,000.00	£140,000.00	£252,500.00	£358,750.00
750	£140.00	£105,000.00	£210,000.00	£378,750.00	£538,125.00
1000	£140.00	£140,000.00	£280,000.00	£505,000.00	£717,500.00
2000	£140.00	£280,000.00	£560,000.00	£1,010,000.00	£1,435,000.00
3000	£140.00	£420,000.00	£840,000.00	£1,515,000.00	£2,152,500.00
4000	£140.00	£560,000.00	£1,120,000.00	£2,020,000.00	£2,870,000.00
5000	£140.00	£700,000.00	£1,400,000.00	£2,525,000.00	£3,587,500.00

Table 8. Typical Costs for a N2W4 Double Sided Barrier

The costs in table 8 and graph 2 are approximate, including average costs for annual repairs and biennial re-tensioning (if the barrier is retained as a TCB), but it is immediately apparent that when comparing costs with concrete barrier costs (table 7) that installation costs for schemes shorter than 250 metres are competitive with concrete barriers, but the repair and replacement costs even for a 50m long barrier is much more expensive than concrete over the 50 year life cycle.

When comparing costs shown in graph 2, the costs of biennial re-tensioning over a 50 year life cycle is an additional £1,062,500, which could be spent elsewhere if the Tensioned Corrugated Beam barriers were replaced.

COMPARISON OF COSTS FOR N2W4 DOUBLE-SIDED CORRUGATED BARRIERS



Graph 2 Comparison of costs for N2W4 double-sided corrugated barriers.

INITIAL INSTALLATION COSTS FOR SINGLE SIDED BARRIERS

Length of Scheme (m)	Concrete Barrier	Single Sided N2W1	Single Sided N2W2	Single Sided N2W4
50	£10,901.20	£11,500.00	£10,000.00	£9,750.00
100	£16,802.40	£18,500.00	£15,500.00	£15,000.00
250	£34,506.00	£39,500.00	£32,000.00	£30,750.00
500	£64,012.00	£74,500.00	£59,500.00	£57,000.00
750	£93,518.00	£109,500.00	£87,000.00	£83,250.00
1000	£123,024.00	£144,500.00	£114,500.00	£109,500.00
2000	£241,048.00	£284,500.00	£224,500.00	£214,500.00
3000	£359,072.00	£424,500.00	£334,500.00	£319,500.00
4000	£477,096.00	£564,500.00	£444,500.00	£424,500.00
5000	£595,120.00	£704,500.00	£554,500.00	£529,500.00

Table 9. Initial installation costs for Single Sided Barriers

INITIAL INSTALLATION COSTS FOR DOUBLE SIDED BARRIERS

Length of Scheme (m)	Concrete Barrier	Double Sided N2W1	Double Sided N2W2	Double Sided N2W4
50	£10,901.20	£8,250.00	£7,500.00	£7,000.00
100	£16,802.40	£16,500.00	£15,000.00	£14,000.00
250	£34,506.00	£41,250.00	£37,500.00	£35,000.00
500	£64,012.00	£82,500.00	£75,000.00	£70,000.00
750	£93,518.00	£123,750.00	£112,500.00	£105,000.00
1000	£123,024.00	£165,000.00	£150,000.00	£140,000.00
2000	£241,048.00	£330,000.00	£300,000.00	£280,000.00
3000	£359,072.00	£495,000.00	£450,000.00	£420,000.00
4000	£477,096.00	£660,000.00	£600,000.00	£560,000.00
5000	£595,120.00	£825,000.00	£750,000.00	£700,000.00

Table 10. Initial installation costs for Double Sided Barriers

COSTS FOR 50 YEAR LIFE CYCLE, INCLUDING MAINTENANCE AND REPAIR

Length (m)	N2W2 Single Sided Corrugated	N2W2 Double Sided Corrugated	H2 Concrete Barrier
100	£53,500.00	£52,500.00	£16,802.40
1000	£454,000.00	£525,000.00	£123,024.00
5000	£2,234,000.00	£2,625,000.00	£595,120.00

Table 11 Costs for 50 year life cycle, including maintenance and repair

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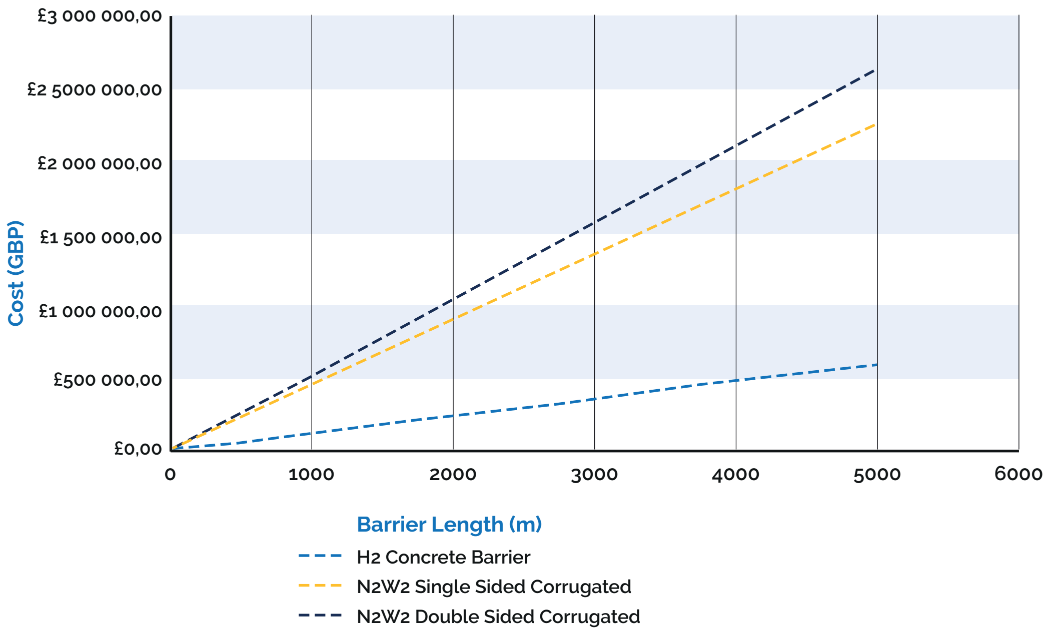
INSTALLATION AND MAINTENANCE COSTS OVER A 50 YEAR LIFE CYCLE

Graph 3 Installation and Maintenance Costs over a 50 year life cycle



Tables 9 and 10 display typical installation costs for single sided and double sided barriers, concrete barriers are assumed to be of a single design, and installation on the verge would involve installing the same as a central reserve barrier, therefore having the same nominal installation cost. Table 11and Graph 3 show a comparison between corrugated barriers (single-sided and double-sided) and concrete barriers at 100m, 1000m, and 5000m length intervals, it can be seen that concrete barriers are less expensive than steel barriers for all cases over a 50 year life cycle. Over a 50 year period the costs of maintenance and repair of the steel barriers cause a rapid deviation from the concrete barrier cost, resulting in steel barriers having a life cycle cost of approximately 4 times larger than the higher containment concrete barrier.

The N2 steel barriers also have lower containment performance, and also deflect, making them unsuitable for protection of static objects near the carriageway, such as bridge piers or abutments. From an installation cost standpoint, depending on the containment level and length required it may be more cost effective to install steel barriers for single sided installations on open verges. For high containment applications such as bridge abutments or retaining walls, the installation of concrete barriers are still probably a better option due to the corrosion issue which affect steel barriers when installed close to bridges and retaining walls (Jones, 2015). The costs of inspection and traffic management related to inspections were not considered, as the costs would be the same throughout.

6.4 SOCIO-ECONOMIC COSTS

Initial installation costs and lifetime maintenance costs are important factors to take into consideration, but there are other costs that should be taken into consideration when choosing a safety barrier system. Socio-economic costs relating to safety barrier systems typically affect the local or national economy, in a variety of different ways, such as:

- Emergency medical treatment and hospital stays are costs borne by the NHS
- Lane closures will delay traffic, resulting in higher travel times and lower fuel efficiency of cargo taken by road.
- Specifically for the A55, a delay may result in a number of vehicles (*inc.* Trans national Heavy Goods Vehicles) missing their Holyhead to Dublin ferry, leading to a decrease in national economic output.
- Persons injured in road accidents may be unable to contribute to the economy while recovering from injuries sustained, some injuries may cause permanent injuries that further reduce economic contribution of the injured persons.
- As well as the emotional cost a fatality will incur a socio-economic cost due to a permanent loss in economic output, as well as the loss of productivity from family and friends.
- There are also insurance costs relating to accident claims in the event of an accident.

AVERAGE VALUE OF PREVENTION PER CASUALTY BY SEVERITY AND ELEMENT OF COST

Injury Severity June 2007 £	Lost Output	Human Costs	Medical and Ambulance	Total
Fatal	556,660	1,080,760	970	1,648,390
Serious	21,830	150,180	13,230	185,220
Slight	2,310	10,990	980	14,280
Weighted* average, all casualties	11,200	39,300	2,350	52,850

Source: DfT 2008

*The average Figure across all casualties is weighted by the relative proportions of fatal, serious and slight casualties from road accident data

Table 12. Average value of prevention per casualty by severity and element of cost (Deloitte, 2009)

AVERAGE VALUE OF PREVENTION OF ROAD ACCIDENT BY SEVERITY AND ELEMENT OF COST

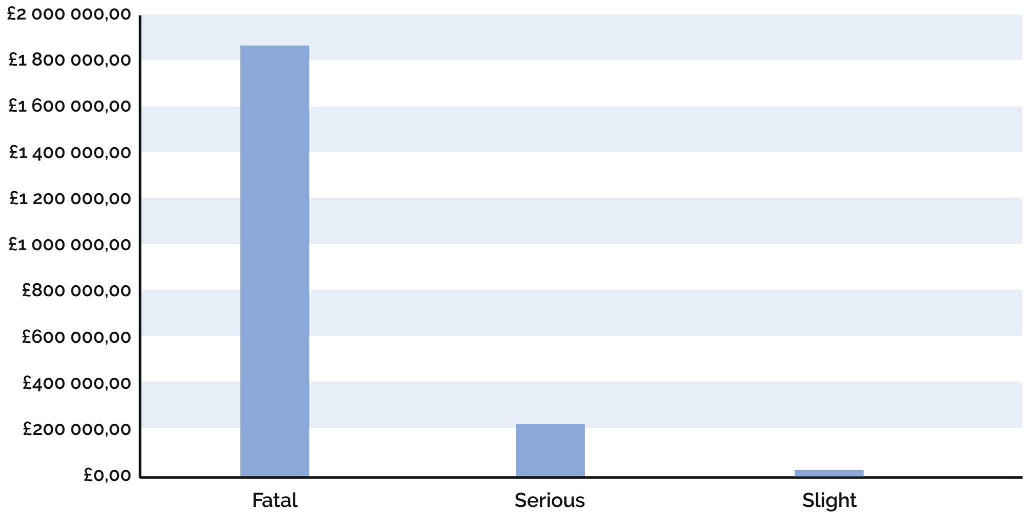
June 2007 £	Casualty Related Costs			Accident Related Costs			
Injury Severity	Lost Output	Medical	Human Costs	Police Costs	Insurance and Admin	Damage to Property	Total
Fatal	624,190	6,310	1,232,800	1,920	300	11,320	1,876,830
Serious	24,940	14,940	169,700	250	190	5,130	215,170
Slight	3,070	1,300	14,620	60	110	3,060	22,230
Weighted* average, all casualties	15,240	3,200	53,470	110	130	3,460	75,610
Damage Only				4	50	1,910	1,970

Source: DfT 2008

*The average Figure across all casualties is weighted by the relative proportions of fatal, serious and slight casualties from road accident data

Table 13. Average value of prevention of road accident by severity and element of cost (Deloitte, 2009)

AVERAGE VALUE OF PREVENTION OF ROAD ACCIDENT BY SEVERITY



Graph 4 Average value of prevention of road accident by severity (Deloitte, 2009)

It can be seen in table 12 that there is a steep increase in cost as accident severity increases, where the average weighted socio-economic cost for a fatal accident is nearly ten times the cost of a serious accident. There is also an increase in cost when taking into account the related costs shown in table 13 and graph 4.

Safety Barriers on the A55 and A483 suffer on average a single impact per kilometre per year, therefore over a 50 year period it can be expected that a one kilometre length will suffer an average of 50 impacts times (not necessarily at the same point), in chapter four it is shown that these impacts will largely be minor accidents, nevertheless, any vehicle impact will incur a cost which can be estimated, and therefore a best choice solution can be made in regards to the type of safety barrier.

The average accident costs for different barrier types was estimated using the three separate accident severity data tables (Tables 3, 4, & 5), and are shown below (Tables 14, 15, & 16).

MEAN COST PER ACCIDENT FOR A55 & A483 STATISTICS

A55 and A483 2005 - 2014 Barrier Impacts	Percentage of Accidents			Mean Cost per Accident
Barrier Type	Slight %	Serious %	Fatal %	
Single Sided Corrugated	76.5	14.7	8.8	£213,796.98
Double Sided Corrugated	84.6	15.4	0	£51,942.76
Box Beam	88.5	7.7	3.8	£107,561.18
Double Sided Box Beam	100	0	0	£22,230.00
Double Rail Box Beam	100	0	0	£22,230.00
Concrete Barrier	100	0	0	£22,230.00

Table 14. Mean Cost per Accident for A55 & A483 Statistics

MEAN COST PER ACCIDENT FOR ROAD DESIGN FOR FUTURE MAINTENANCE -LIFE -CYCLE COST ANALYSIS FOR ROAD BARRIERS

Road Design for Future Maintenance -Life -cycle Cost Analysis for Road Barriers. Karim.H 2011	Percentage of Accidents			Mean Cost per Accident
Barrier Type	Slight %	Serious %	Fatal %	
W-Beam (N2W4 - W5)	83.7	14.6	1.7	£81,927.44
Cable (N2W4 - W6)	94.4	4.7	0.9	£47,989.58
Pipe (N2W4)	81.9	18.1	0	£57,152.14
Concrete (H2)	89.8	10.2	0	£41,909.88

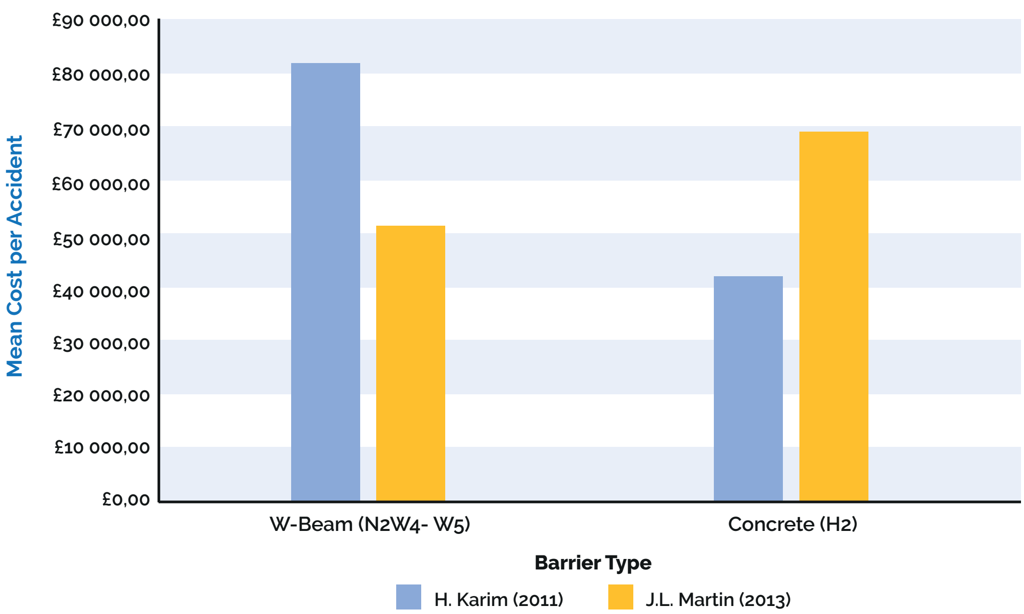
Table 15. Mean Cost per Accident for Road Design for Future Maintenance -Life -cycle Cost Analysis for Road Barriers. (Karim, 2011)

MEAN COST PER ACCIDENT FOR LONG-TERM ANALYSIS OF THE IMPACT OF LONGITUDINAL BARRIERS ON MOTORWAY SAFETY

Long term analysis of the impact of longitudinal barrier of motorway safety J.-L. Martin et al. 2013	Percentage of Accidents			Mean Cost per Accident
Barrier Type	% Slight/ None	% Injuries	% Fatalities	
Single Sided Corrugated	89.4	10.1	0.5	£50,989.94
Double Sided Corrugated	87.5	12.2	0.3	£51,332.48
Box Beam	87.4	12.2	0.4	£53,187.08
Concrete Barrier	79.9	19.6	0.5	£69,319.24

Table 16. Mean Cost per Accident for Long-term analysis of the impact of longitudinal barriers on motorway safety. (J.L. Martin, 2013)

MEAN COST PER ACCIDENT FOR STEEL CORRUGATED AND CONCRETE BARRIERS



Graph 5 Mean cost per accident for steel corrugated and concrete barriers

The Swedish pipe barrier is included in the tables for completeness, but probably would never be installed on the UK road network. By comparing the mean accident cost of the three studies it is obvious there are discrepancies in the A55 & A483 data, due to low number of Box Beam and Concrete Barrier impacts. The A55 and A483 data also shows a significantly higher mean accident cost for single sided corrugated beams and single sided box beams, which are due to a high proportion of fatalities. If unreported impacts were assumed to be of a low accident severity the mean cost would likely be much lower.

Table 12 shows that corrugated beams have a highest mean accident cost, with concrete barriers performing the best. Whereas Table 13 shows that Concrete barriers are the worst overall performer, but there seems to be a general consensus that the majority of safety barrier types have a mean cost per accident of approximately £50,000 – 60,000. The difference between the accident severity statistics, which results in the discrepancy shown in graph 5, has already been speculated as being due to a number of factors including weather, types of vehicles popular in both countries, or other unknown factors.

6.5 WHOLE LIFE CYCLE COSTS

Whole life cycle costs were estimated for a 100m, and a 5km length, the costs included installation costs, annual average repair costs, and the estimated average value of accident prevention cost (Table 17 & 18). The central reserve of the A55 and A483 is mainly composed of long lengths of safety barriers, which may be a kilometre or longer in total length. The verge barriers found on the A55 and A483 are typically only installed to protect specific hazards, such as bridge piers/ abutments, road signs, fibre optic cable boxes, lighting columns etc. as such, the verge side barriers are typically much shorter, many are of approximately 50m – 100m in length. It is because of this variation in barrier length that it was decided to compose a whole life cycle analysis for the short and long lengths of barriers that would typically be installed on the A55 and A483.

Whole Life Cycle costs determine the total average cost that a safety barrier will incur during an entire life cycle. These costs include the material cost of the barrier itself, the installation of the barrier and ancillary components, routine maintenance costs, steady state maintenance costs, removal of the barrier, and any other costs that would be incurred in the event of an accident impact.

The whole live cycle costs were calculated for new installations, and as such, the non-proprietary barriers (Tensioned Corrugated Beams and Open Box Beams) were not included. Because of the significantly larger number of recorded impacts that were used to calculate Table 12 and Table 13 mean accident costs, it was decided to provide Whole Life Cycle costs using all three sets of accident data. It was assumed that inspection costs and traffic maintenance costs would be independent of the type of barrier installed (varying only with length), and as such they have not been included in the WLC analysis. The WLC analysis was performed over a period of 50 years, which is the guaranteed design life of a concrete barrier, and assumed an average accident rate of 1 accident per kilometre per year. Steel Barriers typically have a design life of 25 years, and will therefore include a re-installation cost at the 25 year mid-way point. The N2W2 single sided barrier costs also assume the installation of a single P4 impact terminal, as opposed to the N2W2 double sided barrier which is assumed to transition to an existing barrier.

50 YEAR WHOLE LIFE CYCLE COST FOR 100M SAFETY BARRIER

WLC Costs for Barriers - 100m Installed Length	WLC Cost (J.L. Martin *et al.*)	WLC Cost (H. Karim)	WLC Cost (A55 & A483)
N2W2 Single Sided Corrugated	£308,449.70	£463,137.20	£1,122,484.90
N2W2 Double Sided Corrugated	£282,912.40	£435,887.20	£285,963.80
H2 Concrete Barrier	£363,398.60	£226,351.80	£127,952.40

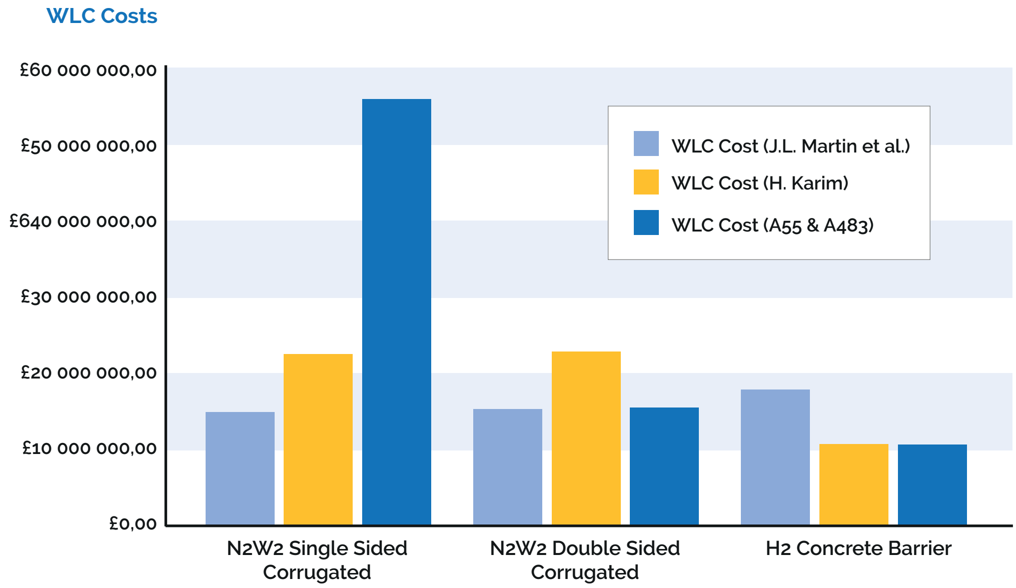
Table 17. 50 year Whole Life Cycle Cost for 100m Safety Barrier

50 YEARS WHOLE LIFE CYCLE COST FOR 5000M SAFETY BARRIER

WLC Costs for Barriers - 5km Installed Length	WLC Cost (J.L. Martin *et al.*)	WLC Cost (H. Karim)	WLC Cost (A55 & A483)
N2W2 Single Sided Corrugated	£14,981,485.00	£22,715,860.00	£55,683,245.00
N2W2 Double Sided Corrugated	£15,458,120.00	£23,106,860.00	£15,610,690.00
H2 Concrete Barrier	£17,924,930.00	£11,072,590.00	£6,152,620.00

Table 18. 50 years Whole Life Cycle Cost for 5000m Safety Barrier

50 YEAR WHOLE LIFE CYCLE COST FOR 5000M LONG BARRIER



Graph 6 50 year Whole Life Cycle cost for 5000m long barrier

The low WLC cost of concrete barriers seen for the A55 and A483 data are due to the low number of reported impacts, resulting in the reported accident severity of concrete barriers of the A55 & A483 as 100% slight injuries (Table 17, 18 & Graph 6). Also the WLC costs using the A55 & A483 accident data show a much higher cost for single sided barriers than the other sets, this is due to the relatively large amount of fatalities attributed to single sided corrugate beams. As noted before, there is an issue with the under-reporting of slight accidents on the A55 and A483, should these incidents have been recorded the WLC cost of the single and double sided corrugated beams would have likely been lower.

There is a significant difference in the conclusions that can be drawn from the three columns, where the French Motorway data provides an overall lower cost for the corrugated beams, but all three types of barriers are comparable in cost (Table 17, 18

& Graph 6). The Swedish Motorway/ Dual Carriageway data gives significantly lower whole life cycle costs for concrete barriers when compared with corrugated beams, which are approximately twice as expensive (Table 17, 18 & Graph 6).

If higher H2 containment is required the choice of concrete would almost eliminate the chance of crossover incidents; which are dangerous and very often fatal, which is an undesirable outcome even when considering socio-economic cost. Also if the proposed barrier is to be installed on a central reserve, two single sided barriers would be required, resulting in a vastly increased WLC cost. Increase in road traffic that are projected for 2010 to 2040 (Department for Transport, 2015) would likely increase the chance of accidents on highways, and a proportional increase in heavy goods vehicle traffic, resulting in a higher WLC cost across all barrier types, but because concrete barriers do not typically require repairs following an accident, this may be beneficial for long term cost efficiency.

The M25 case study mentioned in the 2007 TRL report, the serious accident severity of steel and concrete barriers are comparable and also concrete shows a lower rate of slight injuries and total accidents compared to steel barriers (Williams, 2007). When taking this data into account the Whole Life Cost of concrete barriers is likely to be much lower than the data from J.L. Martin *et al.* would imply. Assuming a comparable accident severity with both types of barrier, the only factor to be considered in installation and maintenance costs, which are shown in Graph 3, and show that for any given length, over a 50 year life cycle, the cost of steel safety barriers is approximately 4 times more expensive than concrete, while also providing a lower level of containment.

The difference between cost data between the French and Swedish data has already been discussed, and may result from weather (snow may cause drivers to drive slower, reducing the severity of accidents etc.), types of vehicles popular in either country, driver behaviour or other factors. A study on the differences in road accidents between motorway networks of different countries may clarify this uncertainty.

Figure 12 Concrete Step Barrier © Febelcem

7. DISCUSSION

When considering the A55 and A483 trunk roads, there is not enough data available on the accident severity of barrier impacts, especially when comparing proprietary steel barriers and concrete barriers, this is largely due to these barriers being a relatively recent addition to the vehicle restraint inventory available, and the low level of deployment of these systems. Further study into the real life accident severity, utilising a larger sample would be beneficial. Currently the accident data gathered from the A55 and A483 is inconclusive in regards to concrete barriers due to the small sample size, data used from the French and Swedish Highway studies point to steel corrugated and concrete barriers being comparable in accident severity. However because of the rigid construction of concrete barriers, there is the potential for increased accident severity. The proportions of fatalities when comparing steel corrugated beams and concrete barriers also seem to be comparable, but concrete has the advantage of providing higher containment, and vastly reducing the risk of a crossover incident.

When taking into account the installation and maintenance costs of the different barrier types that would likely be installed on the A55 and A483, the costs associated with concrete barriers are significantly lower than those of steel corrugated beams for any length, while simultaneously providing higher containment than an N2 steel barrier. The large number of lighting columns and other hazards that can be found along the central reserve of the A55 and A483 would also be protected from errant vehicles due to concrete barriers not deflecting under a typical vehicle impact. Potential crossover incidents would also be virtually eliminated through the use of higher containment H2 concrete barriers.

Accounting for the mean cost per accident along with the related socio-economic costs the data sets used provide contradictory conclusions. When comparing steel and concrete whole life cycle costs using the French highway data, the costs over a 50 year period are roughly comparable (Approximately £15,000,000 – 18,000,000 for all types of barriers), with N2W2 steel barriers shown as the less expensive option. When comparing the Whole Life Cycle costs that used the Swedish highway accident data the concrete barrier option has a WLC cost of approximately half that of steel barriers (£11,072,590.00 for a 5km length, which is approximately half the cost of a steel corrugated barrier at £23,106,860.00), the steel barrier WLC cost using Swedish data is also significantly more expensive than the WLC cost calculated using French highway accident data. There is insufficient accident data from the A55 and A483 to provide a conclusive WLC cost, and it is recommended that an expanded scale study be undertaken utilising multiple UK highway authorities. The 2007 TRL report echoes the conclusion of H. Karim of concrete barriers being overall a safer option (Williams, 2007) (Karim, 2011), and along with being more cost effective, the installation of concrete barriers is recommended for new works on the Trunk Road network.

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ANNEX A – LIFE CYCLE COST ANALYSIS INCLUDING LONG TERM DISCOUNT RATES

INTRODUCTION

The original cost comparison did not take into account the discount rates typically calculated for long term projects. It was decided to perform a Life Cycle Cost Analysis for both a concrete step barrier, and a typical double-sided proprietary corrugated beam using published discount costs. The comparison would follow the original calculations, and would compare the cost of a 5km length of safety barrier over a 50 year life cycle. As before the 50 year life cycle is the guaranteed life cycle for a concrete barrier. Steel barriers typically have a life cycle of 25 years, and the cost comparison would include a new installation on the 25 year midpoint.

Adjusted discount rates for both types of barriers were used, from both the EUPAVE guidance on Life Cycle Cost Analysis (LCCA) (EUPAVE, 2018), and also the UK Treasury Green Book (HM Treasury, 2018), which is the central government guidance on appraisal and evaluation for policies, projects and programmes. The same approach was used; however the Green Book discount rates vary with year (3,5% from year 1 to 30; 3% from year 31 to 50), while the LCAA guidance uses a flat 3% discount rate.

The cost comparison for the steel safety barrier includes an average repair cost, and a biennial inspection regime, using cost data provided by NMWTRA (North Mid Wales Trunk Road Agent). The concrete barrier also includes the biennial inspection regime, however due to the low damage potential from vehicle impact we have not included repair costs. “By contrast the surface mounted CSB (Concrete Step Barrier) does not deform under impact and does not require repair, following the EN1317 test for H2 containment.” (Britpave, 2008).

COST COMPARISON

Two main types of safety barriers were compared, using a 5km installed length, over a 50 year life cycle. As previously mentioned the life cycle of a concrete barrier is 50 years, whereas steel barriers typically have a 25 year life cycle. The cost comparison therefore includes a complete re-install for the steel barrier at the 25 year mark.

The original pricing for both types of barriers were used, where a discount rate was applied based on years in service. The steel safety barrier assumed a biennial inspection regime, and on average a repair cost of £4500 per km, per year. The concrete barrier assumed a biennial inspection scheme, however because of increased durability, the average annual repair cost was ignored. Significant impacts that would necessitate repairs are thankfully rare.

INSTALLATION AND MAINTENANCE COSTS

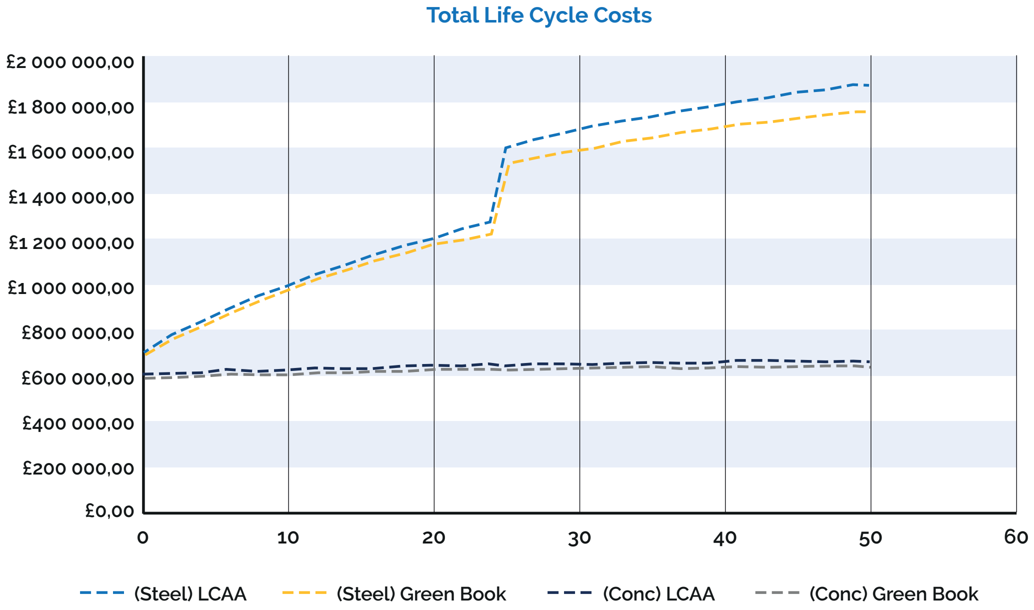
Initial unadjusted costs for both types of barriers were taken from the main document. During the service life of the structure various costs are incurred from inspection and maintenance, and these were discounted based on both the EUPAVE publication on LCCA and the Green book methods. A spreadsheet program was used to calculate these new discounted costs, and the accumulated life cycle costs. Table 1 below shows the total cost at the end of the 50 year life cycle. It is immediately apparent that the concrete barrier is significantly more economical over the long term. Two main factors account for the increased costs of the steel barrier; the reduced life span of 25 years, which necessitates a full replacement, and the increased maintenance costs from impact damage. In a real world situation these costs may be lower due to certain portions being replaced due to impact damage, and not needing replacement after the initial 25 years. Also costs may be recovered when recycling old steel barriers.

INSTALLATION AND MAINTENANCE COSTS

Barrier Type	50 Year Total Cost (5km barrier) Unadjusted Costs	LCCA (flat discount rate of 3%)	Green Book (variable discount rate)
Double Sided Corrugated Steel Barrier	£3,023,168.00	£1,868,031.60	£1,763,414.46
Slipformed Concrete Step Barrier	£708,280.00	£652,514.64	£647,873.38

Table 1. Installation and Maintenance Costs

GRAPH SHOWING ACCUMULATED COSTS OVER 50 YEAR LIFE



Graph 1 Graph showing accumulated costs over 50 year life.

DISCOUNTED WHOLE LIFE ACCIDENT COSTS

Over a 50 year life cycle it can be expected that the safety barrier is subject to impact as some point in its life. The impact rate of errant vehicles on the A55 and A483 is approximately 1per km per year, over a 50 year life span a 5 km long stretch of barrier can be expected to be hit 250 times. There are other factors such as road alignment that can affect this rate, and thankfully the majority of impacts do not result in major injuries or fatalities. However the cost incurred on the country from lost production, healthcare costs, insurance, or emergency services should be taken into account as well.

An average accident cost was derived from the accident statistics used in the original text, the A55 and A483 accident rates were omitted due to the small sample size of the rate of impacts against concrete barriers.

AVERAGE COST PER ACCIDENT

Barrier Type	Average Cost Per Accident			
	Karim, 2011	J.L. Martin et al, 2013	Average	per 5km/yr
Double Sided Barrier	£81,927.44	£51,332.48	£66,629.96	£333,149.80
Concrete Barrier	£41,909.88	£69,319.24	£55,614.56	£278,072.80

Table 2. Average cost per accident

AVERAGE ACCIDENT COSTS FOR 50 YEARS

Barrier Type	50 Year Total Cost (5km barrier)		
	Unadjusted Costs	LCCA (flat discount rate of 3%)	Green Book (variable discount rate)
Double Sided Corrugated Steel Barrier	£16,657,490.00	£8,448,662.00	£7,765,455.00
Slipformed Concrete Step Barrier	£13,903,640.00	£7,051,912.00	£6,481,655.00

Table 3. Average accident costs for 50 years

It can be seen from both tables two and three that the concrete barrier has the overall lowest cost per accident. When the discounted rates are applied the costs are halved, and because the accident rate is assumed to remain flat the concrete barrier again is cheaper, however the difference is obviously reduced. This does not take into account any future improvements to road safety, such as the development of autonomous vehicles, improved car safety, or improvements in safety barrier design.

CONCLUSION

The application of discounted costs have not changed the original recommendations, that overall concrete safety barriers provide better containment performance, as well as reduced accident severity and cross over incident potential. The reduced maintenance requirements also improve safety for road workers who would otherwise be required to work alongside live traffic when replacing damaged steel barriers. The discounted life cycle cost analysis provides more quantifiable cost savings, and the future capital can be used for other schemes and projects.

When applying the discount to both construction and maintenance costs, it is apparent that there are significant savings to be made in choosing a concrete barrier safety barrier, and improved cost benefit can make future road safety schemes more attractive to the client.

GLOSSARY OF TERMS AND ABBREVIATIONS

AADT	Annual Average Daily Traffic
BBS	Britpave Barrier Systems
CSB	Concrete Step Barrier
DfT	Department for Transport
DROBB	Double Rail Open Box Beam - A Higher containment Non-Proprietary Safety Barrier Systems
DSOBB Systems	Double Sided Open Box Beam - A type of Non-Proprietary Safety Barrier
DSTCB	Double Sided Tensioned Corrugated Beam - A type of Non-Proprietary Safety Barrier Systems
EU	European Union
GIS	Geographical Information System - A computer program for managing data relating to a geographical location e.g. road accidents.
HGV	Heavy Goods Vehicle
IAN	Interim Advice Note - A type of document from the UK Design Manual for Road and Bridges
LCCA	Life Cycle Cost Analysis
NMWTRA	North Mid Wales Trunk Road Agent - A government agency responsible for the trunk road network in north and mid Wales.
NPSBS	Non-Proprietary Safety Barrier Systems - Safety barriers designed by the UK government, and designs are made available to manufacturers.
OBB	Open Box Beam - Type of NPSBS
Safety Barrier	Also known as VRS, Guardrails, or crash barriers, a designed barrier to prevent errant vehicles from leaving the carriageway.
TCB	Tensioned Corrugated Beam - Type of NPSBS
TD	Technical Document - A type of document from the UK Design Manual for Road and Bridges
TRL	Transport Research Laboratory - A company offering transport consultancy and research.
UK	United Kingdom
VRS	Vehicle Restraint System - Other term to describe safety barriers, guard rails, or crash barriers.
YGC	Ymgynhoriaeth Gwynedd Consultancy - An engineering consultancy run by local government Gwynedd Council, in the UK.

LIST OF GRAPHS, TABLES AND FIGURES

LIST OF GRAPHS AND TABLES OF ANNEX A

Figure 13 E42 Belgium, Froyennes © Febelcem

June 2019

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